# Overview of Methodology of Combined Regional Metallogenic and Tectonic Analysis

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## Abstract

The compilation, synthesis, description, and interpretation of metallogenesis and tectonic history of major regions, such as the Circum-North Pacific (Russian Far East, Alaska, and Canadian Cordillera) and Northeast Asia, constitute a complex process. The complex process includes (1) definitions of key terms, (2) compilation of a regional geologic base map that can be interpreted according to modern tectonic concepts and definitions, (3) compilation of a mineral deposit database that enables the determination of mineral deposit models, relation of deposits to host rocks, and tectonic origins, (4) synthesis of a series of mineral deposit models that characterize the known mineral deposits and inferred undiscovered deposits of the region, (5) compilation of a series of maps of metallogenic belts constructed on the regional geologic base map, and (6) formulation of a metallogenic and tectonic model. This paper presents an overview of the methodology used for the Circum-North Pacific and Northeast Asia and an example of a metallogenic and tectonic model for the origin of Late Cretaceous and early Tertiary igneous-arc-related deposits in the Circum-North Pacific. This paper also describes how a high-quality metallogenic and tectonic analysis and synthesis of an associated metallogenic and tectonic model will provide the following benefits: (1) refinement of mineral deposit models and of the understanding of deposit genesis, (2) improvement of assessments of undiscovered mineral resources as part of quantitative mineral resource assessment studies, (3) data to consider in land use and mineral exploration planning, (4) improvement of interpretations of origins of host rocks, mineral deposits, and metallogenic belts, and (5) guidelines for new research.

## Introduction

This paper presents an overview of the methodology and key definitions for combined regional metallogenic and tectonic analysis, provides a theoretical example of this type of analysis, and describes an example for this type of analysis for Late Cretaceous and early Tertiary igneous-arc-related deposits in the Circum-North Pacific (Russian Far East, Alaska, and Canadian Cordillera). The major sections of this paper are (1) definitions, compilations, and syntheses needed for a combined metallogenic and tectonic analysis, (2) theoretical example of methodology, (3) synthesis of a combined metallogenic and tectonic model, (4) benefits of performing a combined regional metallogenic and tectonic analysis, and (5) summary.

In the past, three types of problems have limited some metallogenic and tectonic analyses: (1) a concentration of some metallogenic studies on the features of mineral deposits and districts without any regional compilation, synthesis, and interpretation, (2) a lack of integration of regional studies of host rocks, structures, and tectonic origins with respect to contained suites of mineral deposits, and (3) in some regions, application of a stabilistic tectonic philosophy. In contrast, this paper demonstrates the power of a combined regional and metallogenic and tectonic analysis that requires (1) use of modern concepts and mineral deposit databases, (2) formulation of mineral deposit models, (3) construction of regional geologic and metallogenic belt maps, (4) interpretation of major geologic units and contained mineral deposits according to latest tectonic methods, and (5) synthesis of an integrated metallogenic and tectonic model.

This paper is derived from relatively recent metallogenic studies by the U.S. Geological Survey, including (1) a series of

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regional geologic, mineral deposit, and metallogenic belt maps of the Russian Far East, Alaska, and the Canadian Cordillera (Nokleberg and others, 1997a,b,c; Nokleberg, West, and others, 1998), (2) a series of metallogenic and tectonic analyses of the same region (Nokleberg and others, 1995, 2000, 2001, 2003; Scotese and others, 2001), and (3) a series of similar publications being prepared for Northeast Asia (Eastern Russia, Mongolia, Northeast China, South Korea, and Japan) (Nokleberg and others, 1999).

## Definitions, Compilations, and Syntheses Needed for a Combined Metallogenic and Tectonic Analysis

For a metallogenic and tectonic analysis, the key goal is to define, analyze, and interpret the crustal origin and evolution of mineralizing systems. To achieve this goal, the following materials are needed: (1) definitions of key terms, (2) a regional geologic base map that can be interpreted according to modern tectonic concepts and definitions, (3) a mineral deposit database that enables the determination of mineral deposit models, relation of deposits to host rocks, and tectonic origins, (4) a series of mineral deposit models that characterize the known mineral deposits and inferred undiscovered deposits of the region, (5) a series of metallogenic belt maps constructed on the regional geologic base map, and (6) a metallogenic and tectonic model. Figure 1 illustrates these materials and the methodology for synthesizing a combined metallogenic and tectonic model. In this figure, parts 1 and 2 portray a regional geologic base map and a metallogenic belt overlay. Part 3 portrays a mineral deposit database and mineral deposit models. Part 4 portrays the major steps for synthesizing a metallogenic and tectonic model. Part 5 portrays one stage of the model. Part 6 portrays the applications resulting from this type of analysis. These applications provide the following benefits: (1) refinement of mineral deposit models and of the understanding of deposit genesis, (2) improvement of assessments of undiscovered mineral resources as part of quantitative mineral resource assessment studies, (3) data to consider in land use and mineral exploration planning, (4) improvement of interpretations of origins of host rocks, mineral deposits, and metallogenic belts, and (5) guidelines for new research.

