

## 2. Methods of Predictive Metallogeny in the USSR

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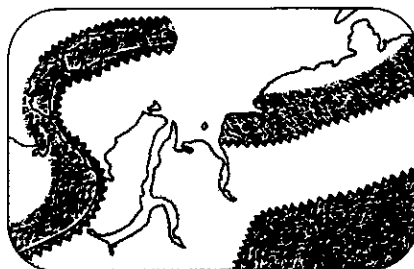
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## 2. Methods of Predictive Metallogeny in the USSR

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### Methods of Prediction

Nowadays one of our main geological tasks is prediction of the development of a program for supplying the country with mineral resources. This includes outlining and evaluating promising areas and discovering new types of deposits and ores for rational distribution of mining industries.

There are two main trends in the prediction of mineral deposits in the USSR: predictions based on the results of regional metallogenic studies, and predictions based on statistical-empirical investigations, aided by information about the deposits (data banks) and regional geology with the aid of computers.

The first trend is a traditional one in the USSR. Its fundamentals were laid down by S.S. Smirnov, Yu. A. Bilibin, V.I. Smirnov, P.M. Tatarinov, V.G. Grushevoy, A.I. Semenov, V.A. Kuznetsov, G.A. Tvalchrelidze, I.G. Magakyan and other Soviet scientists. The second trend is now being worked out in various scientific and industrial geological institutions throughout the country. Among well known developments in this latter trend is the "Region" prediction system (devised in the International Scientific Research Institute of Control Programs, Moscow), comparable both in terms of the problems solved and the software of the system to that employed in the "Appalachians" project in Canada. In the "Region" system interaction between the geologist and the computer is of primary importance, as is the choice of prediction variants made on the basis of genetic hypotheses. We shall concentrate here

upon the first, metallogenic, trend developed in VSEGEI, the head institution of the USSR Ministry of Geology dealing with regional and predictive metallogenic studies.

Studies in the prediction of mineral resources are carried out in different ways, depending on the final aim. The aims and analytical methods of "special" and "regional" predictive-metallogenic studies are quite distinct. "Special" predictive-metallogenic studies are determined by the necessity to supply the mining and processing industries with ores of a particular composition. This scientific trend of investigation is based on the analysis of distribution patterns of the deposits discovered, on the establishment of the controlling factors of mineralization and, hence, the criteria for prediction (Fig. 1). The above initial data, summarized from all the deposits of the type under consideration, are later employed in the analysis of new territories. As a result, the local areas of promise are outlined and the quantitative evaluation of predictive resources is made. This method has been employed in several areas, e.g., the systems of prediction directed toward supplying the industry of the Kola Peninsula with ferruginous quartzites, manganese oxide ores and copper-nickel ores, supplying the Ural smelters and the copper-molybdenum industrial enterprises of Kazakhstan with copper sulphide ores and supplying Siberian areas with potash salts, etc. The principles and methods of special predictive metallogenic studies are summarized in the book "Kriterii prognoznoi otsenki" (1978).

"Regional" or "combined" predictive metallogenic studies are carried out during the planned geological investigation of Soviet territory. The targets of investigation in this case are areas of various scales: provinces, zones, districts. By these investigations, we hope to determine the whole complex of economic minerals that may be found in the particular territory, to define the main deposit types and to outline and evaluate the promising areas. Predictive-metallogenic studies of this character are based on regional geological research, i.e., geological, geophysical and geochemical survey data. The analysis is based on a classification of zones; established regularities (metallotects) are widely used, e.g., the association of ores with particular zone types, their period of evolution and their geological formations. Accordingly, predictive metallogenic studies presuppose in this case metallogenic division, accompanied by the outlining of types of zones (in space) and stages (in time), subsequent detailed formational analysis and, after the promising mineralization types are defined, the employment of the whole complex of methods of special metallogeny (Fig. 1).

Evaluation of the territories of Karelia and the Kola Peninsula, Timan, the North Urals and the territory along the Baikal-Amur railway (now under construction), for the whole complex of economic minerals can be taken as examples of regional combined predictive metallogenic studies on scales of 1:1,000,000—1:1,500,000. The scientists of VSEGEI took an active part in these programs. The principles and methods of regional predictive-metallogenic studies are summarized in the book "Rudonosnost'i geologichskie formatsil ..." (1981).

"Special" and "regional" metallogeny supplement each other and work most effectively when employed together. As seen from Figure 1, these two scientific trends differ in the sequence of the initial opera-

tions during analysis. In the first case we proceed from the deposit type being sought, in the second, from the area being analyzed. In the final stages of analysis, those of outlining the promising areas, evaluating them quantitatively and choosing the work types, special and regional metallogenic methods are analogous.

Quantitative prediction presupposes appraisal of prospective ores or metals in tons, points or conventional units, or by the number of large, medium and small deposits of the type predicted. The categories (1-3) are also mentioned, depending upon the degree to which they were substantiated.

