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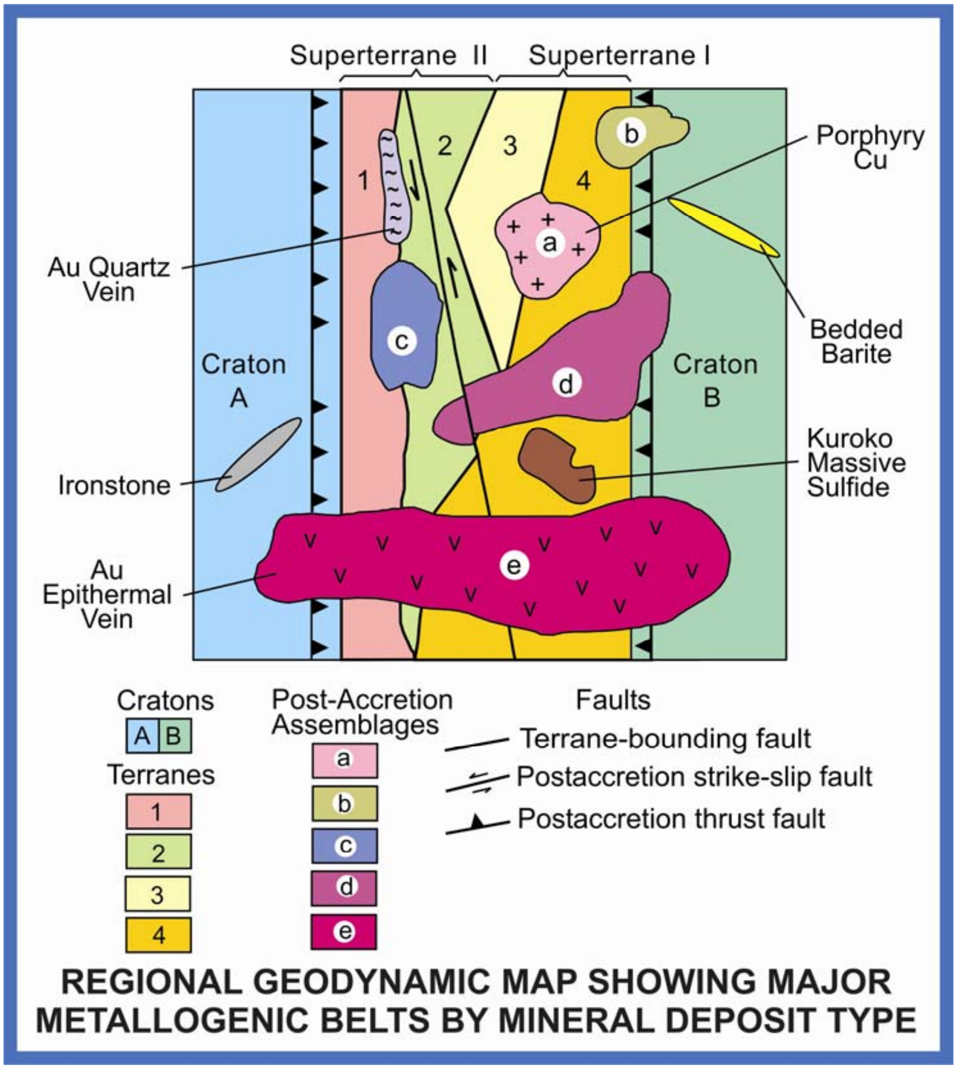
Methodology of Combined Regional Metallogenic and Tectonic Analysis



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Methodology of Combined Regional Metallogenic and Tectonic Analysis

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Methodology of Combined Regional Metallogenic and Tectonic Analysis

Introduction

The compilation, synthesis, description, and interpretation of metallogenesis and tectonics of major regions, such as Northeast Asia (Eastern Russia, Mongolia, Northern China, South Korea, and Japan) and the Circum-North Pacific (Russian Far East, Alaska, and Canadian Cordillera), require a complex methodology. The key goal for metallogenic and tectonic analysis is to define, characterize, and interpret the origin and evolution of mineralizing systems. To achieve this goal, a methodology is needed for combined regional metallogenic and tectonic analysis. The methodology, as developed in major international collaborative mineral resource studies led by the U.S. Geological Survey for the Circum-North Pacific and Northeast Asia, consists of the following steps: (1) definition of key terms; (2) compilation of a regional geologic base map that can be interpreted according to modern tectonic concepts and definitions; (3) interpretation of tectonic environments that formed major geologic units and structures that control the origin and distribution of metallogenic belts; (4) description of significant mineral deposits (database) that enable the determination of mineral deposit models, relations of deposits to host rocks, and tectonic origins; (5) establishment of mineral deposit models that characterize the known deposits and inferred undiscovered deposits of the region; (6) compilation of a series of metallogenic belt maps on a regional geologic base map; and (7) synthesis and interpretation of a metallogenic and tectonic model.

This chapter presents an overview of the methodology for regional metallogenic and tectonic analysis, provides a theoretical example of this type of analysis, and describes an example for the Middle Jurassic to Early Cretaceous of Northeast Asia. The major sections of this chapter are: (1) definitions, compilations, and syntheses needed for a combined metallogenic and tectonic analysis; (2) a theoretical example of metallogenic and tectonic analysis; (3) description of a theoretical example of synthesizing a metallogenic and tectonic model; (4) example of a compilation of a regional geologic base map; (5) a discussion of interpreting tectonic environments; (6) a discussion of compiling descriptions of significant mineral deposits and of synthesizing mineral deposit models; (7) an example of compilation of a metallogenic belt map; (8) an example of a combined metallogenic and tectonic model; and (9) a description of the benefits of performing a combined regional metallogenic and tectonic model.

A major goal of this chapter is to demonstrate that the methodology of regional metallogenic and tectonic analysis is a useful theoretical tool for defining, characterizing, and interpreting the origin and evolution of mineralizing systems through geological space and time. This methodology eliminates past problems that have limited some metallogenic and tectonic analyses, which include (1) concentration of some metallogenic studies on local features of mineral deposits and districts without an understanding of their regional setting; (2) lack of integration of regional studies of host rocks, structures, and tectonic origins with respect to suites of mineral deposits; and (3) in some cases, application of a stabilistic tectonic philosophy.

The methodology described in this chapter was developed for the international collaborative studies on mineral resources, metallogenesis, and tectonics of Northeast Asia and the Circum-North Pacific (Russian Far East, Alaska, and the Canadian Cordillera) that were led by the U.S. Geological Survey. These studies have produced two broad types of publications. One type is a series of regional geologic, mineral deposit, and metallogenic-belt maps and companion descriptions for the regions. Examples of major publications of this type are Nokleberg and others (1998, 2004), Obolenskiy and others (2003, 2004), Parfenov and others (2003, 2004a, b), Nokleberg and others (2004), Rodionov and others (2004), and Naumova and others (2006). The other type of publication is a suite of metallogenic and tectonic analyses of these same regions. Major examples of this type are Scotese and others (2001), Nokleberg and others (2000, 2004, 2005), Rodionov and others (2004), and Naumova and others (2006). A summary of the major products of this project are contained on the Web at: http://pubs.usgs.gov/of/2006/1150/PROJMAT/RFE-Ak-Can_Cord_Proj_Pamph.doc and in Appendix A.

Relatively few combined metallogenic and tectonic analyses for large regions have been published in the last two decades. Most studies on this theme are on relatively smaller districts, such as that for the Maniwaki-Gracefield district in southwestern Quebec by Gauthier and Brown (1986). The major example of a regional analysis is for the Circum-North Pacific (Russian Far East, Alaska, and the Canadian Cordillera) (Nokleberg and others, 1997a, b, c, 1998, 2000, 2005).

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Key Terms for Metallogenic and Tectonic Analysis

For the compilation, synthesis, description, and interpretation of metallogenic belts, the following definitions related to mineral deposits, metallogeny, and tectonics are employed, as derived from Nokleberg and others (2000, 2005) or cited references.

Accretion. Tectonic juxtaposition of terranes to a craton or craton margin. Accretion of terranes to one another or to a craton margin also produces a major change in the tectonic evolution of terranes and craton margins.

Accretionary-wedge terrane. Fragment of a mildly to intensely deformed complex consisting of varying amounts of turbidite deposits, continental-margin rocks, oceanic crust and overlying units, and (or) oceanic mantle. Geologicnits are interpreted to have formed during tectonic juxtaposition in a zone of major thrusting (subduction) of one lithospheric plate beneath another, generally along the margin of a continent or an island arc. May include large fault-bounded fragments with a coherent stratigraphy. Many accretionary-wedge terranes contain fragments of oceanic crust and associated rocks that exhibit a complex structural history in a major thrust zone, and possess blueschist-facies metamorphic assemblages.

Amalgamation. Tectonic juxtaposition of two or more terranes before accretion to a craton or continental margin.

Continental-margin arc terrane. Fragment of an igneous belt of coeval plutonic and (or) volcanic rocks and associated sedimentary rocks that formed above a subduction zone dipping beneath a continent. Either has or inferred to possess a sialic basement.

Craton. Chiefly regionally metamorphosed and deformed shield assemblages of Archean, Paleoproterozoic, and (or) Mesoproterozoic sedimentary, volcanic, and plutonic rocks, and overlying platform successions of Paleoproterozoic, Paleozoic, and local Mesozoic and Cenozoic sedimentary and lesser volcanic rock.

Craton margin. Chiefly Neoproterozoic to Jurassic sedimentary rocks deposited on a continental shelf or slope. Consists mainly of platform successions. Locally has, or may have had, an Archean, Paleoproterozoic, and (or) Mesoproterozoic cratonal basement.

Cratonal terrane. Fragment of a craton.

Island-arc terrane. Fragment of an igneous belt of plutonic rocks and (or) coeval volcanic rocks, and associated sedimentary rocks that formed above an oceanic subduction zone. Either has or inferred to possess a simatic basement.

Metallogenic belt. A geologic unit (area) that either contains or is favorable for containing a group of coeval and genetically-related, significant lode and (or) placer deposits. A metallogenic belt has the following characteristics: (1) is favorable for containing known or inferred mineral deposits of specific type or types; (2) may be irregular in shape and variable in size; (3) need not contain known deposits; and (4) is based on a geologic map as the primary source of information for delineation of areas that are favorable for specific deposit models. An essential part of the definition is that a belt is the geologically-favorable area for a group of coeval and genetically-related mineral deposit models. This definition provides a predictive character for undiscovered deposits in each belt.

Metamorphic terrane. Fragment of a highly metamorphosed or deformed assemblage of sedimentary, volcanic, or plutonic rock that cannot be assigned to a single tectonic environment, because the original stratigraphy and structure are obscured. May include structural mélange that contains fragments of two or more terranes.

Mine. A site where valuable minerals or rocks have been extracted.

Mineral deposit. A site with concentrations of potentially valuable minerals for which grade and tonnage estimates have been made.

Mineral occurrence. A site of potentially valuable minerals on which no visible exploration has occurred, or for which no grade and tonnage estimates have been made.

Oceanic crust, seamount, and ophiolite terrane. Fragment of part or all of a suite of deep-marine sedimentary rocks, pillow basalt, gabbro, and ultramafic rock (former eugeosynclinal suite) that are interpreted as parts of oceanic crustal sedimentary and volcanic rocks and upper mantle. Includes both inferred offshore oceanic and marginal ocean-basin rock, minor arc-derived volcaniclastic rock, and major marine volcanic accumulations formed on a hotspot, fracture zone, or spreading axis.

Overlap Assemblage. A postaccretion unit of sedimentary rocks deposited on, or igneous rocks that were intruded into, two or more adjacent terranes.

Passive continental-margin terrane. Fragment of a craton margin.

Prospect. A site of potentially valuable minerals where excavation has occurred.

Significant mineral deposit. A mine, mineral deposit, prospect, or occurrence that is judged as being important for the metallogenesis of a geographic region.

Superterrane. An aggregate of terranes that is interpreted to share either a similar stratigraphic affinity or a common geologic history after accretion. An approximate synonym is *composite terrane*.

Tectonic Collage. A series of linear island arcs or continental margin arcs and tectonically-linked (companion) accretionary wedge (subduction) zones, and(or) fore-arc and back-arc basins that formed during a major tectonic event in a relatively narrow geologic time span. Some collages consist of fragments of craton margin and cratonal terranes that were amalgamated before accretion to a continent. The ages of collages with accretionary wedge units are based on the time of active formation of the accretionary wedge in a subduction zone, rather than the ages of rock units that comprise the accretionary wedge.

Tectonic Linkage. A genetic relation of a continental margin arc or island arc with a companion accretionary wedge formed in a subduction zone that was adjacent to, and underthrust the arc. A tectonically-linked arc terrane and an accretionary wedge terrane comprise a *tectonic collage*.

Tectonostratigraphic terrane (terrane). A fault-bounded geologic entity or fragment characterized by a distinctive geologic history that differs markedly from that of adjacent terranes (Jones and others, 1983; Howell and others, 1985).

Turbidite-basin terrane. Fragment of a basin filled with deep-marine clastic deposits in either an orogenic forearc or back-arc setting. May include continental-slope and continental-rise turbidite deposits, and submarine-fan turbidite deposits on oceanic crust. May also include minor epiclastic and volcaniclastic deposits.

Theoretical Example of Metallogenic Analysis

Figures 1A and 1B (derived from Nokleberg and others, 1998) are used to illustrate a theoretical example of metallogenic analysis. Figure 1A is a schematic map that portrays a suite of metallogenic belts that are hosted in several geologic units including cratons, terranes, and overlap assemblages, or along major faults between terranes. Figure 1B, a series of stratigraphic columns for the units depicted in Figure 1A, illustrates the stratigraphic and metallogenic history of the map area.

The orogenic belt map shown in fig. 1A is modeled after the major geodynamic units for Northeast Asia. On figure 1A, Cratons A and B are simplified portrayals of the North Asian Craton and Craton Margin, and the Sino-Korean Craton. The various terranes and postaccretion overlap assemblages on figure 1A are simplified portrayals of those between the two major cratons. Major faults cutting the terranes and overlap assemblages between Cratons A and B on figure 1A are simplified portrayals of those between the two major cratons.