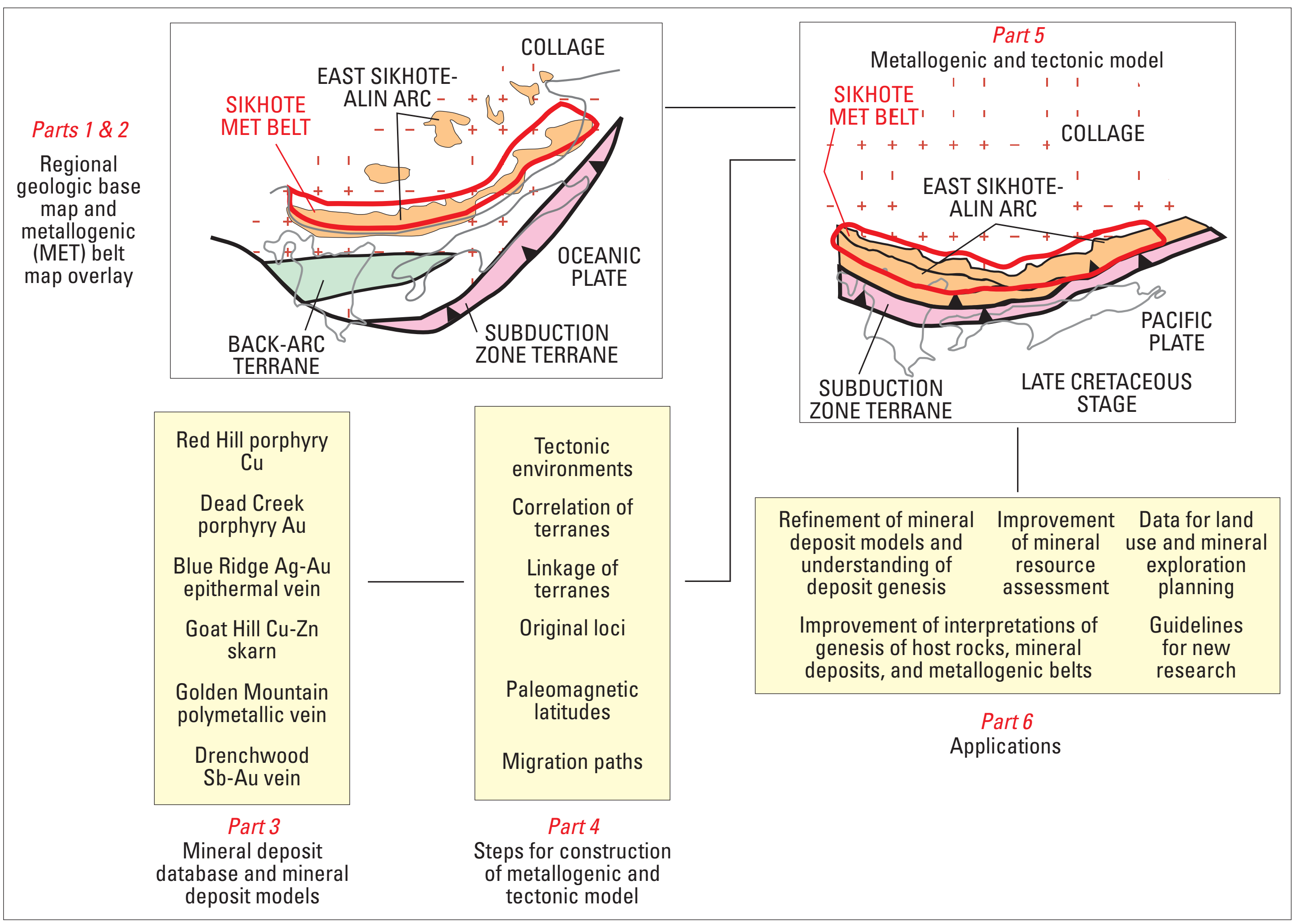


**Figure 1.** Diagram showing major components of a metallogenic analysis and synthesis of a metallogenic and tectonic model.

## Key Definitions for a Metallogenic and Tectonic Analysis

For the compilation, synthesis, description, and interpretation of metallogenic belts, the following mineral deposit, metallogenic, and tectonic definitions are used. The definitions are adapted from Coney and others (1980), Jones and others (1983), Howell and others (1985), Monger and Berg (1987), Wheeler and others (1988), Nokleberg, Bundtzen, and others (1994), Nokleberg, Parfenov, and others (1994), Nokelberg and others (2001), and Scotese and others (2001).

**accretion** Tectonic juxtaposition of two or more terranes, or tectonic juxtaposition of terranes to a craton margin. Accretion of terranes to one another or to a craton margin also defines a major change in the tectonic evolution of terranes and craton margins.

**accretionary wedge and subduction-zone 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 oceanic mantle. Divided into units composed predominantly of turbidite deposits or predominantly of oceanic rocks. Units are interpreted to have formed during tectonic juxtaposition in a zone of major thrusting of one lithosphere plate beneath another, generally in zones of thrusting along the margin of a continent or an island arc. May include large fault-bounded units having a coherent stratigraphy. Many subduction-zone terranes contain fragments of oceanic crust and associated rocks that exhibit a complex structural history, occur in a major thrust zone, and possess blueschist-facies metamorphism.

**collage of terranes** Groups of tectonostratigraphic terranes, generally in oceanic areas, for which insufficient data exist to separate units.

**continental-margin arc terrane** Fragment of an igneous belt of coeval plutonic and volcanic rocks and associated sedimentary rocks that formed above a subduction zone dipping beneath a continent. Inferred to possess a sialic basement.

**craton** Chiefly regionally metamorphosed and deformed shield assemblages of Archean and Early Proterozoic sedimentary, volcanic, and plutonic rocks, and overlying platform successions of Paleoproterozoic, Paleozoic, and local Mesozoic and Cenozoic sedimentary rocks containing some volcanic rocks.

**craton margin** Chiefly Late Proterozoic through Jurassic sedimentary rocks deposited on a continental shelf or slope. Consists mainly of platform successions. Locally has, or may have had, an Archean and Early Proterozoic cratonal basement.

**cratonal terrane** Fragment of a craton.

**deposit** A general term for any lode or placer mineral occurrence, mineral deposit, prospect, and (or) mine.

**island-arc terrane** Fragment of an igneous belt of plutonic rocks, coeval volcanic rocks, and associated sedimentary rocks that formed above an oceanic subduction zone. Inferred to possess a simatic basement.

**metallogenic belt** A geologic unit (area) that either contains or is favorable for a group of coeval and genetically related, significant lode and placer deposits described by deposit models (Nokleberg and others, 1997a,b; Nokelberg, West, and others 1998). A metallogenic belt (1) is favorable for known or inferred mineral deposits of a specific type or types, (2) can be of irregular shape and variable size, (3) need not contain known deposits, and (4) is based on a geologic map as the primary source of information for delineating areas that are favorable for deposits described by various deposit models. An essential part of the definition is that a belt is defined as the geologically favorable area for a group of coeval and genetically related mineral deposits. 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 rocks that cannot be assigned to a single tectonic environment because the original stratigraphy and structure are obscured. Includes intensely deformed structural mélanges that contain intensely deformed fragments of two or more terranes.

**metamorphosed-continental-margin terrane** Fragment of a passive continental margin, in places moderately to highly metamorphosed and deformed, that cannot be linked with certainty to the nearby craton margin. May be derived either from a nearby craton margin or from a distant site.

**mine** A site where valuable minerals have been extracted.

**mineral deposit** A site having concentrations of potentially valuable minerals for which grade and tonnage estimates have been made.

**mineral occurrence** A site having 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 eugeoclinal deep-marine sedimentary rocks, pillow basalt, gabbro, and ultramafic rocks that are interpreted as oceanic sedimentary and volcanic rocks and the upper mantle. Includes both inferred offshore oceanic and marginal ocean basin rocks, minor volcaniclastic rocks of magmatic arc derivation, and major marine volcanic accumulations formed at a hotspot, fracture zone, or spreading axis.

**overlap assemblage** A postaccretion unit of sedimentary or igneous rocks deposited on, or intruded into, two or more adjacent terranes. The sedimentary and volcanic parts either depositionally overlie, or are interpreted to have originally depositionally overlain, two or more adjacent terranes or terranes and the craton margin. Overlapping plutonic rocks, which may be coeval and genetically related to overlap volcanic rocks, link or stitch together adjacent terranes or a terrane and a craton margin.

**passive-continental-margin terrane** Fragment of a craton margin.

**postaccretion rock unit** Suite of sedimentary, volcanic, or plutonic rocks that formed in the late history of a terrane, after accretion. May occur also on adjacent terranes or on the craton margin either as an overlap assemblage or as a basinal deposit. A relative-time term denoting rocks formed after tectonic juxtaposition of one terrane to an adjacent terrane.

