Metallogenesis and Tectonics of Northeast Asia
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Chapter 9

Tectonic and Metallogenic Model for Northeast Asia

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Introduction

This article presents a major new tectonic and metallogenic model of Northeast Asia from the Neoproterozoic through the Present (1000 to 0 Ma). This article is the final chapter in a major book on the metallogenesis and tectonics of Northeast Asia. The other major chapters in the book are an overview of the regional geology, metallogenesis, tectonics of the region (Chapter 1), a review of the methodology for the metallogenic and tectonic analysis of this region (Chapter 2), descriptions of mineral-deposit models (Chapter 3), and Archean through Present metallogenesis and tectonics (Chapters D through H). In addition, three appendices contain information on project publications (appendix A), descriptions of major geologic units (appendix B), and summaries of metallogenic belts (appendix C).

Compilations Employed for Synthesis, Project Area, and Previous Study

This tectonic and metallogenic model is based on a major compilation of regional geologic and metallogenic data and synthesis of interpretations (appendix A) that were done by a major international collaborative study of the metallogenesis and tectonics of Northeast Asia that was led by the U.S. Geological Survey (USGS). These studies have produced two broad types of publications. One type of publication is a series of regional geologic, mineral deposit, and metallogenic belt maps and companion descriptions for the regions. Examples of major publications of this type are Obolenskiy and others (2003, 2004), Parfenov and others (2003, 2004a,b), Nokleberg and others (2004), Rodionov and others (2004), and Naumova and others (2006). The other type of publication is a suite of metallogenic and tectonic analyses of these same regions. Examples of major publications of this type are Rodionov and others (2004), Nokleberg and others (2000, 2004, 2005), Scotese and others (2001), Naumova and others (2006), and Seltman and others (2007). Detailed descriptions of lode deposits are available in Ariunbileg and others (2003). For more detail than presented in this chapter, refer to the detailed descriptions of geologic units and metallogenic belts in the publications listed above.

The Northeast Asia project area consists of eastern Russia (most of Siberia and most of the Russian Far East), Mongolia, Northern China, South Korea, Japan, and adjacent offshore areas (fig. 1). This area is approximately bounded by 30 to 82° N. latitude and 75 to 144° E. longitude. The major participating agencies are the Russian Academy of Sciences; Academy of Sciences of the Sakha Republic (Yakutia); VNIIOkeangeologia and Ministry of Natural Resources of the Russian Federation; Mongolian Academy of Sciences; Mongolian University of Science and Technology; Mongolian National University; Jilin University, Changchun, China; the China Geological Survey; the Korea Institute of Geosciences and Mineral Resources; the Geological Survey of Japan/AIST; University of Texas Arlington; and the USGS.

The Northeast Asia project extends and build on data and interpretations from a previous project on the "Major Mineral Deposits, Metallogenesis, and Tectonics of the Russian Far

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East, Alaska, and the Canadian Cordillera" (below figure) that was conducted by the USGS, the Russian Academy of Sciences, the Alaska Division of Geological and Geophysical Surveys, and the Geological Survey of Canada. A summary of the major products of this project are contained online at http://pubs.usgs.gov/of/2006/1150/PROJMAT/RFE-Ak-Can_Cord_Proj_Pamph.pdf and in appendix A.

Geologic Time Sca- scale units are according to the IUGS Global Stratigraphic Chart (Remane, 1998). In this study, for descriptions of some Proterozoic geologic units in Russia, the term *Riphean* is used for the Mesoproterozoic through middle Neoproterozoic (1650 to 600 Ma), and the term *Vendian* is used for Neoproterozoic III (650 to 540 Ma) (Harland and others, 1989).

General Tectonic Concepts

Construction of a tectonic and metallogenic model in order to adequately describe specific geologic structure is the most important task of tectonic investigations. The plate tectonics concept permits recognizing fundamental events of the Earth's evolution and the formation of major geologic and tectonic belts. A model must be consistent with geologic data and be based on the modern principles of plate tectonics. The importance of a model is both to portray a unified interpretation of earth formation and evolution and to permit prediction of regions of past and present tectonic events, and prediction of areas with potential for undiscovered mineral and fuel

Figure 1. Regional summary geographic map for Northeast Asia showing major regions and countries

resources. A model provides a better understanding of tectonics and the interrelation of major geologic units, enables the understanding of the tectonic origin of metallogenic belts, and provides the ability to define areas with potential for undiscovered mineral deposits.

The major tectonic (orogenic) belts between the North Asian and Sino-Korean cratons in Central Asia formed over a long period from the Proterozoic through the Mesozoic. In Northeast Asia major tectonic (orogenic) belts are Mesozoic and Cenozoic age and occur mainly along the western margin of the Pacific Ocean. Many tectonic models for Central and Northeast Asia have been proposed over the last 20 years (Zonenshain and others, 1976, 1990; Pecherskiy and Didenko, 1995; Ruzhentsev and Pospelov, 1992; Mossakovskiy and others, 1994; Parfenov, 1984; Berzin, Dobretsov, 1994; Şengör and Natal'in, 1996; Parfenov and others, 1993; Ren Jishun and others, 1999; Nokleberg and others, 2000; Scotese and others, 2001; Yakubchuk, 2002). Although all are based on plate tectonics, the models differ greatly because of being based on differing and evolving field geologic-data sets. In addition, a model must consider the precision geochronological, geochemical, paleobiogeographic, paleomagnetic, and other data. As a result the models for Central Asia are highly debated.

Following the pioneer work of Zonenshain and others (1976, 1990), many authors constructed models based on relationships between the terranes of orogenic belts and paleotectonic elements such as island arcs, microcontinents, and oceanic plates. With this methodology, independent island arcs, microcontinents, and other units were recognized for every time span, and with exotic terranes and fragments of the Gondwana supercontinent (Mossakovskiy and others, 1994). In contrast, Şengör and Natal'in (1996) interpreted that a single giant island arc formed along the southern margin of the North Asian craton and cratonal margin from the Neoproterozoic through nearly the end of the Mesozoic. The arc migrated from east to west (present-day coordinates) with fragments accreting sequentially to the southern margin of the North Asian craton and cratonal margin to form tectonic belts of varying age. In contrast, this study analyzes the Neoproterozoic through Present tectonic and metallogenic evolution of the entire region framing the North Asian craton and cratonal margin, the Sino-Korean craton, other major microcontinents, and the western margin of the Pacific Ocean. This study thereby produces a new interpretation of the major tectonic and metallogenic events that can be applied to the formation and evolution of major intracontinental tectonic belts.

The methodology of this study is derived from previous detailed investigations carried out early in the 1980s in the Russian Far East, Alaska, and the Canadian Cordillera. These investigations showed that the region consists of tectonic collage (see definition, table 1) or mosaic of terranes (fault-bounded crustal blocks) that differ in structure and geologic history (Coney and others, 1980; Jones and others, 1983; Howell, 1989; Howell and others, 1985). Terranes are derived from larger tectonic units, such as island arcs, subduction zones, cratons, and active and passive continental margins. Accretion and collision of terranes with each other or with continents produced major tectonic (orogenic) belts and were accompanied by major zones of subduction, obduction, regional thrusting, and regional strike-slip faulting. In some cases, accretions caused dismembering of previously single tectonic units, their dispersion and subsequent recombination into a new major tectonic unit. The conducted studies clearly show that construction of a model for the formation of an orogenic belt and paleotectonic reconstructions must be preceded by hard work that consists of recognizing terranes, establishing their geodynamic nature, and mutual correlations, a type of study now defined as terrane analysis (Parfenov and others, 1998; Nokleberg and others, 2000, 2005; Scotese and others, 2001).

Principles of Construction of the Model

Three main principles are utilized for construction of the Northeast Asia tectonic and metallogenic model.

First, an actualistic principle of plate tectonics is employed for elaborating a Neoproterozoic and Phanerozoic model for the formation of Late Precambrian and Phanerozoic orogenic belts. This principle employs the interpretation that island arc systems (arcs, forearcs, backarcs, and tectonically-linked subduction zones), whose ancient fragments can be established in most orogenic belts, originally extended for many thousands of kilometers. These elongate island-arc systems (tectonic collages or collages) surrounded ancient continents, much like modern arcs on the eastern margin of Asia. During the accretion, these island-arc systems were dismembered into various fragments and dispersed over large distances. Detailed studies of the orogenic belts (tectonic collages), for example in the North American Cordillera, show that dispersion of tectonic elements of the orogenic belts may also occur after the accretion of island arcs, mainly during longitudinal strike-slip faults. The displacements may be for hundreds to thousands of kilometers, and are roughly parallel to the continent-ocean boundary (Plafker and Berg, 1994; Monger andNokleberg, 1996; Nokleberg and others, 2000). A similar mechanism is interpreted to have occurred in Central Asia (Şengör and others, 1993; Berzin and Dobretsov, 1994; Berzin, 1995). Inherent to this interpretation is the correlation and original continuity of dispersed fragments (terranes) of once continuous island-arc systems and component parts and the determination of original and evolving position with respect to major cratons on the basis of paleomagnetic, paleobiogeographic, structural, and other data.

Second, a tectonic model must not only adequately describe the relative positions of components relative to one another and to the adjacent craton at different time spans, but also deduce the kinematics and reasons for major deformational events. The model that most closely meets these requirements is that proposed by Şengör and others (1993) and Şengör and Natal'in (1996) for the formation of orogenic

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

[Adapted from Howell and others (1985), Jones and others (1983), Nokleberg and others (2000, 2005), or cited references.]

Term	Definition
Accretion	Tectonic juxtaposition of terranes to a craton or continental margin. Accretion of terranes to one another or to a cratonal margin also defines a major change in the tectonic evolution of terranes and cratonal margins.
Amalgamation	Tectonic juxtaposition of two or more terranes before accretion to a continental margin.
Collage	A series of linear island arcs or continental-margin arcs and tectonically-linked (companion) subduction zones, and (or) fore-arc and back-arc basins that formed in a major tectonic event during a relatively narrow geologic time span. A few collages consist of fragments of cratonal margin and cratonal terranes that were amalgamated before accretion to a continent.
Continent	A large section of continental crust surrounded by oceans on all sides, which 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 volcanic rocks and associated sedimentary rocks that formed above a subduction zone dipping beneath a continent. Inferred to possess a sialic basement.
Craton	Chiefly regionally metamorphosed and deformed shield assemblages of Archean, Paleoproterozoic, and Mesoproterozoic sedimentary, volcanic, and plutonic rocks, and overlying platform successions of Paleoproterozoic, Paleozoic, and local Mesozoic and Cenozoic sedimentary and lesser volcanic rock.
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 Early Proterozoic 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 rocks, coeval volcanic rocks, and associated sedimentary rocks that formed above an oceanic subduction zone. Inferred to possess a simatic basement.
Metallogenic belt	A geologic unit (area) that either contains or is favorable for a group of coeval and genetically-related, significant lode and placer deposit models. A metallogenic belt has the following characteristics: (1) is favorable for known or inferred mineral deposits of specific type or types; (2) may be irregular in shape and variable in size; (3) need not contain known deposits; and (4) is based on a geologic map as the primary source of information for delineation of areas that are favorable for specific deposit models. An essential part of the definition is that a belt is defined as the geologically-favorable area for a group of coeval and genetically-related mineral deposit models. This definition provides a predictive character for undiscovered deposits in each belt.
Metamorphic terrane	Fragment of a highly metamorphosed or deformed assemblage of sedimentary, volcanic, or plutonic rocks that cannot be assigned to a single tectonic environment because the original stratigraphy and structure are obscured. Includes intensely deformed structural melanges that contain intensely deformed fragments of two or more terranes.
Mine	A site where valuable minerals have been extracted.
Mineral deposit	A site where 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 deposit, 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 have been made.

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

[Adapted from Howell and others (1985), Jones and others (1983), Nokleberg and others (2000, 2005), or cited references.]