The steps used in this theoretical example are as follows.

(1) A regional geologic base map is constructed. Figure 1A, a map view of an orogenic belt (consisting of two cratons and several intervening terranes), portrays two major cratons (A, B), several fault-bounded terranes (1, 2, 3, 4) between the two cratons, one accretionary assemblage (a), and four postaccretion overlap assemblages (b, c, d, e).

(2) A group of mineral deposit models appropriate for the geology are identified and defined, and a mineral deposit database is prepared. For this theoretical example, the major applicable mineral deposit models are low-sulfide Au quartz vein (orogenic gold), ironstone, Au epithermal vein, porphyry Cu, bedded barite, and kuroko massive sulfide.

(3) Metallogenic belts are delineated. For simplicity in this example, each belt is assumed to contain only a single mineral deposit type. The two cratons (A, B) each contain distinctive, preaccretionary metallogenic belts including ironstone and bedded barite deposits that formed early in their geologic history. Island-arc terrane 4 contains a preaccretionary belt of kuroko massive sulfide deposits that formed during marine arc volcanism. Between terranes 3 and 4 is accretionary assemblage *a* that consists of a collisional granitic pluton with a porphyry Cu belt that formed during accretion of terrane 3 against terrane 4. Between terranes 1 and 2 is an assemblage of rocks that contain a group of Au quartz vein deposits that formed during accretion of terrane 1 against terrane 2. Overlying all of the terranes and both cratons is postaccretion overlap assemblage *e* that contains a metallogenic belt with epithermal Au vein deposits.

(4) The genesis of bedrock geologic units, structures, and contained metallogenic belts and mineral deposits is interpreted using modern tectonic concepts. Examples are: kuroko massive sulfide deposits forming in an island arc environment; porphyry Cu and low-sulfide Au quartz vein deposits forming in a collisional environment; and epithermal Au vein deposits forming in a continental margin arc environment.

And (5) by carefully defining each metallogenic belt to be geologically favorable for a group of coeval and genetically-related mineral deposits, a predictive character is established within each belt for possible undiscovered deposits.

Example of a Metallogenic and Tectonic Model

Figure 2 illustrates the six steps for conducting a combined metallogenic and tectonic analysis.

Parts 1 and 2 portray the compilation and synthesis of a regional geologic base map and a metallogenic belt overlay. For delineation of metallogenic belts, the following main principles are used (Nokleberg and others, 2005; Rodionov and others, 2004). (1) *Mineral Deposit Association.* Each metallogenic belt includes a single mineral deposit type or a group of spatially and genetically-related mineral deposits types. (2) *Tectonic Event for Formation of Mineral Deposits.* Each metallogenic belt includes a group of coeval and genetically related mineral deposits that formed as the result of a specific tectonic event (e.g., subduction-related igneous arc, collision, accretion, rifting, etc.). (3) *Favorable Geological, Geochemical, and Geophysical Environment.* Each metallogenic belt contains host rocks, structures, geochemical anomalies or signatures, and(or) geophysical anomalies or signatures that are favorable for the occurrence of a particular suite of mineral deposit types. (4) *Geological or Tectonic Boundaries.* Each metallogenic belt typically is bounded by contacts of favorable stratigraphic or magmatic units, or by major faults (sutures) along which substantial translations have commonly occurred.

Part 3 lists the compilation of a mineral deposit database and assignment of mineral deposit models.

Part 4 consists of several major steps. (1) Tectonic environments for the cratons, craton margins, orogenic collages of terranes, overlap assemblages, and contained metallogenic belts are assigned from regional compilation and synthesis of stratigraphic, structural, metamorphic, isotopic, paleomagnetic, faunal, and provenance data (e.g., Nokleberg and others, 2000; Scotese and others, 2001). (2) Correlations are made among terranes, fragments of overlap assemblages, and fragments of contained metallogenic belts. (3) Tectonic linkages are established between related terranes, such as an igneous-arc terrane and associated subduction-zone terrane. As an example of the use of tectonic linkages in a tectonic model, these linked terranes and their contained metallogenic belts, can be grouped into coeval, curvilinear arc-subduction-zone complexes that make up a tectonic collage. (4) By using geologic, faunal, and paleomagnetic data, the original positions (loci) of terranes and their metallogenic belts are interpreted. (5) Paths of tectonic migration of terranes and contained metallogenic belts are constructed, and the timings and nature of accretions of the terranes and contained collision-related metallogenic belts are determined from geologic, age, and structural data. And (6) additional data for constructing the model are obtained from the geologic characteristics of postaccretionary overlap assemblages and contained metallogenic belts that overlie and stitch together the underlying and accreted or amalgamated terranes.

Part 5 portrays the time span of a simplified tectonic model that was synthesized using these data and the interpretations in parts 1-4. This and a series of preceding and succeeding time-stage diagrams portray all major metallogenic and tectonic events for the region.

Part 6 shows the applications resulting from this type of analysis. These applications include: (a) refining mineral deposit models and deposit genesis; (b) improving assessments of undiscovered mineral resources as a part of quantitative mineral-resource assessment studies; (c) providing important data for land-use and mineral exploration planning; (d) improving interpretations of the origins of host rocks, mineral deposits, and metallogenic belts; and (e) providing guidelines for new research.

Compilation of a Regional Geologic Base Map

To compile a metallogenic belt map for a metallogenic analysis, a regional geologic base map must be constructed that permits the display of metallogenic belts and their relations to host rock geology or host-rock structures (Nokleberg and others, 1997b, c; Parfenov and others, 2003, 2004a, b). To facilitate the analysis of the crustal origin and evolution of mineralizing systems, the geologic base map must be constructed at a scale that shows the major geologic data required for a synthesis. The synthesis should reveal the tectonic origin of host-rock geologic units and structures that controlled the formation of groups of mineral deposits in the metallogenic belts.

As an example of a regional geologic base map adapted to a page-size illustration, figure 3 shows a summary geodynamics map for Northeast Asia (derived from Parfenov and others, 2003, 2004a, b). As illustrated in this example, the regional geologic base map displays host rock geology and structures that are related to the origin of metallogenic belts, including (1) regional surface extent of major geologic units (cratons, craton margins, tectonic collages of island arc, continental margin arc, accretionary wedge, and passive continental margin terranes, volcanic and plutonic igneous arcs); (2) major fault and rift systems; and (3) active subduction zones. The regional geologic base map should also provide descriptive data on the tectonic origins of major host-rock geologic units (e.g., explanation for figure 3) that are needed to establish geologic controls for the metallogenic belts. Figure 3 utilizes the concept of tectonic collage (see above definition). This definition enables: (1) depiction at small (regional) scales of major geologic units and structures that formed in a single tectonic event; and (2) depiction of major metallogenic belts related to the tectonic collages.

Interpretation of Tectonic Environments

For a modern metallogenic and tectonic analysis, interpretation of tectonic environments is essential for determining the geologic origins of major units and the contained mineral deposits and metallogenic belts. The interpretation of tectonic environment permits the linking of geologic origins for these sometimes disparate datasets. For tectonic analyses of Northeast Asia and the Circum-North Pacific (Nokleberg and others, 1997b, c, 2000, 2005; Scotese and others, 2001; Obolenskiy and others, 2003; this volume; Parfenov and others, 2003, 2004a, b), the major geologic units (terranes, overlap assemblages, plates), mineral deposits, mineral deposit types, and metallogenic belts, are interpreted according to the following tectonic environments: (1) cratonal and craton margin; (2) passive continental margin; (3) metamorphosed continental margin; (4) continental-margin arc and back-arc; (5) island arc and back-arc; (6) oceanic crust, seamount, or ophiolite related to rifting and sea-floor spreading; (7) accretionary wedge and subduction zone; (8) turbidite basin; (9) collisional; (10) transform continental-margin faulting and associated bimodal volcanic-plutonic belt; (11) plume; and (12) metamorphic. Definitions of these tectonic environments are provided above. For terranes with complex geologic histories, the chosen tectonic environment is the one most prevalent during the history of the terrane. The assignment of tectonic environments should result in a higher-quality interpretation for the origin of mineral deposits and metallogenic belts and for the origin of geologic units or structures in which the deposits and belts formed.

Description of Significant Mineral Deposits and Synthesis of Mineral Deposit Models

Part of the core data set for a metallogenic analysis is a high-quality description of significant known mineral deposits (see above definition) of the region. As an example of mineral deposit data for a metallogenic analysis, table 2 provides sample descriptions of selected major Middle Jurassic to Early Cretaceous lode deposits for Northeast Asia (Ariunbileg and others, 2003). This table also contains descriptive data that enable the determination of mineral deposit models, age and relation of deposits to host rocks, and tectonic origins.

Modern metallogenic analysis of a large region requires development of mineral deposit models appropriate for the region. The models can subsequently be used to classify mines, mineral deposits, and prospects that can be interpreted as forming during various regional tectonic processes. The beginning of this type of correlation between models and tectonic process is evident in many of classic compilations of mineral deposits models (Eckstrand, 1984; Cox and Singer, 1986; Singer, 1993). Table 3 is an example of mineral deposit models employed for a large region and lists the mineral deposit models that were defined and described for a metallogenic analysis of Northeast Asia. For this large and complex region, 122 mineral deposit models were required to describe the characteristic features of the 1674 lode deposits and 75 placer districts (Obolenskiy and others, 2003, this volume). The models include previous descriptions from Eckstrand (1984), Cox and Singer (1986), and Nokleberg and others (1997a), with modifications by Obolenskiy and others (2003, this volume).

The mineral deposit models in table 3 consist both of descriptive and genetic information that is systematically arranged in order to define the essential properties of a class or type of mineral deposit. However, some models are based mainly on descriptive (empirical) information, in which case the various attributes are recognized as essential even though the nature of their relationships is unknown. An example of a descriptive mineral deposit model is the basaltic Cu type in which the empirical datum of a geologic association of Cu sulfides with relatively Cu-rich metabasalt or greenstone is the essential attribute. Some other models are defined by genetic (theoretical) considerations in which case the attributes are related through some fundamental geologic process. An example is the W skarn deposit model for which the genetic process of contact metasomatism is the essential attribute. For additional information on the methodology for defining mineral deposit models, the reader is referred to discussions by Eckstrand (1984), Kirkham (1993), and Cox and Singer (1986).

Compilation of a Metallogenic Belt Map

Many metallogenic maps display major mineral deposits and (or) districts on a regional geologic base map. These maps are typically complicated because of a high density of deposits. In order to simplify data and increase understanding of regional patterns, the concept of a metallogenic belt map was developed for Northeast Asia and the Circum-North Pacific (Nokleberg and others, 1998; Obolenskiy and others, 2003, 2004). The display of metallogenic belts, as defined above, enables the depiction of major groups of coeval and genetically-related, significant lode and placer deposits that can be interpreted as having formed in a single major geologic or tectonic event. A requirement of a metallogenic belt map is that the metallogenic belts can be related to major geologic units or structures as portrayed on the map and companion explanation. As an example of a metallogenic belt map for Northeast Asia, figure 3 displays the major Middle Jurassic to Early Cretaceous metallogenic belts, and table 4 provides summary descriptions of belts, and also summarizes the major characteristics and interpretations for each belt.

The sections below summarize the main characteristics of the major Middle Jurassic to Early Cretaceous metallogenic belts of Northeast Asia. The summary is adapted from Parfenov and others (2004b) and Rodionov and others (2004).

Metallogenic Belts Related to Accretionary Zones Between Major Superterranes and Cratons

Metallogenic Belts Related to Accretionary Zone Between the Kolyma-Omolon Superterrane and North Asian Craton Margin

In the northern part of Northeast Asia, important metallogenic belts occur along, or adjacent to, major accretionary fault systems between the Kolyma-Omolon superterrane and the North Asian Craton Margin, or in large collisional granitoids that occur along the fault systems (fig. 3, table 4). The belts contain significant vein and replacement deposits related to the Main, Northern, and Transverse granitoid belts. The major metallogenic belts are the Adycha-Nera (AN), Allakh-Yun (AY), Chybagalakh (CH), Kular (KU), Polousny (PO), Tompo (TO), Verkhoyansk (VK), and Yana-Adycha (YA).

The Main, Northern, and Transverse granitoid belts host several metallogenic belts and extend for several thousand kilometers around the margin of the accreted Kolyma-Omolon superterrane (fig. 3). The Main granite belt consists of large elongate plutons (with areas from several hundered to 2,000 km^2) composed of hornblende-biotite and two mica granite and granodiorite with ^{40}Ar-^{39}Ar isotopic ages of 143 to 138 Ma. The Northern granite belt, which extends 700 km in a north-south direction along northern margin of the Kolyma-Omolon superterrane, consists of large, elongated plutons composed of quartz diorite, monzodiorite, and biotite granite, as well as amphibole-biotite granodiorite, biotite granite, and two-mica granite. Granites in this belt have ^{40}Ar-^{39}Ar isotopic ages of 138 to 120 Ma. The Transverse granite belt consists of several belts of granitic rocks that extend up to several hundred km and radiate outwards from the southwestern bend of the Kolyma-Omolon superterrane. The belt tapers out to the southwest and north and comprises fault-related plutons and dike swarms composed mainly of diorite, granodiorite, and granite. ^{40}Ar-^{39}Ar isotopic ages range from 132 to 124 Ma.

A wide variety of granitoid-related mineral deposits occur in these metallogenic belts (table 4). The major mineral deposit types are Au in shear zone and quartz vein, cassiterite-sulfide-silicate vein, and stockwork, granitoid-related Au vein, polymetallic Pb-Zn ± Cu (±Ag, Au) vein and stockwork, Sn-B (Fe) skarn (ludwigite), Sn-W greisen, stockwork, and quartz vein, and W±Mo±Be skarn.

