**Metallogenesis and Tectonics of Northeast Asia**
**Edited by Warren J. Nokleberg**
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# Chapter 1

# Introduction

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## Executive Summary

The major purpose of this volume is to provide a comprehensive synthesis of the regional geology, tectonics, and metallogenesis of Northeast Asia for readers who are unfamiliar with the region and for researchers who desire detailed information on the region. The major parts of the volume are (1) an introductory chapter; (2) a chapter on methodology of regional metallogenic and tectonic analysis; (3) a chapter on mineral deposit models for the region; (4) five chapters that describe the regional metallogenesis and tectonics of the region from the Archean through the Present for successive time stages; (5) a chapter on a metallogenic and tectonic model for the region; and (6) three appendixes, including on a description of the project and products, a description of map units for the Northeast Asia geodynamics map, and a summary table of metallogenic belts for the region.

An important goal of the volume is to demonstrate how a high-quality metallogenic and tectonic analysis, including construction of an associated metallogenic-tectonic model, greatly benefits other mineral resource studies by (1) synthesizing of mineral-deposit models, (2) improving prediction of undiscovered mineral deposits as part of quantitative mineral-resource-assessment studies, (3) assisting land-use and mineral-exploration planning, (4) improving knowledge of regional geology; (5) improving interpretations of the origins of host rocks, mineral deposits, and metallogenic belts, and (6) suggesting new research.

Research on the metallogenesis and tectonics of such major regions as Northeast Asia requires a complex methodology including (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 a determination of mineral-deposit models and clarification of the relations 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 in the region, (5) compilation of a series of metallogenic-belt belts constructed on the regional geologic base map, and (6) construction of a unified metallogenic and tectonic model.

The Northeast Asia study area consists of eastern Russia (most of eastern Siberia and the Russian Far East), Mongolia, northern China, South Korea, Japan, and adjacent offshore areas. Major cooperative agencies are the Russian Academy of Sciences; the Academy of Sciences of the Sakha Republic (Yakutia); VNIIOkeangeologia and Ministry of Natural Resources of the Russian Federation; the Mongolian Academy of Sciences; the Mongolian University of Science and Technology; the Mongolian National University; Jilin University, Changchun, People's Republic of China; the China Geological Survey; the Korea Institute of Geosciences and Mineral Resources; the Geological Survey of Japan/AIST; the University of Texas, Arlington; and the U.S. Geological Survey (USGS).

This study builds on and extends the data and interpretations from a previous project on the *Major Mineral Deposits, Metallogenesis, and Tectonics of the Russian Far East, Alaska, and the Canadian Cordillera* conducted by the USGS, the Russian Academy of Sciences, the Alaska Division of

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Geological and Geophysical Surveys, and the Geological Survey of Canada. The major products of the Northeast Asia project are described in appendix A.

# Definitions, Geologic Time Scale, and Tectonic Environments

To illustrate the regional geology and tectonics of Northeast Asia, figure 2 applies the concept of a tectonic collage, herein defined as a series of linear island or continental-margin-arcs and tectonically linked (companion) subduction zone and (or) forearc and backarc basins that formed in a major tectonic event during a relatively brief geologic timespan. A few these tectonic collages consist of fragments of cratonal and cratonal margin terranes that were amalgamated before accretion to a continent. This definition enables (1) a readily understood conceptual framework for understanding the regional geology and tectonics Northeast Asia, (2) depiction at small scales of major geologic units and structures that formed in a single tectonic


**Figure 1.** Regional summary regional geographic map of Northeast Asia, showing locations of major regions, countries, and capitals. International boundaries of onshore areas are approximate and do not imply endorsement by participating countries.

event, and (3) depiction of the major metallogenic belts related to tectonic collages. Definitions of other key terms for metallogenic and tectonic analysis, adapted from Jones and others (1983), Howell and others (1985), Nokleberg and others (2000, 2004, 2005) are listed in table 1; geologic time terms are from the International Union of Geological Sciences Global Stratigraphic Chart (Remane, 1998). For this study, in the descriptions of some Proterozoic geologic units in Russia, the term Riphean is used for Mesoproterozoic through middle Neoproterozoic (1,600 to 650 Ma), and Vendian is used for Neoproterozoic III (650 to 540 Ma)

For a modern metallogenic and tectonic analysis, an interpretation of tectonic environments is essential for determining the origins of major geologic units and contained mineral deposits and metallogenic belts. Such an interpretation permits linking the geologic origins for these sometimes-disparate datasets. As described below, interpretation of the tectonic environments for mineral deposits is also important for constructing mineral-deposit models. For the tectonic analyses of Northeast Asia and the Circum-North Pacific (Nokleberg and others, 1997b,c, 2000, 2004, 2005; Scotese and others, 2001; Obolenskiy and others, 2003 and this volume, chap. 3; Parfenov and others, 2003, 2004a,b), we interpreted the major geologic units (terranes, overlap assemblages, plates), mineral deposits, mineral-deposit types, and metallogenic belts according to the following tectonic environments (table 1) (1) cratonal and cratonal margin, (2) passive-continental-margin, (3) low-grade metamorphosed continental margin, (4) continental-margin-arc and backarc, (5) island arc and backarc, (6) oceanic crust, seamount, or ophiolite related to rifting and sea-floor spreading, (7) subduction zone, (8) turbidite basin, (9) collisional, (10) transform continental-margin faulting and associated bimodal volcanic-plutonic belt, (11) plume, and (12) metamorphic. For terranes with complex geologic histories, the chosen tectonic environment is the one most prevalent during the history of the terrane.

# Regional Geologic Map–A Basis for Metallogenesis

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

For the synthesis and interpretation of the metallogenesis and tectonics of Northeast Asia (fig. 1), a regional-geodynamics map was compiled at a scale of 1:5,000,000 to display major features the host rock geology and structures (Nokleberg and others, 1997b,c; Parfenov and others, 2003, 2004a,b) and major belts of mineral and fuel resources. To illustrate these major features on a page-size illustration (fig. 2), a summary regional-geodynamics map was synthesized display (1) the surface extent of major geologic units (cratons, cratonal margins, tectonic collages of island-arc, continental-margin-arc, subduction-zone, and passive-continental-margin terranes, and volcanic and plutonic igneous arcs), (2) major fault and rift systems, and (3) active subduction zones. A list of the major host-rock geologic units is provided in the explanation to figure 2, and the major geologic units are described in an appendix B. The regional geologic map also provides descriptive data on the tectonic origins of major host-rock geologic units needed to establish geologic controls on the formation of metallogenic belts.

# Methodology of Regional Geologic and Tectonic Analysis

The methodology used to construct figure 2 consists of the following three steps (1) correlation of major geologic units, (2) tectonic linking (pairing) of major geologic units, and (3) alignment of coeval arc and tectonically linked subduction zones into curvilinear complexes. This methodology, which was originally established for the tectonic synthesis of the Circum-North Pacific by Nokleberg and others (2000) and modified for Northeast Asia by Parfenov and others (1998), is explained in detail by Nokleberg and others (this volume, chapter 2).

In step 1, correlations are attempted for major geologic units that are interpreted as originally contiguous but subsequently tectonically displaced during rifting or major thrusting, or displaced along strike-slip faults and for all tectonic units (cratons, cratonal margins, terranes, and overlap assemblages) that are interpreted to have the same origin, (*that is*, as parts of a single elongate passive-continental-margin, continental-margin-arc, island arc, or subduction zone) contemporaneously and originally on strike with each other. This correlation of major geologic units also illustrates the original continuity of lithologic units, provides important constraints on past regional tectonics, and provides a series of interpretations to be further evaluated by additional stratigraphic, geochemical, isotopic, paleomagnetic, and geophysical studies.

In step 2, tectonic links (pairings) are accomplished (1) between subduction-related igneous arcs, now preserved as various igneous-arc terranes or overlap assemblages, and former subduction zones, now preserved as subduction-zone terranes, (2) between belts of anatectically-related igneous rocks and major faults (sutures) that bound the collisional margins of terranes, between terranes and cratonal margin, and (3) between belts of igneous rocks that are coeval with, and occur along, major transpressional fault zones. These tectonic links are based on an examination of the detailed geology and

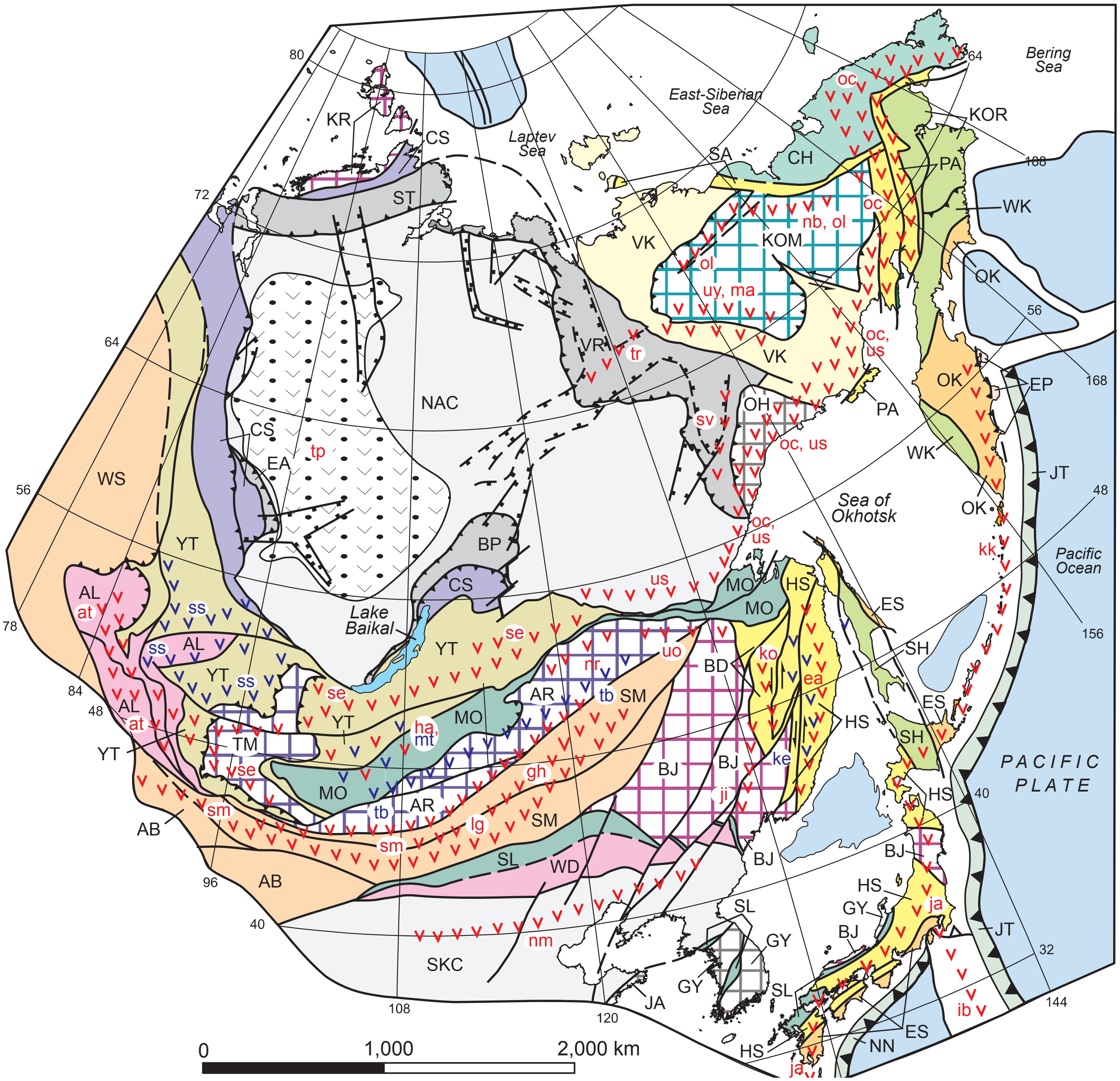


**Figure 2.** Northeast Asia summary geodynamics map (scale, approx 1:34,000,000) showing locations major geologic and tectonic units including cratons, cratonal margins; cratonal terranes and superterranes; tectonic collages; overlap and transform continental-margin-arcs; island arcs, and sea and ocean units. From (1) a generalized geodynamics map of Northeast Asia (scale, 1:10,000,000) by Parfenov and others (2004), (2) a more detailed geodynamics map Northeast Asia (scale 1:5,000,000 and (3) tectono-stratigraphic terrane maps of the western part of a Circum-North Pacific (scale, 1: 10,000,000) by Nokleberg and others (1997). Tectonic interpretations are based on the major interpretative reports of collaborative international studies of Northeast Asia (Nokleberg and others, 2004) and the Circum-North Pacific (Nokleberg and others, 2000, 2004), with descriptions of geologic units adapted from reports by Nokleberg and others (2000, 2004) and Parfenov and others (2004). See appendix B for descriptions of map units.

# EXPLANATION

## Cratons and Cratonal Margins

Cratons: NAC - North Asian (Archean and Proterozoic); SKC - Sino-Korean (Archean and Proterozoic)

Cratonal Margin: BP - Baikal-Patom (Riphean through Cambrian and older basement; EA - East Angara (Riphean and older basement; ST - South Taimyr (Ordovician through Jurassic); VR - Verkhoyansk (Devonian through Jurassic).

## Tectonic Collages Between the North Asian and Sino-Korean Cratons

CS - Circum-Siberia (Proterozoic)

YT - Yenisey-Transbaikal (Vendian through Early Ordovician)

AL - Altay (Vendian to Ordovician)
WD - Wundurmiao (Riphean through Ordovician)

AB - Atasbogd (Ordovician through Permian); SM - South Mongolia-Khingan (Ordovician through Carboniferous); WS - West Siberian (Ordovician through Carboniferous)

MO - Mongol-Okhotsk (Devonian through Late Jurassic); SL - Solon (Carboniferous and Permian)

## Tectonic Collages Along the Northern and Eastern Margins of North Asian and Sino-Korean Cratons

CH - Chukotka (Paleozoic and Triassic)

VK - Verkhoyansk-Kolyma Paleozoic through Early Jurassic)

BD - Badzhal (Triassic through Early Cretaceous); PA - Penzhina-Anadyr (Late Jurassic and Cretaceous); HS - Honshu-Sikhote-Alin (Jurassic and Early Cretaceous); SA - South Anyui (Permian through Jurassic);

KOR - Koryak (Late Jurassic through Paleocene; SH - Sakhalin-Hokkaido (Cretaceous); WK - West Kamchatka (Mid-Cretaceous through Early Tertiary)

ES - East Sakhalin (Late Cretaceous and Early Tertiary); OK - Olyutorka-Kamchatka (Late Cretaceous to Paleocene)

EP - East Kamchatka Peninsular (Mainly Paleocene)

## Active Subduction Zones

JT- Japan Trench (including Kuril-Kamchatka trench) (Miocene through Holocene;
NN - Nankai (Miocene through Holocene)

## Cratonal Terranes and Superterranes

Cratonal terranes (Archean and Proterozoic): GY - Gyeonggi-Yeongnam; JA - Jiaonan; OH - Okhotsk

Late Proterozoic and Cambrian superterranes: AR - Argun-Idermeg; TM - Tuva-Mongolia

Archean through Permian superterranes: BJ - Bureya-Jiamusi; KR - Kara

Jurassic Superterrane: KOM - Kolyma-Omolon (Archean through Jurassic)

## Pelagic and Oceanic Rocks

Surficial deposits

Oceanic crust

## Overlap Continental-Margin Arcs and Igneous Belts

at - Altay arc (Devonian and early Carboniferous, 381 to 290 Ma)
ea - East Sikhote-Alin arc (Late Cretaceous through early Tertiary, 96-65 Ma)
gh - Gobi-Khankaisk-Daxing'anling arc (Permian, 295 to 250 Ma)
ha - Hangay arc (Late Carboniferous and Early Permian, 320 to 272 Ma)
ji - Jihei arc (Permian, 295 to 250 Ma)
ko - Khingan arc (Early and mid-Cretaceous)
lg - Lugyngol arc (Permian and Triassic, 295 to 250 Ma)
ma Main granite belt (Late Jurassic, 144 to 134 Ma)
nb - Northern granite belt (Early Cretaceous, 138 to 120 Ma)
nm - North Margin (Late Carboniferous and Permian, 320 to 272 Ma)
nr - Norovlin arc (Devonian and Early Carboniferous, 410 to 255 Ma)
oc - Okhotsk-Chukotka arc (Late Cretaceous and early Tertiary, 96 to 53 Ma)
ol - Oloy arc (Late Jurassic, 154 to135 Ma)
se - Selenga arc (Permian through Jurassic, 295 to135 Ma)
sm - South Mongolian arc (Carboniferous through Triassic, 320 to 203 Ma
ss - South Siberian arc (Devonian)
sv - South Verkhoyansk granite belt (Late Jurassic through mid-Cretaceous, 157 to 93 Ma)
tr - Transverse granite belt (Early Cretaceous, 134 to 124 Ma)
uo - Umlekan-Ogodzhin arc (Cretaceous, 135 to 65 Ma)
us - Uda-Murgal and Stanovoy arc (Jurassic and Early Cretaceous, 203 to 96 Ma)
uy - Uyandina-Yasachnaya arc (Late Jurassic and Early Cretaceous, 154 to 120 Ma)

## Plume-Related Igneous Province

tp - Tungus Plateau igneous province - (Late Permian and Early Triassic, 245 Ma)

## Active Arcs

ib - Izu-Bonin (late Cenozoic, 20 to 0 Ma)
ja - Japan (late Cenozoic, 23 to 0 Ma)
kk - Kuril-Kamchatka (late Cenozoic, 11 to 0 Ma)

## Transpressional Arcs

ke - Kema (Mid-Cretaceous)
mt - Mongol-Transbaikal (Late Triassic through Early Cretaceous, 230 to 96 Ma)
ss - South Siberian (Early Devonian, 415 to 400 Ma)
tb - Transbaikalian-Daxinganling (Middle Jurassic through Early Cretaceous,175 to 96 Ma)

## Symbols, Faults, and Contacts

Overlap-continental-margin arc
Transform-continental-margin arc
Active subduction zone
Thrust
Strike-slip fault
Fault
Contact
Riphean aulacogen
Devonian aulacogen
Modern rift system (Gakkel Ridge)
os Metallogenic belt