**preaccretion rock unit** Suite of sedimentary, volcanic, or plutonic rocks that formed in the early history of a terrane, before accretion. Constitutes the stratigraphy and igneous geology inherent to a terrane. A relative-time term denoting rocks formed before tectonic juxtaposition of one terrane to an adjacent terrane.

**prospect** A site having potentially valuable minerals in which excavation has occurred.

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

**subterrane** A fault-bounded unit within a terrane that exhibits similar, but not identical, geologic history relative to another fault-bounded unit in the same terrane.

**superterrane** An aggregate of terranes that is interpreted to share either a similar stratigraphic kindred or affinity or a common geologic history after accretion (Moore, 1992). An approximate synonym is "composite terrane" (Plafker and Berg, 1994).

**tectonic linkage** The interpreted association of a suite of coeval tectonic units that formed in the same region and as the result of the same tectonic processes. An example is the linking of a coeval continental-margin arc, fore-arc deposits, a back-arc rift assemblage, and a subduction-zone complex, all related to the underthrusting of a continental margin by oceanic crust.

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

**transform continental-margin arc** An igneous belt of coeval plutonic and volcanic rocks and associated sedimentary rocks that formed along a transform fault that occurs along the margin of a craton, passive continental margin, and (or) collage of terranes accreted to a continental margin.

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

## Regional Geologic Base Map

To define a metallogenic belt map for a metallogenic analysis, a regional geologic base map must be constructed that permits the display of a belt as a function of the host-rock geology or host-rock structures (Nokleberg and others, 1997a,b,c; Nokleberg, West, and others, 1998). To facilitate analysis of geologic relations and permit the estimation of undiscovered mineral deposits, the geologic base map must be constructed at the scale of the assessment and show the major geologic data that can be related to the presence of mineral deposits in each belt. Because metallogenic belts are generally of large areal extent, interpretation of the tectonic origin of host-rock geologic units must be considered in order to display the geologic controls over formation of groups of mineral deposits in a specific metallogenic belt.

An example of regional geologic base maps is portrayed in figure 2, which illustrates (1) a regional terrane and overlap assemblage (regional geologic) map for the Russian Far East (derived from Nokleberg and others, 1997b,c; Nokleberg, West, and others, 1998) and (2) major Late Cretaceous and early Tertiary igneous-arc-related metallogenic belts for the region. On the figure are the major Cretaceous and Cenozoic continental-margin arcs that host a large suite of igneous-arc-related metallogenic belts. The two major arcs are the East Sikhote-Alin arc and the Okhotsk-Chukotka arc. As background, the map also displays cratons, craton margins, previously accreted terranes of various types (cratonal, island arc, continental-margin arc, subduction zone, accretionary wedge), fore-arc and back-arc basins, major faults (sutures) bounding terranes, major active continental-margin arcs (Kuril-Kamchatka and Aleutian arcs), companion, outboard active subduction zones, and active faults.

Two major considerations exist for constructing a regional geologic map for a metallogenic analysis. (1) The regional geologic base map should display host-rock geology and structures that are related to metallogenic belts. For the Russian Far East (fig. 2), the regional geologic map displays the extent of surface outcrops of the major volcanic-plutonic arcs (East Sikhote-Alin and Okhotsk-Chukotka) that have and (or) are assessed to have potential for undiscovered igneous-rock-related mineral deposits described by deposit models (Nokleberg and others, 1997b,c; Nokleberg, West, and others, 1998). (2) Inclusion of graphic and descriptive data on the tectonic origin of host-rock geologic units is needed to establish the geologic controls for formation of groups of mineral deposits in metallogenic belts.

## Tectonic Environments

For a modern metallogenic and tectonic analysis, interpretation of tectonic environments is essential for interpreting the geologic origin of major units and contained mineral deposits and metallogenic belts. The interpretation of tectonic environment is a key method for linking geologic origins of these sometimes disparate datasets. In addition, as described below, interpretation of tectonic environments for mineral deposits is also an important facet of developing mineral deposit models. For tectonic analyses of the Circum-North Pacific and Northeast Asia (Nokleberg and others, 1999, 2001, 2003; Scotese and others, 2001), major geologic units (terranes, overlap assemblages, plates), mineral deposits, mineral deposit types, and metallogenic belts are described according to the following interpreted dominant tectonic environments: (1) cratonal, (2) passive continental margin, (3) metamorphosed continental margin, (4) continental-margin arc, (5) island arc, (6) oceanic crust, seamount, or ophiolite, (7) accretionary wedge and subduction zone, (8) turbidite basin, and (9) metamorphic, for terranes that are so highly deformed and