Metallogenic Belt Related to Accretionary Zone Between Bureya and Khanka Continental-Margin Arc Superterranes and North Asian Craton Margin

In the central part of the Russian Far East, the large Kerbi-Selemdzha metallogenic belt (KS) contains veins associated with collisional (anatectic) granitoids that intrude the Tukuringra-Dzhagdy and Badzhal accretionary wedge terranes (part of Mongol-Okhotsk tectonic collage) (fig. 3, table 4). The granitoids are mainly granodiorite porphyry and diorite porphyry. Applicable mineral deposit models are Au in shear zone and quartz vein, cassiterite-sulfide-silicate vein and stockwork, and granitoid-related Au vein.

METALLOGENIC BELTS HOSTED IN CONTINENTAL-MARGIN ARC ASSEMBLAGES

Metallogenic Belt Related to Uyandina-Yasachnaya Volcanic Belt and Ilin–Tas Back-Arc Basin

In northeastern Northeast Asia, the large Erikit metallogenic belt (ER) occurs in the Late Jurassic Uyandina-Yasachnaya volcanic belt and in the Ilin–Tas back-arc basin (part of Kular-Nera passive continental margin tectonic collage) that extend for about 1,500 km along an east-west strike (fig. 3, table 4). The enclosing Late Jurassic Uyandina-Yasachnaya volcanic belt comprises a thick assemblage of andesite, basalt, dacite, rhyolite lava, and tuff, together with shallow marine sandstone, siltstone, and conglomerate. The Late Jurassic Ilin'-Tas back-arc basin sequence consists of a conglomerate, alkali basalt, sandstone, siltstone, and shallow marine and continental black shale. The only type of deposit is volcanogenic Zn-Pb-Cu massive sulfide (Kuroko, Altai types) (table 4).

Metallogenic Belts Related to Stanovoy Plutonic Belt

In the east-central part of Northeast Asia, three large metallogenic belts occur in the Stanovoy plutonic belt (part of unit us, fig. 3) that extends for a few hundred kilometers along an east-west strike (fig. 3, table 4). The metallogenic belts are the Chara-Aldan (CA), Djeltu-laksky (DL), and North Stanovoy (NS). The enclosing and genetically-related Jurassic and Early Cretaceous Stanovoy granite belt extends for several thousand kilometers in the central part of the Russian Far East. The granite belt consists of multiphase, fractured, older plutons of gabbro and diorite, and younger plutons of granodiorite, granite, and granosyenite. Epizonal granodiorite batholiths are most common. The belt occurs along the southern margin of the southern North Asian Craton and extends westward into the eastern Transbaikalia region.

The granitoids are calc-alkaline and in the western part of the belt range from Triassic to Neocomian and young eastward to Late Jurassic to Neocomian. The granite belt is the western continuation of the Uda volcanic arc (also part of unit us, fig. 3) to the east. A wide variety of igneous-rock-related mineral deposits occur in these metallogenic belts (table 4). The major mineral deposit types are Au in shear zone and quartz vein, Au potassium metasomatite, Au skarn, Au-Ag epithermal vein, charoite metasomatite, and granitoid-related Au vein.

Metallogenic Belt Related to Umlekam-OgodzhinVolcanic-Plutonic Belt

In the central Russian Far East, the large North Bureya metallogenic belt (NB) occurs in the Umlekam-Ogodzhin volcanic-plutonic belt (unit uo, fig. 3; table 4) that consists chiefly of: (1) Early Cretaceous sandstone, conglomerate, and mudstone with sparse flora and freshwater fauna; (2) Early Cretaceous calc-alkaline andesite, dacite, and tuff; (3) Late Cretaceous alkalic basalt and rhyolite; and (4) Early Cretaceous granite, granodiorite, diorite, and monzodiorite. The only mineral deposit model is granitoid-related Au vein (table 4).

Metallogenic Belts Related to Jilin-Liaoning-East Shandong Volcanic and Pluton Belt, and Yanliao Volcanic and Sedimentary Basin and Plutonic Belt

In eastern China, the large Bindong (BD), Jiliaolu (JLL), and Yanshan (YS) metallogenic belts occur in the Jilin-Liaoning-East Shandong volcanic and plutonic belt, and in the Yanliao volcanic and sedimentary basin and plutonic belt that extend hundreds of kilometers along north-south to northeast-southwest strikes (fig. 3, table 4). These geologic units form extensive Jurassic and Cretaceous assemblages that overlap the eastern Sino-Korean Craton.

The Jilin-Liaoning-East Shandong volcanic and plutonic belt consists of: (1) Middle Jurassic andesite and pyroclastic rock; (2) Early Cretaceous andesite, dacite, and pyroclastic rock; (3) Late Cretaceous andesite and trachyte; and (4) Early Jurassic and Early Cretaceous calc-alkali monzonite and lesser granite, potassic granite and granodiorite, and minor intermediate diabase and quartz diorite that form small, widely-distributed intrusions. The volcanic rocks are calc-alkalic or locally alkaline.

The Yanliao volcanic and sedimentary basin and plutonic belt consists of Early Jurassic through Early Cretaceous volcanic and sedimentary basins and plutonic rock. The main volcanic and sedimentary units are basalt, andesite, rhyolite, and andesitic lava and pyroclastic units that are intercalated conglomerate and sandstone, and lesser interlayered conglomerate and coal, and tuffaceous sandstone.

A variety of igneous-rock-related mineral deposits occur in these metallogenic belts (table 4). The major mineral deposit types are Au-Ag epithermal vein, Cu (±Fe, Au, Ag, Mo) skarn, Fe skarn, granitoid-related Au vein, polymetallic Pb-Zn ± Cu (±Ag, Au) vein and stockwork, volcanic-hosted Au-base metal metasomatite, W±Mo±Be skarn, and Zn-Pb (±Ag, Cu) skarn.

Metallogenic Belt Related to Hiroshima Granitic Plutonic Belt

In southern Japan, the large Kitakami metallogenic belt (KT) occurs in the Early Cretaceous part of Hiroshima granitic plutonic belt that extends several hundred km along a northeast-southwest strike (fig. 3, table 4). The granitic plutonic belt consists mainly of coarse-grained leucogranite. This belt is mostly overlain by the modern Japan arc and is too small to depict on figure 3. The metallogenic belt contains only granitoid-related Au vein deposits (table 4).

Metallogenic Belts Related to Transtensional Continental-Margin Faults and Intraplate Faults

Metallogenic Belts Related to Trans-Baikalian-Daxinganling Sedimentary-Volcanic-Plutonic Belt and Companion Mongol-Okhotsk Fault

In the central part of Northeast Asia, major metallogenic belts contain mineral deposits hosted in veins, volcanic complexes, and granitoids related to the Trans-Baikalian-Daxinganling sedimentary-volcanic-plutonic belt (unit tr, fig. 3; table 4). The major metallogenic belts are the Aginskiy (AG), Dzid-Selenginskiy (DS), Daxinganling (DX), East Mongolian-Priargunskiy-Deerbugan (EMA), Eravninsky (ERA), Govi-Tamsag (GT), Hartolgoi-Sulinheer (HS), Khilokskiy (KR), Mushgaihudag-Olgiihiid (MH), Nerchinsky (NE), Onon-Chikoiskiy (OCH), Shilkinsko-Tukuringrskiy (SH), and Verkhne-Ingodi (VIG).

The Trans-Baikalian-Daxinganling volcanic and sedimentary belt extends several thousand km in Russia, Mongolia, and northern China (fig. 3). In southern Siberia, the sedimentary-volcanic-plutonic belt comprises volcanic and sedimentary formations that occur in northeast-trending rift-related depressions. The volcanic and plutonic rocks consist of: (1) Middle and Late Jurassic shoshonite and latite; (2) Late Jurassic and Early Cretaceous trachybasalt, trachyrhyolite, and comendite; and (3) mostly Middle and Late Jurassic calc-alkaline and subalkaline plutons, leucogranite, and shallow intrusions. In southeastern Mongolia, the belt includes Late Jurassic and Early Cretaceous volcanic and sedimentary rock. In northern China, the belt consists mainly of calc-alkalic basalt, trachyandesite, trachydacite, and dacite, and local alkalic and subalkalic intrusions. The Trans-Baikalian-Daxinganling volcanic and sedimentary belt is interpreted herein as having formed during and after transform-continental-margin faulting and magmatism along the Mongol-Okhotsk and related faults during closing of the Mongol-Okhotsk Ocean, after closing, as left-lateral transtensional movement continued along the fault system.

A wide variety of igneous-rock related mineral deposits occur in these metallogenic belts (table 4). The major mineral deposit types are Au skarn, Au-Ag epithermal vein, carbonate-hosted Hg-Sb, cassiterite-sulfide-silicate vein and stockwork, fluorspar vein, granitoid-related Au vein, polymetallic Pb-Zn ± Cu (±Ag, Au) vein and stockwork, porphyry Cu-Mo (±Au, Ag), porphyry Mo (±W, Bi), REE-Li pegmatite, Sn-W greisen, stockwork, and quartz vein, Ta-Nb-REE alkaline metasomatite, W-Mo-Be greisen, stockwork, and quartz vein, and Zn-Pb (±Ag, Cu) skarn.

Metallogenic Belt Related to Southern Korean Peninsula Transtensional Zone

In the southern Korean Peninsula, the Gyeonggi (GY) and Taebaegsan (TA) metallogenic belts occur in Early Jurassic mafic-ultramafic plutons and granitoids that extend a few hundred kilometers along a northeast-southwest strike (fig. 3, table 4). The plutonic rocks are part of the Jurassic Daebo granite belt, too small to depict on figure 3, that consists of granite, granodiorite, subordinate tonalite and gabbro, and local muscovite granodiorite and two-mica granite. The granite belt is herein interpreted as having formed along a major continental-margin transform fault. The Gyeonggi metallogenic belt contains mafic-ultramafic related Ti-Fe (±V), polymetallic Pb-Zn ± Cu (±Ag, Au) vein and stockwork, W±Mo±Be skarn deposits; the Taebaegsan metallogenic belt contains Fe skarn, polygenic REE-Fe-Nb, REE-Li pegmatite, W±Mo±Be skarn, and Zn-Pb (Ag, Cu, W) skarn deposits (table 4).

Metallogenic Belt Related to Kuznetsk-Altai Fault Zone

In southwestern Siberia, the Kurai-Tolbo Nuur metallogenic belt (KTN) occurs along the Kuznetsk-Altai fault zone that extends for a few hundred kilometers along a northwest-southeast strike (fig. 3, table 4). The belt contains Early and Middle Jurassic replacement deposits and is hosted in the West Sayan and Hovd terranes (part of the Altay tectonic collage, fig 3; table 4). The more common mineral deposit types are Ag-Pb epithermal vein, Ag-Sb vein, Au-Ag epithermal vein, carbonate-hosted Hg-Sb, clastic sediment-hosted Hg±Sb, Ni-Co arsenide vein, silica-carbonate (listvenite) Hg, and volcanogenic Pb-Zn (±Cu) massive sulfide deposits (table 4). The main deposit-controlling structures are the large Kurai-Kobdinsk fault and the conjugate Aktash and Chagan-Uzun thrust faults.

Metallogenic Belt Related to Tanlu Strike-Slip Fault System

In eastern China, the North Jilin metallogenic belt (NJ) occurs in the North marginal plutonic belt that intrudes the Sino-Korean Craton along the major Tanlu strike-slip fault system (fig. 3, table 4). The belt contains Early and Middle Jurassic replacement deposits and I-type granitoids that are too small to depict on figure 3. The major mineral deposit types are Au-Ag epithermal vein, fluorspar vein, granitoid-related Au vein, porphyry Cu (±Au), polymetallic (Pb, Zn±Cu, Ba, Ag, Au) volcanic-hosted metasomatite, porphyry Mo (±W, Bi), and Zn-Pb (±Ag, Cu) skarn (table 4).

Metallogenic Belt Related to Buried Fault System in Central Russian Far East

In the central Russian Far East, the Kondyor-Feklistov metallogenic belt (KD) extends for a few hundred kilometers along a northwest strike within the North Asian Craton (fig. 3, table 4). The belt contains Early Cretaceous zoned mafic-ultramafic intrusions that are too small to depict on figure 3. The mineral deposit type is zoned mafic-ultramafic Cr-PGE (table 4). The metallogenic belt is herein interpreted to have formed along a major buried fault system.

Metallogenic Belts Related to Mafic and Ultramafic Igneous Plutons Associated with Continental-Margin Subduction Zones

Metallogenic Belt Hosted in Mafic-Ultramafic and Granitoid Plutons in Southern Russian Far East

In the southern Russian Far East, the adjacent Ariadny (AG) and Samarka (SA) metallogenic belts extend for a few hundred kilometers along a northeast strike (fig. 3, table 4). The Ariadny belt (AG) contains Late Jurassic unzoned and zoned mafic-ultramafic intrusions, too small to depict on figure 3, that intrude the Late Jurassic and older Samarkina accretionary wedge terrane (part of Honshu-Sikhote-Alin collage, unit HS, fig. 3). The plutons are mainly pyroxene-hornblende gabbro, olivine gabbro, pyroxenite, layered pyroxene-hornblende gabbro, and pyroxenite intrusions. The major mineral deposit types are mafic-ultramafic-related Ti-Fe (±V) and zoned mafic-ultramafic Cr-PGE (table 4).

The Samarka metallogenic belt (SA) contains Early to mid-Cretaceous vein deposits in granitoids in part of the Khungari-Tatibi granite belt, that are too small to depict on figure 3, and that also intrude the Late Jurassic and older Samarka accretionary wedge terrane and the outboard (eastward). The Late Jurassic and Early Cretaceous Zhuravlevsk-Amur River transform-continental-margin turbidite terrane (both part of Honshu-Sikhote-Alin collage, unit HS, fig. 3). The granite belt consists mainly of mid-Cretaceous, multi-phase granitoid plutons composed of diorite, quartz diorite, monzonite, granomonzonite, granodiorite, biotite-hornblende granite, granite porphyry, leucocratic granite, and aplite that intrude along the Central Sikhote-Alin fault. The major mineral deposit types are porphyry Cu-Mo (±Au, Ag), porphyry Mo (±W, Sn, Bi), and W±Mo±Be skarn (table 4).

On the basis of regional geologic and structural data, both the Ariadny and Samarka metallogenic belts are herein interpreted as having formed during generation of bimodal igneous plutons immediately after accretion of the Samarkina accretionary wedge terrane and outboard Zhuravlevsk-Amur River terrane.