Term	Definition
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 the upper mantle. Includes both inferred offshore oceanic and marginal ocean basin rocks, minor volcaniclastic rocks of magmatic-arc derivation, and major marine volcanic accumulations formed at a hotspot, fracture zone, or spreading axis.
Overlap Assemblage	A postaccretion unit of sedimentary or igneous rocks deposited on, or intruded into, two or more adjacent terranes.
Passive continental-margin terrane	Fragment of a craton (continental) margin.
Subduction-zone terrane	Fragment of a mildly to intensely deformed complex consisting of varying amounts of turbidite deposits, continental-margin rocks, oceanic crust and overlying units, and oceanic mantle. 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.
Superterrane	A fault-bounded geologic entity or fragment that is characterized by a distinctive geologic history that differs markedly from that of adjacent terranes (Jones and others, 1983; Howell and others, 1985).
Tectonic collage	A series of linear island arcs or continental-margin arcs and tectonically-linked (companion) subduction zones, and (or) fore-arc and back-arc basins that formed in a major tectonic event during a relatively narrow geologic time span. The collages of igneous arcs and companion subduction-zone terranes have been successively accreted to the margins of major cratons. The ages of collages with subduction zone units are for time of active formation of a subduction zone, rather than the older range of units that comprise the subduction zone. A few collages consist of fragments of cratonal margin and cratonal terranes that were amalgamated before accretion to a continent. Approximate synonyms are tectonic belt, orogenic belt, and fold belt.
Tectonic linkage	A genetic relation of a continental-margin arc or an island arc with a companion accretionary wedge that formed in a subduction zone that was adjacent to and was underthrusting the arc.
Tectonostratigraphic terrane (terrane)	An aggregate of terranes that is interpreted to share either a similar stratigraphic kindred or affinity, or a common geologic history after accretion (Jones and others, 1983; Howell and others, 1985). An approximate synonym is composite terrane (Plafker and Berg, 1994).
Turbidite terrane	Fragment of a basin filled with deep-marine clastic deposits in either an orogenic fore-arc or back-arc setting. May include continental-slope and continental-rise turbidite deposits, and submarine-fan turbidite deposits deposited on oceanic crust. May include minor epiclastic and volcaniclastic deposits.

belts of Central Asia. Their model delineates an island arc that existed from the Neoproterozoic through the Middle Mesozoic and that extended latitudinally (present-day coordinates) for several thousand kilometers, roughly parallel to the southern margin of the North Asian craton and cratonal margin. Formation of orogenic belts is related to the east-westward (present-day coordinates) movement of the arc and consecutive accretion of its western fragments to the southern margin of the North Asian craton and cratonal margin. However, there is a major objection to this model. In Central Asia, no island-arc terranes and fossil active continental margins are recognized that existed from the Neoproterozoic through the Mesozoic, as is assumed by the model. On the contrary, island arcs of differing ages occur, including Late Riphean, Vendian-Early Cambrian, and Silurian-Mississippian. Our study shows that island arcs in each age group were independent island-arc systems that were successively accreted. Along with the island arcs are former active continental margins with ages of Vendian, late Paleozoic, late Paleozoic-Early Triassic, and Late Triassic-Early Cretaceous.

Third, as discussed by Şengör and others (1993) and Şengör and Natal'in (1996), large longitudianl strike-slip faulting played a decisive role in the formation of tectonic (orogenic belts) in Central Asia. The strike-slip nature of the largest faults of the Gorny Altay, East Sayan, and Sikhote-Alin regions was determined starting the 1960s (Kuznetsov, 1963; Berzin, 1967; Ivanov, 1972). Later, early Mesozoic, late Paleozoic, and Devonian strike-slip faults were recognized in the late Riphean through early Paleozoic orogenic belts of the Altay-Sayan region, with displacements of hundreds to even thousands of kilometers (Berzin, 1995; Buslov, 1998; Şengör and others, 1994; Vladimirov and others, 1996; Buslov and others, 2001). Evidence for large left-lateral strike-slip motions that define the structure of the Mongol-Okhotsk orogenic belt was published in several studies (Parfenov and others, 1992b; Yakubchuk and Edwards, 1999). The existence of longitudinal left-lateral strike-slip motions along the Mongol-Okhotsk orogenic belt, caused by the eastward (present-day coordinates) movement of Paleozoic orogenic belts, located to the east of the Mongol-Okhotsk belt, is supported by paleomagnetic data (Kravchinskiy and others, 2002a,b).

Utilization of Paleomagnetic Data

The proper use of paleomagnetic data for paleotectonic reconstructions is important. However, even the best of these data, obtained at the best national laboratories and evaluated by the main tests of paleomagnetic analysis, cannot be regarded as absolute. As an example, the paleomagnetic and paleobiogeographic data for Permian units in the central Mongol-Okhotsk orogenic belt differ greatly (Parfenov and others, 1999b, c). Other examples of discrepancies are given below.

Paleomagnetic data indicate that the North Asian craton rotated counter-clockwise in the Neoproterozoic and early Paleozoic and rotated clockwise and from the Silurian through the late Mesozoic (Pecherskiy and Didenko, 1995). (However, a recent hypothesis of only clockwise rotation of the craton, beginning in the Early Cambrian, was proposed by Kazanskiy (2002).) Accordingly, Silurian-Mesozoic left-lateral strike-slip faults and Neoproterozoic and early Paleozoic right-lateral strike slips are to have been active within the orogenic belts surrounding the craton. At the same time, based on geological data, prevailing right-lateral strike slips of early and middle Paleozoic age are reconstructed for the southern margin of the North Asian craton (Berzin, 2001). The inconsistency between the direction of the craton rotation and the kinematics of motions along the strike-slip faults may be only apparent, assuming that in the middle Paleozoic, the oceanic plate and the terranes moved in the same direction as did the North Asian craton, but at a higher rate. After the accretion, with reduced space, the rotation of the North Asian craton resulted in the transformation of dextral strike-slip faults into sinistral ones and in initiation of new left-lateral strike-slip faults.

Construction of Time Stages of Tectonic Model

In this study, the formation of major tectonic events is portrayed in a series of paleotectonic reconstructions that are compiled for a series of time spans from the Neoproterozoic through the Present. The reconstructions were started with the Present time stage and sequentially progressed to older ones in order to eliminate the effect of late deformations superposed on the older structures. The restoration of mutual positions of terranes prior to their motions along large longitudinal strike-slip faults was an important interpretation. For instance, reconstruction of the middle Paleozoic South Mongol-Khingan island-arc system in Central Asia is based on the assumption that the South Mongol collage (orogenic belt) represents a once single island arc that was subsequently duplexed by the left-lateral strike-slip faults.

Previous studies of the related Mesozoic and Cenozoic tectonics of Northeast Asia and the Circum-North Pacific include those of Parfenov and others (1999a,b), Nokleberg and others (2000, 2005), and Scotese and others (2001). These prior reconstructions were used in this study with additions and refinements for Northeast Asia. The global paleotectonic reconstructions of Scotese (1997) also were utilized.

Major Geologic and Tectonic Units of Northeast Asia

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.

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

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

(3) 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 preRiphean basement of the North Asian craton.

(4) 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.

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

(6) 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 occur along the margins of the North Asian and Sino-Korean cratons and are interpreted as rifted and reaccreted fragments of these cratons.

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

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

(3) 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 being a fragment of the North Asian craton and cratonal margin that was rifted in the Late Devonian or Early Carboniferous.

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

The Proterozoic through Cambrian Argun-Idermeg superterrane (AR) 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 Proterozoic through Permian Bureya-Jiamusi superterrane (BJ) 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 being 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) consists of the late Neoproterozoic through Ordovician Kara continental-margin turbidite terrane. This superterrane is interpreted as being a rifted fragment of the North Asian craton that was reaccreted in the Jurassic.

The Archean through Jurassic Kolyma-Omolon superterrane (KOM) 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.

The late Riphean and older Tuva-Mongolia superterrane (TM) 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.

Tectonic Collages between 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, contain one or more island arcs and tectonically linked subduction zones. Because of these successive accretions, the collages are generally young southward; however, this pattern is locally disrupted because some tectonic collages, or parts them were interspersed by subsequent strike-slip faulting.

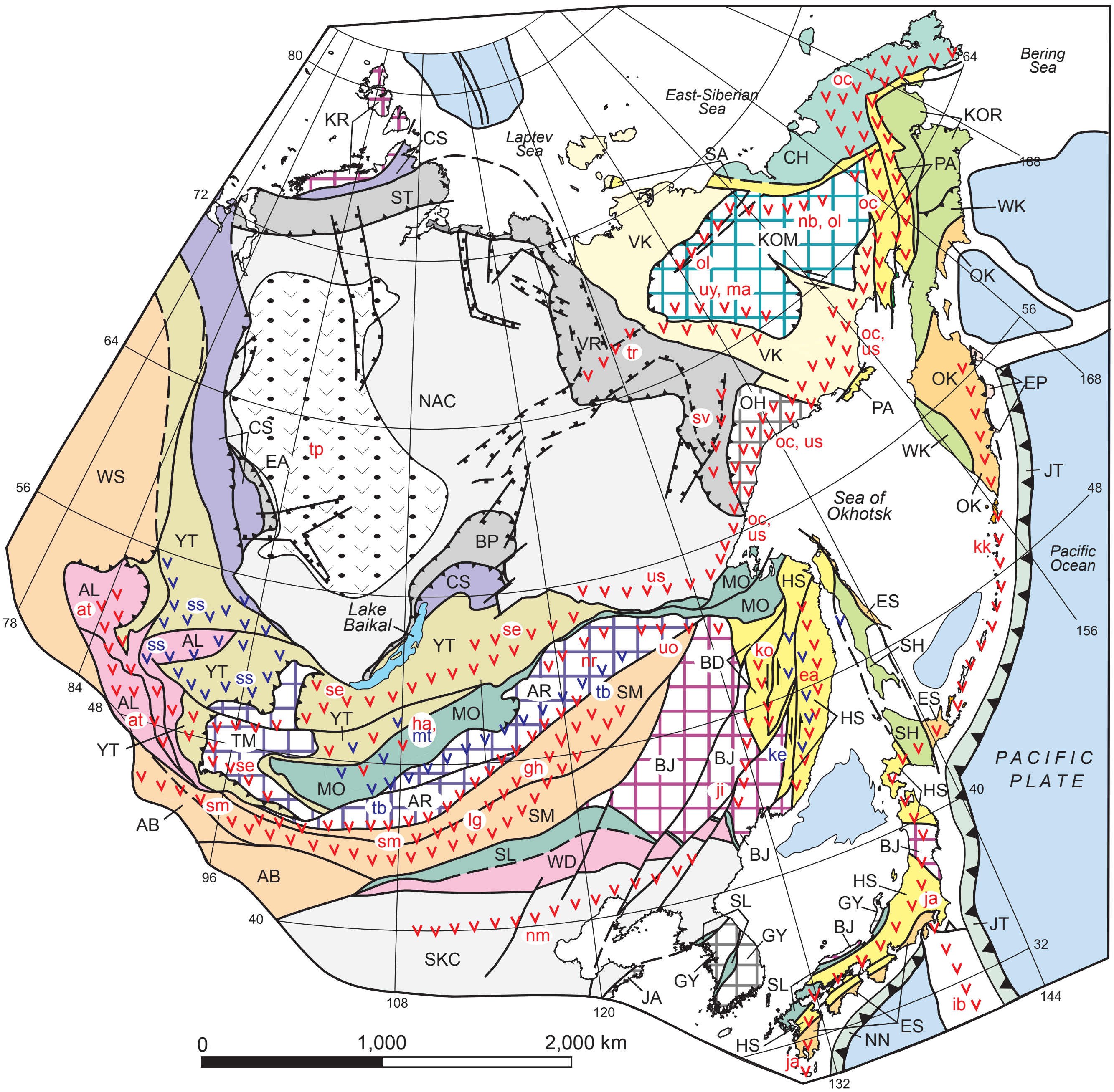


Figure 2. Northeast Asia summary geodynamics map. Map is derived from (1) a Generalized Northeast Asia Geodynamics Map at 10 million scale (Parfenov and others, 2004); (2) a more detailed Northeast Asia Geodynamics Map at 5 million scale (Parfenov and others, 2003); and (3) the western part of a Circum-North Pacific tectono-stratigraphic terrane map at 10 million scale (Nokleberg and others, 1997). Map shows locations of 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. Refer to text for unit descriptions

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.