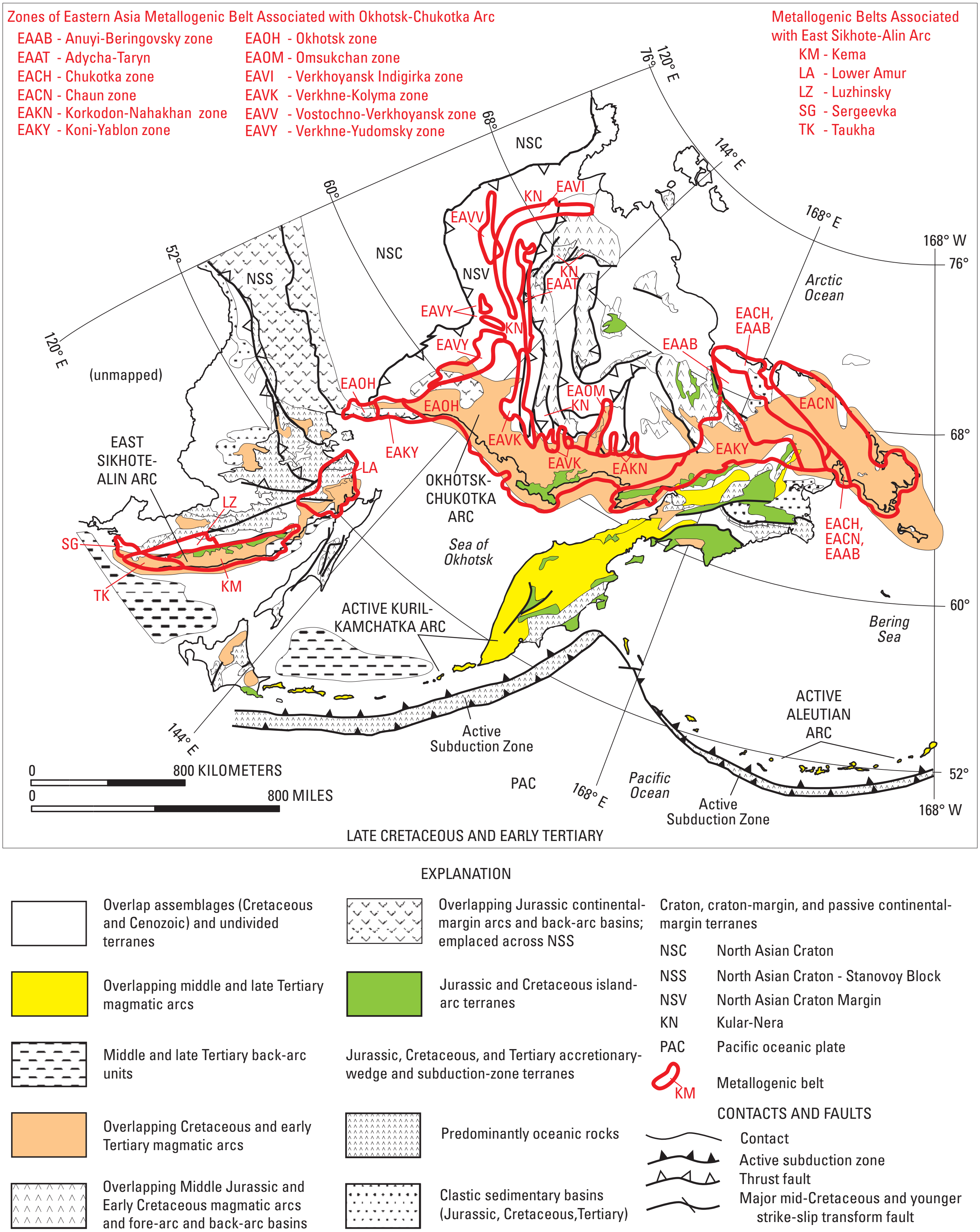


**Figure 2.** Regional geologic and tectonic map showing major postaccretionary, igneous-arc-related metallogenic belts hosted in Late Cretaceous through early Tertiary continental-margin igneous arcs in the Russian Far East. Adapted from Nokleberg and others (1997b,c) and Nokleberg, West, and others (1998).

(or) metamorphosed that determination of the original tectonic environment is difficult. For terranes having complex geologic histories, the chosen tectonic environment is the one most prevalent during the history of the terrane. Definitions of these tectonic environments are provided above.

## Mineral Deposit Descriptions

Part of the core dataset for a metallogenic analysis is a high-quality description of the significant known mineral deposits of the region. The descriptions need to systematically characterize the significant mineral deposits with sufficient detail that one can determine their classification by mineral deposit model and origin, and the descriptions should provide tonnage and grade data if available (Nokleberg and others, 1997a). The term "significant mineral deposit" is often used. As an example of mineral deposit data for a metallogenic analysis, table 1 provides sample descriptions of selected Cretaceous igneous-arc-related deposits for the Russian Far East.

## Mineral Deposit Models

Modern metallogenic analyses of large regions require that mineral deposit models appropriate for the region be characterized, synthesized, and grouped so that they can be correlated with the regional tectonic processes that formed the known deposits. The beginning of this type of correlation between models and tectonic process is evident in many of the classic compilations of mineral deposit models (Eckstrand, 1984; Cox and Singer, 1986; Singer, 1993). As an example of mineral deposit models used in a large region, table 2 lists the mineral deposit models that were defined and described for a metallogenic analysis of the Circum-North Pacific (Russian Far East, Alaska, and the Canadian Cordillera). For this large and complex region, a suite of 38 mineral deposit models was sufficient to describe the characteristic features of the 1,079 lode deposits and 148 placers (Nokleberg and others, 1996, 1997a). The models include previous descriptions from Eckstrand (1984) and Cox and Singer (1986), with modifications by the authors.

The mineral deposit models listed in table 2 usually consist of both descriptive and genetic information that is systematically arranged to define the essential properties of a class or type of mineral deposits. However, some model types are based mainly on descriptive (empirical) information, in which instance the various attributes are recognized as essential even though their relations are 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 types of 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, in 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) and Cox and Singer (1986).

Correlation of major tectonic events and environments with mineral deposit types (models) allows the necessary synthesis of mineral deposit models for a modern metallogenic analysis (Nokleberg and others, 1997a,b). Detailed analysis reveals that only a few types of tectonic events and corresponding environments exist for a wide array of mineral deposit models for this region. For the Russian Far East, Alaska, and the Canadian Cordillera (table 3), only seven tectonic environments are needed to classify the origins of the 1,079 lode deposits of this large and complex region (Nokleberg and others, 2000, 2001, 2003). These tectonic environments are (1) subduction-related arc, (2) collisional (anatectic)-related arc, (3) postcollisional extension, (4) oceanic rift, (5) continental rift, (6) back-arc rift, and (7) transform continental-margin faulting and associated bimodal volcanic-plutonic belt.

## Metallogenic Belt Map

Metallogenic belt maps, along with an underlying regional geologic map (for example, terrane and overlap assemblage map), are basic elements of a regional metallogenic and tectonic analysis. For delineation of metallogenic belts, the following main principles are used (Nokleberg and others, 2000).

1. *Mineral deposit association*. Each metallogenic belt includes deposits described by a single mineral deposit model or by a group of mineral deposit models describing coeval, closely located, and genetically related deposits.
2. *Tectonic event for formation of mineral deposits*. Each metallogenic belt includes a group of coeval and genetically related mineral deposits that were formed as the result of a specific tectonic event (for example, subduction-related igneous arc, collision, accretion, rifting).
3. *Favorable geological, geochemical, and geophysical environment*. Each metallogenic belt contains host rocks, structures, geochemical anomalies or signatures, and 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 usually is bounded by contacts of favorable stratigraphic or magmatic units or by major faults (sutures) along which substantial translations commonly have occurred.

For the example of a metallogenic analysis for the Russian Far East, a regional metallogenic belt map (fig. 2) portrays areas that contain and (or) are assessed to have potential for undiscovered igneous-rock-related deposits. The models for these deposits include Au-Ag epithermal vein, volcanic-hosted Hg (Plamennoe type), polymetallic vein, Sb-Au vein (simple Sb deposit), Cu (±Fe, Au, Ag, Mo) skarn, Zn-Pb (±Ag, Cu, W) skarn, Au, Co, and As skarn, Fe (±Au,

**Table 1.** Examples of selected granitoid-related Au deposits for the Russian Far East.

[Adapted from Nokleberg and others (1997a). g/t, grams per metric ton; t, metric ton]