**Figure 2.**—Continued.

**Table 1.** Definitions of key terms for analysis of regional geology and metallogenesis.

[Adapted from Jones and others (1983), Howell and others (1985), Nokleberg and others (2000, 2004, 2005)]

| Term | Definition |
|---|---|
| Accretion | Tectonic juxtaposition of terranes to a cratonal or continental 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. |
| Amalgamation | Tectonic juxtaposition of two or more terranes before accretion to a cratonal or continental margin. |
| Continent | A large section of continental crust surrounded by oceans on all sides that consists, in its core, of one or more cratons framed by younger tectonic collages (accretionary and collisional orogenic belts). |
| 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. May 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, locally Mesozoic and Cenozoic sedimentary and lesser volcanic rocks. |
| Cratonal margin | Chiefly Neoproterozoic 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 Paleoproterozoic, and (or) Mesoproterozoic cratonal basement. |
| Cratonal terrane | Fragment of a craton. |
| Island-arc system | An island arc and tectonically linked subduction zone terranes. |
| Island-arc terrane | Fragment of an igneous belt of plutonic and (or) coeval volcanic rocks and associated sedimentary rocks that formed above an oceanic subduction zone. May possess a simatic basement. |
| Metallogenic belt | A geologic unit (area) that either contains or is favorable for the occurrence of a group of coeval and genetically related, significant lode and (or) placer deposits. Has the following characteristics: (1) is favorable for the occurrence of known or inferred mineral deposits of specific types; (2) may be irregular in shape and vary in size; (3) need not contain known deposits; and (4) is based on geologic mapping as the primary source of information for the delineation of areas that are favorable for the occurrence of specific deposit types. |
| 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. May include structural melange 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. In this study, also used as a general term for any mineral occurrence or prospect. |
| Mineral occurrence | A site of potentially valuable minerals on which no visible exploration has occurred or for which no grade and tonnage estimates are available. Synonymous with prospect. |
| Oceanic crust, seamount, and ophiolite terrane | Fragment of part or all of a suite of deep-marine sedimentary rocks, pillow basalt, gabbro, and ultramafic rocks (former eugeoclinal suite) that are interpreted as oceanic sedimentary and volcanic rocks and upper mantle. Includes both inferred offshore oceanic and marginal ocean-basin rocks, minor arc-derived volcaniclastic rocks, and major marine volcanic accumulations formed at a hotspot, in a fracture zone, or along a spreading axis. |
| Overlap assemblage | A postaccretionary unit of sedimentary or igneous rocks deposited on or intruding two or more adjacent terranes. |
| Passive-continental-margin terrane | Fragment of a cratonal (continental) margin. |

**Table 1.** Definitions of key terms for analysis of regional geology and metallogenesis. —Continued

[Adapted from Jones and others (1983), Howell and others (1985), Nokleberg and others (2000, 2004, 2005)]

| Term | Definition |
|---|---|
| Subduction zone terrane | Fragment of a mildly to intensely deformed accretionary complex consisting of varying amounts of turbidite deposits, continental-margin rocks, oceanic crust and overlying units, and oceanic mantle. 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 fragments with 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. Synonymous with accretionary wedge terrane. |
| Superterrane | An aggregate of terranes that is interpreted to share either a similar stratigraphic affinity or a common geologic history after accretion. Approximately synomous with *Composite terrane*. |
| Tectonic collage | A series of linear island arcs or continental margin arcs and tectonically linked (companion) subduction zones and (or) forearc and backarc basins that formed during a major tectonic event within a relatively narrow geologic timespan. May consist of fragments of cratonal and cratonal-margin terranes that were amalgamated before accretion to a continent. |
| Tectonic linkage | A genetic relation of a continental margin or island arc to a companion accretionary wedge that formed in a subduction zone which was adjacent to and underthrusting the arc. |
| Tectonostratigraphic terrane (terrane) | A fault-bounded geologic unit or fragment characterized by a distinctive geologic history which 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 backarc setting. May include continental-slope and continental-rise turbidite deposits, submarine-fan turbidite deposits, and minor epiclastic and volcaniclastic deposits deposited on oceanic crust. |

ages (fossil and geochronologic) of lithologic units, and the interpretation of an originally adjacent loci.

The first type of tectonic link is based on (1) interpreting an original physical proximity between an arc and a subduction zone, (2) determining the similarity in age of formation of an igneous-arc and subduction-zone terrane, (3) determining a subduction polarity from tectonic-transport direction in a melange for subduction-zone terranes, where not disrupted by later deformation, and (4) recognizing the occurrence of disrupted layers of arc-derived volcanic or volcaniclastic rocks from a specific igneous arc in the melange of the linked subduction-zone terrane. The second type of tectonic link is based on the spatial and temporal (age) association of collisional (S-type) granitic plutons and associated volcanic rocks (1) with major fault zones (sutures) between terranes or between a terrane and a cratonal margin, and (or) (2) with belts of highly deformed, regional-grade metamorphic rocks that occur along fault zones. Collision-related igneous belts are interpreted as having formed either during accretion of one terrane to another or during accretion of one or more terranes to a craton or cratonal margin. The third type of tectonic link is based on the spatial and temporal (age) association of mainly intermediate-composition and silicic igneous belts that are coeval with, and intrude along major transpressional fault zones.

In step 3, terranes and overlap assemblages are grouped into larger entities that probably were once continuous and coeval igneous arcs and companion subduction zones, on the basis, to varying degrees, of (1) similar stratigraphy, fauna, lithologic-unit age, and structure, (2) paleomagnetic data, and (3) assumed simplicity rather than complexity. As a result of these groupings, coeval igneous-arc overlap assemblages and igneous-arc terranes and tectonically linked (companion) subduction-zone terranes are aligned with coeval, curvilinear arc-subduction-zone complexes herein termed *tectonic collages*. Thus, this grouping represents an interpretation of single rather than multiple continental-margin or island/arc-subduction-zone complexes.

# Summary of Regional Geology and Tectonics

The major geologic and tectonic units of Northeast Asia (fig. 1) are cratons and cratonal margins; cratonal terranes and superterranes, tectonic collages, overlap and transform continental-margin-arcs, island arcs, and pelagic and oceanic rocks (fig. 2). Detailed descriptions of geologic units were provided by Nokleberg and others (2000, 2004) and Parfenov and others (2004b). The abbreviations in parentheses in the following list are the same as those used on the summary geodynamics map (fig. 2); more detailed descriptions of map units are provided in appendix B. Two geologic ages are stated for each collage; one for the time of formation of the contained units and another for the time of accretion (formation) of the tectonic collage to another terrane, superterrane, or continent.

## Major Cratons and Cratonal Margins

The backstop or core tectonic units for Northeast Asia (fig. 1) are six Archean and Proterozoic cratons and their cratonal margins:

The North Asian craton (NAC), which consists of Archean and Proterozoic metamorphic basement and non-deformed, flat-laying platform cover consisting of late Precambrian, Paleozoic, and Mesozoic sedimentary and volcanic rocks.

The Sino-Korean craton (SKC), which consists of several major Archean and Proterozoic metamorphic-basement terranes and later Paleozoic through Cenozoic overlap units.

The Baikal-Patom cratonal margin. (BP), which consists of a fault-bounded basin containing Riphean carbonates and terrigenous sedimentary rocks, and later Vendian and Cambrian sedimentary rocks that discordantly overlie a fragment of pre-Riphean basement of the North Asian craton.

The East Angara cratonal margin (EA), which consists of late Riphean terrigenous carbonate sedimentary rocks (sandstone, siltstone, and mudstone with interlayered dolomite and limestone) that overlie a fragment of the North Asia craton.

The South Taimyr cratonal margin (ST), which consists chiefly of a thick wedge of Ordovician through Jurassic cratonal margin and deep basin deposits.

The Verkhoyansk (North Asian) cratonal margin (VR), which consists chiefly of a thick wedge of Devonian through Jurassic miogeoclinal deposits.

## Cratonal Terranes and Superterranes

Three cratonal terranes that occur along the margins of the North Asian and Sino-Korean cratons and are interpreted as rifted and reaccreted fragments of these cratons:

The Okhotsk terrane (OH) consists of Archean and Proterozoic gneiss and schist and early and middle Paleozoic miogeoclinal sedimentary rock. The terrane is interpreted as a fragment of the North Asian craton and cratonal margin that was rifted in the Late Devonian or Early Carboniferous.

The Gyenggi-Yeongnam terrane (GY) consists of two major Archean and Proterozoic basement rock terranes. The terrane is interpreted as a displaced fragment of the Sino-Korean craton, or possibly a fragment of the South China (Yangzi) craton.

The Jiaonan cratonal terrane (JA) consists of a Paleoproterozoic major high pressure terrane that is interpreted as a displaced fragment of the Sino-Korean craton.

Along the margins of the North Asian and Sino-Korean cratons are several superterranes, which are interpreted as rifted and reaccreted fragments of these cratons and others interpreted as having originally formed elsewhere:

The Proterozoic through Cambrian Argun-Idermeg superterrane (AR), which consists of the Paleoproterozoic through late Paleozoic Argunsky, and Idermeg, passive continental-margin terranes. This superterrane may be either exotic with respect to the North Asian craton or a rifted fragment of that craton.

The late Riphean and older Tuva-Mongolia superterrane (TM), which consists of a series of Archean and Paleoproterozoic cratonal terranes (Gargan and Baydrag), the Sangilen passive continental-margin terrane, and the Muya metamorphic terrane. All of these terranes are interpreted as having been accreted together to form the backarc of the Baikal-Myra island arc described below.

The Proterozoic through Permian Bureya-Jiamusi superterrane (BJ), which consists of a tectonic collage of early Paleozoic metamorphic, continental-margin-arc, subduction zone, passive continental-margin and island-arc terranes. This superterrane is interpreted as a fragment of Gondwana that was accreted to the Sino-Korean craton in the Late Permian and accreted to the North Asian craton in the Late Jurassic during final closure of the Mongol-Okhotsk Ocean.

The Proterozoic through Ordovician Kara superterrane (KR), which consists of the late Neoproterozoic through Ordovician Kara continental-margin turbidite terrane. This superterrane is interpreted as a rift fragment of the North Asian craton that was reaccreted in the Jurassic.

The Archean to Jurassic Kolyma-Omolon superterrane (KOM), which consists of a tectonic collage of cratonal, passive-continental-margin, island-arc, and ophiolite terranes. The cratonal and passive-continental core of this superterrane was rifted from the North Asian craton and cratonal margin in the Late Devonian or Early Carboniferous, and after subsequent building of overlying island arcs, reaccreted to the North Asian cratonal margin in the Late Jurassic with the formation of collisional granites of the Main and Northern granite belts.

## Tectonic Collages Between the North Asian and Sino-Korean Cratons

Between the North Asian and Sino-Korean cratons are a series of accreted tectonic collages composed primarily of Paleozoic island arcs and tectonically linked subduction zones. Most of these tectonic collages, which were successively accreted southward during closures of the Paleo-Asian and Solon Oceans, collages contain one ore more island arcs and tectonically linked subduction zones. Because of these successive accretions, the collages generally young southward; however, this pattern is locally disrupted because some tectonic collages or parts them were interspersed by subsequent strike-slip faulting.

The Circum-Siberia tectonic collage (CS; Paleoproterozoic and Mesoproterozoic, accreted in the Neoproterozoic), which consists of the Baikal-Muya island arc, the Near Yenisey Ridge island arc, and the Zavhan continental-margin-arc, all of Neoproterozoic age, as well as small fragments of cratonal and metamorphic terranes of Archean and Proterozoic age. These three separate Neoproterozoic island-arc systems formed south (present-day coordinates) of the North Asian craton and cratonal margin.

The Yenisey-Transbaikal tectonic collage (YT; Vendian through Devonian, accreted in the Vendian through Early Ordovician), which consists of the Vendian through Middle Cambrian Kuznetsk-Tannuola and the Dzhida-Lake island-arc terranes, tectonically linked backarc basins, and now tectonically eroded subduction-zone terranes. This tectonic collage is interpreted as a linear array of island-arc systems that formed south (present-day coordinates) of the North Asian craton and cratonal margin and previously accreted terranes. The eastern part of the tectonic collage includes the West Stanovoy metamorphosed terrane, which may be a displaced fragment of the North Asian craton or of another craton.

The Altay tectonic collage (AL; Vendian through Ordovician, accreted in the Late Silurian), which consists of the Vendian through Early Ordovician Salair island-arc terrane and various fragments of arc-related turbidite terranes, subduction-zone terranes, metamorphic terranes derived from arc-related rocks, thick Cambrian and Ordovician overlap turbidites that formed on a continental slope and rise, and fragments of originally adjacent oceanic terranes. This tectonic collage is interpreted as an island-arc system that was active near the southwestern margin (present-day coordinates) of the North Asian craton and previously accreted terranes.

The Wundurmiao tectonic collage (WD; Mesoproterozoic through Silurian, accreted in the Late Silurian), which consists of the Late Ordovician and Silurian Laoling island-arc terrane, the Mesoproterozoic through Middle Ordovician Wundurmiao subduction-zone terrane, and the Neoproterozoic Seluohe subduction-zone terrane. The collage is interpreted as the Laoling island-arc system that formed near Sino-Korean craton. Both the island-arc system and craton were widely separated from the North Asian craton in the early Paleozoic.

The Atasbogd tectonic collage (AB; Ordovician through Permian, accreted in the Late Carboniferous or Early Permian), which consists of: the Ordovician through Permian Waizunger-Baaran terrane, the Devonian and Carboniferous Beitianshan-Atasbogd terrane, and (3) the Paleoproterozoic through Permian Tsagaan Uul-Guoershan continental-margin-arc terrane. This tectonic collage is interpreted as a southwestard continuation (present-day coordinates) of the South Mongolia-Khingan island arc that formed southwest and west (present-day coordinates) of the North Asian craton and cratonal margin and previously accreted terranes. This tectonic collage was initially separated from the North Asian craton by a large backarc basin.

The South Mongolia-Khingan tectonic collage (SM; Ordovician through Carboniferous, accreted in the Late Carboniferous or Early Permian), which consists of the South Mongolia-Khingan island-arc and tectonically linked subduction-zone terranes. This tectonic collage is interpreted as a major island-arc system that formed southwest and west (present-day coordinates) of the North Asian craton and cratonal margin and previously accreted terranes. This tectonic collage was initially separated from the North Asian craton by a large backarc basin.

The West Siberian tectonic collage (WS; Ordovician through Carboniferous, accreted in the Late Carboniferous or Early Permian), which consists of the Late Silurian through Early Carboniferous Rudny Altai island arc and the tectonically linked Ordovician through Early Carboniferous Kalba-Narim subduction-zone terrane. This tectonic collage is interpreted as a northwest continuation (present-day coordinates) of the South Mongolia-Khingan tectonic collage.

The Mongol-Okhotsk tectonic collage (MO; Devonian through Late Jurassic, accreted in the late Paleozoic through early Mesozoic), which consists mainly of the Permian through Jurassic Selenga, the Late Carboniferous and Early Permian Hangay, and the Uda-Murgal and Stanovoy continental-margin-arcs. These arcs are composed of continental-margin igneous overlap assemblages, continental-margin turbidite terranes, and tectonically linked, outboard subduction-zone terranes and overlap the southern margin of the North Asian craton and cratonal margin, and previously accreted terranes. This tectonic collage is interpreted as having formed during long-lived closure of the Mongol-Okhotsk Ocean with oblique subduction of terranes beneath the southern margin of the North Asian craton and previously accreted terranes.

The Solon tectonic collage (SL; Carboniferous to Permian, accreted in the late Paleozoic through early Mesozoic), which consists of the Carboniferous and Early Permian North Margin, the Late Carboniferous to Permian Solon, the Devonian Imjingang, the Paleozoic Ogcheon, and the Silurian through Permian Sangun-Hidagaien-Kurosegawa subduction-zone terranes. Parts of this tectonic collage are interpreted as fragments of the Solon Ocean plate that were subducted to form the South Mongolian, Lugyngol, Gobi-Khankaisk-Daxing'anling, and Jihei continental-margin-arcs, and other parts are interpreted as fragments of the Solon Ocean plate that were subducted to form the North Margin continental-margin-arc on the Sino-Korean craton.

## Tectonic Collages East of the North Asian and Sino-Korean Cratons

East of the North Asian and Sino-Korean cratons are a series of tectonic collages that were successively accreted from eastward during closures of parts of the ancestral and modern Pacific and older oceans in the region (fig. 1). Thus, these tectonic collages generally young eastward; however, this pattern is locally disrupted because some of them were interspersed by subsequent strike-slip faulting. Except for the first two collages (Verkhoyansk-Kolyma and Chukotka) the others contain one or more island arcs or continental-margin-arcs and tectonically linked subduction-zone terranes.

The Verkhoyansk-Kolyma tectonic collage (VK, late Paleozoic through Early Jurassic age, accreted in the Late Jurassic and Early Cretaceous), which consists of a deformed passive-continental-margin, accreted ophiolites, and subduction zone and is interpreted as having formed during accretion of the outboard Kolyma-Omolon superterrane.

The Chukotka tectonic collage (CH, Paleozoic and Triassic; accreted in the Late Jurassic and Early Cretaceous), which consists of passive continental-margin terranes that formed along the long-lived Neoproterozoic through early Mesozoic North American continental margin. This collage is interpreted as having been accreted to the northern Verkhoyansk-Kolyma tectonic collage in the Late Cretaceous after subsequent rifting of the North American cratonal margin in the Late Jurassic and Early Cretaceous and subsequent translation.

The South Anyui collage (SA, Permian through Early Jurassic; accreted in the Late Cretaceous), which consists of the Oloy island arc and tectonically linked subduction-zone terranes.

The Penzhina-Anadyr collage (PA, Late Jurassic and Early Cretaceous; accreted in the Late Cretaceous), which consists of the Murgal island-arc terrane and tectonically linked subduction-zone terranes to the east. This collage rims the eastern Kolyma-Omolon superterrane and Verkhoyansk-Kolyma tectonic collage and is also linked to the Uda continental-margin-arc.

The Badzhal collage (BD, Triassic through Early Cretaceous; accreted in the Late Cretaceous), which consists of the Umlekan continental-margin-arc and tectonically linked subduction-zone terranes to the east with Tethyan fauna.