Methods of quantitative prediction, on the whole, are analogous to those employed in Canada and in other countries.

"Evaluation by experts" and the method of analogies are most commonly used. In calculating by the method of analogies one defines the specific ore content of a thoroughly examined "standard" territory, very similar to the territory being analyzed, in terms of its geological development, complexes of formations, tectonic setting and time of formation. Then a formula proposed by N.A. Bykhover is used:  $Q = KqV$ , where Q represents prospective reserves within the zone, V = its geometric characteristics, q = specific ore content of the standard territory and K = coefficient which takes into account the dissimilarity of the territories in some features. In some cases our estimates are based on the area of the promising territory, in other instances we take into account the length of the perimeter of the ore-bearing zone or fracture, and in still other cases we look at the number of promising ore clusters indicated by the intersections of the ore-controlling structures. As for the extensively studied deposit types and territories, a direct calculation method for the resources predicted is used, e.g., one which is based on regression analysis of the relations between resources and the intensity of manifestation of ore-controlling factors. When data on the clarkes of chemical elements and dispersions of their distribution in rocks and soils are available, we can employ one of the geochemical methods of estimation proposed by L.I. Ovchinnikov, E.M. Kvyatkovsky, N.I. Safronov, A.P. Solovov, A.A. Smyslov and others ("Kolichestvennoye prognozirovaniye...", 1979).

In the large- and medium-scale metallogenic analysis (1:500,000—1:50,000) the principal structural-material objects of investigation are a formational complex, geological and ore formations and spatial and temporal metallogenic units compatible with them (Table I).

The principle of step-by-step detailing of territory is believed to be a common methodological approach to solving the problems of special and regional metallogeny. The essence of the principle consists in the employment (for the purpose of territory evaluation) of various criteria proceeding from general regional criteria, which allow the rejection of large territories, to more detailed ones which localize the promising areas within the territories outlined earlier. As seen from Figure 1, the basic factors in prediction are the accumulated and generalized data on the classification of zones, geological formations and deposits. Important factors determining the effectiveness of the prediction system under consideration are a complete as possible usage of the data and the employment (during analysis) of information about simi-

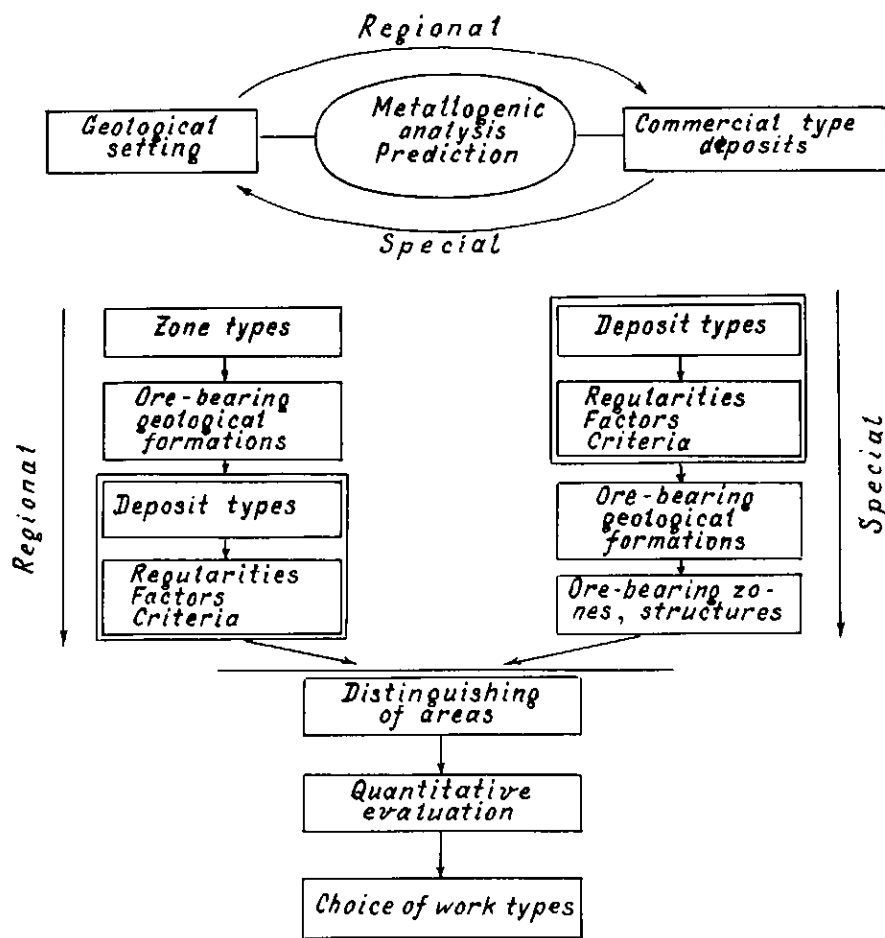


Figure 1 Succession of operations in regional and special predictive-metallogenic studies.