<table>
<tr><th>Deposit No.<br>Latitude<br>Longitude<br>Summary and References</th><th>Deposit Name<br>Metallogenic Belt</th><th>Major Metals<br>Minor Metals<br>Deposit Model</th><th>Grade and Tonnage</th></tr>
<tr><td>K53-10<br>42 52 18N<br>132 49 46E</td><td>Progress<br>Sergeevka</td><td>Au<br><br>Granitoid-related Au</td><td>Average grade of 5.89 g/t Au.</td></tr>
<tr><td colspan="4">Consists of sulfide-poor pyrite-arsenopyrite-gold-quartz veins, small veinlets, poorly mineralized fracture zones, zones of mylonite, and zones altered to metasomatic carbonate-chlorite-sericite rocks. Deposit hosted in a Late Cretaceous granitic pluton that cuts a sequence of granite and gabbro of Sergeevka Complex with a Cambrian age of 500 to 527 Ma (J.N. Aleinikoff, written commun., 1992). The deposit is prospected to depths of a few tens of meters. This lode is also the source for nearby placer Au deposits. References: A.N. Rodionov, written commun., 1991.</td></tr>
<tr><td>N51-03<br>54 27 00N<br>124 14 00E</td><td>Kirovskoe<br>Stanovoy</td><td>Au<br><br>Granitoid-related Au</td><td>About 10 t Au produced.</td></tr>
<tr><td colspan="4">Consists of northwest-striking gold-quartz-sulfide veins hosted in an Early Cretaceous granodiorite stock. Veins commonly occur along contacts of diabase porphyry dikes that cut the granodiorite. Contacts of veins are generally sharp, although host rock is hydrothermally altered. Veins range from 0.5 to 1.0 meter in thickness, and the surrounding altered rock ranges from 5.0 to 9.0 meters in thickness. Altered rocks consist mainly of quartz, albite, sericite, and hydromica; the veins consist predominantly of 40 to 95 percent quartz. Main sulfides are pyrrhotite, arsenopyrite, and chalcopyrite, with less abundant galena, sphalerite, bismutite, and tennantite-tetrahedrite. Gold ranges up to 0.28 millimeter in diameter. Fineness of 844 to 977. Deposit source for the placer deposits of the Dzhalinda, Yannan, and Ingagli Rivers, the largest in the Russian Far East. Mined until 1961. References: Gurov, 1969; G.P. Kovtonyuk, written commun., 1990.</td></tr>
<tr><td>N52-02<br>53 27 00N<br>126 27 00E</td><td>Pioneer<br>North Bureya</td><td>Au<br><br>Granitoid-related Au</td><td>Average grade of 2.7 g/t Au and 5.2 g/t Ag. Reserves of 17.1 t Au and 20.1 t Ag.</td></tr>
<tr><td colspan="4">Consists of quartz, quartz-feldspar, quartz-tourmaline, and quartz-carbonate veins and zones of altered quartz-potassium feldspar-sericite-albite rocks. Zones are 1 to 50 meters thick and in plan commonly branch and change trends. Ore zones are large, have low Au content and no visible boundaries. Extent of deposit determined by geochemical sampling. Gold and gold-sulfide ore assemblages are distinguished. Gold assemblage consists of quartz-adularia-carbonate veins; gold-sulfide assemblage consists of quartz veins with pyrite, galena, stibnite, and silver sulfosalts. Deposit hosted along margin of an Early Cretaceous granodiorite intrusion, both within the intrusion and in adjacent contact metamorphosed Jurassic sandstone and siltstone. References: N.E. Malyamin and V.E. Bochkareva, written commun., 1990; V.N. Akatkin, written commun., 1991.</td></tr>
<tr><td>P55-35<br>61 27 32N<br>148 48 09E</td><td>Shkolnoe<br>Eastern Asia-Arctic, Verkhne-Kolyma zone</td><td>Au<br>Bi, Te, Ag<br>Granitoid-related Au</td><td>Total reserves 32 t Au. Averages 29 g/t Au and 45 g/t Ag. Has produced 17 t Au and 17 t Ag since start of mining in 1991. Annual production of 3 t Au and 3 t Ag.</td></tr>
<tr><td colspan="4">An en echelon system of quartz veins trending generally east-west. Veins occur in a multiphase granitoid stock about 4 square kilometers in size composed mainly of granodiorite and adamellite. Stock is intruded by dikes of granite-porphyry, rhyolite, pegmatite, aplite, and lamprophyre. Quartz veins are surrounded by zones of beresitic and argillic alteration; skarnlike and greisenlike alteration is present locally. Mineralization occurred in two stages separated by intrusion of lamprophyre dikes: (1) gold-polymetallic stage marked by molybdenite, arsenopyrite, loellingite, native bismuth, bismuth tellurides, and native gold; (2) the most economically important stage, marked by arsenopyrite, pyrite, polymetallic sulfides, gold, electrum, freibergite, tetrahedrite, lead-antimony and silver sulfosalts, argentite, and stibnite. Gold ore bodies extend to great depth into a large zone of complicated mineralogy, geochemistry, and structure. References: Orlov and Epifanova, 1988; Palymsky and Palymskaya, 1990; Voroshin and others, written commun., 1990; Banin, written commun., 1993; Goncharov, 1995.</td></tr>
</table>

**Table 2.** List of lode mineral deposit models used for metallogenic analysis of the Russian Far East, Alaska, and the Canadian Cordillera.

[Adapted from Nokleberg and others (1997a,b, 2000). Only some of these models were needed to describe the characteristic features of the 1,079 lode deposits]

| Deposit group | Deposit model |
|---|---|
| Deposits related to marine felsic to mafic extrusive rocks | Kuroko Zn-Pb-Cu massive sulfide (Ag, Au, Cd, Sn, Sb, Bi, barite)<br>Besshi Cu-Zn massive sulfide (Cu, Zn, Ag)<br>Cyprus Cu-Zn-Ag massive sulfide (Au, Pb, Cd, Sn)<br>Volcanogenic Mn<br>Volcanogenic Fe |
| Deposits related to subaerial extrusive rocks | Au-Ag epithermal vein<br>Volcanic-hosted Hg (Plamennoe type)<br>Hot-spring Hg<br>Silica-carbonate Hg<br>Volcanic-hosted Sb (Au, Ag, As) vein<br>Rhyolite-hosted Sn<br>Sulfur-sulfide (S, $FeS_2$ ) |
| Stratiform deposits in fine-grained clastic and siliceous sedimentary rocks | Sedimentary-exhalative Zn-Pb-Ag<br>Bedded barite |
| Stratabound deposits in coarse-grained clastic sedimentary rocks and subaerial basalts | Sediment-hosted Cu (Kupferschiefer and Redbed)<br>Basaltic Cu (Dzhalkan type)<br>Clastic sediment-hosted Hg (Nikitovka type)<br>Sandstone-hosted U |
| Deposits in carbonate and chemical-sedimentary rocks | Kipushi Cu-Pb-Zn<br>Southeast Missouri Pb-Zn<br>Korean Pb-Zn massive sulfide<br>Ironstone (Superior Fe)<br>Stratabound W (Austrian Alps-type)<br>Carbonate-hosted Hg (Khaidarkan type)<br>Stratiform Zr (Algama Type)<br>Sedimentary phosphorite |
| Deposits related to calc-alkaline and alkaline granitic intrusions - veins and replacement deposits | Polymetallic veins<br>Sb-Au veins (simple Sb deposits)<br>Sn quartz veins (Rudny Gory or replacement Sn)<br>Sn silicate-sulfide veins (Cornish type)<br>Sn polymetallic veins (Southern Bolivian type)<br>Co-arsenide polymetallic veins<br>Carbonatite-related Ta, Nb, REE stockwork and vein |
| Deposits related to calc-alkaline and alkaline granitic intrusions - skarns and greisens | Cu (±Fe, Au, Ag, Mo) skarn (contact metasomatic)<br>Zn-Pb (±Ag, Cu, W) skarn (contact metasomatic and associated Manto replacement deposits)<br>Au, Co, and As skarn<br>W skarn and greisen<br>Fe (±Au, Cu, W, Sn) skarn<br>Sn greisen and skarn<br>Sn-B (Fe) skarn (Ludwigtite type)<br>Boron skarn (datolite type)<br>Fluorite greisen |
| Deposits related to calc-alkaline and alkaline granitic intrusions - porphyry and granitic pluton-hosted deposits | Porphyry Cu-Mo (Au, Ag)<br>Porphyry Mo (±W, Sn, Bi)<br>Porphyry Sn<br>Granitoid-related Au<br>Felsic plutonic U-REE<br>W vein |