The Honshu-Sikhote-Alin collage (HS, Jurassic and Early Cretaceous; accreted in the Cretaceous), which consists of fragments of island-arc, continental-margin turbidite (flysch), and subduction-zone terranes. This collage is interpreted as having formed along a transform continental margin.

The Koryak collage (KOR, Late Triassic through Cretaceous; accreted in Late Cretaceous), which consists of the Late Jurassic and Early Cretaceous Manitskiy island arc and tectonically linked subduction-zone terranes to the east.

The Sakhalin-Hokkaido collage (SK; Cretaceous; accreted in the Eocene), which consists of the Late Cretaceous flysch terranes of Sakhalin and Hokkaido Islands, and tectonically linked subduction-zone terranes to the east. This collage is interpreted as a continental-margin forearc basin and tectonically linked subduction-zone terranes that are associated with the East Sikhote-Alin continental-margin-arc.

The West Kamchatka tectonic collage (WK; mid-Cretaceous to early Tertiary; accreted in the early Cenozoic), which consists of late Paleozoic through Cretaceous subduction-zone terranes in the Russian Northeast. This collage was tectonically linked to Okhotsk-Chukotka continental-margin-arc.

The East Sakhalin collage (ES, Late Cretaceous to early Tertiary; accreted in the early Tertiary), which consists of the Late Cretaceous to middle Eocene Terpeniy-Tokoro-Nemuro-Shmidt island arc and tectonically linked subduction-zone terranes.

The Olyutorka-Kamchatka tectonic collage (OK, Late Cretaceous and Paleocene; accreted in the early Cenozoic), which consists of the Olyutorka island-arc and tectonically linked subduction-zone terranes to the east.

The East Kamchatka Peninsula tectonic collage (EP, mainly Paleocene, and accreted in the Pliocene), which consists of the Kronotskiy island arc and associated ophiolite.

## Carboniferous and Permian Continental-Margin-Arcs South of the North Asia Craton and on the Sino-Korean Craton

Several major continental-margin-arcs occur on previously accreted terranes south of the North Asian craton and on the Sino-Korean craton. These arcs are interpreted as related to subduction of the late Paleozoic and early Mesozoic Solon Ocean plate beneath the North Asian and Sino-Korean cratons. The Solon Ocean lay between the Argun-Idermeg superterrane to the north (present-day coordinates) and the Sino-Korean craton to the south.

The Altay continental-margin arc (at; Devonian and early Carboniferous), which occurs on the Altay and Yenisey-Transbaikal collages. This arc is interpreted as having formed along an active continental margin in an oblique subduction zone environment.

The Gobi-Khankaisk-Daxing'anling continental-margin arc (gh, Permian) which occurs on the Argun-Idermeg superterrane, South Mongolian and Solon collages. The arc is interpreted as having formed during subduction of the northern part of Solon Ocean plate under the southern margin (present-day coordinates) of the Argun-Idermeg superterrane.

The South Mongolian continental-margin arc (sm; middle Carboniferous through Triassic), which overlies and intrudes the South Mongolian and Atasbogd collages. This arc is interpreted as having formed during subduction of the northern part of Solon Ocean plate under the Argun-Idermeg superterrane.

The Lugyngol continental-margin arc (lg; Permian), which occurs on the South Mongolian and Solon collages. This arc is interpreted as having formed during subduction of the northern part of Solon Ocean plate under the southern margin (present-day coordinates) of the Argun-Idermeg superterrane.

The Jihei continental-margin arc (ji; Permian), which occurs on the South Mongolia-Khingan collage and intrudes the Bureya-Jiamusi superterrane and South Mongolia-Khingan collage, is interpreted as having formed during subduction of the northern part of Solon Ocean plate under the southern margin (present-day coordinates) of the Bureya-Jiamusi superterrane and adjacent units.

The North Margin continental-margin arc (nn; Late Carboniferous to Permian), which occurs on the northeastern margin (present-day coordinates) of Sino-Korean craton. This arc is interpreted as having formed during subduction of the southern (present-day coordinates) part of Solon Ocean plate under the northeastern margin of Sino-Korean craton.

## Devonian Through Early Cretaceous Continental-Margin-Arcs Along the Southeastern Margin of the North Asian Craton and Adjacent Accreted Terranes

Several major continental-margin-arcs occur along the southeastern margin of the North Asian craton or on adjacent accreted terranes. These arcs are interpreted as related to subduction of the late Paleozoic and early Mesozoic Mongol-Okhotsk Ocean plate beneath the North Asian craton and cratonal margin. The Mongol-Okhotsk Ocean lay between the North Asian craton to the north and the Argun-Idermeg superterrane to the south (present-day coordinates).

The Norovlin continental-margin arc (nr; Devonian through Early Carboniferous), which occurs on the Argun-Idermeg superterrane (Amur microcontinent - Argunsky and Idermeg passive continental-margin terranes). This arc is interpreted as having formed during subduction of the Mongol-Okhotsk Ocean plate beneath northern margin (present-day coordinates) of the Argun-Idemeg superterrane (Amur microcontinent).

The Hangay continental-margin arc (ha; Late Carboniferous to Early Permian, which occurs on the Yenisey-Transbaikal collage and Mongol-Okhotsk collage. This arc is interpreted as having formed during subduction of the northern part of Mongol-Okhotsk Ocean plate under the North Asian cratonal margin and previously accreted terranes.

The Selenga continental-margin arc (se; Permian through Jurassic), which overlies and intrudes the Yenisey-Transbaikal collage and Tuva-Mongolia superterrane. This arc is interpreted as having formed during oblique subduction of the Mongol-Okhotsk Ocean plate under the North Asian cratonal margin and previously accreted terranes.

The Uda-Murgal and Stanovoy continental-margin arcs (us; Jurassic and Early Cretaceous), which occur on the southern margin of the North Asian craton. These arcs are interpreted as having formed during final stage of subduction of the Mongol-Okhotsk Ocean plate.

## Jurassic and Early Cretaceous Island Arcs on or Adjacent to the Kolyma-Omolon Superterrane

Two major island arcs occur along the margin of the Kolyma-Omolon superterrane:

The Uyandina-Yasachnaya island arc (uy; Late Jurassic and Early Cretaceous), which is interpreted as having formed during subduction of the Oimyakon Ocean plate between the North Asian cratonal margin and the Kolyma-Omolon superterrane. Remnants of Oimyakon oceanic crust are preserved in small obducted ophiolites along the western margin of superterrane. This Oimyakon ocean lay between the Verkhoyansk (North Asian) cratonal margin to the southwest (present-day coordinates)and the Kolyma-Omolon to the northeast.

The Oloy island arc (ol; Late Jurassic), which is interpreted as having formed on the Kolyma-Omolon superterrane during subduction of the South Anyui Ocean plate beneath this superterrane to form the South Anyui subduction-zone terrane. The South Anyui ocean formed north (present-day coordinates)of the Kolyma-Omolon superterrane.

## Jurassic through Early Tertiary Continental-Margin-Arcs and Granite Belts Along the Eastern Margin of Northern Asia

A series of Jurassic through early Tertiary continental-margin arcs and granite belts occur along the eastern margin of the North Asian and Sino-Korean cratons and outboard accreted terranes to the east:

The Umlekan-Ogodzhin continental-margin arc (uo; Jurassic and Cretaceous, which occurs along the margin of the Kolyma-Omkolon superterrane. This arc is interpreted as having formed during subduction of the ancestral Pacific Ocean plate to form the Badzhal and Nadanhada terranes (parts of the Badzhal collage).

The South Verkhoyansk granite belt (sv; Late Jurassic through mid-Cretaceous), which occurs in central Russian Far east. This belt, which extends longitudinally along the central part of the South Verkhoyansk synclinorium in the Verkoyansk (North Asian) cratonal margin, is interpreted as having formed during the accretion of the outboard Okhotsk terrane.

The Main granite belt (ma; Late Jurassic), which occurs along the adjacent margins of the North Asian cratonal margin and Kolyma-Omolon superterrane. This belt is interpreted as having formed during and immediately after collision of the Kolyma-Omolon superterrane with the North-Asian cratonal margin.

The Transverse granite belt (tv; Early Cretaceous), which radiates outwards from the southwestern bend in the Kolyma-Omolon superterrane. This belt is interpreted as having formed during the late stage of accretion of the Kolyma-Omolon superterrane.

The Northern granite belt (nb; Early Cretaceous, 138 to 120 Ma), which occurs along the northwestern margin of the Kolyma-Omolon superterrane. The belt is interpreted as having formed during the subduction of oceanic crust in a closure of a small oceanic basin during the late stage of accretion of the Kolyma-Omolon superterrane.

The Khingan-Okhotsk continental-margin arc (ko; Early and mid-Cretaceous), which occurs in the Russian Southeast and consists of the Khingan-Okhotsk volcanic-plutonic belt. This arc was tectonically paired to the Early Cretaceous

Zhuravlevsk-Amur River and Kiselevka-Manoma subduction-zone terranes (part of the Honshu-Sikhote-Alin collage).

The Okhotsk-Chukotka continental-margin arc (oc; Late Cretaceous through early Tertiary), which occurs along the eastern margin of the central and northern Russian Far East. This arc is interpreted as having formed during subduction of the ancestral Pacific Ocean plate with formation of the West Kamchatka, Ekonay, and Yanranay subduction-zone terranes.

The East Sikhote-Alin continental-margin arc (ea; Late Cretaceous to early Tertiary), which occurs along the margin of southern Russian Far East. This arc is interpreted as having formed during subduction of the ancestral Pacific Ocean plate with formation of the older part of the Hidaka, the younger part of the Aniva, terrane, and the Nabilsky and Tokoro subduction-zone terranes.

### Active Continental-Margin-Arcs Along the Eastern Margin of Northern Asia

Three active continental-margin arcs occur along the eastern margin of the North Asian and Sino-Korean cratons and outboard accreted terranes to the east:

The Izu-Bonin continental-margin arc (ib; Miocene through Holocene), which occurs south of southern Japan, where it consists of a volcanic arc composed chiefly of basalt to rhyolite, associated volcaniclastic rock, and intercalated hemipelagic mudstone. This arc is interpreted as having formed from subduction of the Philippine Sea Plate with the creation of the Nankai subduction zone.

The Japan continental-margin arc (ja; Miocene through Holocene), which occurs along the Japan Islands and consists of extensive Quaternary volcanic and associated rocks. This arc is interpreted as having formed during subduction of the Pacific Ocean and Philippine Sea Plates with formation of the Japan Trench and the Nankai subduction zones.

The Kuril-Kamchatka continental-margin arc (kk; Miocene through Holocene), which occurs along the Kamchatka Peninsula and the Kuril Islands and consists of the Pliocene to Quaternary Central Kamchatka volcanic belt, central Kamchatka volcanic and sedimentary basin, and the East Kamchatka volcanic belt. This arc is interpreted as having formed during subduction of the Pacific Ocean Plate with the creation of the Japan Trench subduction zone.

### Transpressional Arcs (Devonian Through Cretaceous)

Four major transpressional arcs occur along the margins of the North Asian craton and previously accreted terranes to the south. These arcs are associated with a combination of strike-slip faulting and local compression and extension.

The Kema arc (ke) (Mid-Cretaceous) occurs in the Russian Southeast and consists of the Kema island arc terrane, and the Late Jurassic and Early Cretaceous Zhuravlevsk-Amur River continental-margin turbidite terrane. The arc is part of the Honshu-Sikhote-Alin collage (Jurassic and Early Cretaceous) described above. The Zhuravlevsk-Amur River continental-margin turbidite terrane and the companion Kema arc terranes are interpreted as forming along a Late Jurassic and Early Cretaceous continental-margin transform fault.

The South Siberian transpressional arc (ss; Early Devonian), which occurs in Southern Siberia and is interpreted as having formed along the southern margin of the North Asian craton and cratonal margin during Early Devonian rifting that successively evolved into a continental-margin transform margin and subsequently a convergent margin.

The Mongol-Transbaikal transpressional arc (mt; Late Triassic through Early Cretaceous), which occurs in northern Mongolia and southern Siberia and is interpreted as having formed during strike-slip faulting and rifting along the Mongol-Okhotsk Fault during and after the final closure of the Mongol-Okhotsk Ocean.

(3) The Trans-Baikal-Daxinganling transpressional arc (tr; Middle Jurassic through Early Cretaceous), which occurs in Southern Siberia, Mongolia, Northeastern China and is interpreted as having formed during strike-slip faulting and rifting along the Mongol-Okhotsk Fault during and after final closure of the Mongol-Okhotsk Ocean.

# Regional Metallogenesis of Northeast Asia

## Synthesis of Mineral-Deposit Models

A modern regional metallogenic analysis requires that appropriate mineral-deposit models be characterized, synthesized, and grouped for correlation with the regional tectonic processes that formed the known mineral deposits. The beginning of this type of correlation between models and tectonic processes is evident in many of the classic compilations of mineral deposits models (Eckstrand, 1984; Cox and Singer, 1986; Singer, 1993). The mineral-deposit models that were defined and described for the metallogenic analysis of Northeast Asia are listed in table 2. For this large and complex region (fig. 2), a suite of 122 mineral-deposit models was sufficient to describe the characteristic features of the 1,674 lode deposits and 75 placer districts (Obolenskiy and others, 2003 and this volume, chapter 3). The models include previous descriptions by Eckstrand (1984), Cox and Singer (1986), and Nokleberg and others (1997a), with modifications by Obolenskiy and others (2003 and this volume, chapter 3).

The mineral-deposit models listed in table 2 consist of both descriptive and genetic information that is systematically arranged to define the essential attributes of each class or type of mineral deposits; however, some models are based mainly on descriptive (empirical) information, whereby the various attributes are recognized as essential even though their relationships are unknown. For example, the basaltic native Cu mineral-deposit type, the geologic association of Cu sulfides with relatively Cu rich metabasalt or greenstone is the essential attribute. Some other mineral-deposit models are defined by genetic (theoretical) considerations, whereby the attributes are related through some fundamental geologic process. For example, the W±Mo±Be skarn deposit mineral-deposit model, the genetic process of contact metasomatism is the essential attribute. For additional information on the methodology for defining mineral-deposit models, see the discussions by Eckstrand (1984) and Cox and Singer (1986).

A major facet of the compilation and synthesis of mineral-deposit models is interpretation of the tectonic environment(s) for each model. This interpretation permits a ready perception of the geologic setting for the formation of each mineral-deposit type. The tectonic environments interpreted for the major mineral-deposit models that were used to classify deposit descriptions for the metallogenic and tectonic analysis of Northeast Asia (fig. 1) are listed in table 3. Only seven major tectonic events are interpreted for the origin of major geologic units and mineral deposits: (1) rifting; (2) sea-floor spreading; (3) continental-margin-arc and backarc; (4) island arc and backarc; (5) collision; (6) transform-continental-margin faulting and associated bimodal volcanic and plutonic belt, and (7) plume intrusion.

## Summary of the Methodology of Metallogenic and Tectonic Analysis

The methodology of metallogenic and tectonic analysis for Northeast Asia (fig. 1) is illustrated in figure 3 from Nokleberg and others (2005).

The steps in this analysisare as follows.

1. A regional geologic base map is constructed. Figure 3A schematically depicts the regional geology of the Northeast Asia, with craton A representing the North Asian craton and craton B representing the Sino-Korean craton, terranes 1 through 4 representing the tectonic collages of intercratonal terranes and accretionary assemblages a through c, and postaccretionary overlap assembagles d and e, representing the major arcs overlying cratons and collages.

2. A series of mineral-deposit models appropriate for the regional geology are identified and defined, and a mineral-deposit database is compiled. In this example, the major mineral-deposit models are low-sulfide Au in shear zone and quartz vein, Au-Ag epithermal vein, porphyry Cu (+Au), bedded barite, and kuroko massive sulfide.

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

4. The genesis of bedrock geologic units, structures, and contained metallogenic belts and mineral deposits is interpreted according to modern tectonic concepts, for example, are kuroko massive sulfide deposits forming in an island-arc environment, porphyry Cu and Au in shear zone and quartz vein deposits forming in a collisional environment, and epithermal Au-Ag vein deposits forming in a continental-margin igneous arc environment.

5. By carefully defining each metallogenic belt to be the geologically favorable area for a group of coeval and genetically related mineral deposits, a predictive characteristic is established within each belt for undiscovered mineral deposits.

### Synthesis of Metallogenic-Belt Maps

Many metallogenic maps display major mineral deposits and (or) districts on a regional geologic base map. These maps are commonly quite complex because of a high density of deposits. To simply data presentation and increase understanding of regional patterns, the concept of a metallogenic-belt map was developed for the studies of Northeast Asia and the Circum-North Pacific (Nokleberg and others, 1997b,c; Obolenskiy and others, 2003, 2004). As an example of the power of a modern-day metallogenic-belt map, the major Archean through Mesoproterozoic metallogenic belts of Northeast Asia are shown in figure 4*A*, which includes the summary geodynamics map as a base layer. Besides displaying important summary map data, figure 4*A* also illustrates how the origins of metallogenic belts can be related to the major geologic units or structures containing the belts through the definition of a metallogenic belt, that is a group 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. For additional information, summary descriptions of the major metallogenic belts in the region are provided in appendix C.