**Table 1** Compatibility of structural-material, spatial and temporal metallogenic units

Mineral formations (substance)	Forms of manifestation (space)	Period of manifestation (time)
Formational complex-regular statistically stable paragenesis of formations, is distinguished by the age- and lateral series of formations	Structural formational zone (in plan), stage (in section) — distribution of a formational complex. Structural-metallogenic zone — area of distribution of mineralization within one complex. In section of stratified formations — structural — metallogenic stage	Stage of tectonic history — separated by intervals of major structural reconstructions — period of emplacement of a formational complex
Geological formation — regular statistically stable paragenesis of rocks. Ore-bearing Geological formation — geological formation with which mineralization is associated in space and time Divided into productive (directly includes mineralization), mother (with associated mineralization but outside the zone and formation) and ore-enclosing ones.	Formational zone (in plan), substage (in section) — distribution of geological formation  Metallogenic zone — zone of distribution of ore-bearing geological formation and the associated mineralization	Phase, substage of tectonic history of folded area, platform, region of activation — period of emplacement of a geological formation
Ore formation — regular statistically stable paragenesis of ores characterized by monotype structure (by zoning)	Ore zone — zone of distribution of an ore formation	Stage of mineralization, magmatism, metamorphism, sedimentogenesis — period of emplacement of an ore formation

lar zones, geological formations and ore content in other regions and on other continents. For instance, evaluating the prospects of the Precambrian rocks in the Karelia-Kola region, in particular the zones of greenstone belts of Archean age, we made good use of the experience gained in studies of the troughs on the Ukrainian Shield, Canada and Australia, and in studying the ore content of granitoid formations we used data obtained from "classical" provinces of the Krasne Hory, Cornwall, Southeastern China, Mongolia, etc.

Let us consider briefly the main results of studies of the ore content studies in metallogenic zones and geological formations, determining local areas for a more detailed prediction and search for minerals.

#### Types of Structural-Metallogenic Zones

In the last two decades methods of predictive-metallogenic studies in the USSR have changed substantially. The changes were conditioned by the transition from distinguishing zones by the period of their development (cycles, etapes and stages of folded areas, platforms and areas of tectonic-magmatic activation) to distinguishing units on the basis of structure and substance. Accordingly, metallogenic analysis nowadays is based on recognition of zones by series of geological formations, the outlining of ore-bearing formations, the employment of geochemical, mineralogical and geophysical criteria for predic-

tion, analysis of the rhythm, zoning of strata, massifs, zones, etc.

Such a change in orientation was necessitated by the fact that time divisions are sometimes considered to be subjective and are thus a subject of controversy. For instance, consider the Adjar-Trilet Cretaceous-Eocene zone of the Caucasus, represented by tholeiite basalts, andesites, rhyolites succeeded by carbonate-terrigenous rocks and then by alkaline basalts, and andesites with intrusives of gabbrodioritic composition. One group of workers assigns this zone to the rift stage; another group assigns this zone to the early- or late-geosynclinal zone and still another group of geologists assigns it to the secondary-geosynclinal one. But from the viewpoint of predictive evaluation based on rock composition, rhythm and specific features of the deep structure, all the workers agree that the zone looks promising in regard to iron ore, skarn, copper- and polymetallic-pyritic and copper-porphyrific deposits.

Classification of structural-metallogenic zones in the USSR was made on the basis of composition of formations, sequence of their formation and alternation in section and structure. A total of 87 zone types has been distinguished, including 50 stratified ones (23 sedimentary amagmatic and 27 sedimentary-volcanogenic), 21 zones with predominant development of "cutting" intrusive and metasomatic formations emplaced along the fractures, 13

zones of high grade metamorphic complexes and 3 zones of weathering crusts of specific composition, which are subsequently subdivided by mineral composition into subtypes. A brief characterization of all the zones and their ore content is given in the book "Rudonosnost' i geologicheskie formatsii..." (1981). As an example, we can enumerate the outlined zones composed of stratified sedimentary and volcanogenic formations, which are frequently represented by rocks metamorphosed to albite-epidote or locally to amphibolite facies. Traditionally, those zones are considered early geosynclinal. Nine such zones have been recognized in the USSR (Fig. 2), each differing in a set of formations and ore content.

Mafic, poorly differentiated zones (Fig. 2) are characterized by the fact that the initial volcanics developed in them belong to the undifferentiated formation of sodic basalts, with a scarce occurrence of differentiated components, sodic basalts and liparites. On the peripheries of the zones the volcanics are replaced by siliceous-carbonate and terrigenous strata. In the axial parts of the troughs sulphur-pyrite deposits and small copper-pyrite occurrences are common; on the periphery there are deposits of iron-ore siliceous formations and manganese braunite-hausmannite-rhodonitic siliceous formations, as well as Mo-V-slates.