**Table 2.** List of lode mineral deposit models used for metallogenic analysis of the Russian Far East, Alaska, and the Canadian Cordillera.—Continued

| Deposit group | Deposit model |
|---|---|
| Deposits related to mafic and ultramafic rocks | Zoned mafic-ultramafic Cr-PGE (±Cu, Ni, Au, Co, Ti, or Fe) (Alaskan PGE)<br>Zoned ultramafic, mafic, felsic, and alkalic PGE-Cr and apatite-Ti<br>Anorthosite apatite-Ti-Fe<br>Gabbroic Ni-Cu<br>Podiform Cr<br>Hornblende-peridotite Cu-Ni<br>Serpentine-hosted asbestos |
| Deposits related to regionally metamorphosed rocks | Au quartz veins (includes concordant vein, and shear-zone Au)<br>Disseminated Au-sulfide (Maiskoe type)<br>Clastic sediment-hosted Sb-Au<br>Cu-Ag quartz vein (vein Cu)<br>Kennecott Cu |

**Table 3.** Summary of major tectonic events and associated mineral deposit models derived from a metallogenic analysis of the Russian Far East, Alaska, and the Canadian Cordillera.

[Adapted from Nokleberg and others (1997a,b, 2000), Nokleberg, West, and others (1998), and Scotese and others (2001)]

| Time | Areas | Tectonic event(s) | Major mineral deposit models |
|---|---|---|---|
| Late Proterozoic, Late Devonian, Early Carboniferous | Northeast Asia and North American craton margin | Rifting | Sedimentary-exhalative Zn-Pb. |
| Late Triassic through mid-Cretaceous | Offshore of North Asia and North American craton margins | Island arc and back arc | Porphyry, epithermal vein, polymetallic vein, skarn. |
| Jurassic through mid-Cretaceous | North Asian and North American continental margins | Accretion | Low-sulfide Au quartz vein, granitoid-related Au. |
| Mid-Cretaceous through present | North Asian and North American continental margins | Continental-margin arc and back arc | Porphyry, epithermal vein, polymetallic vein, skarn. |
| Late Jurassic through Early Cretaceous, Late Cretaceous through early Tertiary, and middle Tertiary | North Asian continental margin | 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. |
| Late Cretaceous through present | North America continental margin | Transform continental-margin faulting and associated bimodal volcanic-plutonic belt | Displacement of previously formed metallogenic belts and host rocks. |

Cu, W, Sn) skarn, Sn greisen and skarn, boron skarn (datolite type), porphyry Cu-Mo, porphyry Sn, granitoid-related Au, and W vein deposit models. The figure illustrates that these metallogenic belts are hosted in Cretaceous and Cenozoic volcanic-plutonic belts constituting major overlap assemblages that formed from Late Cretaceous through early Tertiary continental-margin arcs.

When the above definitions and principles are applied, the areas defined for metallogenic belts encompass favorable geological environments and possess a specific mineral deposit type and associations. For the Russian Far East example (fig. 2), the various metallogenic belts delineate areas that contain and (or) are favorable (predictive) for igneous-arc-related deposits that are hosted in major Late Cretaceous and early Tertiary continental-margin arc units. The synthesis and compilation of metallogenic belt maps provide 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 exploration planning and for establishing guidelines for future research.

# Theoretical Example of Methodology

The first parts of the methodology for metallogenic and tectonic analysis are illustrated in figure 3 (derived from Nokleberg and others, 1997a). Figure 3*A* is a schematic map that portrays a suite of metallogenic belts that are hosted in several geologic units, including cratons, terranes, and overlap