# Benefits of Performing a Combined Regional Metallogenic and Tectonic Analysis

As described above, a high-quality metallogenic and tectonic analysis, including synthesis of a metallogenic and

**Table 2.** List of lode mineral deposit models employed for metallogenic analysis of Northeast Asia.

[Adapted from Obolenskiy and others 2003; chapter 3 this volume]

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

**Table 2.** List of lode mineral deposit models employed for metallogenic analysis of Northeast Asia.—Continued

[Adapted from Obolenskiy and others 2003; chapter 3 this volume]

| Deposit Group | Deposit Name |
|---|---|
| Deposits related to subaerial extrusive rocks | Ag-Pb epithermal vein<br>Ag-Sb vein<br>Au-Ag epithermal vein<br>Au-Kmetasomatite (Kuranakh type)<br>Barite vein<br>Basaltic native Cu (Lake Superior type)<br>Be tuff<br>Carbonate-hosted Ag-Pb<br>Carbonate-hosted As-Au metasomatite<br>Carbonate-hosted fluorspar<br>Carbonate-hosted Hg-Sb<br>Clastic sediment-hosted Hg±Sb<br>Epithermal quartz-alunite<br>Fluorspar vein<br>Hg-Sb-W vein and stockwork<br>Hydrothermal Iceland spar<br>Hydrothermal-sedimentary fluorite<br>Limonite<br>Mn vein<br>Ni-Co arsenide vein<br>Polymetallic Ni vein<br>Polymetallic (Pb, Zn, Ag) carbonate-hosted metasomatite<br>Polymetallic (Pb, Zn±Cu, Ba, Ag, Au) volcanic-hosted metasomtite<br>Rhyolite-hosted Sn<br>Silica-carbonate (listvinite) Hg<br>Sulfur-sulfide (S, FeS2)<br>Trapp related Fe skarn (Angara-Ilim type)<br>Volcanic-hosted Au-base-metal metasomatite<br>Volcanic-hosted Hg<br>Volcanic-hosted U<br>Volcanic-hosted zeolite |
| Deposits related to hydrothermal-sedimentary processes | Bedded barite<br>Carbonate-hosted Pb-Zn (Mississippi Valley type)<br>Chemical-sedimentary Fe-Mn<br>Evaporate halite<br>Evaporate sedimentary gypsum<br>Korean Pb-Zn massive sulfide<br>Polygenic REE-Fe-Nb deposits (Bayan-Obo type)<br>SEDEX (Sedimentary exhalative Pb-Zn)<br>Sedimentary bauxite<br>Sedimentary celestite<br>Sedimentary Fe-V<br>Sedimentary phosphate<br>Sedimentary siderite Fe<br>Sediment-hosted Cu<br>Stratiform Zr (Algama Type) |

**Table 2.** List of lode mineral deposit models employed for metallogenic analysis of Northeast Asia.—Continued

[Adapted from Obolenskiy and others 2003; chapter 3 this volume]

| Deposit Group | Deposit Name |
|---|---|
| Deposits related to metamorphic processes | Au in black shale<br>Au in shear zone and quartz vein<br>Banded iron-formation (Algoma type)<br>Banded iron-formation (Superior type)<br>Clastic-sediment-hosted Sb-Au<br>Clastic-sediment-hosted U<br>Cu-Ag vein<br>Homestake Au<br>Metamorphic graphite<br>Metamorphic sillimanite<br>Phlogopite skarn<br>Piezoquartz<br>Rhodusite-asbestos<br>Sedimentary-metamorphic borate<br>Sedimentary-metamorphic magnesite<br>Serpentinite-hosted asbestos<br>Talc (magnesite) replacement |
| Deposits related to surficial processes | Bauxite (karst type)<br>Laterite Ni<br>Placer and paleoplacer Au<br>Placer diamond<br>Placer PGE<br>Placer Sn<br>Placer Ti-Zr<br>Weathering crust and karst phosphate<br>Weathering crust Mn(±Fe)<br>Weathering crust REE-Zr-Nb-Li carbonatite |
| Exotic deposits | Impact diamond |

tectonic model, will (1) greatly benefit other mineral resource studies (fig. 3), including synthesis of mineral-deposit models (Eckstrand, 1984; Cox and Singer, 1986; Singer and Cox, 1988), (2) improve prediction of undiscovered mineral depisuts as a part of quantitative mineral-resource-assessment studies (Cox, 1993; Singer, 1993, 1994), (3) assist land-use and mineral-exploration planning, (4) improve interpretations of the origins of host rocks, mineral deposits, and metallogenic belts, and (5) suggest new research.

Following are three examples of these benefits. (1) Indepth understanding of the tectonic and metallogenic origins of potential host rocks for mineral deposits may enable the prediction of undiscovered mineral deposits according to favorable host-rock geology. This capability is crucial for a mineral-resource assessment because the outlines of permissive tracts (that is, areas with a potential for undiscovered mineral-deposit types) must be drawn for each mineral-deposit type according to a favorable geologic environment. (2) Regional metallogenic and tectonic analyses, such as those we have performed for Northeast Asia and the Circum-North Pacific, enable the identification and location of continuations of ore-hosting terranes and permissive tracts around the world that were separated by various tectonic processes which have operated throughout geologic 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 tectonic collage in the center of a continent. Tectonic analysis of the origin of the island-arc terranes and their correlations with each other will result in a 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 of metallogenic analysis and mineral-resource assessment. (3) An understanding of the metallogenic setting and history of host rocks and ore-forming processes is commonly important for estimating the number of undiscovered mineral deposits in a permissive tract for a mineral-resource assessment. For example, the number of volcanogenic massive sulfide

**Table 3.** 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 (event) | Major Mineral-Deposit Models (table 2) |
|---|---|---|
| Northeast Asia and North American cratons and cratonal margins | Rifting | SEDEX, polygenic REE, Cyprus Cu-Zn massive sulfide, volcanogenic massive sulfide, carbonate-hosted sulfide. |
| Ocean | Sea-floor spreading | Cyprus Cu-Zn massive sulfide, volcanogenic massive sulfide, podiform chromite. |
| North Asian and North American continental margins | Continental-margin arc and backarc | Porphyry, epithermal vein, polymetallic vein, skarn, greisen, pegmatite, volcanogenic massive sulfide, Besshi Cu-Zn-Ag massive sulfide. |
| Ocean | Island arc and backarc | 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 | 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 Cr-PGE; W skarn, porphyry Cu-Mo(±Au, Ag_, Au-Ag epithermal vein, Au quartz vein, basaltic native Cu, Cu-Ag vein. |
| North Asian and North American cratons | Plume intrusion | Mafic-ultramafic-related Cu-Ni-PGE and Ti-Fe(±V), REE(±Ta, Nb, Fe) carbonatite, skarn, metamorphic graphite, diamond-bearing kimberlite, porphyry, pegmatite. |

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 in a volcanic forearc, axial arc, or backarc tectonic setting. Conversely, no deposits of this type might be estimated for a tract of similar rocks in an extensional cratonic setting.

# Summary of Major Metallogenic Belts in Northeast Asia

The following summaries of major metallogenic belts in Northeast Asia (fig. 1) by time period are adapted from detailed descriptions of metallogenic belts by Rodionov and others (2004). Detailed descriptions of lode deposits in each belt were presented by Ariunbileg and others (2003), and summary descriptions of the major metallogenic belts in the region are presented in appendix C.

## Major Archean Metallogenic Belts

The major Archean (>2.5 Ga) metallogenic belts in the region (fig. 1) are the Jidong, Liaoji, Sharizhalgaiskiy, Sutam, West Aldan belts, and Wutai (fig. 4*A*; see appendix C), all of which possess geologic units favorable for, and all contain, major stratiform banded iron-formation deposits in the (1) Sino-Korean terrane in northern China, and (2) granite-greenstone, orthogneiss, and gneiss terranes in southern Siberia that are interpreted as tectonic fragments derived from either the North Asian craton, or possibly, other cratons. Some of the banded iron-formation deposits are interpreted as having formed in an Archean backarc basin and (or) island arc. The isotopic ages of the stratiform deposits in the region range from about 3.5 to 2.5 Ga. Lesser Archean deposit types include stratiform volcanogenic massive sulfide, Au in shear-zone and quartz vein that formed during later retrograde metamorphism, and talc (magnesite) deposits that formed during later replacements. The isotopic ages of the younger

Au in shear-zone and quartz vein range from less than 1.7 to 2.5 Ga. The stratiform banded iron-formation and volcanogenic massive sulfide deposits formed early in the geologic history of the region.

## Major Paleoproterozoic Metallogenic Belts

The major Paleoproterozoic (2.5 to 1.6 Ga) metallogenic belts in the region (fig. 1)are the Baydrag, Jiliaojiao, Kalar-Stanovoy, Luliangshan, Nimnyr, Qinglong, Tyrkanda-Stanovoy, and Uguy-Udokanskiy belts (fig. 4*B*; see appendix C).

### Metallogenic Belts Related to Sedimentary Basins Formed on Craton or Cratonal Margins

Several belts possess geologic units favorable for major stratiform sediment-hosted deposits, including the Baydrag, Jiliaojiao, Luliangshan, Qinglong, and Uguy-Udokanskiy with banded iron-formation, sedimentary-metamorphic borate and magnesite, sediment-hosted Cu, clastic-sediment-hosted Sb-Au, and Korean Pb-Zn massive sulfide deposits. The deposits are mainly hosted in sedimentary basins in the Tuva-Mongolia superterrane, the Sino-Korean craton, and cratonal terranes derived either from the North Asian craton, or possibly other cratons. Isotopic ages of the deposits range from about 2.23 to 2.8 Ga. Favorable geologic environments for the metallogenic belts occurred in sedimentary basins on cratons or cratonal margins, and locally, in rift basins.

### Metallogenic Belts Related to Rifting or Terrane Collision

Two metallogenic belts possess geologic units favorable for major deposits hosted in alkaline igneous rocks and

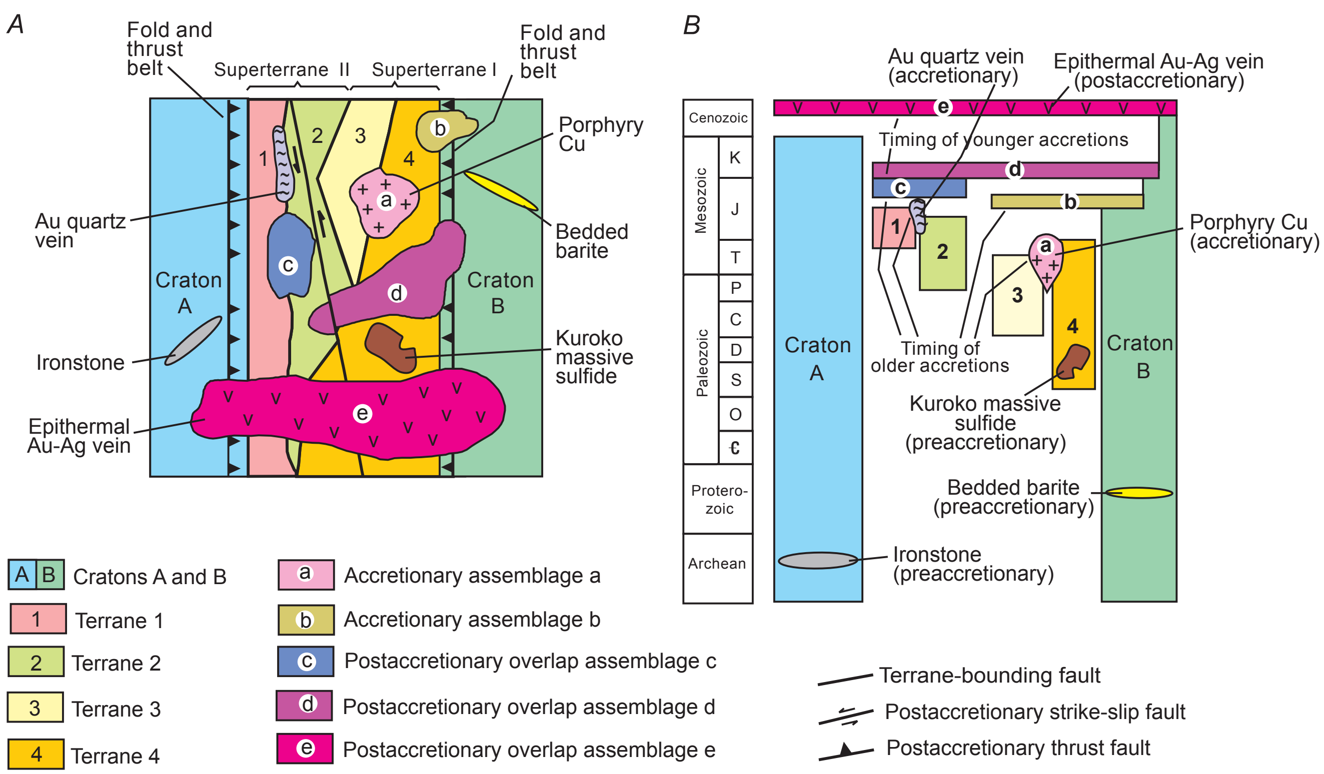


**Figure 3.** Schematic diagram of an orogenic belt, illustrating methodology for metallogenic analysis of cratons, terranes, accretionary assemblages, overlap assemblages, and contained metallogenic belts (fig. 1). *A*, Map view. *B*, Stratigraphic column. From Parfenov and others (1998) and Nokleberg and others (2005).

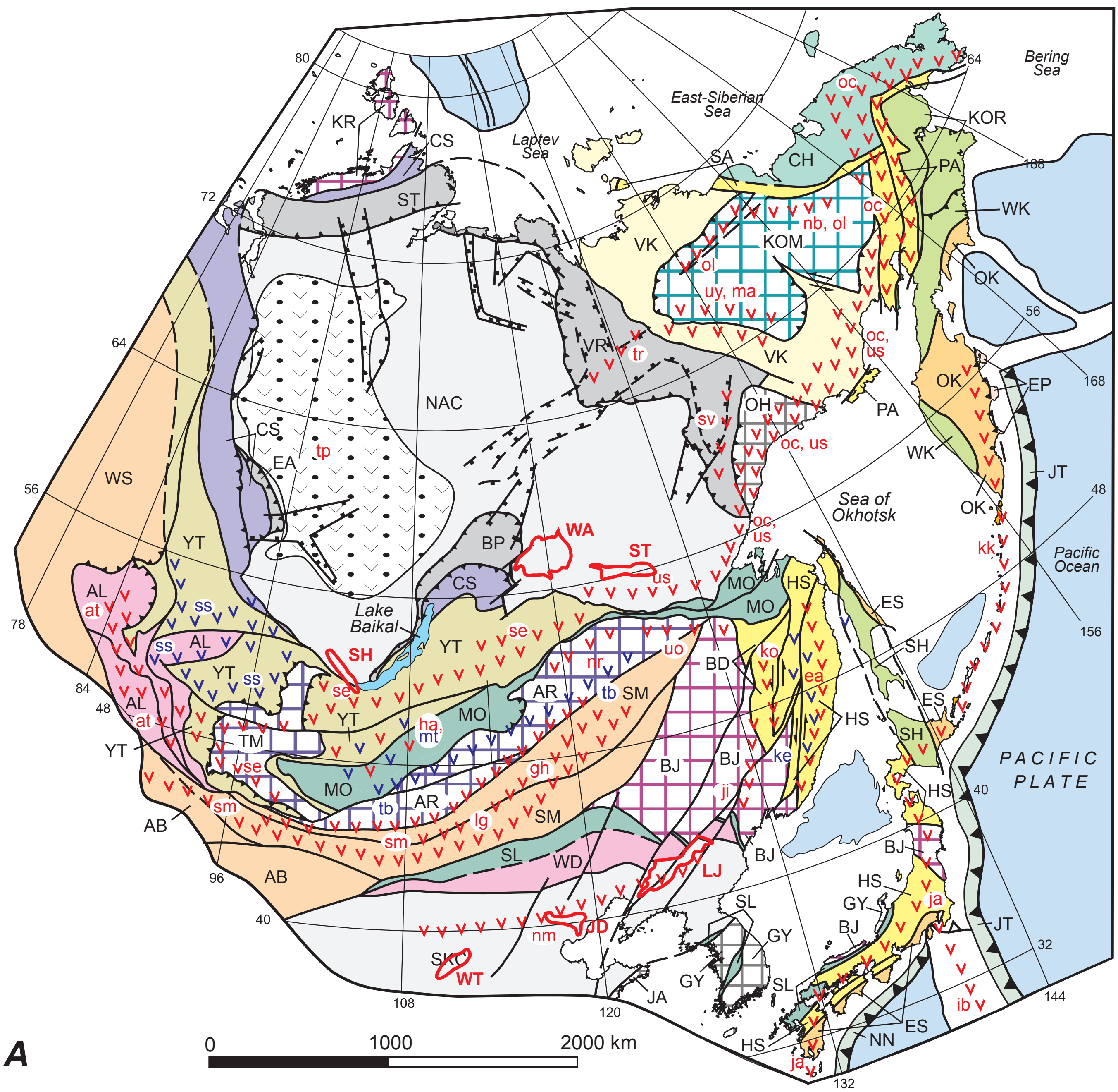


**Figure 4.** Generalized maps of Northeast Asia, showing locations of major metallogenic belts and major geologic units during various time periods: Archean (*A*), Paleoproterozoic and Mesoproterozoic (*B*). Neoproterozoic (*C*), Cambrian through Silurian (*D*), Devonian through Early Carboniferous (*E*), Late Carboniferous through Middle Triassic (*F*), Late Triassic through Early Jurassic (*G*), Middle Jurassic through Early Cretaceous (*H*), Cenomanian through Campanian (*I*), and Maastrichtian through Quaternary (*J*). Same symbols as in figure 2. Outlines of metallogenic belt adapted from Obolenskiy and others (2003, 2004) and Parfenov and others (2003, 2004). Metallogenic belts for area to east of 144 E (east boundary of study area) were described and interpreted by Nokleberg and others (2003). See appendix C for summary description of metallogenic belts.

carbonatite: the Nimnyr and Uguy-Udokanskiy belts apatite carbonatite, Ta-Nb-REE alkaline metasomatite, and zoned mafic-ultramafic Cr (PGE) deposits that are interpreted as formed during rifting of craton or cratonal terranes. Isotopic ages range from about 2.0 to 1.6 Ga. The igneous host rocks overlie or intrude cratonal terranes that are interpreted as derived from the North Asian craton, or possibly, other cratons.

Four metallogenic belts possess geologic units favorable for major Au in shear-zone and quartz vein deposits: the Jiliaojiao, Kalar-Stanovoy, Luliangshan, and Tyrkanda-Stanovoy. The host veins hosting the deposits intrude the North Asian and Sino-Korean cratons. These deposits are related to low-grade metamorphism and deformation that is interpreted as having occurred during terrane collision.