In the most typical case, mafic differentiated zones (Fig. 2) occur in the Urals

(many copper-pyritic and iron ore skarn deposits associate with them). They are characterized by multiple rhythmic alternation of the following formations: trachybasalts—sodic basalts—sodic basalts and liparites—basalt-andesitic formation. Volcanics closely alternate with a slate formation or siliceous, siliceous-tuffogenic and terrigenous-carbonate units.

Alkaline-mafic zones (Fig. 2) are noted for their potash basalt-trachyte formation which plays the leading role among the volcanic rocks composing the zone. Mafic-salic zones are characteristic of "second-

ary" eugeosynclinal troughs and are defined by extensive development of sodic basalt formation with which polymetal pyritic deposits associate spatially and genetically.

Among the zones in which volcanics are practically lacking, a number of types have been recognized by predominant constituents: terrigenous, carbonate, siliceous and black slate zones. For the accompanying mineralization, natural series are outlined here which reflect the association of ore types with geological formation: phosphorites, hematite-quartz, braunite-

hausmannite--rhodonite ores and others associated with siliceous formations: gold ore with black slate, lead-zinc with black slate; bauxites, barite-lead-zinc ores and others with carbonate reef formations.

Of primary importance in the analysis of the real ore content of structural-metallogenic zones is quantitative correlation between formations composing the zone, their thickness, order of alternation in space and time, complete or incomplete development and composition of the basement. The following are some examples.

Copper pyrite deposits are common in geosynclinal zones with normal homodrome trend of volcanism (a sequence from basic to acid), with a great variety of rocks in some rhythms, from basalts to quartz keratophyres and albitophyres. A vertical section displays an upward change of mineralization, with an increasing role of zinc and lead in their higher stages.

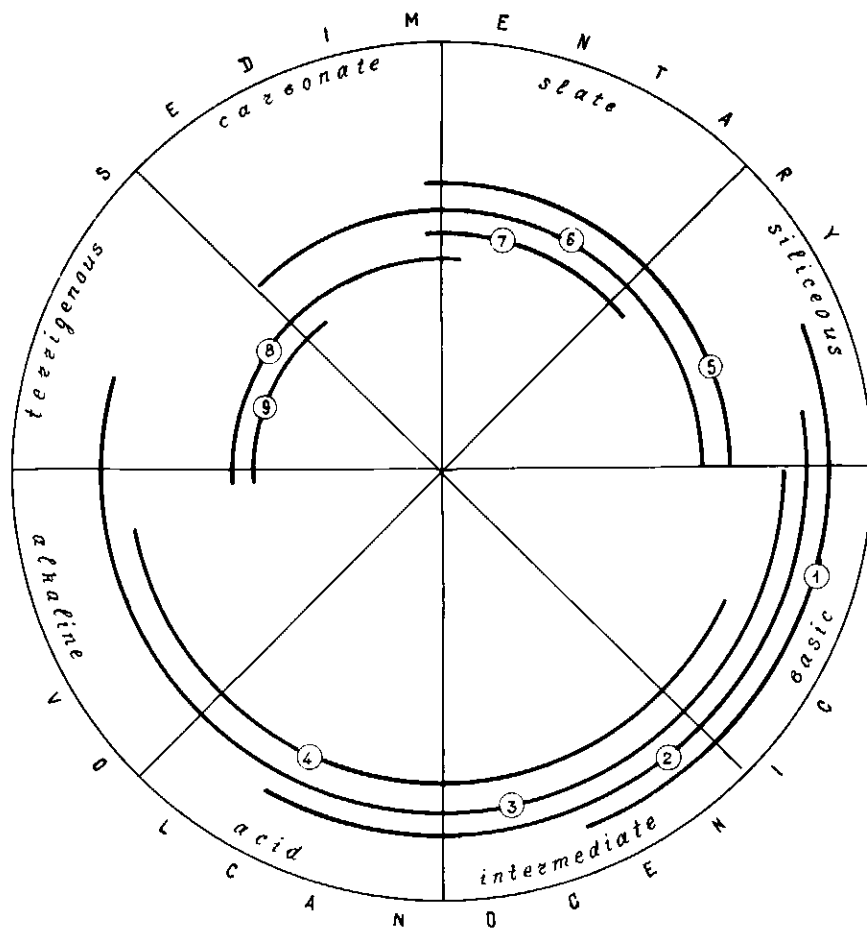
Copper-nickel deposits of the Pechenga type are characteristic of riftogenic zones of mafic composition, but with the antidrome trend of volcanism, from tholeiitic basalts to picrites or komatiites.