(1) The Altai tectonic collage (AL; Vendian through Ordovician, accreted in the Late Silurian) 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 being an island-arc system that was active near the southwestern margin (present-day coordinates) of the North Asian craton and previously accreted terranes.

(2) The Atasbogd tectonic collage (AB; Ordovician through Permian, accreted in the Late Carboniferous or Early Permian) 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 being 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.

(3) The Circum-Siberia tectonic collage (CS; Paleoproterozoic and Mesoproterozoic, accreted in the Neoproterozoic) 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.

(4) The Mongol-Okhotsk tectonic collage (MO; Devonian through Late Jurassic, accreted in the late Paleozoic through early Mesozoic) 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 they 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.

(5) The Solon tectonic collage (SL; Carboniferous through Permian, accreted in the late Paleozoic through early Mesozoic) consists of the Carboniferous and Early Permian North Margin, the Late Carboniferous through 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 being 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 being fragments of the Solon Ocean plate that were subducted to form the North Margin continental-margin arc on the Sino-Korean craton.

(6) The South Mongolia-Khingan tectonic collage (SM; Ordovician through Carboniferous, accreted in the Late Carboniferous or Early Permian) consists of the South Mongolia-Khingan island-arc and tectonically linked subduction-zone terranes. This tectonic collage is interpreted as being 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.

(7) The Wundurmiao tectonic collage (WD; Mesoproterozoic through Silurian, accreted in the Late Silurian) 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 being the Laoling island-arc system that formed near the ino-Korean craton. Both the island-arc system and craton were widely separated from the North Asian craton in the early Paleozoic.

(8) The West Siberian tectonic collage (WS; Ordovician through Carboniferous, accreted in the Late Carboniferous or Early Permian) onsists 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 being a northwest continuation (present-day coordinates) of the South Mongolia-Khingan tectonic collage.

(9) The Yenisey-Transbaikal tectonic collage (YT; Vendian through Devonian, accreted in the Vendian through Early Ordovician) 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 being 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.

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 eastward during closures of parts of the ancestral and modern Pacific and older oceans in the region (fig. 1). Thus, these tectonic collages are generally younger toward the east; 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.

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

(2) The Chukotka tectonic collage (CH, Paleozoic and Triassic; accreted in the Late Jurassic and Early Cretaceous) 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.

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

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

(5) The Honshu-Sikhote-Alin collage (HS, Jurassic and Early Cretaceous; accreted in the Cretaceous) 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.

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

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

(8) The Penzhina-Anadyr collage (PA, Late Jurassic and Early Cretaceous; accreted in the Late Cretaceous) 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.

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

(10) The Sakhalin-Hokkaido collage (SK; Cretaceous; accreted in the Eocene) 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 being a continental-margin forearc basin and tectonically linked subduction-zone terranes that are associated with the East Sikhote-Alin continental-margin arc.

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

(12) The West Kamchatka tectonic collage (WK; mid-Cretaceous through 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 the Okhotsk-Chukotka continental-margin arc.

Carboniferous and Permian Continental-Margin Arcs Occurring South of the North Asian 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.

(1) The Altay continental-margin arc (at; Devonian and early Carboniferous) 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.

(2) 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.

(3) The Jihei continental-margin arc (ji; Permian) 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 the Solon Ocean plate under the southern margin (present-day coordinates) of the Bureya-Jiamusi superterrane and adjacent units.

(4) The Lugyngol continental-margin arc (lg; Permian) 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.

(5) The North Margin continental-margin arc (nn; Late Carboniferous through Permian) occurs on the northeastern margin (present-day coordinates) of the 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 the Sino-Korean craton.

(6) The South Mongolian continental-margin arc (sm; middle Carboniferous through Triassic) 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.

Devonian through Early Cretaceous Continental-Margin Arcs Occurring 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).

(1) The Hangay continental-margin arc (ha; Late Carboniferous through Early Permian 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.

(2) The Norovlin continental-margin arc (nr; Devonian through Early Carboniferous) 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).

(3) The Selenga continental-margin arc (se; Permian through Jurassic) 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.

(4) The Uda-Murgal and Stanovoy continental-margin arcs (us; Jurassic and Early Cretaceous) 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 through Early Cretaceous Island Arcs Occurring on or Adjacent to Kolyma-Omolon Superterrane

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

(1) The Oloy island arc (ol; Late Jurassic) 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.

(2) The Uyandina-Yasachnaya island arc (uy; Late Jurassic and Early Cretaceous) 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 the 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.

Jurassic through Early Tertiary Continental-Margin Arcs and Granite Belts Occurring 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.

(1) The East Sikhote-Alin continental-margin arc (ea; Late Cretaceous through early Tertiary) 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.

(2) The Khingan-Okhotsk continental-margin arc (ko; Early and mid-Cretaceous) 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).

(3) The Main granite belt (ma; Late Jurassic) 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.

(4) The Northern granite belt (nb; Early Cretaceous, 120 to 138 Ma) 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.

(5) The Okhotsk-Chukotka continental-margin arc (oc; Late Cretaceous through early Tertiary) 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.

(6) The South Verkhoyansk granite belt (sv; Late Jurassis through mid-Cretaceous) 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.

(7) The Transverse granite belt (tv; Early Cretaceous) 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.

(8) The Umlekan-Ogodzhin continental-margin arc (uo; Jurassic and Cretaceous 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).

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.

(1) The Izu-Bonin continental-margin arc (ib; Miocene through Holocene) occurs south of southern Japan and 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.

(2) The Japan continental-margin arc (ja; Miocene through Holocene) 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.

(3) The Kuril-Kamchatka continental-margin arc (kk; Miocene through Holocene) 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 Early 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.

(1) 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 having formed along a Late Jurassic and Early Cretaceous continental-margin transform fault.

(2) The Mongol-Transbaikal arc (mt) (Late Triassic through Early Cretaceous, 230 to 96 Ma) occurs in northern Mongolia and southern Transbaikal regions. The arc is preserved in the Late Triassic through Early Cretaceous Mongol-Transbaikal region volcanic-plutonic belt (mt) that consists of volcanic rocks in separate major basins and is composed of trachyandesite, dacite, and trachyrhyolite flows, stocks, necks, and extrusive domes. The arc also includes coeval granite plutons composed of granodiorite, alkaline gabbro-granite, granite, leucogranite, and Li-F granite. The arc 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. The arc is also referred to as the North Gobi arc.

(3) The South Siberian arc (ss) (Early Devonian, 400 to 415 Ma) occurs in the Eastern Altai-Sayan region and consists of the South Siberian volcanic-plutonic belt. Volcanic rocks are composed of bimodal mafic and siliceous volcanic rock including andesite, olivine basalt, trachybasalt, essexite, phonolite, alkaline trachyte, trachyandesite, and trachyrhyolite. Plutonic rocks are composed of subalkaline to alkaline gabbro to granite, alkaline-syenite, granosyenite, leucogranite, and latite-bearing subalkaline gabbro, monzonite, and syenogranite. The arc 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 transpressive-fault margin and into a convergent margin.

(4) The Trans-Baikal-Daxinganling arc (tb) (Middle Jurassic through Early Cretaceous, 175 to 96 Ma) occurs in the Transbaikal region, Mongolia, Northeastern China, and consists of the Trans-Baikalian-Daxinganling sedimentary-volcanic-plutonic belt. Volcanic rocks are composed of shoshonite, latite, trachyte, trachyandesite, trachybasalt, trachyrhyolite, shoshonite, latite subalkaline basalt, and basalt andesite. Plutonic rocks are composed of large calc-alkaline to subalkaline plutons of granite, leucogranite, quartz syenite, quartz monzonite, granodiorite, and biotite-amphibole diorite, and small calc-alkaline subvolcanic bodies of dacite and rhyolite. The arc 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.

Riphean (1000 to 650 Ma) (Early and Middle Neoproterozoic) Stage of Tectonic and Metallogenic Model

Major Tectonic Events

Cratons, Passive Continental-Margin, and Cratonal Terranes

The major tectonic events in the Neoproterozoic for cratons, passive continental margins, and cratonal terranes (fig. 3) were as follows.

(1) Passive continental margins formed on the submerged margins of the North-Asian craton, including the East Angara (EA), Baikal-Patom (BP), and Verkhoyansk (VK) cratonal margins. In addition, passive continental margins formed on the Argun-Idermeg superterrane (Argunsky, Central Angara, Idermeg, West Angara passive continental-margin terranes).

(2) Widespread intracontinental rifting was initiated along these passive continental margins.

(3) Platform cover accumulated onto the inner parts of the North Asian craton.

(4) Shallow-water marine sediments accumulated on the Sino-Korean craton.

(5) Several major island-arc systems and tectonically-linked subduction zones formed offshore or far away from the North Asian craton, including the Near-Yenisey, Baikal-Muya, and Zavhan magmatic arcs.

Near-Yenisey Island Arc

Remnants of the Late Proterozoic Near-Yenisey arc are part of the Circum-Siberia collage (figs. 2, 3), that was accreted in the Neoproterozoic. The major units in the arc are the Isakov (IS) and Predivinsk (PR) island-arc terranes (Kuzmichev and others, 2001; Vernikovskiy, 1996, Vernikovskiy and Vernikovskaya, 2001). The terranes are overthrust eastwards onto the East Angara (EA) passive continental-margin terrane and older units of the North Asian craton. The polarity of the subduction zone based on the structural position of the ophiolite-clastic melange is interpreted as dipping oceanward, away from continent (fig. 3). The age of the arc is still a question. Dating of island-arc plagiogranites and volcanic units has yielded ages ranging from 630 to 700 Ma (Vernikovskiy and Vernikovskaya, 2001). The Isakov terrane is unconformably overlapped by the Neoproterozoic through Vendian sediments of the Vorogovka-Chapa basin.

Baikal-Muya Island Arc

Remnants of the Neoproterozoic Baikal-Muya arc are part of the Circum-Siberia collage that was accreted in the Late Neoproterozoic (figs. 2, 3). The arc is preserved in the Baikal-Muya (BM) and Sarkhoy (SR) terranes in the Transbaikal region and northern Mongolia (Berzin and Dobretsov, 1994; Konnikov and others, 1994; Kuzmichev and others, 2001; Obolenskiy and others, 1999). Remnants of the arc are unconformably overlapped by Vendian-Cambrian rocks of the Upper Angara Basin and Huvsgol-Bokson overlap assemblage.

Tectonically paired to the Baikal-Muya island arc was a subduction zone that is now preserved in the Hug (HU) and Olokit-Delunuran subduction-zone (OD) terranes (fig. 2). The position of subduction-zone terranes relative to the island-arc igneous-rock units, and the lack of subduction units along the periphery of the Baikal-Patom passive continental margin suggest that the subduction zone dipped to the southeast under the island arc (fig. 3) (Berzin and Dobretsov, 1994). Strike-slip faulting occurred between the Baikal-Muya and Near-Yenisey arcs along the Main Sayan strike-slip fault (fig. 3). The arc is associated with back-arc, forearc, rift, and mélange units in the Kuvai terrane (KUV). The terrane is unconformably overlapped by the Vendian through Cambrian sediments of the Mana Basin.

Zavhan Magmatic Arc

A fragment of the Late Proterozoic Zavhan magmatic arc occurs in Central Mongolia in the Zavhan (ZA) active continental-margin terrane (Tomurtogoo, 1989) that is also a part of the Circum-Siberia collage (figs. 2, 3) that was accreted in the Neoproterozoic. The initial relation of the magmatic arc to the adjacent Baydrag (BY) cratonal terrane is unknown. The Zavhan and Baydrag terranes are unconformably overlapped by the latest Neoproterozoic through Middle Cambrian Huvsgol-Bokson sedimentary assemblage. The subduction zone was southwest of the magmatic arc. Alpine-type ultramafic and associated units in the Tasuul terrane form part of a subduction-zone assemblage that was obducted onto the western margin of the Zavhan terrane (Tomurtogoo, 1989). The western and eastern ends of the magmatic arc occurred along dextral shear zones that were subparallel to the continental margin (fig. 3).