Metallogenic Belt Hosted in Ultramafic Units of an Ophiolite Incorporated into Subduction Zone Terranes in Northern Japan

In northern Japan, the Kamuikotan metallogenic belt (KM) extends for a few hundred kilometers along a north-south strike (fig. 3, table 4). The belt contains serpentinized ultramafic rock that constitutes part of an ophiolite in a tectonic mélange of the Early Cretaceous and younger Shimanto accretionary wedge terrane (part of the Sakhalin-Hokkaido tectonic collage, unit SH, fig. 3). The major mineral deposit type is podiform chromite. The metallogenic belt and host ultramafic rock are herein interpreted to be part of ophiolite sequence that was formed along a Late Jurassic and Early Cretaceous oceanic ridge.

Metallogenic Belt Hosted in Oceanic Sedimentary and Volcanic Units Incorporated into Subduction Zone

Terranes in Southern Japan

In southern Japan, the Sambagawa-Chichibu-Shimanto metallogenic belt (SCS) extends for several hundred kilometers along a northeast-southwest strike (fig. 3, table 4). The belt is hosted by the Early Jurassic and to Late Cretaceous (and older) Shimanto and Mino Tamba Chichibu accretionary wedge terranes and by the Sambagawa metamorphic terrane (derived from metamorphosed Late Jurassic and older ocean-floor sedimentary units). All three terranes are part of the Sakhalin-Hokkaido tectonic collage (unit SH, fig. 3). The major mineral deposit types are Besshi Cu-Zn-Ag massive sulfide (Cu, Zn, Ag), volcanogenic-sedimentary Mn, and Cyprus Cu-Zn massive sulfide. The Mn deposits are herein interpreted as having formed in ocean-floor sediments; the Besshi and Cyprus deposits are herein interpreted as having formed during submarine volcanism that occurred along a Late Jurassic and Early Cretaceous oceanic ridge or less likely along a back-arc ridge.

Power of Regional Metallogenic Analysis

By applying the above definitions and principles, the areas defined as metallogenic belts encompass favorable geological environments with specific mineral-deposit types and associations. The synthesis and compilation of metallogenic belt maps is an extremely powerful tool for a variety of purposes because the metallogenic belts constitute favorable areas for undiscovered mineral resources. This predictive methodology is extremely useful for land-use planning, environmental studies, and mineral exploration, and establishing guidelines for future research.

Example of a Metallogenic and Tectonic Model

Figure 4 illustrates one time stage for a metallogenic and tectonic model using the Middle Jurassic to Early Cretaceous of Northeast Asia as an example. This figure depicts the major (Middle Jurassic to Early Cretaceous) geologic units and related metallogenic belts that were forming during this time span, and previously-formed, older units. The major units are mainly a series of peripheral continental margin arcs and related, outboard subduction zones, and a series of igneous belts that formed along major strike-slip faults. Also shown are large areas of previously-accreted terranes and large cratonal units including the North Asian Craton and Craton Margin and the Sino-Korean Craton. Listed below, in groups of similar tectonic origin, are descriptions of the large metallogenic belts for the Middle Jurassic to Early Cretaceous for Northeast Asia. The interpretations below of tectonic origins of major geologic units and metallogenic belts are summarized from the more detailed syntheses of Nokleberg and others (2000, 2005), Parfenov and others (2004b), and Rodionov and others (2004). For describing this example of one time stage of a metallogenic and tectonic model, figure 3 illustrates the major metallogenic belts on the regional summary geodynamics map and figure 4 illustrates the belts on the tectonic model for the Middle Jurassic to Early Cretaceous.

This Middle Jurassic to Early Cretaceous stage (175 to 96 Ma) of the tectonic model for Northeast Asia encompasses about 79 m.y. (Remane, 1998) and illustrates the following major tectonic events (fig. 4). (1) In the northern part of the model for the Late Jurassic, convergence and accretion occurred between the Kolyma-Omolon superterrane and the Verkhoyansk passive continental margin. During convergence, the Uyandina-Yasachnaya magmatic arc formed on the superterrane margin under which Oimyakon oceanic crust was subducted. In the latest Late Jurassic, the Kolyma-Omolon superterrane collided with the Verkhoyansk (North Asian) Craton Margin, thereby resulting in the formation of several collisional granite belts (Main, Northern, Transverse). (2) In the east-central part of the tectonic model, the Stanovoy plutonic belt, Uda-Murgal arc, and Umlekam-Ogodzhin magmatic belt were active as continental-margin arcs during the closing of the Mongol-Okhotsk Ocean. These igneous belts formed on opposite sides of the ocean, with the Stanovoy plutonic belt and Uda-Murgal arc forming on the southern margin of the North Asian Craton to the north, and the Umlekam-Ogodzhin magmatic belt forming along the northern margin of the Burea superterrane to the south. (3) With closure of the ocean along the major Mongol-Okhotsk fault, an extensive system of strike-slip and extensional faults (transtensional faults) formed across a wide expanse of the west-central to east-central part of the tectonic model. Associated with the transtensional tectonism was widespread formation of the Late Jurassic-Early Cretaceous bimodal volcanic and plutonic units, and continental clastic units of the Trans-Baikalian-Daxinganling igneous belt. (4) In the southeast part of the tectonic model, the Jihei volcanic-plutonic belt formed along a major transform continental-margin fault system. And (5) also in the southeast part of the tectonic model, a continental-margin arc containing the Hiroshima granitic plutonic belt formed during outboard subduction of the ancestral Pacific Ocean plate.

Metallogenic Belts Related to Accretion of Superterranes to Cratons

In the northern part of the tectonic model, large metallogenic belts, that contain Au vein, replacement, and granitoid-related deposits, occur along, or adjacent to, large accretionary fault systems between the Kolyma-Omolon superterrane and the North Asian Craton Margin (figs. 3, 4; table 4). The metallogenic belts are the Adycha-Nera (AN), Allakh-Yun (AY), Chybagalakh (CH), Kular (KU), Polousny (PO), Tompo (TO), Verkhoyansk (VK), and Yana-Adycha (YA). These belts are herein interpreted as having formed during regional metamorphism and collisional granitoid intrusion that occurred with the Late Jurassic accretion of the Kolyma-Omolon superterrane (unit KOM, fig. 3) and the Omolon cratonal terrane (unit OM, fig. 3) to the northeastern margin of the Verkhoyansk (North Asian) Craton Margin (unit VR, fig. 3).

In the east-central part of the tectonic model, the Kerbi-Selemdzha metallogenic belt (KS) and its contained Au vein and Sn vein deposits are herein interpreted as having formed during Late Jurassic to Early Cretaceous accretion of the Bureya superterrane (part of Bureya-Jiamusi supterterrane, unit BJ, fig. 3) to the south with the North Asian Craton (unit NAC, fig. 3) to the north (fig. 4). The latter was thrust over the craton-bounding the Tukuringra-Dzhagdy and Badzhal accretionary wedge terranes (parts of unit MO, fig. 3), resulting in the generation of hydrothermal fluids and anatectic granite.

In the east-central part of the tectonic model, the Djeltulaksky (DL) and North Stanovoy (NS) metallogenic belts and their granitioid-related Au vein deposits are herein interpreted to have formed during generation of collisional granitoids (fig. 4) during the Early Cretaceous closing of the Mongol-Okhotsk Ocean with accretion of the Bureya superterrane (part of Bureya-Jiamusi supterterrane, unit BJ, fig. 3) against the North Asian Craton (unit NAC, fig. 3).

Metallogenic Belts Hosted in Continental-Margin Arc Assemblages

In the northern part of the tectonic model, the Erikit metallogenic belt (ER) and its contained volcanogenic massive sulfide deposits, are hosted in the Late Jurassic Uyandina-Yasachnaya volcanic belt and Ilin–Tas back-arc basin (fig. 4) (both part of unit uv, fig. 3) that overlie the Kolyma-Omolon superterrane (unit KOM, fig. 3). These metallogenic belts and their host rocks are herein interpreted as having formed in a subduction-related magmatic arc on the southwest margin of the Kolyma-Omolon superterrane (unit KOM, fig. 3), immediately before accretion to the Verkhoyansk (North Asian) Craton Margin (unit VR, fig. 3).

In the east-central part of the tectonic model, the Stanovoy granite belt (part of unit us, fig. 3), that hosts the Chara-Aldan (CA) metallogenic belt, with Au vein, and skarn deposits, is herein interpreted to have formed in a suite subalkaline and alkaline plutonic rocks in the back-arc region of the plutonic belt (fig. 4). This plutonic belt was part of an Andean-type continental-margin arc that formed along the Jurassic and Early Cretaceous margin of the North Asian Craton (unit NAC, fig. 3), adjacent to the Mongol-Okhotsk Ocean to the south.

In the east-central part of the tectonic model, the North Bureya metallogenic belt (NB), that contains Au vein and granitoid Au deposits, is hosted in the Umlekam-Ogodzhin volcanic-plutonic belt (unit uo, fig. 3). The metallogenic belt and host igneous belt are herein interpreted as having formed in the Umlekan-Ogodzhin continental-margin arc along the margin of the Burea superterrane (part of unit BJ, fig. 3) to the south, during closure of the Mongol-Okhotsk Ocean to the north.

In the southeastern part of the tectonic model, the Early Cretaceous part of the Hiroshima granitic plutonic belt and its contained Kitakami (KT) metallogenic belt, with Cu skarn and granitoid Au deposits, are herein interpreted to have formed during early-stage intrusion of granitoids along a continental-margin arc (fig. 4).

Metallogenic Belts Related to Transtensional Continental-Margin Faults and Intraplate Faults

In the southwestern part of the tectonic model, the Kurai-Tolbo Nuur metallogenic belt (KTN), and contained Ag and Au vein deposits and associated igneous-rock-related mineral deposits (table 4), are herein interpreted as having formed during alkaline basalt magmatism during intraplate rifting and strike-slip block faulting along the complex, major Kuznetsk-Altai fault (fig. 4). This major fault or suture comprises a system of large regional faults and feathering branches that separate early Paleozoic island arc, seamounts, and ophiolite terranes, and overlapping middle and late Paleozoic basins, and Mesozoic and Cenozoic intermontane basins.

In the central part of the tectonic model, the Trans-Baikalian-Daxinganling sedimentary-volcanic-plutonic belt (unit tr, fig. 3) and contained metallogenic belts are herein interpreted to have formed during transform-continental margin faulting along the regional Mongol-Okhotsk fault and related transtensional structures and during associated magmatism and sedimentation during and after closure of the Mongol-Okhotsk Ocean (fig. 4). Major metallogenic belts are the Aginskiy (AG), Dzid-Selenginskiy (DS), Daxinganling (DX), East Mongolian-Priargunskiy-Deerbugan (EMA), Eravninsky (ERA), Govi-Tamsag (GT), Hartolgoi-Sulinheer (HS), Khilokskiy (KR), Mushgaihudag-Olgiihiid (MH), Nerchinsky (NE), Onon-Chikoiskiy (OCH), Shilkinsko-Tukuringrskiy (SH), and Verkhne-Ingodi (VIG). Table 4 list the mineral deposits types that occur in these belts.

In the east-central part of the tectonic model, the Kondyor-Feklistov metallogenic belt (KD) and contained zoned mafic-ultramafic Cr-PGE deposits are interpreted as having formed during intrusion of mafic-ultramafic plutons along a deep-seated, buried fault (fig. 3) along the North Asian Craton during Early Cretaceous collision and accretion of outboard terranes (fig. 4).

In the southeastern part of the tectonic model, the North Jilin metallogenic belt (NJ), with its contained Au-Ag epithermal vein, fluorspar vein, granitioid Au deposits, polymetallic Pb-Zn, porphyry Mo, and Zn-Pb deposits, are interpreted to have formed during magmatism along the Tanlu strike-slip fault system (fig. 3) that was a major transpressional zone along a transform plate boundary (fig. 4).

Also in the southeastern part of the model, the Jurassic Daebo granite belt and the contained Gyeongii (GY) and Taebaegsan (TA) metallogenic belts, with polymetallic Pb-Zn, Fe, and W skarn deposits, Au vein, polygenic REE vein, and mafic-ultramafic Ti-Fe deposits, are herein interpreted as having formed along a significant transtensional zone on a transform continental-margin boundary (fig. 4).

Also in the southeastern part of the model, the Jihei volcanic and plutonic belt and contained Bindong metallogenic belt (BD), the Jilin-Liaoning-East Shandong volcanic-plutonic belt and contained Jiliaolu metallogenic belt (JLL), and the Yanliao volcanic and sedimentary basin and plutonic belt and contained Yanshan (YA) metallogenic belt, are herein interpreted to have formed during magmatism that occurred during extensional tectonism and faulting related to oblique subduction of the ancestral Pacific Ocean plate beneath the East Asian continental margin (fig. 4).

Metallogenic Belts Related to Mafic and Ultramafic Igneous Plutons Associated with Transform Continental-Margin and Continental-Margin Subduction Zones

In the southeastern part of the tectonic model, the Ariadny metallogenic belt (AG) and contained mafic-ultramafic related Ti-Fe (±V) and zoned mafic-ultramafic Cr-PGE deposits, and the Samarkina metallogenic belt (SA) and contained porphyry Cu and Mo and W skarn deposits are herein interpreted as having formed during generation of bimodal igneous plutons during accretion and underthrusting of the Kula oceanic ridge along a transform continental margin (fig. 4).

Also in the southeastern part of the tectonic model, the Kamuikotan metallogenic belt (KM) and contained podiform Cr deposits are herein interpreted to have formed during generation of an ophiolite along a Late Jurassic to Early Cretaceous oceanic ridge (fig. 4). The ophiolite was subsequently incorporated into the accretionary wedge of the Shimanto terrane (part of unit SH, fig. 3) during Cretaceous and early Tertiary subduction of the ancestral Pacific Plate beneath the East Asia continental margin.