In orogenic regions the basement composition acquires great importance for prediction. The deposits of copper-porphyrific formations are emplaced, as a rule, in structures on a mafic basement which have the homodrome trend of volcanism evolving from andesites to dacites and quartz porphyries. The tin ore deposits of rhyolite and silicate-cassiterite formations are characteristic of orogenic zones with antidrome trend observed in large rhythms and homodrome trends in small ones, and are emplaced in the troughs on the salic basement.

When analyzing formation series of structural-metallogenic zones, one can find a number of common features in localization of mineralization:

1. In comparing various cases of succession in rock evolution and the associated ore formations, one can observe a certain correlation: the wider the evolutionary range of substance composition in the course of rock development, the more varied the composition of ore mineral parageneses will be.

Deposits constituting "long" evolutionary mineral series are associated with the "long" evolutionary series of magmatic rocks, with many stages of mineralization overlapping (and, as a consequence, with distinct zoning). The more compositionally homogenous deposits with less pronounced differentiation of products during the mineralizing process associate with a "short" evolutionary series. For example, tin-tungsten greisen deposits, characterized by a distinct step-by-step process, are



**Figure 2** Types of structural-metallogenic zones of volcanogenic-sedimentary and sedimentary troughs of the folded areas in the Phanerozoic: 1. mafic poorly-differentiated; typical mineralization: Cu, Zn, Fe, Mn, phosphorites; Tyan-Shan' (Kirghizian) type; 2. mafic differentiated, Fe, Cu, Zn Uralian (Tagil-Magnitogorsk) type; 3. alkaline-mafic, Mn, Fe, Cu; Eastern-Kamchatka type; 4. mafic-salic, Pb, Zn, Cu; Rudny Altai type; 5. siliceous slate,

Fe, Mn; phosphorites; Far East (Udsk-Shantarsk) type; 6. siliceous-slate-carbonate, Fe, Mn, Zn, Pb, barite, phosphorites, Kazakhstan (Atasui) type; 7. slate, Cu, Zn, Pb, Co, Caucasian (Filizchaisky) type; 8. terrigenous-carbonate; Pb, Zn, Au, bauxites, magnesite, Fe, Hg, fluorite; South Kazakhstan (Karatau) type; 9. terrigenous, Au, Cu, Zn, Pb, Sb, Northeast (Verkhoyansk) type.

believed to form in association with a "long" evolutionary series of magmatism; molybdenum-tungsten deposits, known for less distinct step-by-step processes, associate with a "short" evolutionary series.

The diamond and chromite deposits ("late magmatic") form in association with "short" evolutionary magmatic series and occur in isolation, without displaying close association with other mineralization types.

In contrast, a wide range of deposits of chromite ("early magmatic"), platinum and titanomagnetite is found to be associated with "long" evolutionary series of rocks (ultra-basic → basic → acid) of the Bushveld complex type. A typical example of "long" evolutionary series is the development of ultrabasic-alkaline intrusives of the "central" type, rich in a variety of minerals (Fe, apatite, phlogopite, occasionally rare metals and rare earths).

2. In comparing various cases of succession in the development of rocks and taking into consideration how widespread some varieties of rock are, we come to a conclusion about the great importance of breaks in the evolutionary processes of rock formation.

From a comparison of different ore districts, we find that the majority of deposits, exogenous and endogenous, were emplaced during the time intervals when the processes of sedimentation, volcanism or magmatism in the given zone (or district) were not active at all, or were extremely slow. The analysis shows that the most promising appear to be those structures which display multiple rhythm in section, stratigraphic breaks, omission of some horizons or a sharp decrease in the thickness of strata synchronous with ore deposition. In the areas where magmatic rocks are widespread, breaks in the rhythms are equally favourable, and these are identified by the appearance of dykes, regionally distributed metasomatites, etc.

This correlation, established in the USSR by A.D. Arkhangelsky, D.G. Sapozhnikov, N.M. Strakhov and others, for many sedimentary deposits (phosphorites, bauxites, manganese and iron ores, Pb-Zn-mineralizations), is observed also in the analysis of deposits emplaced by endogenous processes: gold-silver, copper-molybdenum, pyritic and others which are confined to localities where the section displays omission or great reduction of volcanic units synchronous with mineralization.

### Ore Content in Geological Formations

After we have defined the zone type and possible ore content of the territory under consideration we proceed to the solution of local problems: the distinguishing of ore-bearing geological formations, an operation that localizes the areas of promise.