Important Geologic Details

(1) The Upper Riphean island arcs, now preserved in the Taimyr, Enisey Ridge, East Sayan, and North Transbaikal regions, are associated with ophiolites and boninites, indicating formation of the island arcs on oceanic crust (Dobretsov and others, 1995; Kuzmichev and others, 2001; Vernikovsky andVernikovskaya, 2001). The island-arc formations are dated by isotopic methods at 730 to 740 Ma (Taimyr), 670 Ma

(Enisey Ridge), and 770 to 920 Ma (North Transbaikal region) (Konnikov and others, 1994; Izokh and others, 1998). Paleomagnetic data are absent, so positions of the arcs with respect to the continent are not defined. The polarity of the arcs is also unknown in most cases.

(2) A characteristic element of the Late Riphean Circum-Siberian collage is the occurrence of relatively small (tens of kilometers across) cratonal terranes composed of Early Precambrian crystalline rocks (Muya terrane in the North Transbaikal region, Gargan and Kan terranes in East Sayan, and Mamontovskiy and Faddeevskiy terranes in Taimyr). These terranes are interpreted as being fragments of the North Asian craton that were detached during the break-up of the Rodinia supercontinent.

(3) Data are limited for the Upper Riphean sediments on the eastern margin of the North Asian craton**.** Present knowledge of the Paleozoic evolution of this margin (Parfenov, 1984) indicates that the Okhotsk and Omolon cratonal terranes and the Prikolyma miogeoclinal terrane were part of the North Asian craton in the Late Riphean. A higher rate of sedimentation in the Late Riphean, the occurrence of highly alkaline basalts in the Upper Riphean rocks in some regions (Prikolyma and Omolon terranes), and occurrence of ultramafic plutons dated at 673 to 752 Ma (Biryukov, 1997) near the cratonal margin suggests rifting.

(4) Accretion of the Late Riphean island arcs to the North Asian craton and accretion of the Late Riphean Circum-Siberian collage occurred in the Late Riphean. Vendian and Cambrian sedimentary units, similar to coeval rocks of the Siberian platform, but much thicker and more marine in nature, overlie, with a sharp unconformity, the Upper Riphean island-arc formations.

(5) In the Central Taimyr superterrane, Zonenshain and others (1990) compare Upper Riphean island-arc formations of this unit with similar formations of the Polar Urals and the basement of the Pechora basin and interpreted an exotic origin. They believed that the Central Taimyr superterrane with Upper Riphean island-arc formations and the more northerly Kara terrane amalgamated in the late Paleozoic, and then were jointly accreted to the North Asian craton in the late Late Jurassic. Positions of the Upper Riphean island-arc formations of Taimyr are similar to those of analogous framing formations of the Enisey Ridge, East Sayan, and the North Transbaikal region, thereby implying a North Asian origin (Khain and others, 2001; Khain and others, 1997).

(6) The northern margin of the Sino-Korean craton is remarkably rectilinear. The Early Paleozoic Wenduermiao orogenic belt adjacent to the craton contains Late Precambrian ophiolites associated with metamorphic schist (Hu Xiao and Niu Shuying, 1986; Chen Qi, 1992; Li, 1996. The boundary of the craton was probably a transform fault.

(7) After the break-up of the Rodinia supercontinent in the Late Riphean, the Sino-Korean and North Asian cratons were relatively close (Scotese, 1997). During the Cambrian through Ordovician, the two cratons migrated apart (Lee and others, 1997). The Sino-Korean craton remained close to the eastern margin of East Gondwana during the entire early Paleozoic, and opening of the ocean was mainly caused by the movement of the North Asian craton away from Gondwana.

Riphean Metallogenesis

Metallogenic Belts Related to Sedimentary Basins formed on Cratonal Margins

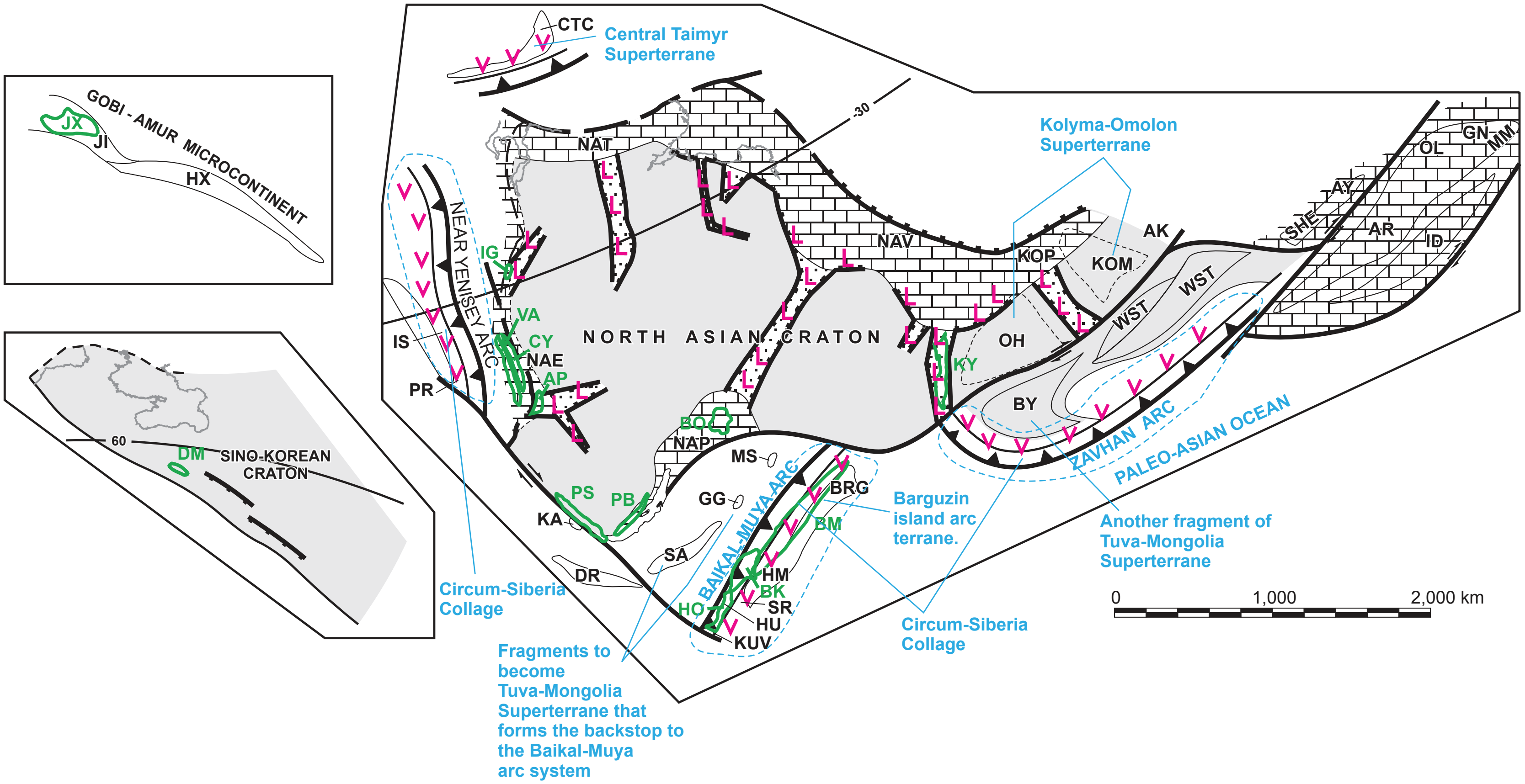
Several metallogenic belts possess geologic units favorable for major stratiform sediment-hosted deposits, including the Angara-Pit belt (with sedimentary siderite Fe and volcanogenic-sedimentary Fe deposits), Bodaibinskiy and Central-Yenisei belts (with Au in black shale deposits), Jixi belt (with banded iron formation--BIF, Algoma Fe deposits), Kyllakh and Pribaikalskiy belts (with carbonate-hosted Pb-Zn deposits), and Vorogovsko-Angarsk belt [with sedimentary exhalative Pb-Zn (SEDEX), and carbonate-hosted Pb-Zn [Mississippi valley type) deposits]. Where known, the fossil or isotopic ages of host rocks or deposits range from Riphean through Vendian. These deposits are hosted either in sedimentary units on the North Asian cratonal margin (Angara-Pit, Bodaibinskiy, and Kyllakh belts), or in sedimentary basins deposited on passive continental-margin terranes that were possibly derived from the cratonal margin (Central-Yenisei and Vorogovsko-Angarsk belts). These favorable geologic units and deposits are interpreted as having formed 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-hosted and/or granite-hosted deposits, including the Baikalo-Muiskiy belt [with volcanogenic-hydrothermal-sedimentary massive sulfide Pb-Zn deposits) and the Lake belt (with volcanogenic Cu-Zn massive sulfide (Urals type), volcanogenic-sedimentary Fe, Cu-skarn, Fe-skarn, granitoid-related Au-vein, mafic-ultramafic related Cu-Ni-PGE, podiform Cr, mafic-ultramafic related Ti-Fe deposits]. These favorable geologic environments were in island-arcs or on sea floors underlying the arcs in the Baikal-Muya island-arc terrane (part of the Circum-Siberia 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 (with sedimentary bauxite deposits) and Central-Yenisei belts that are hosted in either the western North Asian craton or the Yenisey-Transbaikal and Circum Siberia collages. These favorable geologic environments consisted of regional metamorphism and hydrothermal



GEOLOGIC UNITS

AK - Avekov terrane
AR - Argunsky terrane
AY - Ayansk terrane
BRG - Barguzin terrane
BY - Baydrag terrane
CTC - Chelyuskin terrane
DR - Derba terrane
GG - Gargan terrane
GN - Gonzha terrane
HM - Hamar-Davaa terrane
HX - Hutaguul-Xilinhot terrane
HU - Hug terrane
ID - Idermeg terrane
IS - Isakov terrane
JI - Jiamusi terrane
KA - Kan terrane
KOM - Kolyma-Omolon superterrane
KOP - Prikolyma terrane
KUV - Kuvai terrane
MM - Mamyn terrane
MS - Muya terrane
NAE - North Asian Craton Margin (East Angara fold and thrust belt
NAP - North Asian Craton Margin (Patom-Baikal fold and thrust belt
NAT - North Asian Craton Margin (South-Taimyr fold belt
NAV - North Asian Craton Margin (Verkhoyansk fold and thrust belt
OH - Okhotsk terrane
OL - Oldoy terrane
PR - Predivinsk terrane
SA - Sangilen terrane
SHE - Shevli terrane
SR - Sarkhoy terrane
WST - West Stanovoy terrane

METALLOGENIC BELTS

AP - Angara-Pit
BK - Bokson-Kitoiskiy
BM - Baikalo-Muiskiy
BO - Bodaibinskiy
CY - Central-Yenisei
DM - Damiao
HO - Hovsgol
IG - Igarsk
JX - Jixi
KY - Kyllakh
PB - Pribaikalskiy
PS - Prisayanskiy
VA - Vorogovsko-Angarsk

Figure 3. Neoproterozoic (850 Ma) time stage of tectonic and metallogenic model and explanation. See text for explanation of tectonic events and origins of major metallogenic belts.

EXPLANATION

Craton

Passive continental margin on subsided craton

Microcontinent

Continental slope

Intracontinental sedimentary basin

Collage of accreted terranes and overlap assemblages

Ocean or sea underlain by oceanic crust; includes continental margin and slope units

Sea underlain by continental crust

SUBDUCTION-RELATED ISLAND ARC AND CONTINENTAL MARGIN ARCS

Mainly volcanic and lesser plutonic units

Mainly plutonic and lesser volcanic units

TRANSFORM-PLATE BOUNDARY, INTRA-PLATE (PLUME) MAGMATIC UNITS

Subalkaline and alkaline volcanic and plutonic belts

Plateau basalt, trap

Rift-related bimodal volcanic and plutonic rocks

Intraplate granitoids

COLLISIONAL GRANITOIDS

CONTACTS, FAULTS, AND SYMBOLS

Subduction zone and its accretionary wedge

Thrust

Strike-slip fault

Normal fault

Fold-and thrust belt formed on the subsided craton margin

Stratigraphic contact

OH Metallogenic belt with abbreviation

Outline and name of tectonic collage or name of major tectonic feature

Chukotka Collage

Figure 3.—Continued.

alteration that were associated with accretion of terranes to the North Asian cratonal margin. 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 for which the tectonic origin is unclear.