Also in the southeastern part of the tectonic model, the Sambagawa-Chichibu-Shimanto metallogenic belt (SCS) and contained volcanogenic massive sulfide deposits (table 4) are interpreted as having formed during eruption of associated submarine volcanism along a Middle Jurassic to Early Cretaceous oceanic ridge, or during ocean-floor sedimentation, or in a back arc (fig. 4). Subsequently, the deposits and host rocks were tectonically incorporated into accretionary wedge units of the Shimanto, Mino Tamba Chichibu, and Sambagawa terranes (part of unit SH, fig. 3) during Cretaceous and early Tertiary subduction of the ancestral Pacific Ocean plate.

Benefits of Performing a Combined Regional Metallogenic and Tectonic Analysis

As described above, a high-quality, combined metallogenic and tectonic analysis can benefit other mineral resource studies (fig. 3), including: (1) synthesis of mineral deposit models (Eckstrand, 1984; Cox and Singer, 1986; Singer and Cox, 1988; Kirkham, 1993); (2) assessment of undiscovered mineral resources as a part of quantitative mineral resource assessments (Cox, 1993; Singer, 1993, 1994); (3) improvement of land-use planning and mineral exploration; (4) improvement of genetic models for mineral deposits and host rocks; and (5) formulation of guidelines for new research.

Following are three examples of these benefits. (1) In-depth understanding of the tectonic and metallogenic origins of potential host rocks for mineral deposits enables the prediction of undiscovered mineral deposits according to favorable host rock geology. It is crucial to have this capability because for a proper mineral resource assessment, the outlines of permissive tracts (i.e., areas with potential for undiscovered mineral deposit types) must be drawn for each mineral deposit type based on knowledge of favorable geologic environments. (2) Regional metallogenic and tectonic analyses, such as those performed for Northeast Asia and the Circum-North Pacific, enable the identification and location of continuations of ore-hosting terranes and permissive tracts worldwide that have been separated by tectonic processes. For example, suppose that a suite of metallogenic belts containing porphyry Cu deposits are hosted in fragments of island-arc terranes that are now dispersed in a collage of terranes in the center of a continent. Tectonic analysis of the origin of the island-arc terranes and correlations with each other can produce grouping of these terranes and their contained metallogenic belts into an originally continuous island-arc and a single, large metallogenic belt. This enlargement of the host rock area and contained metallogenic belt will establish larger data set that can greatly improve the quality of metallogenic analysis and mineral resource assessment.

And (3) understanding the metallogenic setting and history of host rocks and ore-forming processes often is important for estimating numbers of undiscovered mineral deposits in a permissive tract. For example, the number of volcanogenic massive sulfide deposits estimated in a permissive tract containing poorly exposed and poorly described mafic to felsic volcanic rocks may vary depending on whether the tract is located in a volcanic fore-arc, axial-arc, or back-arc tectonic setting. Conversely, no deposits of this type would be estimated for a tract of similar rocks in an extensional cratonic setting.

Summary

This article presents an overview of the methodology of combined regional metallogenic and tectonic analysis, including definitions, theoretical examples, and known examples for the Middle Jurassic to Early Cretaceous of Northeast Asia. This article also describes how a high-quality metallogenic and tectonic analysis, and synthesis of an associated metallogenic-tectonic model, can benefit: (1) refinement of mineral deposit models and deposit genesis; (2) assessment of undiscovered mineral resources as a part of quantitative mineral resource assessment studies; (4) land-use planning and mineral exploration; (5) interpretations of the origins of host rocks, mineral deposits, and metallogenic belts; and (6) guidelines for new research. A major goal of this article is to demonstrate that the methodology of regional metallogenic and tectonic analysis, as summarized herein, is a powerful theoretical tool for defining, analyzing, and interpreting the crustal origin and evolution of mineralizing systems through geologic space and time.

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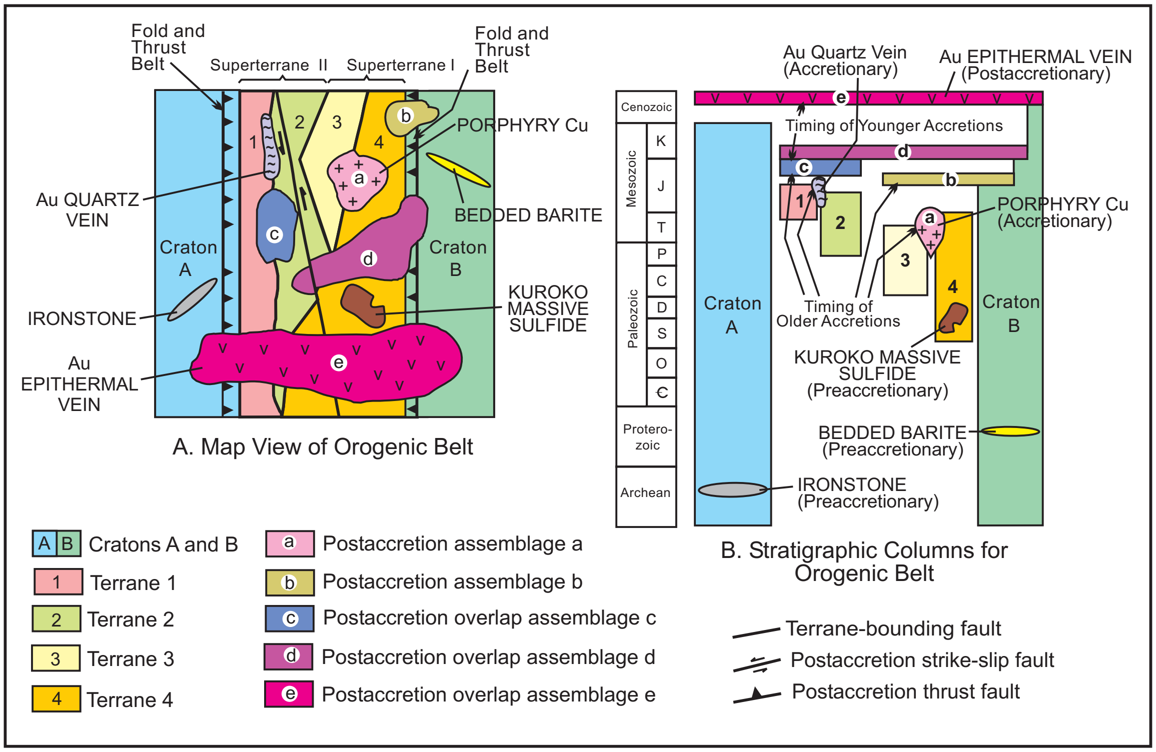

Figure 1. Schematic figure illustrating the methodology for metallogenic analysis of cratons, terranes, accretionary assemblages, overlap assemblages, and contained metallogenic belts. A. Map view of orogenic belt. B. Stratigraphic columns for orogenic belt. Adapted from Parfenov and others (1998).

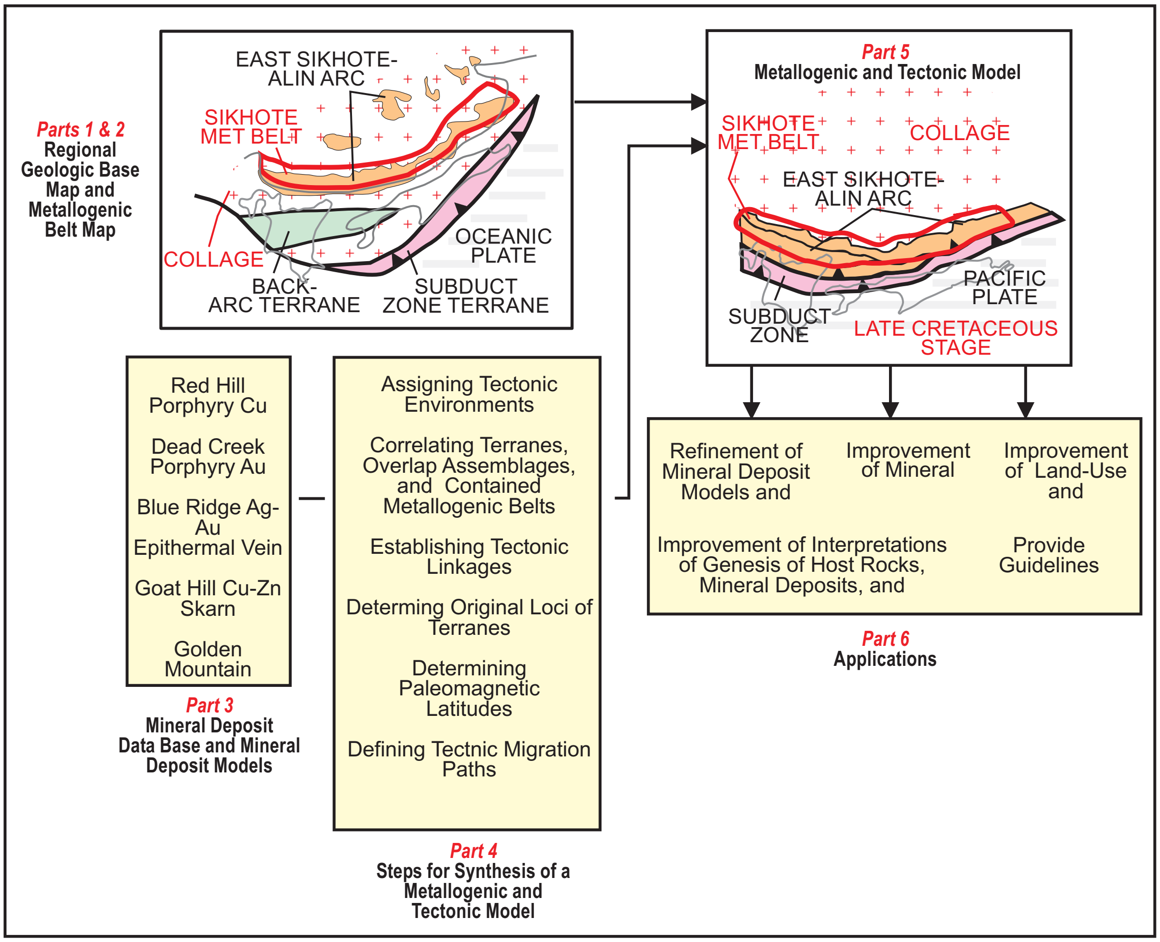

Figure 2. Major components of a metallogenic analysis and synthesis of a metallogenic and tectonic model. Parts 1 and 2 Regional geologic base map and metallogenic belt map. Part 3 Mineral deposit database and mineral deposit models. Part 4 Steps for synthesis of a metallogenic and tectonic model. Part 5 Metallogenic and tectonic model. Part 6 Applications.

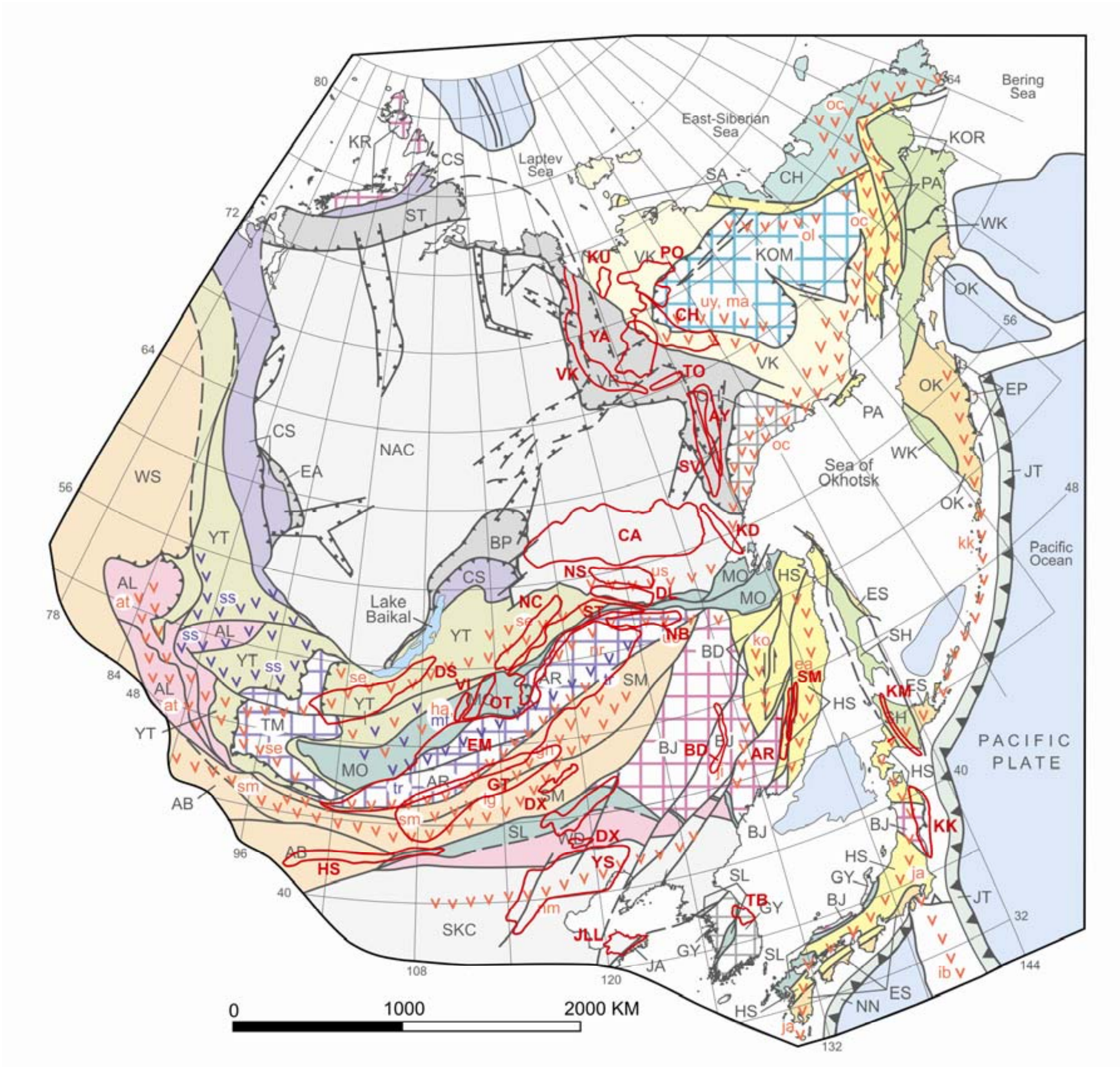

Figure 3. Regional summary geodynamics map for Northeast Asia showing outlines of major metallogenic belts for the Middle Jurassic to Early Cretaceous. Adapted from Obolenskiy and others (2003, 2004) and Parfenov and others (2003, 2004). Regional geology for area east of 144º E longitude (eastern boundary of Northeast Asia project area) are described and interpreted by Nokleberg and others (2000, 2005).