Formational analysis resulting in recognition of specialized ore-bearing formations, among which productive, mother and enclosing rocks are singled out ("Kriterii rudonosnosti...", 1978), has developed rapidly in the USSR in recent decades, and has been linked with the solution of problems of prediction. As a result, we have systematized the geological formations and characterized the ore content of 59 sedimentary, 45 magmatic, 24 metamorphic and 15 hydrothermal-metasomatic formations, as well as 14 formations of weathering crusts and products of their direct redeposition, including placers ("Rudnost'i geologicheskii formatii...", 1981). It is necessary to emphasize, however, that the potential ore content is realized only in certain cases, i.e., when a formation is localized within a required zone type of certain age, and when a favourable combination of stratified, "cutting" intrusive, metamorphic, metasomatic or weathering crust formations is observed. It is these circumstances, as well as several structural features (which define to what extent the ore deposition system is closed or open), that determine whether the mineralization will be a large economic one or will be represented only by small occurrences on which there is no need to waste money. For example, iron-titanium mineralization and copper-nickel mineralization in the USSR display associations with the same formations: peridotite-pyroxenite-noritic, gabbro-diabasic, basalt-doleritic and gabbro-wehrlitic (Fig. 3). Large iron-titanium deposits, however, associate only with gabbro-diabases (Kusin deposit), whereas important copper-nickel deposits associate with peridotite-pyroxenite-noritic (Monchegorsk) and gabbro-wehrlitic formations (Pechenga).

Along with the geological formations, 150 ore formations of main economic deposit types have been recognized. It was found

here that in order to work out a system of prediction this number of ore formations was insufficient. For such ore formations as siliceous-hematitic, manganese braunite-hausmannitic, skarn iron ore, high alumina nepheline-feldspathic, rare metal-pegmatitic, copper-molybdenum porphyric and many others, we had to single out subformations which would differ in the geological setting in which mineralization is manifested, in association with various geological formations and, respectively, with various criteria for prediction. For instance, the sulphide copper-nickel deposits usually are assigned to one genetic type and one ore formation. Nevertheless, for purposes of prediction it is necessary to distinguish here at least 5 subformations ("Kriterii rudonosnosti...", 1978). These subformations actually represent a series of ore objects associated with different geological formations. The extreme members of this series are the ore-bearing, deep-seated, layered peridotite-pyroxenite-noritic plutons (Monchegorsk type) on one side, and on the other side ore-bearing minor intrusives of olivinite-gabbroic, gabbro-wehrlitic formations, localized among volcanogenic and sedimentary rocks near the surface (Norilsk, Pechenga type).

With this diversity of ore formations and subformations, the following appears to be promising: first, the distinguishing of common regional criteria, valid for the whole group of ore formations and subformations, and individual local criteria for every subtype. Second, the distinguishing of series of formations and subformations which differ in composition, structure and geological setting in which mineralization is manifested and, consequently, in the criteria for prediction.

In the above example of copper-nickel mineralization the outlined series reflect the substantiated change in geological condi-

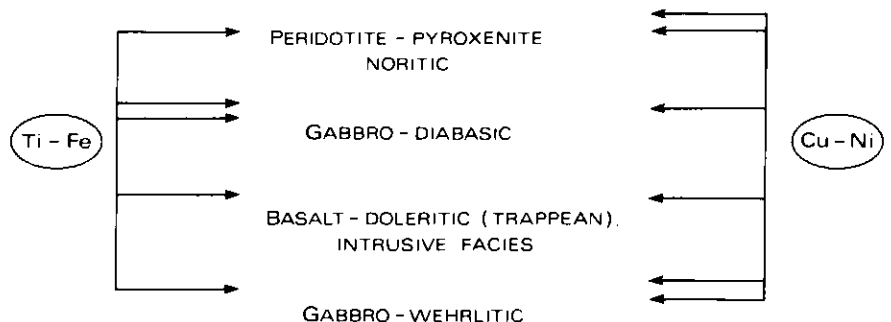


Figure 3 Relation between scales of mineralization and geological formations of various compositions. Double arrows indicate

formations with which the largest ore concentrations associate.

tions in which ultrabasic magmatism and mineralization manifest themselves: depth, the scale of the magmatism, how open or closed the system of ore deposition was, specific effect on physical-chemical characteristics of the environment (sulphur, reducers, etc.). Accordingly, the Monchegorsk type arises at depth, in a comparatively closed system, in conditions of slight specific interaction between melts, solutions and the environment. In contrast, the Pechenga type deposits form near the surface, in an open system, in conditions of melts and solutions intensively interacting with the wallrocks rich in sulphur and other reducers.

The diversity of ore formations and subformations indicates that for the purpose of prediction it is advisable to devise models of manifestation of various genetic mineralization types whose number will be considerably smaller than the number of ore formations and subformations.

It is of paramount importance in prediction to take into account the "absolute" and "relative" (in the course of a megacycle, cycle, rhythm) period of the emplacement of geological and ore formations. For each type of mineral deposit one or two, (rarely three) epochs of the maximal manifestation of the given type of mineralization can be outlined. Such epochs might be global and regional. In the European and Asiatic parts of the USSR one can observe two maxima of phosphorite deposition: the Late Riphean-Ordovician (750-450 Ma) and the Upper Cretaceous-Pleistocene (after 80 Ma). It is characteristic that the Permian phosphorites, which are so typical of other regions of the world (the Cordillera), are represented in the USSR only by small occurrences in the fore-Urals and in the Caucasus.