Vendian (Neoproterozoic III) through Early Cambrian (650 to 520 Ma) Stage of Tectonic Model

Major Tectonic Events

The major tectonic events in the Vendian through Early Cambrian (figs. 2, 4) were as follows.

(1) Completion of Neoproterozoic accretion of several major island-arc systems and tectonically-linked subduction zones onto the North Asian craton, including the Near-Yenisey, Baikal-Muya, and Zavhan magmatic arcs.

(2) Formation of new island-arc systems, including the Salair, Kuznetsk-Tannuola and Dzhida-Lake arcs and tectonically-linked subduction zones. The island arcs consist mainly of Vendian ophiolites and Vendian through Early and Middle Cambrian igneous rock-units. The Salair arc also includes Late Cambrian and early Early Ordovician igneous rock-units. These Late Neoproterozoic through Early Cambrian magmatic arcs formed a sublatitudinal system that extended along the northern border of the Siberian continent (ancient coordinates) (fig. 2) and according to paleomagnetic data, was close to the equator (Berzin and Kungurtsev, 1996; Kazanskiy, 2002; Kungurtsev and others, 2001).

(3) Associated with these arcs was subduction of the Paleo-Asian ocean plate to form the Alambai (AL), Amil (AI), Borus (BS), Dzhebash (DZE), Ih Bogd (IB), Kurtushiba (KRT), and Teletsk (TL) oceanic and subduction-zone terranes (figs. 2, 4). Behind the island arcs were the Minusa-Tuva and the Transbaikal marginal seas that are interpreted as the fragments of an oceanic plate separated by island arcs. The most intense island-arc activity occurred in the Early Cambrian and the beginning of the Middle Cambrian.

(4) Passive continental margins formed on the submerged margins of the North-Asian craton (East Angara, Baikal-Patom, South Taimyr and Verkhoyansk fold-and-thrust belts).

(5) Intracontinental rifting formed on the eastern part of the North Asian craton (Omolon and Kharaulakh rifts). On the western North Asian craton occurred a shallow-water basin filled with lagoonal sediments with evaporites, while in the east there was a deep-water basin accumulating black shales. The basins were separated by the Anabar-Sinsk barrier reef, one of the largest worldwide.

Major Units

Dzhida-Lake Island Arc

Remnants of the Dzhida-Lake island arc are preserved in the Yenisey-Transbaikal collage (figs. 2, 4). This collage has an age range of Vendian through Devonian and a timing of accretion of Vendian through Early Ordovician. The collage occurs in Transbaikalia, Northern and Central Mongolia. The collage includes the Lake, Eravna, Orkhon-Ikatsky, and Dzhida terranes that are separated by dextral strike-slip faults that have resulted in major modification of original positions (compare figures 3 and 4).

Kuznetsk-Tannuola Island Arc

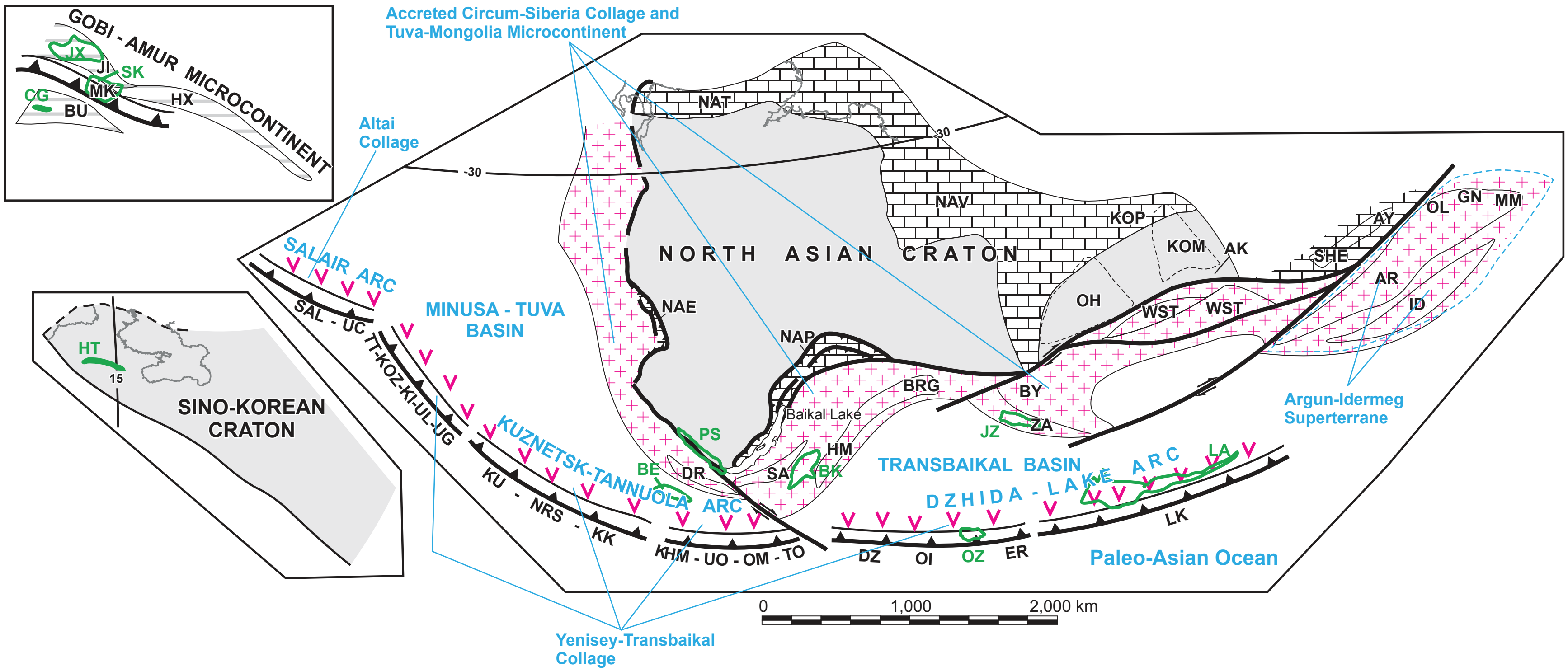
Remnants of the Kuznetsk-Tannuola island arc occur in a Z-shaped belt that is part of the Yenisey-Transbaikal collage (figs. 2, 4). The arc consists of the Telbes-Kitat (TT), Uimen-Lebed (UL), North Sayan (NRS), Khamsara (KHM), Ulugo (UO), Ondum (OM), and Tannuola (TO) terranes (fig. 4). Oceanward of, and parallel to, the Kuznetsk-Tannuola island arc were tectonically-linked subduction-zone terranes, including the Teletsk (TL), Dzhebash (DZE), Amil (AI), Borus (BS), and Kurtushiba (KRT) terranes that consist of Late Neoproterozoic and Early Cambrian oceanic crustal rock, upper mantle rocks, and turbidite deposits. Blueschist facies assemblages occur in the Borus and Kurtushiba terranes. During the Vendian, Early and Middle Cambrian, mainly sedimentary rocks were deposited in the Minusa-Tuva Basin that separated the island arc from the North Asian cratonal margin.

Salair Island Arc

Remnants of the Salair island arc are preserved in the Altai collage (figs. 2, 4; appendix B) in the Salair (SAL) and Ulus-Cherga (UC) island-arc terranes that are tectonically linked to the Alambai (AL) and Baratal (BR) subduction-zone terranes. As with the eastern segments of the Late Neoproterozoic and Cambrian island-arc system occurring south of the North Asian craton and cratonal margin, the major igneous activity occurred in the Early Cambrian. The Salair arc is the westernmost extent of the Late Neoproterozoic and Cambrian island-arc system.

Origin of Late Neoproterozoic (Vendian) through Early Cambrian Island Arcs

The Late Neoproterozoic through Early Cambrian island-arc units are interpreted by most workers as having formed from subduction of the Paleo-Asian Ocean plate (fig. 4) (Berzin and Dobretsov, 1994; Gordienko, 1987; Mossakovskiy and



GEOLOGIC UNITS

North Asian Craton Margin

NAE - East Angara
NAP - Patom-Baikal
NAT - South-Taimyr
NAV - Verkhoyansk

Terranes

AK - Avekov terrane
AR - Argunsky terrane
AY - Ayansk terrane
BRG - Barguzin terrane
BU - Bureya terrane (Metamorphic)
BY - Baydrag terrane
DR - Derba terrane
DZ - Dzhida terrane (Island arc)
ER - Eravna terrane (Island arc)
GN - Gonzha terrane
HM - Hamar-Davaa terrane
HX - Hutaguul-Xilinhot terrane
ID - Idermeg terrane
JI - Jiamusi terrane
KHM - Khamsara terrane (Island arc)
KI - Kanim terrane (Island arc)
KK - Kizir-Kazir terrane (Island arc)
KOM - Kolyma-Omolon superterrane
KOP - Prekolyma
KOZ - Kozhukhov terrane (Island arc)
KU - Kurai terrane (Island arc)
LK - Lake terrane (Island arc)
MK - Malokhingansk terrane (Accretionary wedge, type B) (Neoproterozoic and Cambrian)
MM - Mamyn terrane
NRS - North Sayan terrane (Island arc)
OH - Okhotsk terrane
OI - Orhon-Ikatsky terrane (Continental margin arc)
OL - Oldoy terrane
OM - Ondum terrane (Island arc)
SA - Sangilen terrane
SAL - Salair terrane (Island arc)
SHE - Shevli terrane
TO - Tannuola subterrane (Island arc)
TT - Telbes-Kitat terrane (Island-arc)
UC - Ulus-Cherga terrane (Island arc)
UG - Ulgey terrane (Island arc)
UL - Uimen-Lebed terrane (Island arc)
UO - Ulugo terrane (Island arc)
WST - West Stanovoy terrane
ZA - Zavhan terrane (Continental margin arc) (Late Neoproterozoic)

METALLOGENIC BELTS

BE - Bedobinsk
BK - Bokson-Kitoiskiy
CG - Chagoyan
HT - Hunjiang-Taizihe
JZ - Jinzhong
JX - Jixi
LA - Lake
PS - Prisayanskiy
OZ - Ozerninsky
SK - South Khingan

Figure 4. Early Cambrian (545 Ma) time stage of tectonic and metallogenic model. See text for explanation of tectonic events and origins of major metallogenic belts and figure 3 for explanation of symbols and patterns.

others, 1994; Pecherskiy and Didenko, 1995; Sengör and others, 1993; Zonenshain and others, 1990**).** The island arcs commenced activity after the formation of the Late Neoproterozoic accretional-collisional belt along the continent and after the jumping of the subduction zone towards into the Paleo-Asian Ocean. The underthrusting of oceanic plate occurred northward (present-day coordinates) toward the North Asian craton and itis confirmed by mutual arrangement of island-arc, subduction-zone, and turbidite terranes**.** It is assumed that the mechanism of the oblique subduction (combination of strike-slip and underthrusting) was proceeding already in the Cambrian (Berzin, 1995).

Associated with magmatic arcs are the Minusa-Tuva and Transbaikal back-arc basins (fig. 4) that were separated by island arcs and fragments of oceanic plates. During the Vendian and Early Cambrian, dominantly carbonate-terrigenous rocks and closely associated underlying sediments were deposited. Coeval sediments unconformably overlapped the Neoproterozoic terrane collage along the periphery of the North Asian craton. These units are preserved in the Mana (ma), Huvsgol-Bokson (hb), Upper Angara (ua), Gazimur (ga), and Argun (ags) overlap units.

The formation of the island arcs is interpreted as having ended in the early Middle Cambrian when oblique subduction changed into dextral-slip faulting along the outboard (ocean-ward) margin of the arcs (Berzin, 1995).