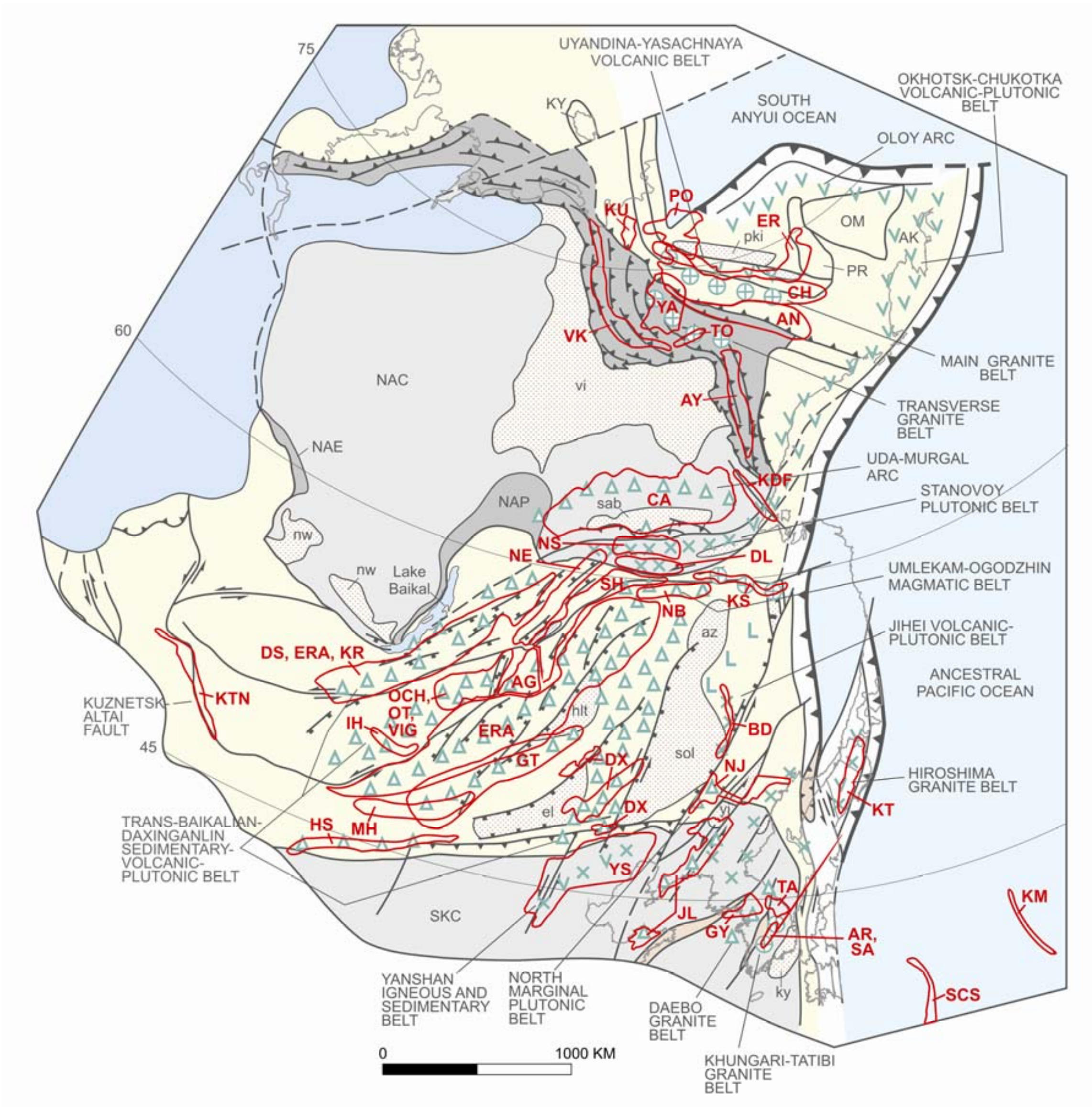

Figure 4A. Middle Jurassic to Early Cretaceous stage of metallogenic and tectonic model for Northeast Asia illustrating the tectonic setting for major metallogenic belts. Metallogenic belts for area to east of 144º E longitude (eastern boundary of Northeast Asia project area) are described and interpreted by Nokleberg and others (2003).

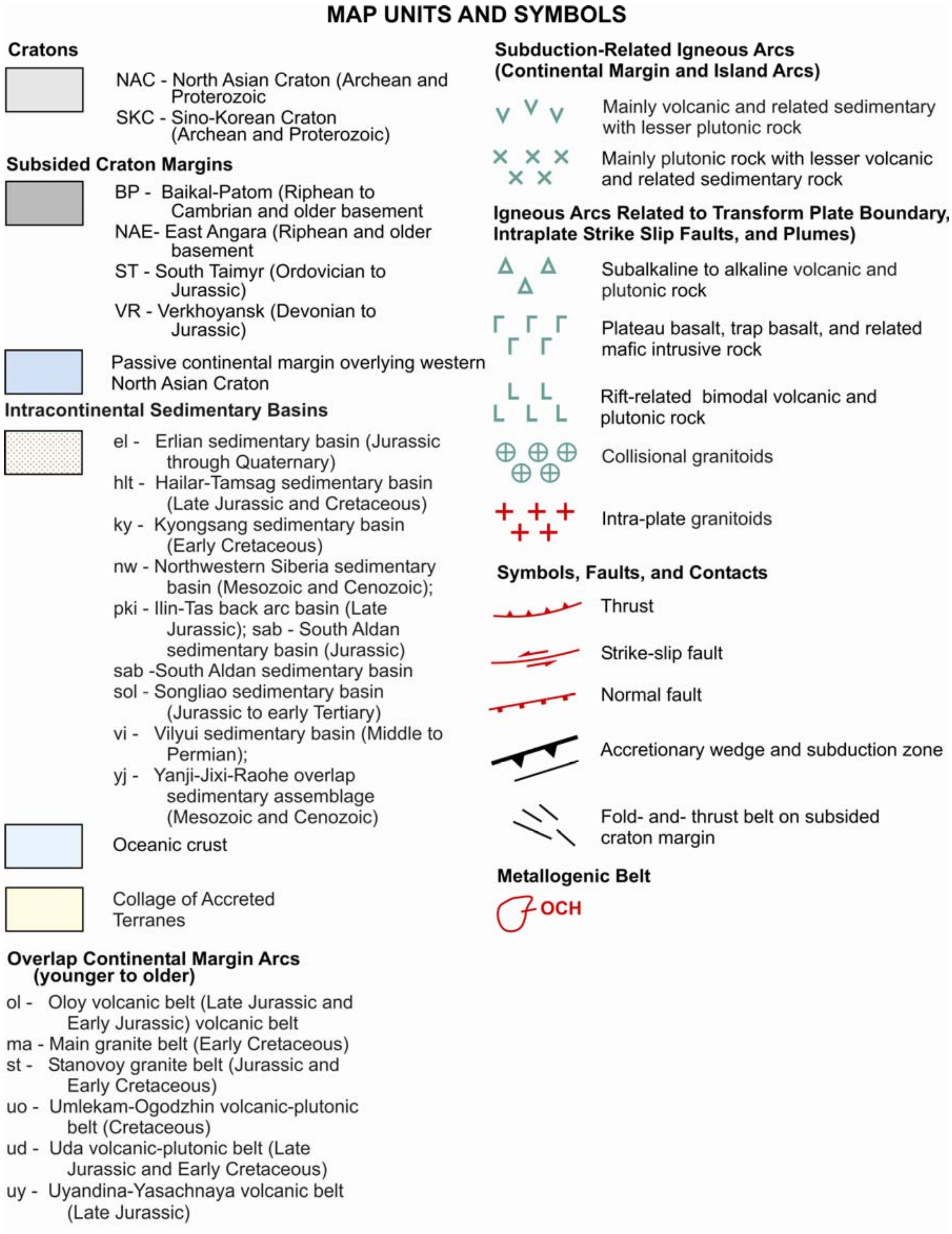

Figure 4B. Explanation for Middle Jurassic to Early Cretaceous stage of metallogenic and tectonic model for Northeast Asia.

Table 1. Summary of major areas, major tectonic environments (events), and associated major lode mineral deposit models. Derived from metallogenic analyses of Northeast Asia, the Russian Far East, Alaska, and the Canadian Cordillera. Adapted from Nokleberg and others (2003), Scotese and others (2001), and Rodionov and others (2004).

Areas	Tectonic Environment(s) or Event(s)	Major Mineral Deposit Models
Northeast Asia and North American Cratons and Craton Margins	Rifting	Sedimentary-exhalative Zn-Pb, polygenic REE, Cyprus massive sulfide, volcanogenic massive sulfide, carbonate-hosted sulfide.
Ocean	Sea floor spreading (oceanic crust, seamount, or ophiolite related to rifting)	Cyprus massive sulfide, volcanogenic massive sulfide, podiform chromite.
North Asian and North American continental margins	Continental-margin arc intruding passive continental margin, turbidite basin, or metamorphosed continental margin. Back-arc. Structurally underlain by subduction zone.	Porphyry, epithermal vein, polymetallic vein, skarn, greisen, pegmatite, volcanogenic massive sulfide, Besshi massive sulfide.
Ocean	Island arc and back-arc	Porphyry, epithermal vein, polymetallic vein, granitoid-related Au vein, skarn, zoned mafic-ultramafic Cr-PGE, mafic-ultramafic related Cu-Ni-PGE.
North Asian and North American continental margins	Collision and metamorphic.	Low-sulfide Au quartz vein, granitoid-related Au, porphyry, skarn, Au in black shale.
North Asian and North American continental margins	Transform-continental margin faulting and associated bimodal volcanic-plutonic belt	Zoned mafic-ultramafic PGE, Cr, and Ti; W skarn, porphyry Cu-Mo, Au-Ag epithermal vein, Au quartz vein, basaltic copper, Cu-Ag quartz vein.
North Asian and North American cratons	Plume intrusion into craton or craton margin	Mafic-ultramafic related Cu-Ni-PGE, Fe-Ti and REE carbonatite, skarn, metamorphic graphite, diamond-bearing kimberlite, porphyry, pegmatite,

Table 2. Examples of selected granitoid-related Au deposits for selected deposits in Northeast Asia. Adapted from Ariunbileg and others (2003).

<table>
<tr><th>Deposit No.
Latitude
Longitude
Summary and References</th><th>Deposit Name
Country
Metallogenic Belt</th><th>Major Metals
Minor Metals
Deposit model</th><th>Grade and Tonnage</th></tr>
<tr><td>M54-1
51 56 00N
138 47 00E</td><td>Agnie-Afanas'evskoye
Russia
Pilda-Limuri</td><td>Au

Granitoid-related Au vein</td><td>Average grade of about 25 g/t Au, maximum grade up to 1-2 kg/t Au. Mined from 1936 to 1962 with production of 12 tonnes Au.</td></tr>
<tr><td colspan="4">Occurs in a vein system that ranges up 0.5 km wide and up to 1.0 km long. System occurs in a anticline formed in Early Cretaceous sandstone and siltstone. Several diorite dikes occur along joints that cross host rock bedding. Veins range from 200-700 m long and 5-10 cm wide, strike northeast, and dip moderately. Veins contain mainly quartz, carbonate, feldspar, chlorite, and sericite with up to 1% ore minerals. Ore minerals are pyrite, arsenopyrite, antimonite, chalcopyrite, sphalerite, chalcocite, and gold, and rare cassiterite, wolframite, scheelite, and molybdenite. Pyrite is dominant and forms disseminations and thin veinlets in quartz. The amount of arsenopyrite is less than pyrite and occurs in high-grade zones. Gold grains range from 1-6 mm, and occur in bunches, thin veinlets, and rare octahedron crystals in fractured quartz. Host rocks are altered near the quartz veins and contain up to 2-4 g/t Au. Reference: Moiseenko and Eyrish, 1996.</td></tr>
<tr><td>N52-5
53 27 00N
126 27 00E</td><td>Pioneer
Russia
North Bureya</td><td>Au

Granitoid-related Au vein</td><td>Average grade of 2.7 g/t Au, and 5.2 g/t Ag. Reserves of 17.1 tonnes Au, 20.1 tonnes Ag.</td></tr>
<tr><td colspan="4">Deposit occurs near the margin of an Early Cretaceous granodiorite intrusion in both the intrusion and in adjacent country rock that consists of contact-metamorphosed Jurassic sandstone and siltstone. Deposit consists of veins of quartz, quartz-feldspar, quartz-tourmaline and quartz-carbonate and altered zones of quartz, K-feldspar, sericite and albite. The veins and zones vary from 1 to 50 m thick and in branch plan view with variable trends. Deposit is large, is low grade and has no visible boundaries. Extent of deposit determined by geochemical sampling. Gold and Au-sulfides occur. The Au deposit mineral assemblage consists of quartz-adularia-carbonate veins and the Au-sulfide type consists of quartz veins with pyrite, galena, stibinite and Ag-sulfosalts. References: N.E. Malyamin and V.E. Bochkareva, written commun., 1990; V.N. Akatkin, written commun., 1991.</td></tr>
<tr><td>N50-16
52 22 00N
115 33 00 E</td><td>Darasunskoye
Russia
Nerchinskiy</td><td>Au