As for the manganese deposits in the USSR, three main epochs of most intensive deposition have been established: the Vendian-Cambrian and Silurian-Devonian, in association with siliceous and carbonate formations, and the Oligocene (Chiatura, Nicopol), in association with calcareous-arenaceous-argillaceous formations. The ore-bearing productive epochs could be global—connected with general changes in atmosphere, hydrosphere, lithosphere (e.g., for phosphorite, manganese, coal, ferruginous quartzites, etc.), or regional—connected with the peculiarities in geologic history of individual regions. Thus the distribution of Cu-Pb-Zn-mineralization in the mid-Devonian is characteristic of the European continent and contiguous territories known for the extensive development of Hercynian tectogenesis. In Eastern Siberia, the Altai-Sayan area's most intensive emplacement of copper and polymetal stratiform mineralization falls in the Riphean. Equally, the maximum emplacement of tin,

copper-molybdenum and a number of other endogenous deposits was substantially different in the Mediterranean and Pacific ocean belts and also within the Russian and Siberian platforms.

In some cases, geological and ore formations of the same type but of different ages are noted for characteristic features of mineral composition and minor elements, which need to be taken into consideration during prediction. Thus, when defining the practical importance of ferruginous quartzite zones we should take into account the quantitative magnetite/hematite ratio in the ores, a ratio which naturally decreases with time, down to the emplacement of pure hematitic quartzites of Riphean age.

These examples indicate the necessity of accumulating more data on the evolution of geological and ore formations in the history of the Earth. It is these new data that will enable us to make various corrections and to introduce some coefficients during estimation of prospective resources by the method of analogy with the districts that have been thoroughly studied.

The formational research carried out in recent years has allowed the establishment of qualitative and quantitative relations between mineralization scales and geological formations. One of the main conclusions is that the rock of economic interest is the one that is a constituent of a particular geological formation, developed within the zone of a certain type and during the favourable time intervals, rather than merely a rock of a certain composition and texture.

Further perfection of the system of predictive studies requires the extension of the theoretical basis for metallogeny and the employment of general correlations in geologic history established in other disciplines, e.g., in tectonics, stratigraphy and geomorphology. Of great importance for the analysis of ore deposition is the Walther-Golovchinsky facies law, which reveals the unity of interrelation of rocks in time and space during sedimentation. In the processes of ore deposition, a similar dependence can constantly be observed, which is expressed in the principle of similarity and in the geogenetic law. The principle of similarity reflects the fundamental similarity of the ore zoning in various spatial units, from metallogenic provinces to ore fields and deposits. The geogenetic law defines the similarity in the development of ore deposition processes on different time scales. The general sequence in the evolution of formations in geologic history is manifested in the individual evolutionary history of particular deposits, as if in a diminished form, on the scale of mineral assemblages and individual minerals.

In devising geological-genetic models of

ore formations and ore-bearing zones for the purpose of prediction of mineralization at depth, one should use the "geoid" and Curie-Shafranovsky principle of symmetry. The "geoid" principle is the empirically established regularity of manifestation of the most intensive mineralization in the Earth's crust near the geoid surface. The crust here plays the role of regional base-level of erosion, the place where oxidation-reduction processes accompanying ore-deposition are believed to change, etc. The geoid principle requires the employment (in metallogenic analysis) of data on paleotopography at the period of ore-deposition, on the extent of ruggedness of the relief and absolute heights. The principle also requires determination of the surfaces of peneplains.

The P. Curie principle, detailed by I.I. Shafranovsky for geological objects, states that the real symmetry of the forming geological bodies reflects the symmetry of the environment. It follows from this that in the gravitational field of the Earth the inner structure (zoning) of various ore-bearing objects being formed is always characterized by unidirectional vertical and bilateral (planal) or central horizontal symmetry. This principle accounts for many features of mineralization distribution in stratiform and "cutting" geological formations.

Among the applied aspects in the further development of theory and methods of predictive metallogenic studies are included the following:

1. improvement in the methods of quantitative prediction
2. ability to work out the criteria for prediction of large and very large deposits and ore districts
3. discovery of a rational complex of methods of prediction for new deposit types

These objectives are believed to be common in the geological investigations of all countries, and their solution requires generalization and analysis of data on the metallogenic zone types, geological formations and distribution patterns of deposits in all the continents of the world.