Important Geologic Details

(1) The Vendian through Early Paleozoic (650 to 410 Ma) (fig. 4) was a period of major sea transgression onto the North Asian craton. Transgression developed from the subsided margins of the craton toward its center. A change of terrigenous sedimentation in the Early Vendian through largely carbonate in the second half of the Vendian was typical (Shenfil', 1991; Mel'nikov and others, 1989a,b). Maximum transgression occurred in the Early to Middle Cambrian (Mel'nikov and others, 1989a,b). The Late Cambrian was marked by sea regression that resulted in the drainage of most of the craton by the Early Devonian, except along the northeastern and northern subsided margins.

(2) After Riphean rifting on the northeastern margin of the North Asian craton, including the Okhotsk and Omolon cratonal terranes and the Prikolyma passive continental-margin terrane, the Verkhoyansk passive continental margin started to form with the accumulation of thick Vendian terrigenous and carbonate sedimentary units, and, subsequently by Cambrian through Lower Devonian largely carbonate units (Parfenov, 1984). The slope and rise of the continental margin are marked by Ordovician turbidite and hemipelagic sedimentary units along the northern margin of the Omulevka terrane (Merzlyakov, 1971).

(3) The passive margin extended far northwest into the South Taimyr region, where the South Taimyr passive continental margin started to form with the accumulation of thick, early Paleozoic carbonate sedimentary units that are similar to those in the Verkhoyansk passive continental margin (Uflyand and others, 1991; Vernikovskiy, 1996; Inger and others, 1999). In the Vendian through early Paleozoic, the South Taimyr passive continental margin was probably part of the Central Taimyr superterrane as compared to the Upper Riphean island-arc units with conglomerate that were unconformably overlain at their bases by the uppermost Upper Riphean clastic units and younger, mostly carbonate rocks of Vendian and Cambrian age (Bezzubtsev, 1981). The overlying Ordovician through Silurian graptolitic clay shale units probably mark the slope and rise of this continental margin.

(4) Paleomagnetic data (Metelkin and others, 2000) indicate that the Kara terrane, including North Taimyr and Severnaya Zemlya Islands, was located 1,500 km to the south of the North Asian craton and cratonal margin. The convergence of the Kara terrane and the South Taimyr continental margin probably occurred along major strike-slip faults that were nearly parallel to the continent margin. This conclusion is supported by the absence of subduction-related magmatic arcs on the adjacent margins of the continent and the Kara terrane.

(5) On the western and southern margins of the North Asian craton, within the Late Riphean Circum Siberian collage, just as in the Taimyr area, Cambrian, Vendian and, locally, uppermost Upper Riphean thick shelf terrigenous-carbonate units were deposited. These units are deposited along an angular unconformity. On the margins of the craton, the sedimentary units are thinner, contain more marine units, and conformably overlie older units. These thick wedges of sedimentary rocks are generally similar to the passive continental margin units, but differ in that away from the craton, they change back-arc basin units that were separated from the ocean by island arcs. The Vendian through Middle Cambrian Dzhida-Ozernaya and Kuznetsk-Tannuola island arcs and the Vendian through Early Ordovician Salair arc were active at this time. The polarity of the island arcs is determined from the position of the conjugate subduction zones. According to paleomagnetic data, the Kuznetsk-Tannuola island arc had a E-NE strike and occurred at 10±5º N (Kungurtsev, and others, 2001), 1,000 to 1,500 km away from the North Asian craton.

(6) In the western part of the well-studied Minusinsk back-arc basin, that formed behind the Kuznetsk-Tannuola island arc, the Late Riphean volcanic oceanic uplifts and islands with shallow-water siliceous-carbonate deposits were deposited. They occur in eastern the Gorny Altay, Kuznetsk Altai and Gornaya Shoriya regions. In the Vendian through early Cambrian, mostly carbonate rocks were deposited in the uplifts, with highly bituminous carbonate-shale sequences forming between them in deeper water.

Middle and Late Cambrian (520 to 500 Ma) and Early Ordovician through Late Silurian (500 to 410 Ma) Stages of Tectonic and Metallogenic Model

Major Tectonic Events

The major tectonic events in the Middle and Late Cambrian (fig. 5) were as follows.

(1) Completion of accretion of the Late Neoproterozoic and Early Cambrian island-arc systems described above.

(2) Start of formation of a passive continental margin along the northern and northeastern periphery of the North Asian craton in the South Taimyr (NAT) and Verkhoyansk (NAV) fold-and-thrust belts.

(3) Formaton of turbidite basins along the southern transform margin of the North Asian craton in the area of accreted terranes.

(4) Deformation of the accreted island arcs and back-arc basins that started at the end of the Middle Cambrian and continued through the Silurian in a transpressional and dextral-slip faulting environment. This deformation was accompanied by intrusions of granitoids, local high-temperature metamorphism, and uplift and accumulation of marine and nonmarine molasses. In some regions, formation of high-temperature metamorphism (Fedorovskiy and others, 1995) resulted in obscuring of initial characteristics of terranes, as in the Hamar-Davaa terrane (HM) in the Transbaikal region. Layered gabbro-hyperbasite plutons intruded local zones of extension of litospheric blocks.

(5) Accumulation of flysch along the North Asian (Verkhoyansk) cratonal margin.

(6) Formation of turbidite units related to a continental margin arc along the southern margin of the North Asian craton in southern Siberia, central and northwestern Mongolia, and adjacent regions of China. These units are preserved in the Anyui-Chuya (ACH), Charysh (CHR), West Sayan (WSY), Altai (AT), Hovd (HV) and Govi-Altai (GA) terranes. These turbidite-margin sediments also occur in the stratigraphic basement of the Middle Paleozoic magmatic arcs in the Mandalovoo-Onor (MO) terrane. The molasse basins were strongly deformed in a transpressive dextral-slip environment.

The major tectonic events in the Early Ordovician through Late Silurian were (figs. 6, 7) as follows.

(1) Continued formation of a passive continental margin along the northern and northeastern periphery of the North-Asian craton in the South Taimyr (NAT) and Verkhoyansk (NAV) fold-and-thrust belts.

(2) Continued accumulation of flysch along the southern Siberian transform continental margin with uplift and erosion and transport of clastic material into abyssal basins. During the filling with the abyssal sediments, the basins evolved into shallow-water types.

(3) Continued deformation of accreted island arcs and back-arc basins in a transpressional and dextral-slip faulting environment. This deformation was accompanied by intrusions of granitoids, local high-temperature metamorphism, uplift and accumulation of marine and nonmarine molasses. Layered gabbro-hyperbasite plutons intruded local zones of extension of lithospheric blocks. Flysch continued to accumulate along the southern margin of the North Asian craton.

(4) Formation of the Early and Middle Ordovician East Mongolia-Khingan continental-margin arc along the southern margin of the North Asian craton and cratonal margin.

(5) Continued formation of turbidite units related to the Early and Middle Ordovician East Mongolia-Khingan continental margin arc that formed along the southern margin of the North Asian craton in southern Siberia and central and northwestern Mongolia, and adjacent regions of China. These units are preserved in the Anui-Chuya (ACH), Charysh (CHR), West Sayan (WSY), Altai (AT), Hovd (HV) and Govi-Altai (GA) terranes. These turbidite-margin sediments also occur in the stratigraphic basement of the Middle Paleozoic magmatic arcs in the Mandalovoo-Onor (MO) terrane.

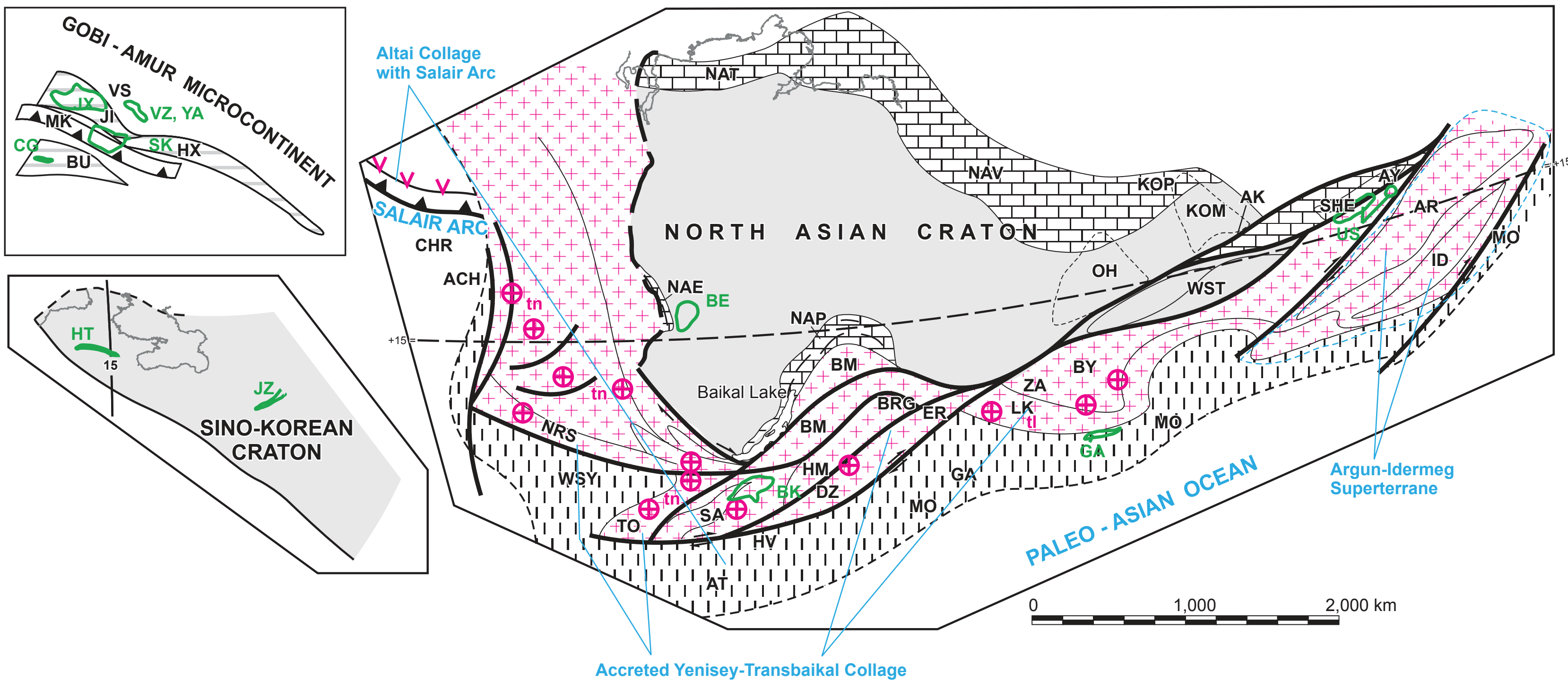
(6) In the eastern North Asian craton (in present-day coordinates) an active continental margin formed along with back-arc rifts.

(7) The position of the Sino-Korean craton relative to the North-Asian craton in the Late Neoproterozoic-Early Paleozoic is not resolved. No sedimentary or magmatic complexes of this age interval exist along the northern periphery of the Sino-Korean craton that might indicate the closing of the Paleo-Asian Ocean.

(8) Fragments of a series of mainly Ordovician magmatic arcs are preserved in terranes in the Wundurmiao collage (figs. 2, 6; appendix B). This complex collage, with a Mesoproterozoic through Silurian age and a late Silurian timing of accretion, occurs along the northern margin of the Sino-Korean craton and southern margin of the North Asian craton and previously-accreted terranes (figs. 2, 6; appendix B). The major terranes are: (1) Dongujimgin-Nuhetdavaa (DN), Nora-Sukhotin-Duobaoshan (ND), and Laolin (LA) island-arc terranes; (2) Tsagaan Uul-Guoershan (TG), and Zhangguangcailing (ZN) continental margin arc terranes; and (3) the Wundurmiao (WD) and Helongjing (HE) subduction-zone terranes (Fig. 6). The formation of these arcs, in contrast to island arcs that were active in the northern Paleo-Asian Ocean, occurred mainly in the Ordovician. The size and time of the origination and duration of associated subduction zones is also unknown.