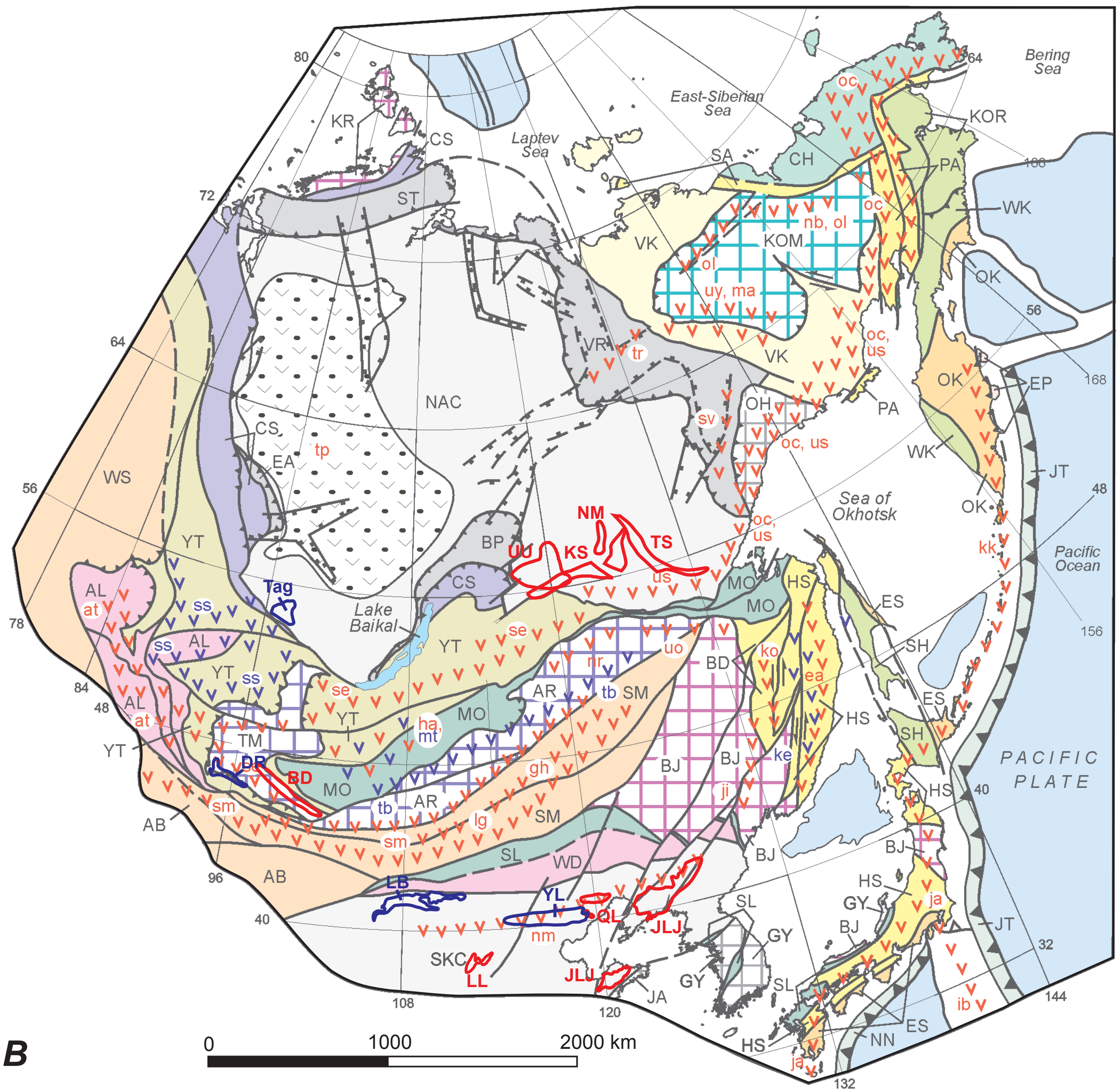


**Figure 4.**—Continued.

## Major Mesoproterozoic Metallogenic Belts

The major Mesoproterozoic (1.6 to 1.0 Ga) metallogenic belts in the region (fig. 1) are the Darvi, Langshan-Bayan Obo, and Yanliao (fig. 4*B*; see appendix C), all of which possess geologic units favorable for major stratiform sediment-hosted deposits: the Darvi (with sedimentary bauxite and sedimentary Fe-V deposits, the Langshan-Bayan Obo with sedimentary exhalative Pb-Zn (SEDEX) and polygenic REE-Fe-Nb deposits, and the Yanliao with chemical-sedimentary Fe-Mn and sedimentary exhalative Pb-Zn (SEDEX)) deposits. The isotopic ages of deposits range from 1.4 to 1.1 Ga. Favorable geologic environments for the metallogenic belts with sediment-hosted deposits occurred in sedimentary basins in passive continental-margin rocks deposited on the Sino-Korean craton or on the cratonal units of the Tuva-Mongolia superterrane that may be derived from the North Asian craton or another craton. The sedimentary exhalative Pb-Zn (SEDEX) and polygenic REE-Fe-Nb deposits in the Langshan-Bayan Obo belt (containing the famous Bayan Obo REE-Fe-Nb Mine) are interpreted as having formed during extrusion of carbonatite magma, associated hydrothermal activity, and deposition of sedimentary overlap assemblages in a rift along the passive-continental-margin of the Sino-Korean craton.

## Major Neoproterozoic Metallogenic Belts

The major Neoproterozoic (1.0 Ga to 540 Ma) metallogenic belts in the region (fig. 1) are the Angara-Pit, Baikalo-Muiskiy, Bodaibinskiy, Bokson-Kitoiskiy, Central-Yenisei, Hovsgol, Jixi, Kyllakh, Lake, Pribaikalskiy, Prisayanskiy, and Vorogovsko-Angarsk (fig. 4*C*; see appendix C).

### Metallogenic Belts Related to Sedimentary Basins Formed on Cratonal Margins

Several metallogenic belts possess geologic units favorable for major stratiform sediment-hosted deposits, including the Angara-Pit with sedimentary siderite Fe and volcanogenic-sedimentary Fe deposits, the Bodaibinskiy and Central-Yenisei with Au in black shale deposits, the Bokson-Kitoiskiy with sedimentary bauxite deposits, the Hovsgol with sedimentary phosphate, volcanogenic-sedimentary Mn, and sedimentary Fe-V deposits, the Jixi with banded iron-formation deposits, the Kyllakh and Pribaikalskiy with carbonate-hosted Pb-Zn deposits, and the Vorogovsko-Angarsk with sedimentary exhalative Pb-Zn (SEDEX) and carbonate-hosted Pb-Zn (Mississippi valley type) deposits. Fossil or isotopic ages of the host rocks or deposits range from Riphean to Vendian. The deposits are hosted in sedimentary rocks deposited either on the North Asian cratonal margin (Angara Pit, Bodaibinskiy, Central-Yenisei, and Kyllakh metallogenic belts), or in basins on passive-continental-margin terranes possibly derived from this cratonal margin (Hovsgol and Vorogovsko-Angarsk metallogenic belts). Favorable geologic environments for the metallogenic belts occurred during sedimentation on continental shelves or during rifting of a continental shelf.

### Metallogenic Belts Related to Island Arcs

Several metallogenic belts possess geologic units favorable for major volcanic- and (or) granite-hosted deposits, including the Baikalo-Muiskiy with volcanogenic-hydrothermal-sedimentary Pb-Zn massive sulfide deposits and the Lake with volcanogenic Cu-Zn massive sulfide (Urals type), volcanogenic-sedimentary Fe, Cu and Fe skarn, granitoid-related Au vein, mafic-ultramafic related Cu-Ni-PGE, podiform Cr, and mafic-ultramafic related Ti-Fe deposits. Favorable geologic environments for the metallogenic belts occurred in island arcs or on sea floors underlying arcs in the Baikal-Muya island-arc terrane (part of the Circum-Siberia tectonic collage ), the Lake island-arc terrane (part of the Yenisey-Transbaikal collage), and island-arc terranes in the Tuva-Mongolia superterrane.

### Metallogenic Belts Related to Terrane Accretion

Several metallogenic belts possess geologic units favorable for Au in shear-zone and quartz vein deposits, including the Bokson-Kitoiskiy and Central-Yenisei which are hosted in either the western part of the North Asian craton or the Yenisey-Transbaikal collage. The Bokson-Kitoiskiy metallogenic belt also contains serpentine-hosted asbestos deposits that are interpreted as having formed in the same tectonic environment. The Prisayanskiy belt is hosted in terranes derived from the North Asian craton and contains REE carbonatite, and mafic-ultramafic-related Ti-Fe deposits that are interpreted as having formed in Neoproterozoic magmatic events. The Jixi metallogenic belt contains minor Homestake Au deposits of unclear tectonic origin. Favorable geologic environments for the metallogenic belts occurred during regional metamorphism and hydrothermal alteration associated with accretion of terranes to the North Asian cratonal margin.

## Major Cambrian Through Silurian Metallogenic Belts

The major Cambrian through Silurian (540 to 410 Ma) metallogenic belts in the region (fig. 1) are the Bayanhongor-1, Bedobinsk, East Liaoning, Govi-Altai, Hovd, Hunjiang-Taizihe, Jinzhong, Kiyalykh-Uzen, Kizir-Kazyr, Martaiginsk, Ozerninsky, South Khingan, and Uda-Shantar belts (fig. 4*D*; see appendix C).

## Metallogenic Belts with Granitoid-Hosted Deposits Related to Continental-Margin-Arcs, Transpression Faulting, or Terrane Accretion

Several metallogenic belts possess geologic units favorable for major granitoid-hosted or granitoid-related deposits, including the Bayanhon-gor with Au in shear-zone and quartz vein, granitoid-related Au vein, Cu-Ag vein, Cu skarn deposits, the Hovd with granitoid-related Au vein, Au and Cu skarn deposits, the Kizir-Kazyr with Fe skarn and granitoid-related Au vein deposits, and the Martaiginsk with granitoid-related Au vein and Au skarn deposits. Isotopic ages of the deposits or host rocks range from 490 to 420 Ma. The Kiyalykh-Uzen metallogenic belt (with Cu, W, and Fe skarn deposits and W-Mo-Be greisen, stockwork, and quartz vein deposits, and the Martaiginsk metallogenic belt with granitoid-related Au vein and Au skarn deposits contain collisional granitoids that are interpreted as having intruded during transpressive (dextral slip) movement along the

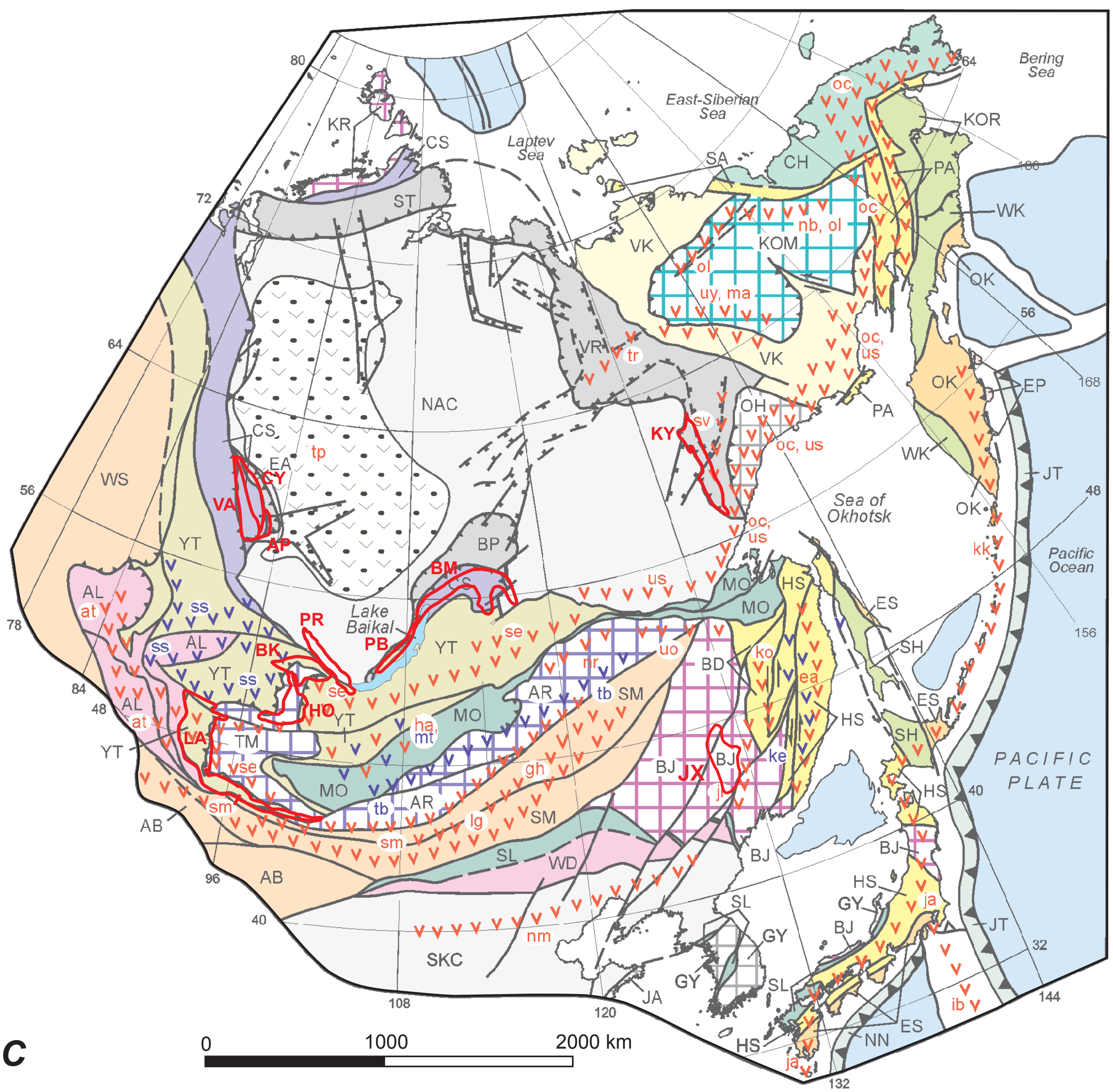


**Figure 4.**—Continued.

Kuznetsk Alatau Fault or during terrane accretion. Favorable geologic environments for the metallogenic belts are in the Altai and Yenisey-Transbaikal collages which are interpreted as having formed in a continental-margin-arc or associated continental-margin turbidite terranes, in a backarc basin associated with continental-margin-arc magmatism, during transform continental-margin faulting, in an island-arc, or during terrane accretion.

## Metallogenic Belts with Volcanic-Hosted Deposits Related to Continental-Margin or Island Arcs

Several metallogenic belts possess geologic units favorable for major volcanic-hosted deposits, including the Govi-Altai, Ozerninsky, and Uda-Shantar with volcanogenic-sedimentary Fe, volcanogenic-sedimentary Mn, volcanogenic-hydrothermal-sedimentary massive sulfide,

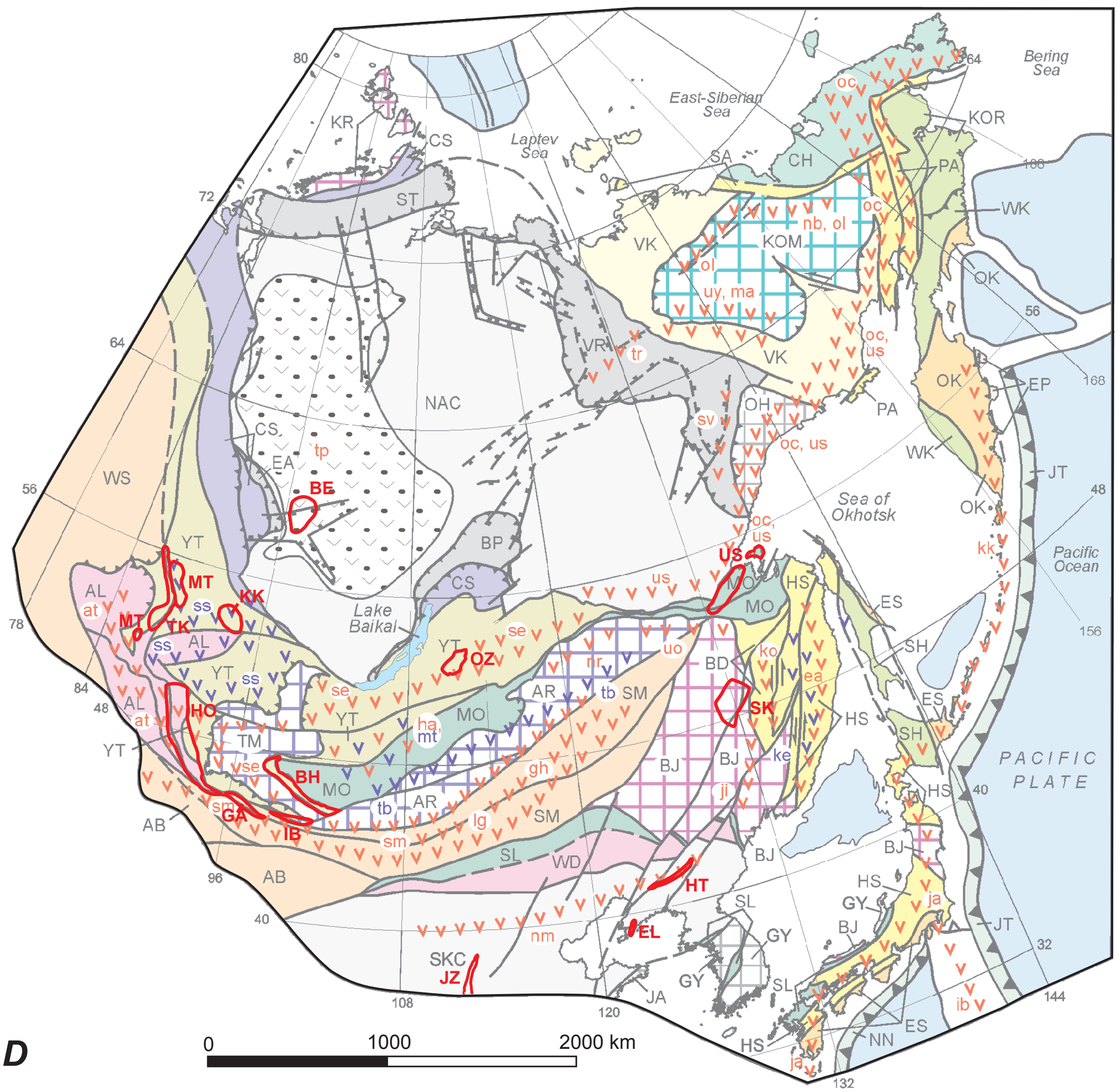


**Figure 4.**—Continued.

and sedimentary phosphate deposits. Fossil ages of the deposits or host rocks range from Cambrian through Silurian. The Bedobinsk metallogenic belt with sediment-hosted Cu deposits, hosted in early Paleozoic sedimentary units of the North Asia craton, is interpreted as having formed in an inland-sea basin during post-saline stage of rock deposition. Favorable geologic units for the metallogenic belts occurred in the Mongol-Okhotsk, South Mongolia-Khingan, and Yenisey-Transbaikal collages, which are interpreted as having formed either in continental-margin or island arcs or by sea floor sedimentation.