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### 3. An Investigation of the Estimation Process of Predictive Metallogeny

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#### Introduction

The substance of this paper is relevant to the subject of predictive metallogeny only to the extent that a quantitative prediction of some resultant of metallogenesis is a primary objective. Identification of prediction as a primary goal imposes on the geologist or team of geologists involved in prediction the necessity of integrating available geodata, data which are often sparse and of poor quality, with respect to those concepts of metallogenesis that can be related to some quantity, e.g., number of deposits or quantity of metal.

For the remainder of this paper, I shall refer to predictive metallogeny as the estimation of mineral endowment, meaning the number of deposits or the tonnage of metal that occurs in the region, given some minimum size of accumulation (deposit), minimum concentration (grade) and maximum depth of occurrence. Because of the often great uncertainty about mineral endowment, the estimate of interest is taken to be a probability distribution for the endowment of the region.

Methods of predictive metallogeny understandably vary with 1) the amount and the quality of geodata, 2) the data available on mineral discoveries and resources of the region, and 3) the time and human resources provided for analysis. Consider prediction for a region for which the geodata that are available on the entire region are at the reconnaissance level. These data may include geologic maps, aeromagnetic maps, gravity maps, geochemical

surveys and maps of mineral occurrence. Exploration may have identified prospects and ore bodies. There may be a few producing mines. Even so, the region is not considered to be well explored, and resource data are either too meagre or are too restricted geographically to support the estimation by multivariate statistical methods of a quantitative relationship between geodata and a quantity of mineral occurrence. This circumstance is one which is frequently encountered in regions which generally are considered to have high potential for mineral occurrence. Regions in Canada and Mexico, for example, would be accommodated by this description.

Given these circumstances, a quantitative estimate of mineral endowment may be pursued by two basically different approaches:

1. The selection of other, well explored areas (control areas) which are geologically similar to the region of interest, and the identification on these control areas of multivariate statistical relationships which can be used to infer mineral endowment.
2. The identification of one or more geological experts who, by virtue of rich experience in exploration on other areas, specific knowledge of the geology of the area of interest and an understanding of concepts and principles of metallogeny are capable of providing subjective estimates in probability terms of the mineral endowment of the area of interest.

Each of these approaches has its advantages and disadvantages; the basis for selecting one of them over the other will not be considered here. The assumption, rather, is made that the latter of these approaches has been selected. Given that assumption, the central issue of this paper is the methodology to support the use of observed geodata by the geologist to describe a probability distribution for a region's mineral endowment. The emphasis of the paper is on the *process or methodology* of subjective estimation of an uncertain quantity, *mineral endowment*.

While it is commonly understood and acknowledged that estimation of mineral endowment is difficult, it is my perception that the difficulty is greater than is commonly perceived. This difficulty arises from three major sources: limitations of geoscience, insufficient geodata and inadequate methodology for probability estimation of mineral endowment.

The use of geodata to infer the presence of a mineral deposit when there is no direct evidence of the presence of the deposit requires a model of the relationship between either the geodata and mineral occurrence or of the processes implied by the geodata and mineral occurrence. Such

a model can be basically empirical, reflecting mainly observed associations, or it may be based upon genetic relations.

Every geologist is aware of the limitations of his science to explain unequivocally all mineral occurrences. Often there is more than one theory for the genesis of a particular deposit. Furthermore, experienced geologists have witnessed the revision of theories as more data become available and as our knowledge of the earth increases.

The limitations of geoscience referred to above include this lack of an unequivocal explanation. But, with respect to the estimation of mineral endowment, these limitations take on a considerably greater dimension. This greater dimension reflects the lack of geoscience, as it is generally understood and practiced, of a scale (magnitude) dimension with regard to mineral occurrence. It is one thing to recognize the necessity for the sequential operation of a sequence of earth processes to form a mineral deposit of a specified kind, but it is quite another to be able to relate the spatial dimensions and intensities of these processes to the *number of deposits* – to the *total quantity of metal* – within the region. It is the latter of these acts that poses great difficulty to the geologist.

The next section discusses generally major methodologies for the subjective estimation of mineral endowment when the estimate is a product of geological analysis and is a probability distribution. Following this general description, a case study is described which allowed for the comparison of two different methodologies for the probabilistic estimation of the uranium endowment of the San Juan Basin of New Mexico. Finally, some thoughts are presented of an improved methodology for the estimation of mineral endowment of frontier regions.

#### Conventional Methods of Subjective Geological Analysis and Probability Estimation

Subjective probability methods for the estimation of mineral or energy endowment have been classified as implicit or explicit (Harris, 1977, 1982). These terms refer to the way in which probability and endowment are related by the methodology to geology. The conventional approach to geologic analysis and subjective probability estimation is of the implicit type.

In the implicit methodology the geologist examines all relevant geodata and resources data, if such are available, and after due integration of these data and reflection upon the geoscience of this particular mode of occurrence, he selects either percentiles or statistics from which the parameters of the endowment distribution may be estimated (Fig. 1). As is evident,