Important Geologic Details

(1) In the Middle Cambrian (fig. 5), the system of island arcs underwent structural reorganization, accompanied by the alkaline basaltic volcanism in the Minusinsk back-arc basin.



GEOLOGIC UNITS

North Asian Craton Margin

NAE - East Angara
NAP - Patom-Baikal
NAT - South-Taimyr
NAV - Verkhoyansk

Terranes

ACH - Anui-Chuya terrane (Continental margin turbidite)
AK - Avekov terrane
AR - Argunsky terrane
AT - Altai terrane (Continental margin turbidite) (Precambrian and Cambrian through Devonian)
AY - Ayansk terrane
BM - Baikal-Muya terrane (Island arc) (Neoproterozoic)
BRG - Barguzin terrane
BU - Bureya terrane (Metamorphic)
BY - Baydrag terrane
CHR - Charysh terrane (Continental margin turbidite) (Cambrian through Devonian)
DZ - Dzhida terrane (Island arc)
ER - Eravna terrane (Island arc)
GA - Govi Altai terrane (Continental-margin turbidite) (Cambrian through Devonian)
HM - Hamar-Davaa terrane
HV - Hovd terrane (Continental-margin turbidite) (Neoproterozoic through Silurian)
HX - Hutaguul-Xilinhot terrane
ID - Idermeg terrane
JI - Jiamusi terrane
KOM - Kolyma-Omolon superterrane
KOP - Prekolyma
LK - Lake terrane (Island arc)
MK - Malokhingansk terrane (Accretionary wedge, type B) (Neoproterozoic and Cambrian)
MO - Mandalovoo-Onor terrane (Island arc) (Middle Ordovician through Early Carboniferous)
NRS - North Sayan terrane (Island arc)
OH - Okhotsk terrane
SA - Sangilen terrane
SHE - Shevli terrane
TO - Tannuola subterrane (Island arc)
VS - Voznesenka terrane (Passive continentalal margin) (Cambrian through Permian)
WST - West Stanovoy terrane
WSY - West Sayan terrane (Continental margin turbidite) (Late Neoproterozoic through Devonian)
ZA - Zavhan terrane (Continental margin arc) (Late Neoproterozoic)

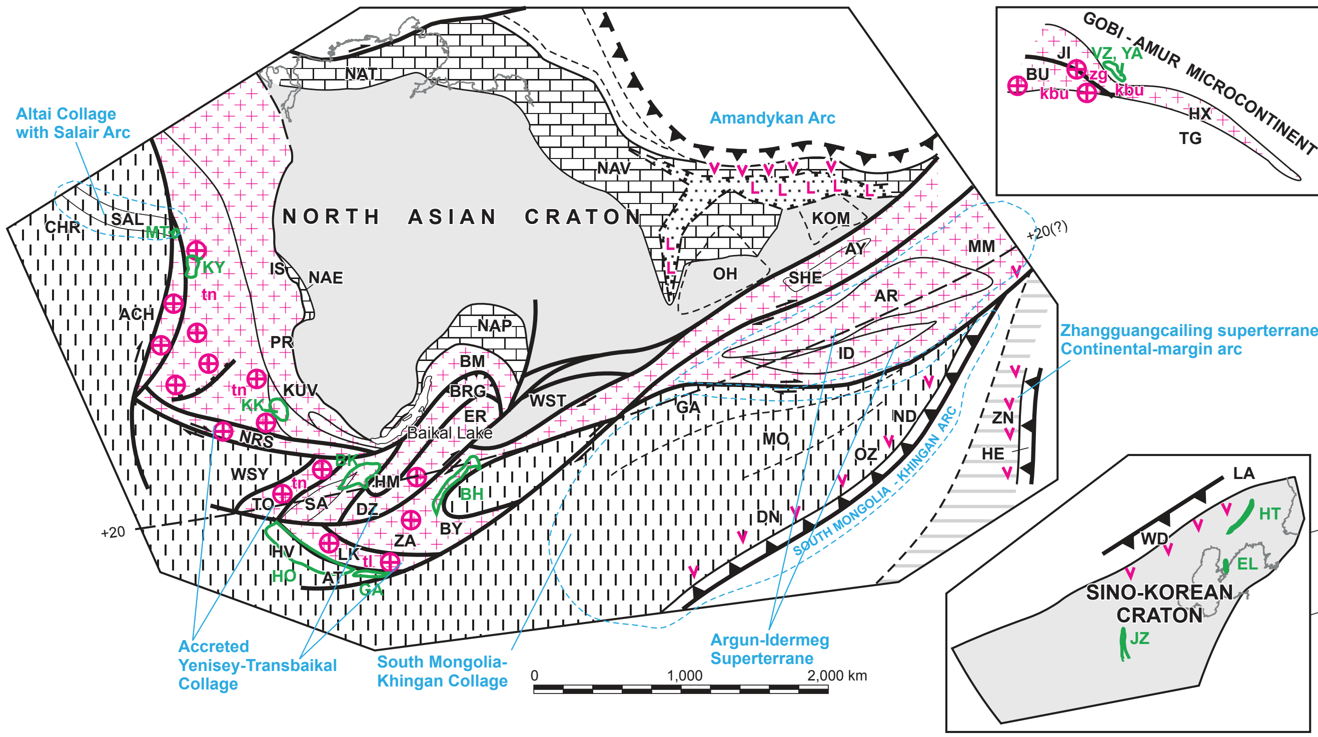
Overlap Continenta-Margin Arcs and Granite Belts

tl - Telmen plutonic belt (Middle Cambrian through Early Ordovician)
tn - Tannuola plutonic belt (Cambrian and Ordovician)

METALLOGENIC BELTS

BE - Bedobinsk
BK - Bokson-Kitoiskiy
CG Chagoyan
GA - Govi-Altai
HT - Hunjiang-Taizihe
JX - Jixi
JZ - Jinzhong
SK - South Khingan
US - Uda-Shantar
VZ - Voznesenka
YA - Yaroslavka

Figure 5. Late Cambrian (500 to 520 Ma) time stage of tectonic and metallogenic model. See text for explanation of tectonic events and origins of major metallogenic belts and figure 3 for explanation of symbols and patterns.



GEOLOGIC UNITS

North Asian Craton Margin

NAE - East Angara
NAP - Patom-Baikal
NAT - South-Taimyr
NAV - Verkhoyansk

Terranes

ACH - Anui-Chuya terrane (Continental margin turbidite)
AR - Argunsky terrane
AT - Altai terrane (Continental margin turbidite) (Precambrian and Cambrian through Devonian)
AY - Ayansk terrane
BM - Baikal-Muya terrane (Island arc) (Neoproterozoic)
BRG - Barguzin terrane
BU - Bureya terrane (Metamorphic)
BY - Baydrag terrane
CHR - Charysh terrane (Continental margin turbidite) (Cambrian through Devonian)
DN - Dongwuzhumuqin-Nuhetdavaa terrane (Island arc) (Cambrian through Middle Devonian)
DZ - Dzhida terrane (Island arc)
ER - Eravna terrane (Island arc)
GA - Govi Altai terrane (Continental-margin turbidite) (Cambrian through Devonian)
HE - Heilongjiang terrane (Accretionary wedge, type B) (Ordovician and Silurian)
HM - Hamar-Davaa terrane
HV - Hovd terrane (Continental-margin turbidite) (Neoproterozoic through Silurian)
HX - Hutaguul-Xilinhot terrane
ID - Idermeg terrane
IS - Isakov terrane (Island arc) (Neoproterozoic)
JI - Jiamusi terrane
KOM - Kolyma-Omolon superterrane
KUV - Kuvai terrane (Accretionary wedge, type A) (Neoproterozoic)
LA - Laoling terrane (Island arc) (Late Ordovician through Silurian)
LK - Lake terrane (Island arc)
MM - Mamyn terrane
MO - Mandalovoo-Onor terrane (Island arc) (Middle Ordovician through Early Carboniferous)
ND - Nora-Sukhotin-Duobaoshan terrane (Island arc) (Neoproterozoic through Early Carboniferous)
NRS - North Sayan terrane (Island arc)
OH - Okhotsk terrane
OZ - Orogen-Zalantun terrane (Metamorphic) (Proterozoic)
PR - Predivinsk terrane (Island arc) (Late Neoproterozoic)
SA - Sangilen terrane
SAL - Salair terrane (Island arc)
SHE - Shevli terrane
TG - Tsagaan Uul-Guoershan Terrane (Continental margin arc) (Paleoproterozoic through Permian)
TO - Tannuola subterrane (Island arc)
WD - Wundurmiao terrane (Accretionary wedge, type B) (Mesoproterozoic through Middle Ordovician)
WST - West Stanovoy terrane
WSY - West Sayan terrane (Continental margin turbidite) (Late Neoproterozoic through Devonian)
ZA - Zavhan terrane (Continental margin arc) (Late Neoproterozoic)
ZN - Zhangguangcailing superterrane (Continental margin arc) (Neoproterozoic through Devonian)

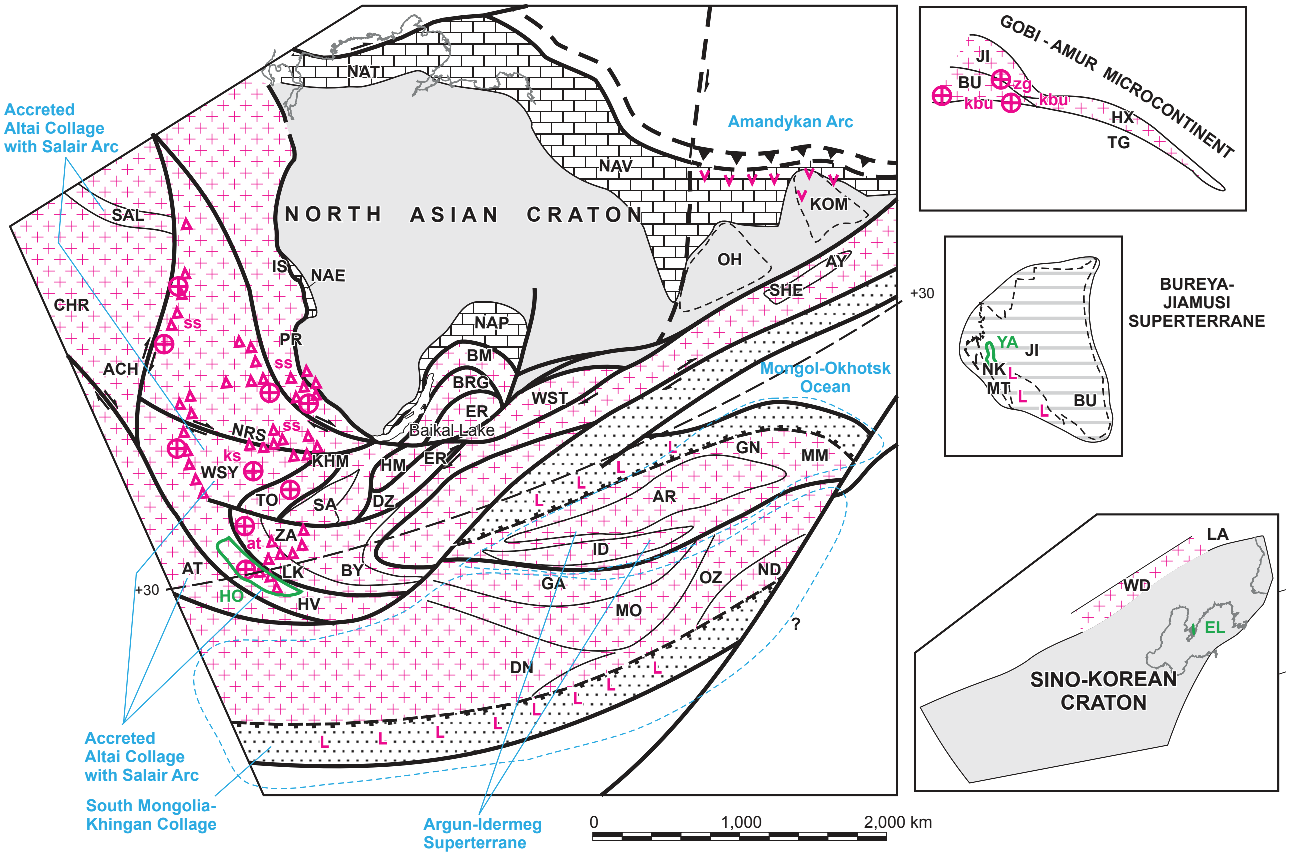
Overlap Continental Margin Arcs and Granite Belts

kbu - Khanka-Bureya granitic belt (Ordovician and Silurian)
tl - Telmen plutonic belt (Middle Cambrian through Early Ordovician)
tn - Tannuola plutonic belt (Cambrian and Ordovician)
zg - Zhangguangcailing plutonic belt (Silurian through Ordovician)

METALLOGENIC BELTS

BH - Bayanhongor
EL - East Liaoning
BK - Bokson-Kitoiskiy
GA - Govi Altai
HO - Hovd
HT Hunjiang-Taizihe
JZ Jinzhong
KK - Kizir-Kazyr
KY - Kiyalykh-Uzen
MT- Martaiginsk
VZ - Voznesenka
YA - Yaroslavka

Figure 6. Early and Middle Ordovician (450 to 500 Ma) time stage of tectonic and metallogenic model. See text for explanation of tectonic events and origins of major metallogenic belts and figure 3 for explanation of symbols and patterns.