Granitoid-related Au vein</td><td>Grades up to a few to 300 ppm Au, with average grade 6.5 ppm Au.</td></tr>
<tr><td colspan="4">Consists of over 120 steeply-dipping quartz-sulfide veins that extend along strike for 1.0-1.2 km. The zone of veins ranges from 100 to 1000 m thick and individual veins range from 5-20 cm thick. A zone of wall rock marginal to the veins is about 0.6-1.5 m thick and contains disseminated sulfides. Main ore minerals are pyrite, arsenopyrite, chalcopyrite, pyrrhotite, galena, sphalerite, Pb, Cu, Ag, Bi, As, Sb sulfosalts, tellurides, native gold, quartz, carbonates, and tourmaline. The principal economic gold-bearing mineral assemblages are: chalcopyrite-gray ore, chalcopyrite-pyrrhotite, pyrite-arsenopyrite, and sphalerite-galena. Gold occurs in arsenopyrite, pyrite, chalcopyrite, pyrrhotite, and gray ore, and is finely dispersed. The deposit ocurs along the Mongol-Okhotsk suture high Middle and late Cretacous K granodiorite-porphyry that intrudes a volcanic dome. Reference: Zvyagin and Sizikov, 1971.</td></tr>
<tr><td>M48-24
48 45 00N
106 09 00E</td><td>Boroo
Mongolia
North Hentii 2</td><td>Au

Granitoid-related Au vein</td><td>Average grade of 3.0 g/t Au. Resource of 40.0 tonnes Au.</td></tr>
<tr><td colspan="4">Deposit hosted by altered units of early Mesozoic gabbro, diabase, and diorite dikes. Deposit extends approximately 2.0 km along strike and ranges from 3-5-34 m thick. The ore mineral assemblages, from older to younger, are: pre-ore epidote-chlorite; quartz-sericite-albite-chlorite; gold-pyrite-arsenopyrite-K-feldspar-quartz; gold-beresite; quartz; gold-sulphide-quartz vein; and post ore calcite. Gold is fine-grained and occurs in pyrite and arsenopyrite, and as free gold in quartz veins. Main ore minerals are pyrite, arsenopyrite, sphalerite, chalcopyrite, galena, tetrahedrite, and gold. Main gangue minerals are quartz, sericite, iron-carbonates, calcite, albite and muscovite. References: Blagonravov and Shabalovskii, 1977; Dejidmaa, 1985.</td></tr>
</table>

J51-10 53 27 00N 126 27 00E	Sanshandao, Shandong Province China Jiliaolu	Au Granitoid-related Au vein	Average grade of 6.13 g/t Au. Reserves of 59 tonnes Au.

Consists of stockwork more than 10 m thick, 1000 m long, several hundred m along the dip. The body is controlled by NE-trending faults. The deposit minerals occur in a veinlet-stockwork and are composed of electrum, native gold, pyrite, galena, sphalerite, molybdenite and quartz and sericite. The host rock alteration include silica alteration, sericite alteration and pyrite alteration and local alteration to K feldspar. Four deposition stages, that is the stages of pyrite-quartz, of quartz-fine pyrite, of quartz-base metallic sulphides and of quartz-carbonates, are recognized. The gold deposition temperature is about 350-230° C and is related to the Cretaceous granite (with a K-Ar isotopic age of 126-137 Ma). Reference: Liu, Jianjun, 1990

Table 3. List of lode mineral deposit models employed for metallogenic analysis of Northeast Asia. Adapted from Obolenskiy and others (2003, this volume).

Deposit Group	Deposit Name
Deposits related to mafic and ultramafic intrusions	Mafic-ultramafic related Cu-Ni-PGE Mafic-ultramafic related Ti-Fe (±V) Zoned mafic-ultramafic Cr-PGE Podiform chromite Anorthosite apatite-Ti-Fe-P Diamond-bearing kimberlite
Deposits related to intermediate and felsic intrusions	Muscovite pegmatite REE-Li pegmatite Fluorite greisen Sn-W greisen, stockwork, and quartz vein W-Mo-Be greisen, stockwork, and quartz vein Ta-Nb-REE alkaline metasomatite Au skarn Boron (datolite) skarn Carbonate-hosted asbestos Co skarn Cu (±Fe, Au, Ag, Mo) skarn Fe skarn Fe-Zn skarn Sn skarn Sn-B (Fe) skarn (ludwigite) W±Mo±Be skarn Zn-Pb (±Ag, Cu) skarn Cassiterite-sulfide-silicate vein and stockwork Felsic plutonic U-REE Granitoid-related Au vein Polymetallic Pb-Zn ± Cu (±Ag, Au) vein and stockwork Porphyry Au Porphyry Cu (±Au) Porphyry Cu-Mo (±Au, Ag) Porphyry Mo (±W, Bi) Porphyry Sn
Deposits related to alkaline intrusions	Apatite carbonatite Fe-REE carbonatite Fe-Ti (±Ta, Nb, Fe,Cu, apatite) carbonatite Phlogopite carbonatite REE (±Ta, Nb, Fe) carbonatite Alkaline complex-hosted Au Peralkaline granitoid-related Nb-Zr-REE Albite syenite-related REE Ta-Li ongonite Charoite metasomatite Magmatic and metasomatic apatite Magmatic graphite Magmatic nepheline
Deposits related to marine extrusive rocks	Besshi Cu-Zn-Ag massive sulfide Cyprus Cu-Zn massive sulfide Korean Pb-Zn massive sulfide Volcanogenic Cu-Zn massive sulfide (Urals type) Volcanogenic Zn-Pb-Cu massive sulfide (Kuroko, Altai types) Volcanogenic-hydrothermal-sedimentary massive sulfide Pb-Zn (±Cu) Volcanogenic-sedimentary Fe Volcanogenic-sedimentary Mn

Deposits related to subaerial extrusive rocks	Ag-Sb vein
	Basaltic native Cu (Lake Superior type)
	Hg-Sb-W vein and stockwork
	Hydrothermal Iceland spar
	Ni-Co arsenide vein
	Silica-carbonate (listvenite) Hg
	Trap related Fe skarn (Angara-Ilim type)
	Au-Ag epithermal vein
	Ag-Pb epithermal vein
	Au potassium metasomatite (Kuranakh type)
	Barite vein
	Be tuff
	Carbonate-hosted As-Au metasomatite
	Carbonate-hosted fluorspar
	Carbonate-hosted Hg-Sb
	Clastic sediment-hosted Hg±Sb
	Epithermal quartz-alunite
	Fluorspar vein
	Hydrothermal-sedimentary fluorite
	Limonite
	Mn vein
	Polymetallic (Pb, Zn±Cu, Ba, Ag, Au) volcanic-hosted metasomatite
	Polymetallic (Pb, Zn, Ag) carbonate-hosted metasomatite
	Rhyolite-hosted Sn
	Sulfur-sulfide (S, FeS_2)
	Volcanic-hosted Au-base-metal metasomatite
	Volcanic-hosted Hg
	Volcanic-hosted U
	Volcanic-hosted zeolite
Deposits related to hydrothermal-sedimentary sedimentary processes	Bedded barite
	Carbonate-hosted Pb-Zn (Mississippi valley type)
	Sediment-hosted Cu
	Sedimentary exhalative Pb-Zn (SEDEX)
	Chemical-sedimentary Fe-Mn
	Evaporate halite
	Evaporate sedimentary gypsum
	Sedimentary bauxite
	Sedimentary celestite
	Sedimentary phosphate
	Sedimentary Fe-V
	Sedimentary siderite Fe
	Stratiform Zr (Algama Type)
	Polygenic REE-Fe-Nb deposits (Bayan-Obo type)
Deposits related to metamorphic processes	Banded iron formation (BIF, Algoma Fe)
	Homestake Au
	Sedimentary-metamorphic borate
	Sedimentary-metamorphic magnesite
	Au in black shale
	Au in shear zone and quartz vein
	Clastic-sediment-hosted Sb-Au
	Cu-Ag vein
	Piezoquartz
	Rhodusite asbestos
	Talc (magnesite) replacement
	Metamorphic graphite
	Metamorphic sillimanite
	Phlogopite skarn

Deposits related to surficial proceses	Bauxite (karst type) Laterite Ni Weathering crust Mn (±Fe) Weathering crust and karst phosphate Weathering crust carbonatite REE-Zr-Nb-Li Placer and paleoplacer Au Placer diamond Placer PGE Placer Sn Placer Ti-Zr REE and Fe oolite
Exotic deposits	Impact diamond

Table 4. Major metallogenic belts in Northeast Asia during the Middle Jurassic through Early Cretaceous (175 to 96 Ma). Adapted from Rodionov and others (2004).

Symbol and Belt Name	Mineral Deposit Types in Belt	Unit or Structure Related to Origin of Belt	Age Range of Belt	Tectonic Event for Origin of Belt
AG Aginskiy	Hg-Sb-W vein and stockwork REE-Li pegmatite Sn-W greisen, stockwork, and quartz vein Ta-Nb-REE alkaline metasomatite	Veins, volcanic complexes, and replacements related to Trans-Baikalian-Daxinganling sedimentary-volcanic-plutonic belt.	Middle Jurassic to Early Cretaceous.	Interpreted as forming during transform-continental margin faulting (Mongok-Okhotsk and related faults) and magmatism during late-stage of closing, and after closing of Mongol-Okhotsk Ocean.
AN Adycha-Nera	Au in shear zone and quartz vein Granitoid-related Au vein Sn-W greisen, stockwork, and quartz vein	Veins in Kular-Nera terrane.	Late Jurassic to Early Cretaceous (Neocomian).	Interpreted as forming during regional metamorphism and collisional granitoid intrusion that occurred with accretion of Kolyma-Omolon superterrane to northeastern margin of the Verkhoyansk (North Asian) Craton Margin.
AR Ariadny	Mafic-ultramafic related Ti-Fe (±V) Zoned mafic-ultramafic Cr-PGE	Plutons intruding Samarka terrane.	Middle Jurassic and Early Cretaceous.	Interpreted as forming during generation of ultramafic and gabbroic plutons with accretion and underthrusting of the Kula oceanic ridge along a transform continental margin.
AY Allakh-Yun'	Au in black shale Au in shear zone and quartz vein Cu (±Fe, Au, Ag, Mo) skarn	Veins in Verkhoyansk (North Asian) Craton Margin.	Late Jurassic.	Interpreted as forming during accretion of the Okhotsk terrane to the Verkhoyansk (North Asian) Craton Margin.
BD Bindong	Fe skarn W±Mo±Be skarn Zn-Pb (±Ag, Cu) skarn	Replacements related to small granitoids in the Mesozoic Jihei volcanic and plutonic belt.	Late Jurassic to Early Cretaceous.	Interpreted as forming along northeast- and east-west-striking regional faults during interplate magmatism that occurred during extensional tectonism related to oblique subduction of the Pacific Oceanic plate beneath Eurasian continental margin.
CA Chara-Aldan	Au in shear zone and quartz vein Au potassium metasomatite Au skarn Charoite metasomatite	Replacements and granitoids related to South Yakutian subalkaline and alkaline igneous belt.	Jurassic to Early Cretaceous.	Interpreted as forming in a suite subalkaline and alkaline plutonic rocks that formed in back-arc region of the Stanovoy plutonic belt that was an Andean type continental-margin arc that formed along the Jurassic and Early Cretaceous margin of the North Asian Craton.
CH Chybaga-lakh	Cassiterite-sulfide-silicate vein and stockwork Granitoid-related Au vein Sn-B (Fe) skarn (ludwigite)	Veins and replacements in Main granite belt.	Late Jurassic to Early Neocomian.	Interpreted as forming during generation of anatectic high-alumina granitoids during accretion of Kolyma-Omolon superterrane to northeastern margin of the Verkhoyansk (North Asian) Craton Margin.
DL Djeltu-laksky	Granitoid-related Au vein	Granitoids related to Stanovoy granite belt.	Early Cretaceous	Interpreted as forming during late-stage accretion of the Bureya superterrane to with the North Asian Craton to the north during final closure of the Mongol-Okhotsk Ocean.

DS Dzid-Selenginskiy	Au skarn Fluorspar vein Granitoid-related Au vein Magmatic and metasomatic apatite Porphyry Mo (±W, Bi) W-Mo-Be greisen, stockwork, and quartz vein	Veins, replacements, and plutons related to Trans-Baikalian-Daxinganling sedimentary-volcanic-plutonic belt.	Middle Jurassic to Early Cretaceous.	Interpreted as forming during subalkaline and alkaline granitoid magmatism associated with transform-continental margin faulting (Mongol-Okhotsk and related faults) and magmatism during late-stage of closing, and after closing of Mongol-Okhotsk Ocean.
DX Daxingan-ling	Au-Ag epithermal vein Cassiterite-sulfide-silicate vein and stockwork Peralkaline granitoid-related Nb-Zr-REE Polymetallic Pb-Zn ± Cu (±Ag, Au) vein and stockwork Sn skarn Zn-Pb (±Ag, Cu) skarn	Veins, replacements, and granitoids related to Trans-Baikalian-Daxinganling sedimentary-volcanic-plutonic belt.	Late Jurassic and Early Cretaceous.	Interpreted as forming during transform-continental margin faulting (Mongol-Okhotsk and related faults) and magmatism during late-stage of closing, and after closing of Mongol-Okhotsk Ocean.
EMA East Mongolian-Priargun-skiy-Deerbugan	Au skarn Au-Ag epithermal vein Carbonate-hosted Hg-Sb Carbonate-hosted As-Au metasomatite Fluorspar vein Granitoid-related Au vein Polymetallic (Pb, Zn, Ag) carbonate-hosted metasomatite Polymetallic (Pb, Zn±Cu, Ba, Ag, Au) volcanic-hosted metasomatite Porphyry Cu-Mo (±Au, Ag) Porphyry Mo (±W, Bi) Sedimentary siderite Fe Sn-W greisen, stockwork, and quartz vein Volcanic-hosted Au-base-metal metasomatite Volcanic-hosted U W-Mo-Be greisen, stockwork, and quartz vein Zn-Pb (±Ag, Cu, W) skarn	Veins, volcanic complexes, replacements, and granitoids related to Trans-Baikalian-Daxinganling sedimentary-volcanic-plutonic.	Middle Jurassic to Early Cretaceous.	Interpreted as forming during transform-continental margin faulting (Mongok-Okhotsk and related faults) and magmatism during late-stage of closing, and after closing of Mongol-Okhotsk Ocean.
ER Erikit	Volcanogenic Zn-Pb-Cu massive sulfide (Kuroko, Altai types)	Uyandina-Yasachnaya volcanic belt and Ilin–Tas back arc basin in Kolyma-Omolon superterrane.	Late Jurassic.	Belt interpreted as related to a subduction-related magmatic arc that formed on the southwest margin of the Kolyma-Omolon superterrane.
ERA Eravninsky	Cassiterite-sulfide-silicate vein and stockwork Carbonate-hosted fluorspar	Replacements, volcanic complexes related to Trans-Baikalian-Daxinganling (trbv) sedimentary-volcanic-plutonic belt.	Middle Jurassic to Early Cretaceous.	Interpreted as forming during transform-continental margin faulting (Mongok-Okhotsk and related faults) and magmatism during late-stage of closing, and after closing of Mongol-Okhotsk Ocean.