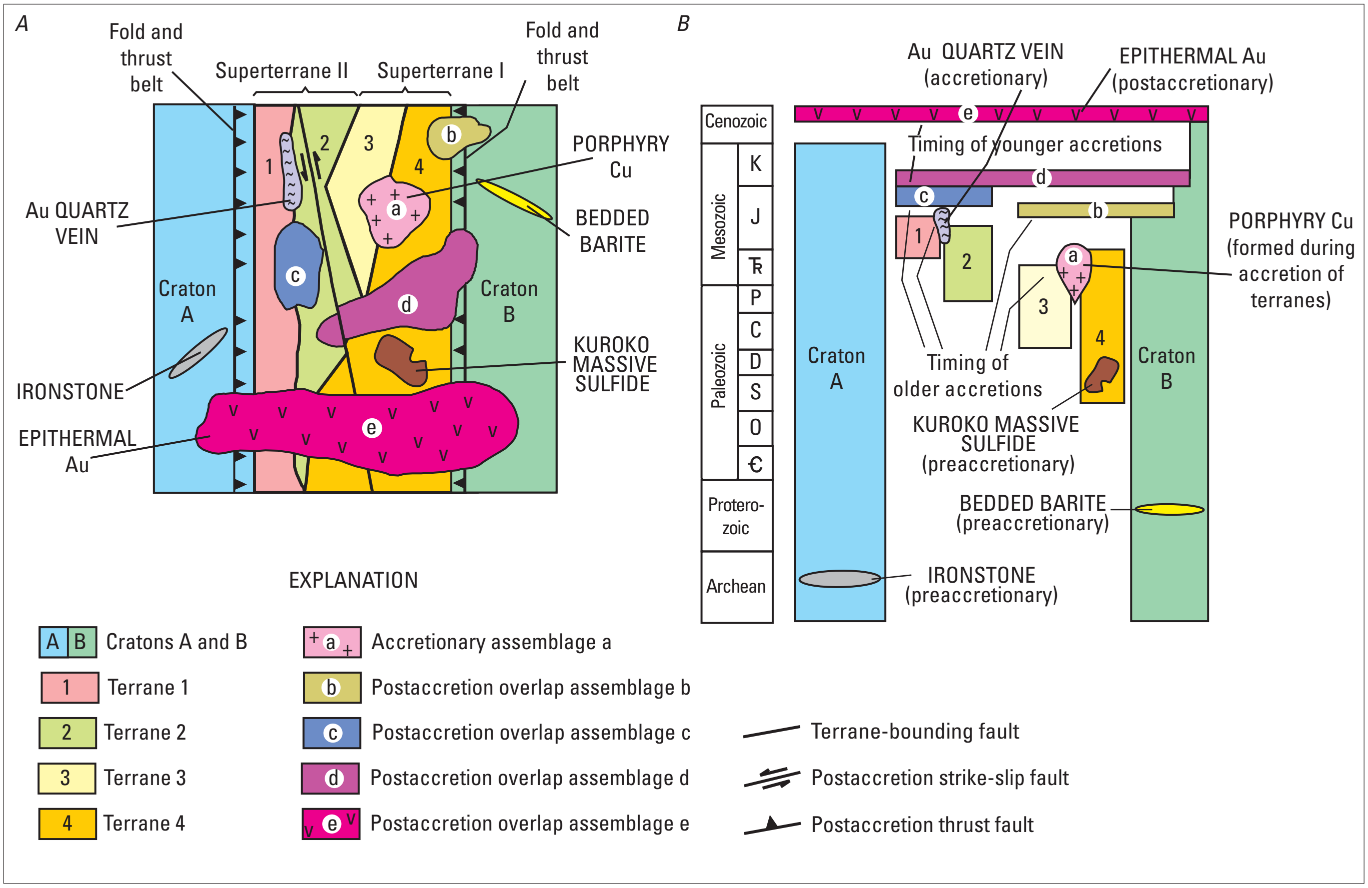


**Figure 3.** Schematics illustrating the methodology for metallogenic analysis of cratons, terranes, accretionary assemblages, overlap assemblages, and contained metallogenic belts. *A*, Map view of orogenic belt. *B*, Stratigraphic columns for orogenic belt. Adapted from Nokleberg and others (1997a).

assemblages, or along major faults between terranes. Figure 3*B*, a series of stratigraphic columns for the units depicted in figure 3*A*, illustrates the stratigraphic and metallogenic history of the map area.

The steps in this theoretical example follow.

1. A regional geologic base map is constructed. Figure 3*A*, 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 series of mineral deposit models appropriate for the geology is identified and defined, and a mineral deposit database is prepared. For this theoretical example, the major mineral deposit models are low-sulfide Au quartz vein, ironstone, epithermal Au 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 with deposits that formed early in their geologic history—ironstone in craton A and bedded barite in craton B. Island-arc terrane 4 contains a preaccretionary belt of kuroko massive sulfide deposits. Between terranes 3 and 4 is accretionary assemblage a, which 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 contains a belt of Au quartz vein deposits that formed during accretion of terrane 1 against terrane 2. Overlying all terranes and both cratons is postaccretion overlap assemblage e containing 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 by using modern tectonic concepts (fig. 3*B*). 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 igneous-arc environment.
5. Because each metallogenic belt is carefully defined to be the geologically favorable area for a group of coeval and genetically related mineral deposits, a predictive character is established within the belt for undiscovered deposits.

## Synthesis of a Combined Metallogenic and Tectonic Model

In the following discussion, the methodology for synthesis of a metallogenic and tectonic model, as practiced in recent international collaborative projects in the Circum-North Pacific (Nokleberg and others, 1995, 1997a,b,c; Nokleberg, Kuzmin, and others, 1998; Nokleberg, West, and others, 1998) and in Northeast Asia (Nokleberg and others, 1999), consists of the following steps.

1. A regional geologic base map, mineral deposit database, and metallogenic belt maps are compiled and synthesized.
2. The 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, faunal, and provenance data (Nokleberg, Parfenov, and others, 1994; Nokleberg and others, 1997c; Greninger and others, 1999).
3. Correlations are made among terranes, fragments of overlap assemblages, and fragments of contained metallogenic belts.
4. Coeval terranes and their contained metallogenic belts are assigned a single metallogenic and tectonic origin, such as a single island-arc or subduction-zone terrane.
5. Igneous-arc and subduction-zone terranes that are interpreted as being tectonically linked together, and their contained metallogenic belts, are grouped into coeval, curvilinear arc-subduction-zone-complexes.
6. By use of geologic, faunal, and paleomagnetic data, the original positions of terranes and their metallogenic belts are interpreted.
7. The paths of tectonic migration of terranes and contained metallogenic belts are constructed.
8. The timings and nature of accretions of terranes and contained collision-related metallogenic belts are determined from geologic, age, and structural data.
9. The timings of postaccretionary overlap assemblages and contained metallogenic belts are determined from geologic and age data.
10. A series of time-stage diagrams is drawn that portrays the successive major metallogenic and tectonic events for the region.
11. The interpretation of the time-stage diagrams is written.

One time stage of the metallogenic and tectonic model is illustrated in figure 4, which shows the tectonic origin for continental-margin igneous-arc-related metallogenic belts in this region for the Late Cretaceous through early Tertiary (Nokleberg and others, 2000, 2001, 2003; Scotese and others, 2001). In addition to depicting the major continental-margin igneous-arc-related metallogenic belts, the model also illustrates, for this time stage, the configuration of cratons, craton margins, previously accreted terranes, actively migrating terranes, continental-margin arcs forming major overlap assemblages, and oceanic ridges.

For this time stage, the major metallogenic-tectonic events are (Nokleberg and others, 2000, 2001, 2003; Scotese and others, 2001) described below.

1. Continuation of a series of continental-margin arcs (East Sikhote-Alin, Okhotsk-Chukotka, Kluane, and Coast arcs), associated metallogenic belts (East Sikhote-Alin, Eastern Asia, Alaska, and Cordilleran), and companion subduction-zone assemblages around the Circum-North Pacific.
2. Completion of opening of the Arctic Basin.
3. Completion of accretion of the Wrangellia superterrane.
4. A change to dextral transpression in the eastern part of the Circum-North Pacific between the Kula Ocean plate and the North American continental margin.
5. Oblique subduction of the Kula-Farallon oceanic ridge under the margins of southern and southeastern Alaska.
6. Northward migration of previously accreted terranes along the margin of the North American Cordillera.

The major metallogenic belts forming during this time span are the East Sikhote-Alin belt hosted in the East Sikhote-Alin arc, the Eastern Asia belt formed in the Okhotsk-Chukotka arc, the Alaska belt formed in the Kluane arc, and the Cordilleran belt formed in the Coast arc. The major mineral deposit types in these belts are porphyry Cu, porphyry Cu-Au, porphyry Cu-Mo, porphyry Mo, porphyry Sn, granitoid-related Au, Au-Ag epithermal vein, polymetallic vein, Sb-Au vein, Sn greisen and skarn, Cu skarn, Zn-Pb skarn, Fe skarn, and Hg hot-spring types. Detailed descriptions of the 12 time stages for the metallogenic and tectonic model were provided by Nokleberg and others (2001, 2003) and Scotese and others (2001).