### Unique Kimberlite Diamond Metallogenic Belts

Three metallogenic belts in the Sino-Korean craton possess unique favorable geologic units: the East Liaoning belt for diamond-bearing kimberlite deposits, the Hunjiang-Taizihe and Jinzhong belts for evaporite sedimentary gypsum deposits in platform sedimentary cover, the South Khingan belt for banded iron-formation deposits in continental-margin sedimentary cover. The latter two belts are interpreted as having formed during sedimentation along a cratonal margin, whereas the origin of the diamond-bearing kimberlite deposits is poorly known.

## Major Devonian through Early Carboniferous Metallogenic Belts

The major Devonian through Early Carboniferous (410 to 320 Ma) metallogenic belts in the region (fig. 1) are the Bayangovi, Botuobiya-Markha, Daldyn-Olenyok, Edrengiin, Edren-Zoolon, Hongqiling, Kizhi-Khem, Mamsko-Chuiskiy, Rudny Altai, Salair, Sette-Daban, Sorsk, Tsagaan-suvarga, Udzha, Ulziit, and Yaroslavka (fig. 4*E*; see appendix C).

### Metallogenic Belts Related to Continental-Margin or Island Arcs

Five metallogenic belts possess geologic units favorable for a wide variety of major granite-hosted deposits: the Altai, Deluun-Sagsai, Rudny Korgon-Kholzun, Salair, and Tsagaan-suvarga belts with volcanic-hosted metasomatite and Fe, polymetallic Pb-Zn vein and stockwork, volcanogenic Zn-Pb-Cu massive sulfide, sediment-hosted Cu, Ag-Pb epithermal vein, Fe skarn, porphyry Cu-Mo, porphyry Au, granitoid related Au vein, and mafic-ultramafic related Ti-Fe deposits. The isotopic ages of the deposits or host rocks range from Devonian through Early Carboniferous. Favorable geologic environments for the metallogenic belts occurred in the Altay continental-margin-arc and the island arc parts of the West Siberian and South Mongolia-Khingan collages.

### Metallogenic Belts Related to Terrane Accretion

Several metallogenic belts possess geologic units favorable for a wide variety of major collisional granite-hosted deposits and related vein deposits, including the Bayangovi, Edren-Zoolon, Muiskiy, Ulziit, and Yaroslavka with granitoid-related Au vein, Au in shear-zone and quartz vein, fluorite greisen, Sn-W greisen, stockwork, and quartz vein, carbonate-hosted Hg-Sb deposits. Fossil or isotopic ages of the deposits or host rocks range from Devonian through Early Carboniferous (440 to 396 Ma). Favorable geologic environments for the metallogenic belts occurred in the Edren island arc and Zoolen subduction-zone terrane (both parts of South Mongolia-Khingan collage), in granitoids and veins of the Barguzin-Vitim granitoid belt intruding the Baikal-Muya island arc and the Muya metamorphic terrane (both parts of the Tuva-Mongolia superterrane), in granitoids intruding the Bureya-Jiamusi superterrane, and in vein replacements in the Govi Altai continental-margin turbidite terrane (part of the South Mongolia-Khingan collage). These granitoids and veins are interpreted as having formed during regional metamorphism and vein emplacement associated with terrane accretion and generation of anatectic granitic plutons.

### Metallogenic Belts Related to Rifting

Two metallogenic belts possess geologic units favorable for a wide variety of rift-related deposits: the Sette-Daban and Udzha with sediment-hosted Cu, basaltic native Cu, REE carbonatite, and carbonate-hosted Pb-Zn. Fossil ages of the deposits or host rocks range from Devonian and Early Carboniferous. Favorable geologic units for the metallogenic belts occurred during rifting of the North Asian craton or cratonal margin.

### Metallogenic Belts Related to Transpressional Faulting

Several metallogenic belts possess geologic units favorable for major vein or plutonic-hosted deposits, including the Hongqiling, Kizhi-Khem, Mamsko-Chuisky, Sorsk, and Teisk (with mafic-ultramafic related Cu-Ni-PGE, mafic-ultramafic related Ti-Fe, muscovite pegmatite, Ta-Nb-REE alkaline metasomatite, W-Mo-Be greisen, stockwork, and quartz vein, porphyry Cu-Mo and Mo, polymetallic (Pb, Zn±Cu, Ba, Ag, Au) volcanic- and carbonate-hosted metasomatite, and Fe, Pb, and Zn skarn deposits. Fossil ages are Devonian and Early Carboniferous and isotopic ages range from 416 to 330 Ma. Favorable geologic environements for the metallogenic belts are (1) mafic and ultramafic plutons intruding and overlapping the Zhangguangcailing superterrane and the Laoling terrane, part of the Bureya-Jiamusi superterrane, (2) veins and dikes in the Mamsky and Konkudero-Mamakansky complexes intruding the Chuja paragneiss terrane, which is included in Baikal-Patom cratonal margin, and (3) the South Siberian volcanic-plutonic belt, which constitutes the South Siberian arc. All these units and deposits are interpreted as having formed during transpressional faulting and associated interplate rifting.

## Unique Metallogenic Belts

Two unique metallogenic belts are hosted in Devonian diamond-bearing kimberlite intruding the North Asian craton: the Botuobiya-Markh and Daldyn-Olenyok belts. The origin of the diamond-bearing kimberlite deposits is poorly known. The unique Edrengiin metallogenic belt with volcanogenic Cu-Zn massive sulfide, volcanogenic-sedimentary Mn and Fe deposits is hosted in the Edren island-arc terrane (part of the South Mongolia-Khingan collage), and is interpreted as having formed during island-arc marine volcanism.

## Major Late Carboniferous Through Middle Triassic Metallogenic Belts

The major Late Carboniferous through Middle Triassic (320 to 230 Ma) metallogenic belts in the region (fig. 1) are the Altay, Angara-Ilim, Barlaksk, Battsengel-Uyanga-Erdenedalai, Buteeliin nuruu, Central Mongolia, Duobaoshan, Harmagtai-Hongoot-Oyut, Hitachi, Kalatongke, Kolyvansk, Kureisko-Tungsk, Maimecha-Kotuisk, Mino-Tamba-Chugoku, Norilsk, Orhon-Selenge, and Shanxi belts (fig. 4*F*; see appendix C).

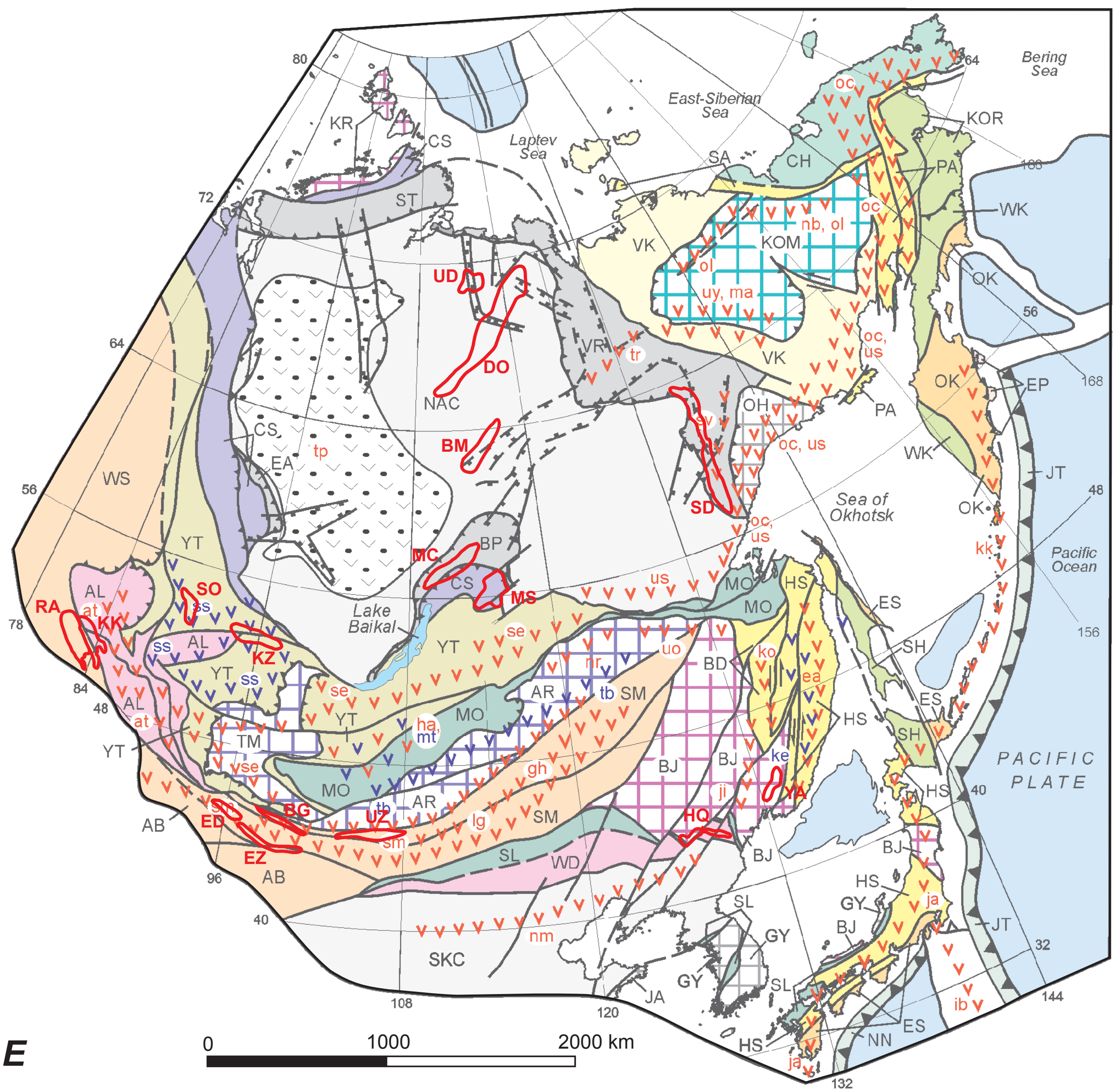


Figure 4.—Continued.

## Metallogenic Belts Related to A Superplume

Four metallogenic belts possess geologic units favorable for a wide variety of major Trapp-magmatism-related deposits: the Angara-Ilim, Kureisko-Tungsk, Maimecha-Kotuisk, and Norilsk with mafic-ultramafic related Cu-Ni-PGE, Fe-Ti and phlogopite carbonatite, metamorphic graphite, basaltic native Cu (Lake Superior type), porphyry Cu-Mo, Fe skarn, and weathering crust carbonatite REE-Zr-Nb-Li deposits. Isotopic ages of the deposits or host rocks range from Devonian through Early Carboniferous. The deposits are related to replacements associated with the Tungus plateau basalt, sills, dikes, and intrusions that intrude or overlie the North Asian craton. The isotopic ages of the deposits or host rocks range from Permian through Triassic (260-200 Ma). The Norilsk metallogenic belt contains the famous mafic-ultramafic related Cu-Ni-PGE deposits in the Norilsk district in northern Siberia. Favorable geologic environments for the metallogenic belts are interpreted as related to widespread development of Trapp magmatism on the North Asian craton during intrusion of a superplume.

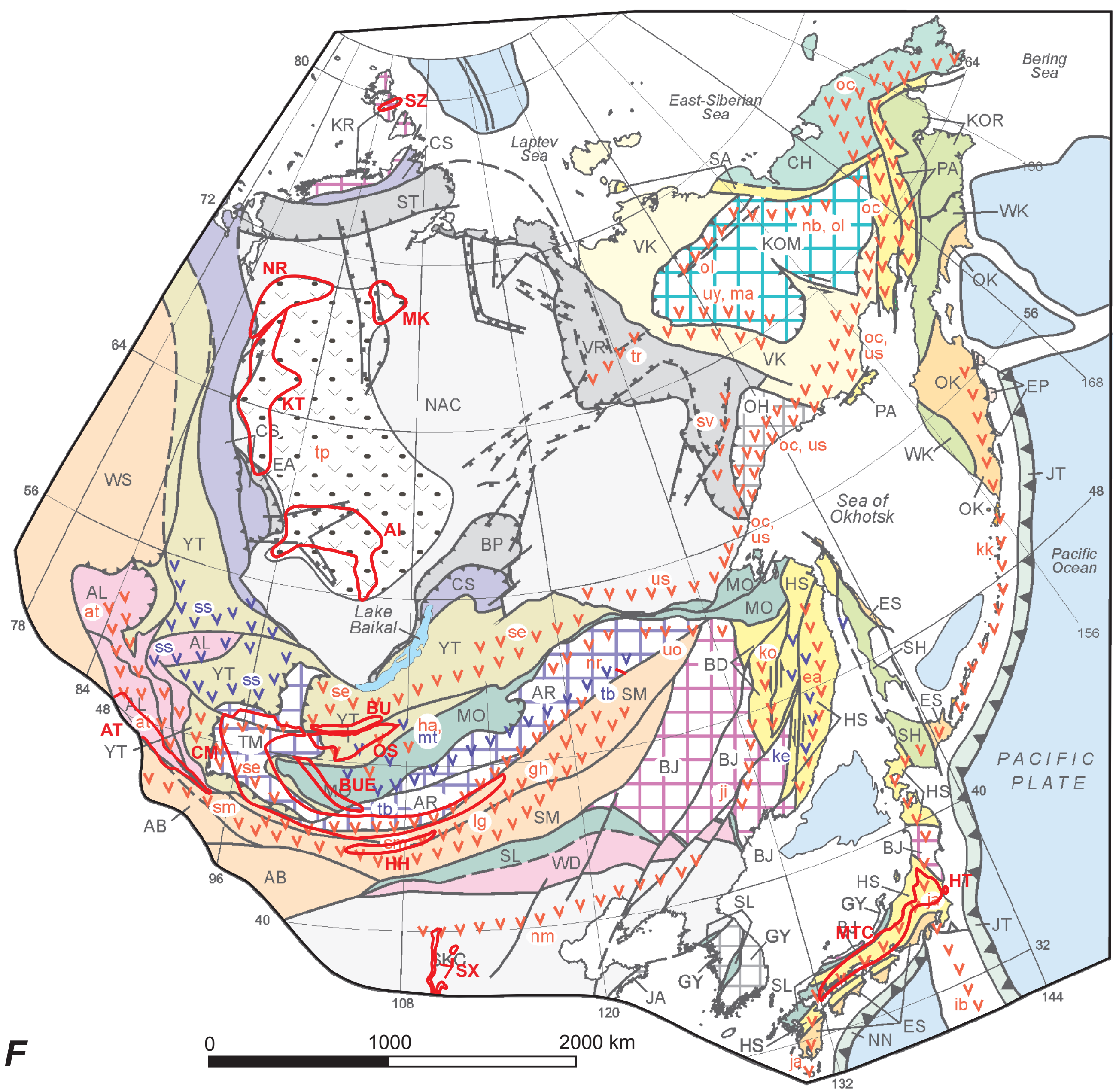


**Figure 4.**—Continued.

## Metallogenic Belts Related to the Selenga and South Mongolian Continental-Margin-Arcs

Four metallogenic belts possess geologic units favorable for a wide variety of granitic magmatism-related deposits: the Battsengel-Uyanga-Erdenedalai, Buteeliin nuruu, Central Mongolia and Orhon-Selenge with Fe-Zn skarn, Sn skarn, Zn-Pb, skarn, W skarn, Cu skarn, porphyry Cu-Mo, porphyry Mo, Au skarn; granitoid related Au vein, W-Mo-Be greisen, stockwork, and quartz vein, peralkaline granitoid-related, REE-Li pegmatite and basaltic native Cu deposits. The belts are hosted in granitoids in the Selenga sedimentary-volcanic plutonic belt that constitutes the Selenga continental-margin-arc that formed on the Yenisey-Transbaikal and the Tuva-Mongolia collages. Isotopic ages of the deposits or host rocks range from 240 to 285 Ma. These belts are interpreted as having formed during oblique subduction of oceanic crust of the Mongol-Okhotsk Ocean plate under the southern margin of the North Asian craton and cratonal margin and previously accreted terranes.

The Harmagtai-Hongoot-Oyut metallogenic belt with porphyry Cu-Mo and Au, granitoid-related Au, and Au-Ag epithermal Au deposits is hosted in granitoids related to the South-Mongolian volcanic-plutonic belt and is interpreted as having formed in the South Mongolian continental-margin-arc that formed along the northern (present-day coordinates) margin of the Mongol-Okhotsk Ocean.

## Metallogenic Belts Related to Island Arcs

Three metallogenic belts possess geologic units favorable for a wide variety of granite- and mafic-plutonic-related deposits and volcanogenic massive sulfide deposits: the Duobaoshan, Hitachi, and Kalatongke with porphyry Cu-Mo, granitoid-related Au vein, mafic-ultramafic related Cu-Ni-PGE, volcanogenic Zn-Pb-Cu massive sulfide deposits. Isotopic ages of the igneous host rocks range from Pennsylvanian through Permian. These belts are interpreted as having formed in an island arc chain south (present-day coordinates) of the North Asian craton and cratonal margin and previously accreted terranes. The island arcs were in the Duobaoshan terrane (part of the South Mongolia-Khingan collage), the South Kitakami terrane (part of the Bureya-Jiamusi superterrane), and the Waizunger-Baaran terrane (part of the Atasbogd collage).

## Metallogenic Belt Related to Collision of Cratons

The Altay metallogenic belt with REE-Li pegmatite and muscovite pegmatite deposits is hosted in veins, dikes, and replacements related to Late Carboniferrous granitoids in the Altai volcanic-plutonic belt, which intrudes the Altai continental margin turbidite terrane. This belt is interpreted as having formed with the intrusion of collisional granite during collision of the Kazakhstan and North Asian cratons, resulting in high-grade metamorphism with crustal melting and generation of anatectic granite.

## Metallogenic Belt Related to Weathering

The Shanxi metallogenic belt with sedimentary bauxite deposits is hosted in Pennsylvanian stratiform units in the upper part of the Sino-Korean platform overlapping the Sino-Korean craton and the West Liaoning terrane. This belt is interpreted as having formed during weathering of metamorphic rocks of the North China platform. The bauxite deposits are hosted in karst and lagoonal basins in a littoral-shallow sea.