GT Govi-Tamsag	Evaporite sedimentary gypsum Sedimentary celestite Sediment-hosted U Volcanic-hosted zeolite	Stratiform units in Trans-Baikalian-Daxinganling sedimentary-volcanic-plutonic belt.	Late Jurassic to Early Cretaceous.	Interpreted as forming during transform-continental margin faulting (Mongok-Okhotsk and related faults) and magmatism during late-stage of closing, and after closing of Mongol-Okhotsk Ocean.
GY Gyeonggi	Mafic-ultramafic related Ti-Fe (±V) Polymetallic Pb-Zn ± Cu (±Ag, Au) vein and stockwork W±Mo±Be skarn	Mafic-ultramafic plutons and granitoids related to Daebo Granite belt.	Early Jurassic.	Belt related to magmatism that formed along transtensional zones along a transform microplate boundary.
HS Hartolgoi-Sulinheer	Au-Ag epithermal vein Ag-Pb epithermal vein Carbonate-Hosted Ag-Pb Carbonate-hosted Hg-Sb Polymetallic Pb-Zn ± Cu (±Ag, Au) vein and stockwork Porphyry Mo Silica-carbonate (Listvenite) Hg W±Mo±Be skarn	Veins and replacements related to latite and lamporphyre dikes in Trans-Baikalian-Daxinganling sedimentary-volcanic-plutonic belt.	Late Jurassic to Early Cretaceous.	Interpreted as forming during transform-continental margin faulting (Mongok-Okhotsk and related faults) and magmatism during late-stage of closing, and after closing of Mongol-Okhotsk Ocean.
JLL Jiliaolu	Cu (±Fe, Au, Ag, Mo) skarn Granitoid-related Au vein Polymetallic Pb-Zn ± Cu (±Ag, Au) vein and stockwork Volcanic-hosted Au-base metal metasomatite Zn-Pb (±Ag, Cu) skarn	Replacements and granitoids related to Jilin-Liaoning-East Shandong volcanic-plutonic belt.	Middle Jurassic to Early Cretaceous.	Interpreted as forming during interplate magmatism that occurred during extensional tectonism related to oblique subduction of the Pacific Oceanic plate beneath Eurasian continental margin.
KD Kondyor-Feklistov	Zoned mafic-ultramafic Cr-PGE	Mafic-ultramafic intrusions intruded along major faults cuitting North Asian Craton and northeastern part of Tukuringra-Dzhagdy terrane.	Early Cretaceous.	Interpreted as forming during intrusion of mafic-ultramafic plutons along a deep-seated fault that formed along the North Asian Craton margin during collision and accretion of outboard terranes.
KM Kamuikotan	Podiform chromite	Ultramafic rocks that comprise part of an ophiolite in Kamuikotan complex in Shimanto accretionary wedge terrane.	Late Jurassic to Early Cretaceous.	Belt is interpreted as forming during generation of an ophiolite that was incorporated into an accretionary wedge.
KR Khilokskiy	Sn-W greisen, stockwork, and quartz vein	Veins, replacements, granitoids, volcanic complexes related to Trans-Baikalian-Daxinganling sedimentary-volcanic-plutonic belt.	Middle Jurassic to Early Cretaceous.	Interpreted as forming during transform-continental margin faulting (Mongol-Okhotsk and related faults) and magmatism during late-stage of closing, and after closing of Mongol-Okhotsk Ocean.
KS Kerbi-Selemdzha	Au in shear zone and quartz vein Cassiterite-sulfide-silicate vein and stockwork Granitoid-related Au vein	Veins in Tukuringra-Dzhagdy terrane and Badzhal terrane	Late Jurassic and Early Cretaceous.	Interpreted as forming during regional metamorphism and intrusion of anatectic granitoids that formed during collision of the Bureya and Khanka continental-margin arc superterranes with the North Asian Craton.

KT Kitakami	Cu (±Fe, Au, Ag, Mo) skarn Granitoid-related Au vein	Replacements associated with Early Cretaceous part of Hiroshima granitic plutonic belt.	Early Cretaceous (Aptian through Albian).	Interpreted as forming during early stage of intrusion of granitoids along a continental-margin arc.
KTN Kurai-Tolbo Nuur	Ag-Pb epithermal vein Ag-Sb vein Au-Ag epithermal vein Carbonate-hosted Hg-Sb Clastic sediment-hosted Hg±Sb Ni-Co arsenide vein, Silica-carbonate (listvenite) Hg Volcanogenic-hydrothermal-sedimentary massive sulfide Pb-Zn (±Cu)	Replacements in West Sayan and Hovd terranes.	Early and Middle Jurassic.	Interpreted as forming during interplate alkaline basalt magmatism that formed during intraplate rifting and strike-slip block faulting along the complex, major Kuznetsk-Altai fault.
KU Kular	Au in shear zone and quartz vein Granitoid-related Au Vein Sn-W greisen, stockwork, and quartz vein	Veins in Kular-Nera terrane.	Late Jurassic to Early Neocomian.	Interpreted as forming during regional metamorphism and collisional granitoid intrusion that occurred with accretion of Kolyma-Omolon superterrane to northeastern margin of the Verkhoyansk (North Asian) Craton Margin.
MH Mushgaihud ag-Olgiihiid	Be-tuff REE (±Ta, Nb, Fe) carbonatite	Stratiform units in Trans-Baikalian-Daxinganling sedimentary-volcanic-plutonic belt.	Late Jurassic to Early Cretaceous.	Interpreted as forming during rifting associated with transform-continental margin faulting (Mongok-Okhotsk and related faults) and magmatism during late-stage of closing, and after closing of Mongol-Okhotsk Ocean.
NB North Bureya	Au-Ag epithermal vein Granitoid-related Au vein	Veins and granitoids related to Umlekam-Ogodzhin volcanic-plutonic belt.	Early Cretaceous.	Interpreted as forming during formation of Umlekan-Ogodzhin continental-margin arc.
NE Nerchinsky	Fluorspar vein Granitoid-related Au vein W-Mo-Be greisen, stockwork, and quartz vein	Granitoids and replacements related to Trans-Baikalian-Daxinganling sedimentary-volcanic-plutonic belt.	Middle Jurassic to Early Cretaceous.	Interpreted as forming during transform-continental margin faulting (Mongol-Okhotsk and related faults) and magmatism during late-stage of closing, and after closing of Mongol-Okhotsk Ocean.
NJ North Jilin	Au-Ag epithermal vein Fluorspar vein Granitoid-related Au vein Porphyry Cu (±Au) Polymetallic Pb-Zn (±Cu, Ba, Ag, Au) volcanic-hosted metasomatite Porphyry Mo (±W, Bi) Zn-Pb (±Ag, Cu) skarn	Replacements and granitoids in the North marginal plutonic belt of North China Platform.	Middle Jurassic to Early Cretaceous.	Interpreted as related to magmatism that formed along transpression zones along a transform micro plate boundary represented by the major Tanlu strike-slip fault system.
NS North Stanovoy	Au-Ag epithermal vein Granitoid-related Au vein	Granitoids related to Stanovoy granite belt.	Early Cretaceous.	Interpreted as forming during transform-continental margin faulting (Mongol-Okhotsk and related faults) and magmatism during late-stage of closing, and after closing of Mongol-Okhotsk Ocean.

OCH Onon-Chikoiskiy	Sn-W greisen, stockwork, and quartz vein W-Mo-Be greisen, stockwork, and quartz vein	Veins, replacements, volcanic complexes and granitoids related to Trans-Baikalian-Daxinganling sedimentary-volcanic-plutonic belt.	Middle Jurassic to Early Cretaceous.	Interpreted as forming during transform-continental margin faulting (Mongol-Okhotsk and related faults) and magmatism during late-stage of closing, and after closing of Mongol-Okhotsk Ocean.
OT Onon-Turinskiy	Cassiterite-sulfide-silicate vein and stockwork Granitoid-related Au vein Porphyry Au	Veins, volcanic complexes, and replacements related to Trans-Baikalian-Daxinganling sedimentary-volcanic-plutonic belt.	Middle Jurassic to Early Cretaceous.	Interpreted as forming during transform-continental margin faulting (Mongol-Okhotsk and related faults) and magmatism during late-stage of closing, and after closing of Mongol-Okhotsk Ocean.
PO Polousny	Cassiterite-sulfide-silicate vein and stockwork Polymetallic Pb-Zn ± Cu (±Ag, Au) vein and stockwork	Granitoids related to Northern granite belt.	Middle Cretaceous (Neocomian to Aptian).	Interpreted as forming during regional metamorphism and collisional granitoid intrusion that occurred with accretion of Kolyma-Omolon superterrane to northeastern margin of the Verkhoyansk (North Asian) Craton Margin.
SA Samarka	Porphyry Cu-Mo (±Au, Ag) Porphyry Mo (±W, Sn, Bi) W±Mo±Be skarn	Replacements and granitoids in Khungari-Tatibi granitic belt.	Early to mid-Cretaceous.	Interpreted as forming during generation of collisional grantitoids during underthrusting of the Kula oceanic ridge and formation of bimodal igneous rocks along a transform continental margin.
SCS Sambagawa-Chichibu-Shimanto	Besshi Cu-Zn-Ag massive sulfide (Cu, Zn, Ag) Volcanogenic-sedimentary Mn, and Cyprus Cu-Zn massive sulfide	Shimanto accretionary wedge terrane, Mino Tamba Chichibu accretionary wedge terrane, and Sambagawa metamorphic terrane.	Early Jurassic and to Late Cretaceous (Campanian).	Mn deposits interpreted as forming in syngenetic setting on the ocean floor. Besshi and Cyprus deposits interpreting as forming during submarine volcanism related to spreading ridge. Deposits subsequently incorporated into an accretionary wedge.
SH Shilkinsko-Tukuringr-skiy	Au skarn Au-Ag epithermal vein Cassiterite-sulfide-silicate vein and stockwork Fluorite vein Granitoid-related Au vein Polymetallic Pb-Zn ± Cu (±Ag, Au) vein and stockwork Porphyry Au Porphyry Mo (±W, Bi) Ta-Nb-REE alkaline metasomatite W-Mo-Be greisen, stockwork, and quartz vein	Granitoids, volcanic rocks, and replacements related to Trans-Baikalian-Daxinganling sedimentary-volcanic-plutonic belt.	Middle Jurassic to Early Cretaceous.	Interpreted as forming during transform-continental margin faulting (Mongol-Okhotsk and related faults) and magmatism during late-stage of closing, and after closing of Mongol-Okhotsk Ocean.
TA Taebaegsan	Au in shear zone and quartz vein Fe skarn Fe-Zn skarn Polygenic REE-Fe-Nb REE-Li pegmatite W±Mo±Be skarn Zn-Pb (Ag, Cu, W) skarn	Replacements and dikes related to Daebo Granite belt.	Middle Jurassic through Early Cretaceous.	Belt related to magmatism that formed along transtensional zones along a transform microplate boundary.

TO Tompo	W±Mo±Be skarn (Agylky); Sn-W greisen, stockwork, and quartz vein	Replacements in Transverse granite belt.	Early Cretaceous (Neocomian)	Interpreted as forming during collision of the Kolyma-Omolon superterrane and the North Asian Craton and associated regional metamorphism and generation of anatectic granitoids.
VIG Verkhne-Ingodi	Cassiterite-sulfide-silicate vein and stockwork	Veins, volcanic complexes, and replacements related to Trans-Baikalian-Daxinganling sedimentary-volcanic-plutonic belt.	Middle Jurassic to Early Cretaceous.	Interpreted as forming during transform-continental margin faulting (Mongol-Okhotsk and related faults) and magmatism during late-stage of closing, and after closing of Mongol-Okhotsk Ocean.
VK Verkho-yansk	Au in black shale Au in shear zone and quartz vein Polymetallic Pb-Zn ± Cu (±Ag, Au) vein and stockwork Sn-W greisen, stockwork, and quartz vein	Veins and replacements in Verkhoyansk (North Asian) Craton Margin.	Cretaceous to Paleogene.	Interpreted as forming during regional metamorphism and collisional granitoid intrusion that occurred with accretion of Kolyma-Omolon superterrane to northeastern margin of the Verkhoyansk (North Asian) Craton Margin.
YA Yana-Adycha	Cassiterite-sulfide-silicate vein and stockwork Sn-W greisen, stockwork, and quartz vein	Replacements in Transverse granite belt.	Mid-Cretaceous.	Interpreted as forming during regional metamorphism and collisional granitoid intrusion that occurred with accretion of Kolyma-Omolon superterrane to northeastern margin of the Verkhoyansk (North Asian) Craton Margin.
YS Yanshan	Au-Ag epithermal vein Cu (±Fe, Au, Ag, Mo) skarn Granitoid-related Au vein Polymetallic Pb-Zn ± Cu (±Ag, Au) vein and stockwork Porphyry Mo (±W, Bi) W±Mo±Be skarn	Veins, replacements, and granitoids related to Yanliao volcanic and sedimentary basin and plutonic belt.	Middle Jurassic to Early Cretaceous.	Interpreted as forming during interplate magmatism that occurred during extensional tectonism related to oblique subduction of the Pacific Oceanic plate beneath Eurasian continental margin.