## Benefits of Performing a Combined Regional Metallogenic and Tectonic Analysis

As described above, a high-quality metallogenic and tectonic analysis and synthesis of an associated metallogenic and tectonic model will provide the following benefits (fig. 1): (1) refinement of mineral deposit models (Eckstrand, 1984; Cox and Singer, 1986; Singer and Cox, 1988) and of the understanding of deposit genesis, (2) assessments of undiscovered mineral resources as part of quantitative mineral resource assessment studies (Cox, 1993; Singer, 1993, 1994; Ludington

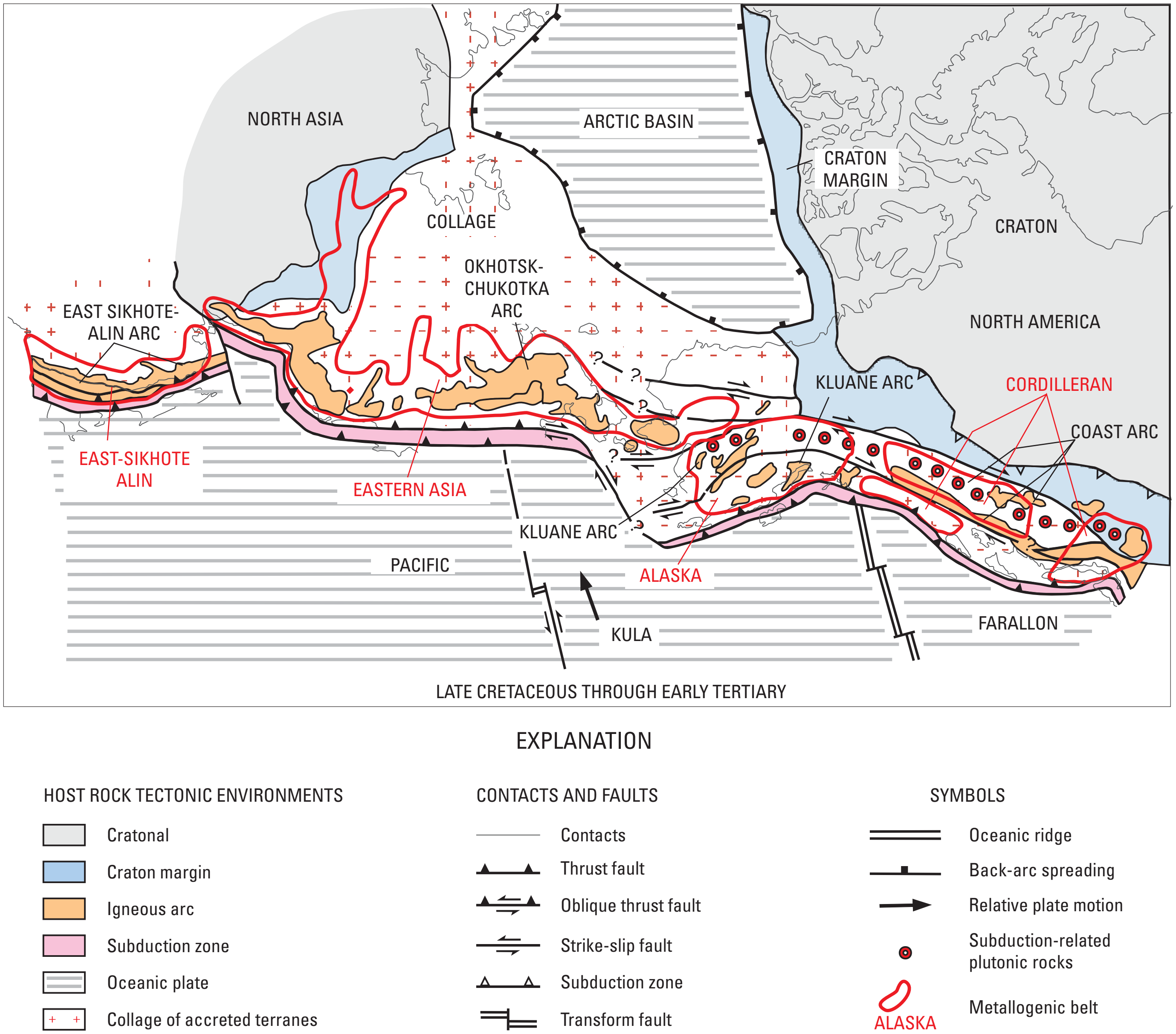


**Figure 4.** Late Cretaceous and early Tertiary stage of the metallogenic and tectonic model illustrating the tectonic setting for igneous-arc-related metallogenic belts hosted in Late Cretaceous through early Tertiary continental-margin igneous arcs in the Russian Far East, Alaska, and the Canadian Cordillera. Adapted from Nokleberg and others (2000, 2001, 2003; Scotese and others, 2001).

and others, 1996), (3) data to consider in land use and mineral exploration planning, (4) improvement of interpretations of origins of host rocks, mineral deposits, and metallogenic belts, and (5) guidelines for new research.

Following are three examples of these benefits.

1. The in-depth understanding of the tectonic and metallogenic origins of potential host rocks for mineral deposits makes it possible to anticipate the types of mineral deposits that can occur in these rocks. It is crucial to have this capability because permissive tracts (that is, areas having potential for undiscovered mineral deposit types) for a mineral resource assessment must be drawn for each mineral deposit type permitted by the geology and geologic processes that operated in the assessment area.

2. Regional metallogenic and tectonic analyses, such as those performed for the Circum-North Pacific and Northeast Asia, make it possible to identify and locate the continuations of ore-hosting terranes and permissive tracts separated around the world by the myriad of plate-tectonic processes operating throughout the Earth's long

history. Suppose that a suite of metallogenic belts containing porphyry Cu deposits is hosted in various 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 possible correlations with each other, will result in 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 provide a larger dataset that should greatly improve the quality studies for metallogenic analysis and (or) for mineral resource assessment.

3. An understanding of 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 a mineral resource assessment. 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, deposits of this type might not be estimated for a tract of similar rocks in an extensional cratonic setting.

## Summary

This paper presents an overview of the methodology of combined regional metallogenic and tectonic analysis. The paper also provides a theoretical example of this type of analysis and describes an example of this type of analysis for a metallogenic and tectonic model for the origin of Late Cretaceous and early Tertiary igneous-arc-related deposits in the Circum-North Pacific (Russian Far East, Alaska, and Canadian Cordillera). This paper also describes how a high-quality metallogenic and tectonic analysis and synthesis of an associated metallogenic and tectonic model will provide the following benefits: (1) refinement of mineral deposit models and of the understanding of deposit genesis, (2) improvement of assessments of undiscovered mineral resources as part of quantitative mineral resource assessment studies, (3) data to consider in land use and mineral exploration planning, (4) improvement of interpretations of origins of host rocks, mineral deposits, and metallogenic belts, and (5) guidelines for new research.

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