## Metallogenic Belt Related to Oceanic Crust

The Mino-Tamba-Chugoku metallogenic belt with volcanogenic-sedimentary Mn, podiform chromite, and Besshi massive sulfide deposits is hosted in the Mino Tamba Chichibu subduction-zone terrane (part of Honshu-Sikhote-Alin collage). This belt contains fragments of late Paleozoic and early Mesozoic oceanic crust in which these deposits originally formed.

# Major Late Triassic Through Early Jurassic Metallogenic Belts

The major Late Triassic through Early Jurassic metallogenic belts in the region (fig. 1) are the Central Hentii, Delgerhaan, Govi-Ugtaal-Baruun-Urt, Harmorit-Hanbogd-Lugiingol, Kalgutinsk, Mongol Altai, North Hentii, North Kitakami, North Taimyr, and Sambagawa-Chichibu-Shimanto belts (fig. 4*G*; see appendix C).

## Metallogenic Belts Related to Transpressional Arcs and Faults and to Terrane Collision

Five metallogenic belts possess geologic units favorable for a wide variety of granite-related deposits: the Central Henti, Delgerhaan, Govi-Ugtaal-Baruun-Urt, Harmorit-Hanbogd-Lugiingol, and North Hentii belts with porphyry Cu, granitoid-related Au vein, Au in shear-zone and quartz vein, Fe-Zn, Cu, Zn-Pb, Sn, and W skarn, Sn-W greisen, stockwork, and quartz vein, Ta-Nb-REE akaline metasomatite, REE carbonatite, peralkaline granitoid-related Nb-Zr-REE, and REE-Li pegmatite deposits. Isotopic ages of the host igneous rocks range from 242 to 199 Ma. These belts are hosted in the Late Triassic and Early Jurassic Mongol-Transbaikalia volcanic-plutonic belt, which constitutes much of the Mongol-Transbaikal transpressional arc that is interpreted as having formed during strike-slip faulting and rifting along the Mongol-Okhotsk Fault during and after final closure of the Mongol-Okhotsk Ocean.

Two other metallogenic belts possess geologic units favorable for a wide variety of granite-related deposits: the Kalgutinsk and Mongol Altai belts with W-Mo-Be greisen, stockwork, and quartz vein, Ta-Nb-REE alkaline metasomatite; and Sn-W greisen, stockwork, and quartz vein deposits. Isotopic ages of the host igneous rocks range from 204 to 183 Ma. These belts are hosted in small granitoids that intruded along major transpressional fault zones (Hovd regional fault zone and companion faults) with a combination of strike-slip, extensional, and compressional displacements. The transpressional-fault zones strike northwest (present-day coordinates).

In addition, the North Taimyr metallogenic belt possesses geologic units favorable for granite-related deposits: W-Mo-Be greisen, stockwork, and quartz vein, W skarn, and porphyry Cu-Mo. Isotopic ages of the host granitoids range from 233 to 223 Ma. This belt is interpreted as having formed with the generation of granitoids during and after collision between the North Asian craton and the Kara superterrane.

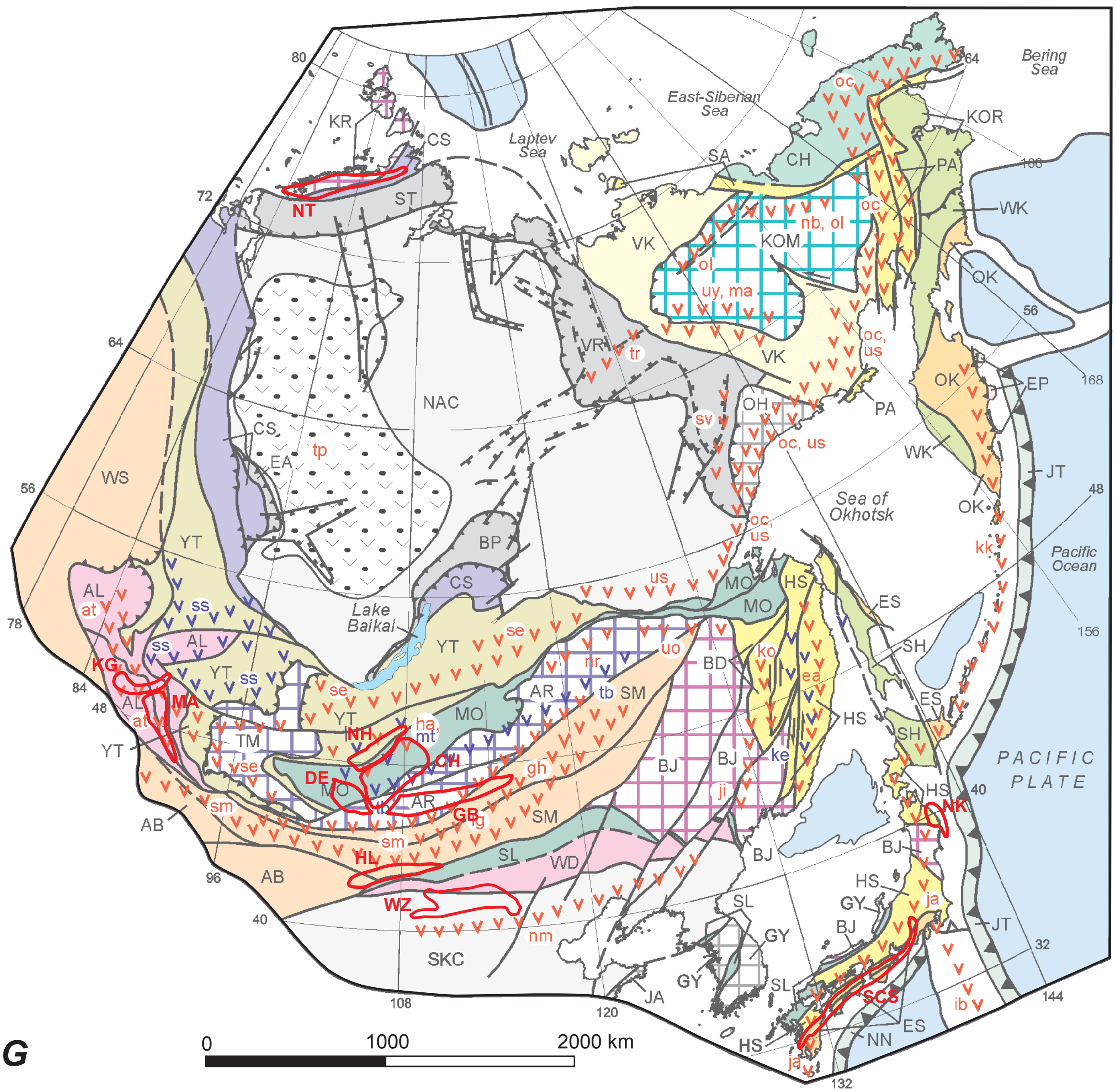


Figure 4.—Continued.

## Metallogenic Belts Related to Oceanic Crust

The Sambagawa-Chichibu metallogenic belt possesses geologic units favorable for stratiform sediment-hosted deposits (Besshi Cu-Zn-Ag and Cyprus Cu-Zn massive sulfide, volcanogenic-sedimentary Mn) that are now preserved in younger subduction-zone terranes: the Mino Tamba Chichibu subduction-zone terrane (part of Honshu-Sikhote-Alin collage), the Sambagawa metamorphic terrane (part of the Honshu-Sikhote-Alin collage), and the Shimanto subduction-zone terrane (part of the Sakhalin-Hokkaido collage). The age of the host rocks is interpreted as Early Jurassic and younger. The volcanogenic-sedimentary Mn deposits are interpreted as having formed in a syngenetic setting on the ocean floor and the Besshi and Cyprus massive sulfide deposits are interpreted as having formed during submarine volcanism related to an ocean spreading ridge.

The North Kitakami metallogenic belt possesses geologic units favorable for Besshi Cu-Zn-Ag and Cyprus Cu-Zn massive sulfide, volcanogenic-sedimentary Mn deposits. This belt and deposits are hosted in the Mino Tamba Chichibu subduction-zone terrane (part of the Honshu-Sikhote-Alin collage). The volcanogenic-sedimentary Mn deposits are interpreted as having formed in a syngenetic setting on the ocean floor, and the kuroko deposits in an island arc. These deposits were subsequently incorporated into the subduction zone.

# Major Middle Jurassic Through Early Cretaceous Metallogenic Belts

The major Middle Jurassic through Early Cretaceous metallogenic belts in the region (fig. 1) are the Allakh-Yun, Ariadny, Bindong, Chara-Aldan, Chybagalakh, Daxinganling, Djeltulaksky, Dzid-Selenginskiy, East Mongolian-Priargunskiy-Deerbugan, Govi-Tams, Hartolgoi-Sulinheer, Jiliaolu, Kitakami, Kondyor-Feklistov, Kular, Nerchinsky, North Bureya, North Jilin, North Stanovoy, Onon-Turinskiy, Polousny, Samarka, Shilkinsko-Tukuringrskiy, South Verkhoyansk, Taebaegsan, Tompo, Verkhne-Ingodinsky, Verkhoyansk, Yana-Adycha, and Yanshan belts (fig. 4*H*; see appendix C).

## Metallogenic Belts Related to Trans-Baikalian-Daxinganling Transpressional Arc

Several metallogenic belts possess geologic units favorable for a wide variety of siliceous igneous-related deposits: the Bindong, Daxinganling, Dzid-Selenginski, East Mongolian-Priargunskiy-Deerbugan, Govi-Tamsag, Hartolgoi-Sulinheer, Nerchinsky, Onon-Turinskiy, Shilkinsko-Tukuringrskiy, and Verkhne-Ingodinsky belts with Au skarn, Au, Sn, W±Mo±Be, and Zn-Pb (±Ag, Cu) skarn, Au-Ag epithermal vein, cassiterite-sulfide-silicate vein and stockwork, fluorspar vein, granitoid-related Au vein, peralkaline granitoid-related Nb-Zr-REE, polymetallic-metasomatite, polymetallic Pb-Zn vein and stockwork, porphyry Au, porphyry Cu-Mo, Mo, and Au, clastic-sediment-hosted U, and Sn-W greisen, stockwork, and quartz vein, Ta-Nb-REE alkaline metasomatite, volcanic-hosted Au-base-metal metasomatite, carbonate-hosted Ag-Pb and Hg-Sb, volcanic-hosted zeolite, and W-Mo-Be greisen, stockwork, and quartz vein. Isotopic ages of the igneous host rocks range from 190 to 125 Ma. These belts are hosted in the major Trans-Baikalian-Daxinganling sedimentary-volcanic-plutonic belt that overlaps terranes which were previously accreted to the southern (present-day coordinates) margin of the North Asian craton. The host rocks and metallogenic belts are interpreted as having formed with the major Trans-Baikalian-Daxinganling transpressional arc that formed along the major Mongol-Okhotsk suture which cuts previously accreted terranes south of the southern margin (present-day coordinates) of the North Asian craton. Displacement along this suture and formation of the arc occurred after closureof the Mongol-Okhotsk Ocean.

## Metallogenic Belts Related to Accretion of the Kolyma-Omolon Superterrane and the Okhotsk Terrane

Eight metallogenic belts possess geologic units favorable for a wide variety of Au vein deposits and collisional granite-related deposits: the Allakh-Yun, Chybagalakh, Kular, Polousny, South Verkhoyansk, Tompo, Verkhoyansk, and Yana-Adycha with Au in shear-zone and quartz vein, granitoid-related Au vein, Cu and W skarn, Au in black shale, polymetallic Pb-Zn vein and stockwork, cassiterite-sulfide-silicate vein and stockwork, Sn-W and W-Mo-Be greisen, stockwork, and quartz vein, and Au-Ag epithermal vein deposits. Isotopic ages of the veins and associated granites range from Late Jurassis through Aptian. The belts and deposits are hosted in veins and granitoids (such as the Main, Northern, and South Verkhoyansk, granite belts) that intrude the Verkhoyansk (North Asian) cratonal margin and (or) the margin of the adjacent Kolyma-Omolon superterrane. The host rocks and metallogenic belts are interpreted as having formed during collision and accretion of the Kolyma-Omolon superterrane to the North Asian cratonal margin which resulted in regional metamorphism and generation of anatectic granitoids and related hydrothermal fluids. The Allakh-Yun and South Verkhoyansk metallogenic belts are interpreted as having formed immediately before accretion of the Okhotsk terrane to the North Asian cratonal margin.

## Metallogenic Belts Related to the Uda-Stanovoy Continental-Margin-Arc

Three metallogenic belts possess geologic units favorable for granitoid-related deposits: the Chara-Aldan, Djeltulaksky, and North Stanovoy with granitoid-related Au vein, Au-Ag epithermal vein, Au skarn, Au in shear-zone and quartz vein, Au-K metasomatite, and charoite metasomatite deposits. Isotopic ages of the host granitoids range from Jurassic through Early Cretaceous. These metallogenic belts are interpreted as having formed during intrusion of granitoids of the Stanovoy granite belt that was part of the Uda-Stanovoy continental margin arc, which is interpreted as having formed during subduction and closure of the Mongol-Okhotsk Ocean beneath the North Asian craton to the north (present-day coordinates).

## Metallogenic Belts Related to Transpressional Faulting

Four metallogenic belts possess geologic units favorable for a wide variety of transpressional granitoid-related deposits: the Jiliaolu, North Jilin, Samarka, and Yanshan with Au-Ag epithermal vein, Cu, W, and Zn-Pb W skarn, fluorspar vein, granitoid-related Au vein, polymetallic Pb-Zn vein and stockwork, polymetallic volcanic-hosted metasomatite, porphyry Cu

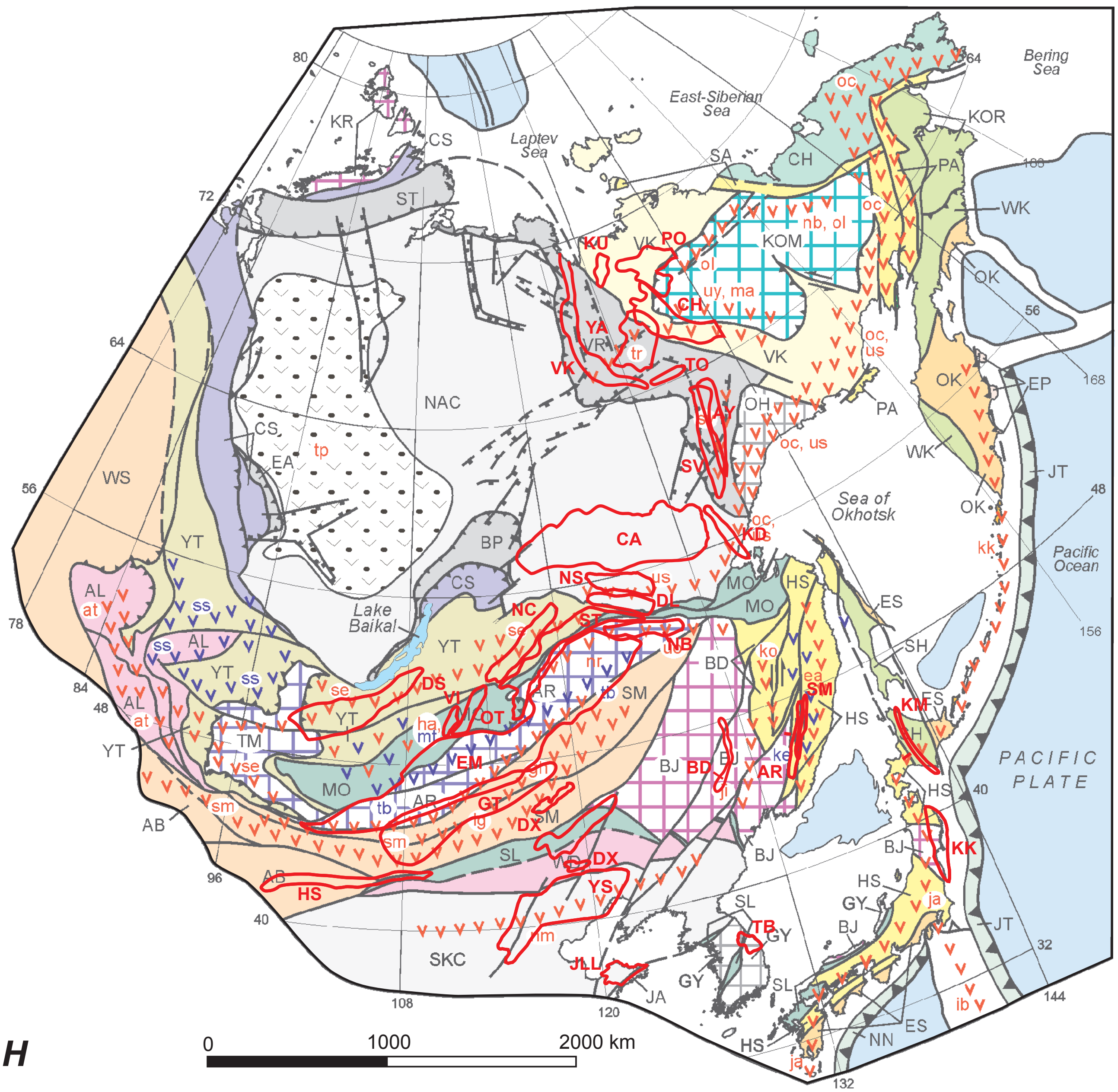


Figure 4.—Continued.

and Cu-Mo, deposits. Isotopic ages of the host granitoids range from 186 to 110 Ma. The granitoids and veins intrude either overlap assemblages on the Sino-Korean craton or the Samarka subduction-zone terrane (part of the Honshu-Sikhote-Alin collage). These metallogenic belts are interpreted as having formed during intrusion of granitoids along transpressional zones along microplate boundaries, underthrusting of the Kula oceanic ridge, and extrusion of bimodal igneous rocks along a transform continental margin or during interplate magmatism associated with extensional tectonism related to oblique subduction of the Pacific Ocean plate beneath the Eurasian plate.

### Unique Metallogenic Belts

Five unique metallogenic belts formed during the Middle Jurassic through Early Cretaceous:

The Kondyor-Feklistov belt with zoned mafic-ultramafic Cr-PGE deposits. This belt is hosted in mafic-ultramafic intrusions and is interpreted as having formed with the intrusion of mafic-ultramafic plutons along a deep-seated fault on the North Asian cratonal margin during collision and accretion of outboard terranes.

The North Bureya belt with Au-Ag epithermal vein and granitoid-related Au vein deposits hosted in the Umlekam-Ogodzhin volcanic-plutonic belt. This belt is interpreted as having formed with the Umlekan-Ogodzhin continental-margin-arc during subduction of part of the ancestral Pacific Ocean plate.

The Ariadny belt with mafic-ultramafic-rock-related deposits hosted in Middle Jurassic and Early Cretaceous plutons that intrude the Samarka subduction-zone terrane (part of the Honshu-Sikhote-Alin collage). This belt is interpreted as having formed with the generation of ultramafic and gabbroic plutons during underthrusting of the Kula oceanic ridge and extrusion of bimodal igneous rocks along a transform continental margin.

The Taebaegsan belt with a wide assortment of granitoid-related deposits hosted in the Late Jurassic and Early Cretaceous Daebo granite. This belt is interpreted as forming during intrusion of granitoids associated with the Daebo granite that in turn are interpreted as parts of a continental-margin-arc which was linked to subduction of the ancestral Pacific Ocean plate.

The Kitakami belt with Cu skarn and granitoid-related Au deposits hosted in the Early Cretaceous Hiroshima granite belt (isotopic age of 120 to 110 Ma). This belt is interpreted as having formed during intrusion of granitoids associated with a continental-margin-arc and siliceous magmatism.

## Major Cenomanian Through Campanian Metallogenic Belts

The major Cenomanian through Campanian metallogenic belts in the region (fig. 1) are the Badzhal-Komsomolsk, Central Polousny, Chelasin, Chokhchur-Chekurdakh, Eckyuchu-Billyakh, Gyeongnam, Gyeongpuk, Hidaka, Inner Zone Southwest Japan, Khandyga, Kukhtuy-Uliya, Luzhkinsky, Malo-Khingan, Pilda-Limuri, Preddzhugdzhursky, Selennyakh, Sergeevka-Taukha, South Verkhoyansk, Tumnin-Anyuy, and Upper Uydoma belts (fig. 4*I*; see appendix C).

### Metallogenic Belts Related to the Okhotsk-Chukotka and East Sikhote-Alin Continental-Margin-Arcs

Seven metallogenic belts possess geologic units favorable for a wide variety of granitoid-related deposits: the Chelasin, Kukhtuy-Uliya, Luzhkinsky, Preddzhugdzhursky, Sergeevka-Taukha, Tumnin-Anyuy, and Upper Uydoma with Au-Ag epithermal vein, boron (datolite) skarn, cassiterite-sulfide-silicate vein and stockwork, granitoid-related Au vein, polymetallic Pb-Zn vein and stockwork, polymetallic volcanic-hosted metasomatite, porphyry Cu, Cu-Mo, and Mo, Cu, Sn-B, and Zn-Pb skarn, porphyry Sn, and Sn-W andW-Mo-Be greisen, stockwork, and quartz vein, and deposits. Isotopic ages of the associated granites range from mid-Cretaceous to Paleocene. These metallogenic belts and deposits are hosted in granitoids in the Okhotsk-Chukotka or the East Sikhote-Alin volcanic-plutonic belts both units are major overlap assemblages in the Russian Far East that are interpreted as parts of the extensive, nearly coeval, colinear continental-margin Okhotsk-Chukotka and East Sikhote-Alin arcs which overlie the North Asian craton and cratonal margin and previously accreted terranes to the east (present-day coordinates).

### Metallogenic Belts Related to Opening of the Eurasia Basin

Several metallogenic belts possess geologic units favorable for a wide variety of vein and replacement and granitoid-related deposits: the Central Polousny, Chokhchur-Chekurdakh, Eckyuchu-Billyakh, Khandyga, and Selennyakh belts (with Ag-Sb vein, Au-Ag epithermal vein, carbonate-hosted As-Au metasomatite, cassiterite-sulfide-silicate vein and stockwork, clastic sediment-hosted Hg±Sb and Sb-Au, Hg-Sb-W vein and stockwork, polymetallic Pb-Zn vein and stockwork, carbonate-hosted Hg-Sb, volcanic-hosted Hg, and Sn-W greisen, stockwork, and quartz vein deposits. Isotopic ages for the vein deposits range from 120 to 97 Ma (Aptian through Late Cretaceous). These belts and deposits are hosted in rocks of the Northern and Transverse granite belts, the Svyatoi Nos volcanic belt, and the Uyandina-Yasachnaya volcanic belt that intrude or overlie the Verkhoyansk (North Asian) cratonal margin and outboard accreted terranes. These belts are interpreted as having formed during extension related to the formation of the Eurasia Basin during initial opening of the Arctic Ocean.

### Metallogenic Belts Related to the Khingan Continental-Margin-Arc

Four metallogenic belts possess geologic units favorable for a wide variety of vein and replacement and granitoid-related deposits: the Badzhal-Komsomolsk, Ezop-Yam-Alin, Malo-Khingan, and Pilda-Limuri belts (with Cu skarn, porphyry Mo, granitoid-related Au vein, polymetallic Pb-Zn, porphyry Sn, rhyolite-hosted Sn, Sn-W and W-Mo-Be greisen, stockwork, and quartz vein, and cassiterite-sulfide-silicate vein and stockwork deposits. Isotopic ages for the granitoids hosting or associated with the deposits range from 100 to 75 Ma. The belts and deposits are hosted in granitoids related to the Khingan-Okhotsk volcanic-plutonic belt that is interpreted as having formed along the Khingan continental-margin-arc, which in turn is related to oblique subduction of ancestral Pacific Ocean plate and formation of the Early Cretaceous Zhuravlevsk-Amur River and Kiselevka-Manoma subduction-zone terranes (parts of the Honshu-Sikhote-Alin collage).

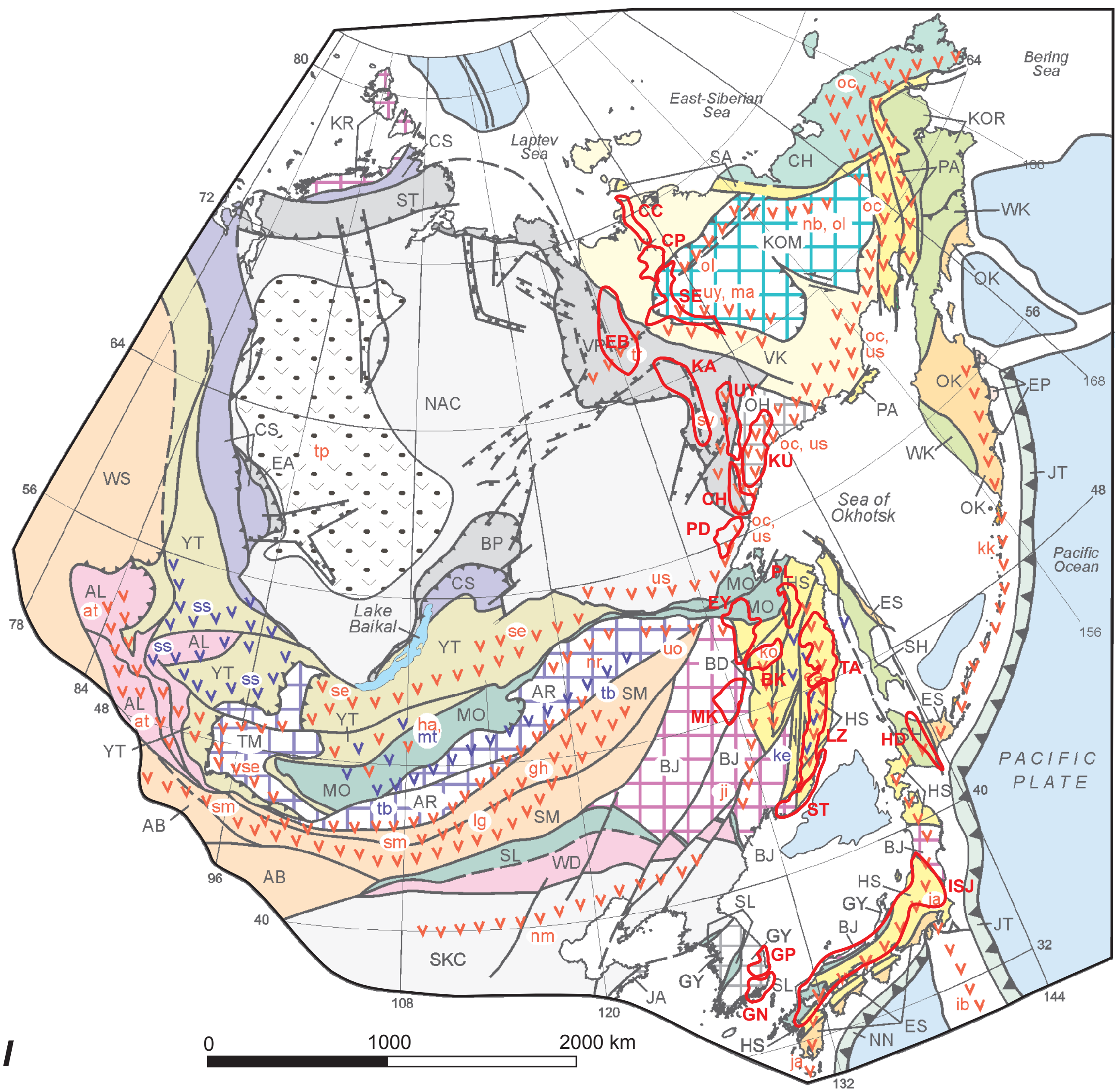


**Figure 4.**—Continued.

## Unique Metallogenic Belts

Three unique metallogenic belts formed during the Middle Jurassic through Early Cretaceous.

The Gyeongpuk and Gyeongnam metallogenic belts with polymetallic Pb-Zn vein and stockwork, Au in shear-zone and quartz vein, porphyry Mo, W-Mo-Be greisen, stockwork, and quartz vein, Sn-W greisen, stockwork, and quartz vein, Fe skarn, and polymetallic Ni vein deposits. Isotopic ages range from the Cenomanian through Campanian. The deposits are hosted in the Cretaceous Bulgugsa granite, which intrudes the Sino-Korean craton. These belt and deposits are interpreted as having formed in a continental-margin-arc during subduction of the ancestral Pacific Ocean plate.

The Hidaka metallogenic belt with Cyprus Cu-Zn massive sulfide deposits is hosted in mid-Cretaceous to Eocene strati-form rocks that occur in tectonic fragments in the Shimanto subduction-zone terrane (part of the East Sakhalin collage). This belt is interpreted as having formed in basalt generated along the Kula-Pacific oceanic ridge, with subsequent structural incorporation of the host rocks and deposits into a subduction zone.

The Inner Zone Southwest Japan metallogenic belt with a wide variety of vein and replacement and granitoid-related deposits, including Cu, W, and Zn-Pb skarn, W-Mo-Be greisen, stockwork, and quartz vein, porphyry Mo, polymetallic Pb-Zn vein and stockwork, fluorspar vein, and metamorphic graphite deposits. The deposits are hosted in the Nohi rhyolite volcanic belt and the coeval Hiroshima granitic belt that overlie previously accreted terranes. Isotopic ages of the host rocks and deposits range from Cretaceous to Paleogene. The host rocks and deposits are interpreted as having formed during generation of granitoids along an East Asia continental-margin-arc that is tectonically linked to subduction of Kula and Pacific Ocean plates. The East Asia continental-margin-arc is interpreted as the southward extension of the East Sikhote-Alin continental-margin arc.

## Major Maastrichtian Through Oligocene Metallogenic Belts

The major Maastrichtian through Oligocene metallogenic belts in the region (fig. 1) are the Kema, Lower Amur, and Popigay (fig. 4J; see appendix C). Two metallogenic belts possess geologic units favorable for a wide variety of vein and replacement and granitoid-related deposits: the Kema and Lower Amur with Ag-Au epithermal vein, porphyry Cu-Mo, Cu, Au, and Mo, Au-Ag epithermal vein, epithermal quartz-alunite, and Sn-W greisen, stockwork, and quartz vein deposits. Isotopic ages for the host granitoids range from Late Cretaceous to Paleocene. These belts and deposits are hosted in granitoids of the East Sikhote-Alin volcanic-plutonic belt that is a major overlap assemblage in the Russian Far East. These belts are interpreted as parts of an extensive continental-margin-arc that formed along the eastern (present-day coordinates) margin of the North Asian craton and cratonal margin and previously accreted terranes to the east during subduction of the ancestral Pacific Ocean plate.

The unique Popigay metallogenic belt contains impact diamond deposits. The isotopic age of the deposits from tagamite (impact melt rock) and impact glasses is 35.7 Ma. This belt, which is hosted in the Popigay ring structure, is interpreted as resulting from meteoritic impact with formation of pseudotachylite, diamond, high-grade shock metamorphic minerals, and allogenic breccia.

## Major Miocene Through Quaternary Metallogenic Belts

The major Miocene through Quaternary metallogenic belts in the region (fig. 1) are the Kyushu, Northeast Hokkaido, Hokuriku-Sanin, Northeast Japan, and Outer Zone Southwest Japan (fig. 4*J*; see appendix C), all five of which possess geologic units favorable for a wide variety of volcanic-related deposits, including Au-Ag epithermal vein, cassiterite-sulfide-silicate vein and stockwork, chemical-sedimentary Fe-Mn, clastic sediment-hosted Hg±Sb and Sb-Au, Ag-Sb, Hg-Sb-W vein and stockwork, limonite from spring water, Mn vein, polymetallic Pb-Zn vein and stockwork, polymetallic volcanic-hosted metasomatite, Sn and Zn-Pb skarn, Sn-W greisen, stockwork, and quartz vein, sulfur-sulfide, volcanic-hosted Hg; Ag-Sb vein, volcanogenic Zn-Pb-Cu massive sulfide, volcanogenic-sedimentary Mn, and W-Mo-Be greisen, stockwork, and quartz vein, and deposits. Isotopic ages of the host igneous rocks range from 15 to 0.3 Ma. The belts and deposits are hosted in the Quaternary Japan volcanic belt and the Neogene Japan sedimentary basin that are interpreted as parts of the modern-day Japan continental-margin-arc, which is tectonically related to subduction of the Pacific Ocean and Philippine Sea plates beneath the East Asian continental margin.

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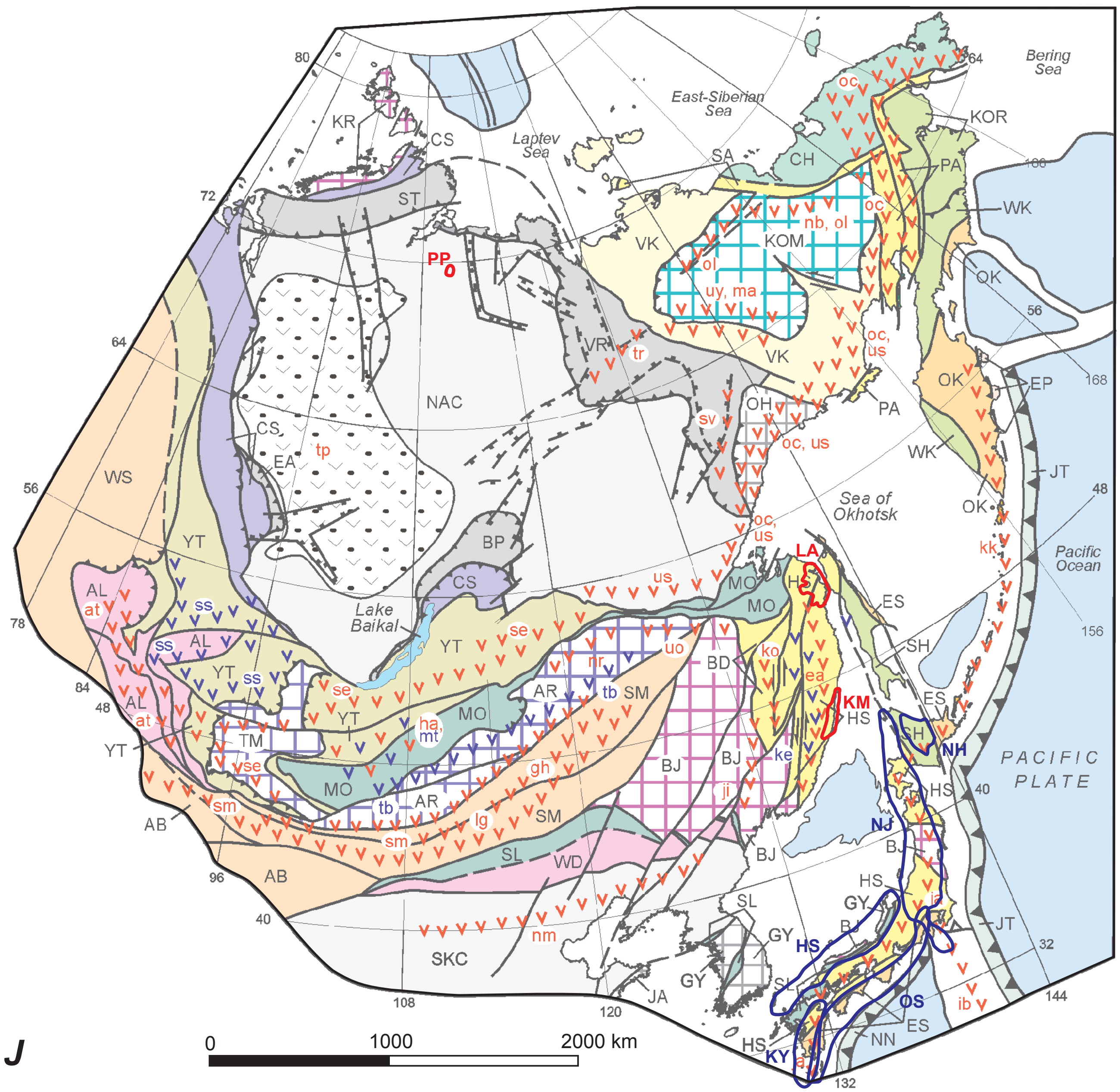


Figure 4.—Continued.

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