GEOLOGIC UNITS

North Asian Craton Margin

NAE - East Angara
NAP - Patom-Baikal
NAT - South-Taimyr
NAV - Verkhoyansk

Terranes

ACH - Anui-Chuya terrane (Continental margin turbidite)
AR - Argunsky terrane
AT - Altai terrane (Continental margin turbidite) (Precambrian and Cambrian through Devonian)
AY - Ayansk terrane
BM - Baikal-Muya terrane (Island arc) (Neoproterozoic)
BRG - Barguzin terrane
BU - Bureya terrane (Metamorphic)
BY - Baydrag terrane
CHR - Charysh terrane (Continental margin turbidite) (Cambrian through Devonian)
DN - Dongwuzhumuqin-Nuhetdavaa terrane (Island arc) (Cambrian through Middle Devonian)
DZ - Dzhida terrane (Island arc)
ER - Eravna terrane (Island arc)
GA - Govi Altai terrane (Continental-margin turbidite) (Cambrian through Devonian)
GN - Gonzha terrane (Passive continental margin) (Late Archean(?), Paleoproterozoic(?), and early Paleozoic)
HM - Hamar-Davaa terrane
HV - Hovd terrane (Continental-margin turbidite) (Neoproterozoic through Silurian)
HX - Hutaguul-Xilinhot terrane
ID - Idermeg terrane
IS - Isakov terrane (Island arc) (Neoproterozoic)
JI - Jiamusi terrane
KHM - Khamsara terrane (Island arc) (Cambrian)
KOM - Kolyma-Omolon superterrane
LA - Laoling terrane (Island arc) (Late Ordovician through Silurian)
LK - Lake terrane (Island arc)
MM - Mamyn terrane
MO - Mandalovoo-Onor terrane (Island arc) (Middle Ordovician through Early Carboniferous)
MT - Matveevka terrane (Metamorphic)
ND - Nora-Sukhotin-Duobaoshan terrane (Island arc) (Neoproterozoic through Early Carboniferous)
NK - Nakhimovka terrane (Metamorphic)
NRS - North Sayan terrane (Island arc)
OH - Okhotsk terrane
OZ - Orogen-Zalantun terrane (Metamorphic) (Proterozoic)
PR - Predivinsk terrane (Island arc) (Late Neoproterozoic)
SA - Sangilen terrane
SAL - Salair terrane (Island arc)
SHE - Shevli terrane
TG - Tsagaan Uul-Guoershan Terrane (Continental-margin arc) (Paleoproterozoic through Permian)
TO - Tannuola subterrane (Island arc)
WD - Wundurmiao terrane (Accretionary wedge, type B) (Mesoproterozoic through Middle Ordovician)
WST - West Stanovoy terrane
WSY - West Sayan terrane (Continental-margin turbidite) (Late Neoproterozoic through Devonian)
ZA - Zavhan terrane (Continental-margin arc) (Late Neoproterozoic)

Overlap Continental-Margin Arcs and Granite Belts

at - Altai volcanic-plutonic belt (Devonian and Early Carboniferous)
kbu - Khanka-Bureya granitic belt (Ordovician and Silurian)
ks - Kuznetsk-Sayan plutonic belt (Early Silurian to Early Devonian)
ss - South Siberian volcanic-plutonic belt (Early Devonian)
zg - Zhangguangcailing plutonic belt (Silurian through Ordovician)

METALLOGENIC BELTS

EL - East Liaoning
HO - Hovd
YA - Yaroslavka

Figure 7. Late Silurian (410 to 420 Ma) time stage of tectonic and metallogenic model. See text for explanation of tectonic events and origins of major metallogenic belts and figure 3 for explanation of symbols and patterns.

Subsequently, volcanism ceased along the entire length of the island-arc systems, except in the Salair arc.

(2) The formation of the Late Cambrian through Early Ordovician Yenisey-Transbaikal collage may be related to the counter-clockwise rotation of the North Asian craton, which caused the amalgamations of island arcs, duplexing, and closure of back-arc basins. As a result, most of the subduction zones and conjugate island arcs disappeared in the Middle Cambrian. In the Late Cambrian through Early Ordovician, collisional granitoid batholiths were emplaced and high-temperature metamorphic belts were formed (Zonenshain and others, 1990; Berzin and Dobretsov, 1994; Fedorovskiy and others, 1995).

(3) Paleomagnetic data indicate that the Kuznetsk-Tannuola island arc (fig. 4) moved into the southern hemisphere (10-15º S.) in the Middle Cambrian and was several hundred kilometers away from the North Asian craton and cratonal margin. Convergence was accompanied by the deformation of the magmatic arc and the back-arc basin, tectonic stacking, and rotation of some fragments of the island arc. As early as the Middle Cambrian, the western part of the arc (Kurai, Uimen-Lebed, Telbes-Kitat terranes) rotated clockwise through approximately 90º, whereas orientation of the central segment (North Sayan terrane) remained unchanged (Kungurtsev and others, 2001).

(4) In the Late Cambrian, Ordovician, and Silurian (figs. 5, 6, 7, on the western and southern margins of the growing North Asian craton and cratonal margin, thick clastic sequences were deposite that consisted of turbidites and hemipelagic rocks at the bottom of the section and grading upward into shelf and littoral units, thereby indicating progradation of the sedimentary wedge towards the adjacent Paleo-Asian Ocean. Stratigraphic breaks, unconformities, and deposit of various Ordovician units on Vendian and Cambrian ophiolites, turbidites, and island-arc units occurred. N.A. Berzin (in Obolenskiy and others, 1999) interprets these thick sedimentary sequences as subduction-zone deposits that formed along the transform margin of the continent. In the Late Silurian, the Altay orogenic belt formed on the transform margin, in a manner similar to the Mesozoic transform margin in the Sikhote-Alin region of the Russian Southeast (Natal'in, 1991; Khanchuk and others, 1989; Khanchuk and Ivanov, 1999; Şengör and Natal'in, 1996).

(5) On the opposite side of the Paleo-Asian Ocean, separating the North Asian and Sino-Korean cratons, in the Early and Middle Ordovician, a series of island arcs formed (fig. 7) for which various fragments occur throughout the entire length of the early Paleozoic Wenduermiao collage. The polarity of the arcs and position relative to the North Asian and Sino-Korean cratons are unknown. Accretion of the arcs to the craton and formation of the Wenduermiao collage occurred in the Late Ordovician, as indicated by Silurian sedimentary units overlying Ordovician units with an angular unconformity.

(6) The Mongol-Okhotsk Ocean likely opened in the late early Paleozoic (fig. 7). The oldest organic remains known within the belt are Silurian. The opening of the Mongol-Okhotsk Ocean may have occurred in the Late Ordovician through Early Silurian.

Cambrian through Silurian Metallogenesis

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

Several metallogenic belts possess geologic units favorable for major granitoid-hosted or related deposits (figs. 4 through 7), including the Bayanhongor belt (with Au in shear zone and quartz-vein, granitoid-related Au-vein, Cu-Ag-vein, Cu-skarn deposits), the Hovd belt (with granitoid-related Au-vein, Au-skarn, and Cu-skarn deposits), the Kizir-Kazyr belt (with Fe-skarn and granitoid-related Au-vein deposits), and the Martaiginsk belt (with granitoid-related Au-vein and Au-skarn deposits). The isotopic ages of the deposits or hosting units range from 420 to 490 Ma. The favorable geologic units and deposits are in the Altai and Yenisey-Transbaikal collage and are interpreted as having formed in a continental-margin arc or associated continental-margin turbidite terranes, back-arc basin associated with continental-margin arc magmatism, transform continental-margin faulting, island arc, or terrane accretion. The Kiyalykh-Uzen belt (with Cu-skarn, W-skarn, Fe-skarn, and W-Mo-Be greisen, stockwork, and quartz-vein deposits) and the Martaiginsk belt (with granitoid-related Au-vein and Au-skarn deposits) contain collisional granitoids that are interpreted as having been intruded during transpressive (dextral-slip) movement along the Kuznetsk Alatau fault, 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-rock hosted deposits (figs. 4 thorugh 7), including the Govi-Altai, Ozerninsky, and Uda-Shantar belts (with volcanogenic-sedimentary Fe, volcanogenic-sedimentary Mn, volcanogenic-hydrothermal-sedimentary massive sulfide, and sedimentary phosphate deposits). The fossil ages of the deposits or host units range from Cambrian through Silurian. The favorable geologic units and deposits are in the Mongol-Okhotsk, South Mongolia-Khingan, and Yenisey-Transbaikal collages and are interpreted as having formed in either continental-margin or island arcs, or in sea floor sedimentation. The Bedobinsk belt with sediment-hosted Cu deposits is hosted in early Paleozoic sedimentary units of the North Asian craton and is interpreted as having formed in an inland-sea basin during the post-saline stage of rock deposition.

Unique Metallogenic Belts

Three unique metallogenic belts (figs. 4 through 7) possess favorable geologic units for diamond-bearing kimberlite deposits in the Sino-Korean craton (East Liaoning belt)--evaporite sedimentary gypsum deposits in platform sedimentary cover on the Sino-Korean craton (Hunjiang-Taizihe and Jinzhong belts) and banded-iron formation (BIF) deposits in continental-margin sedimentary cover on the Sino-Korean craton (South Khingan belt). The latter two belts formed during sedimentation along a cratonal margin. The origin of the diamond-bearing kimberlite deposits is not well known.

Devonian through Early Carboniferous (410 to 320 Ma) Stage of Tectonic and Metallogenic Model

Major Tectonic Events

The major tectonic events in the Devonian through Early Carboniferous (fig. 8) were as follows.

(1) Formation of the South Mongolia-Khingan arc and associated subduction zone.

(2) Back-arc spreading behind the South Mongolia-Khingan island arc resulting in formation of the Bayanleg back-arc basin.

(3) Beginning assembly of cratonal and passive continental-margin terranes in the Russian Far East and Northeastern China to form the Bureya-Jiamusi superterrane.

(4) Inception of the North Okhotsk continental-margin arc and associated subduction zones that were associated with subduction of the Mongol-Okhotsk ocean plate.

(5) Oblique convergence between the Mongol-Okhotsk ocean plate and the North Asian craton, resulting in transform displacement and oroclinal wrapping of the southern and western margins of the North Asian craton and formation of the South Siberian and Altai transpressional arc.

(6) Continued sea-floor spreading in the PaleoAsian, Mongol-Okhotsk, and Ancestral Pacific Oceans.

(7) Rifting and associated sedimentation along the northeast continental margin of the North Asian craton.

Important Geologic Details

(1) In the Devonian and Early Carboniferous (410 to 320 Ma) (fig. 8), near the western and southwestern margins of the North Asian craton and cratonal margin was the extensive South Mongol-Khingan island arc (part of the South Mongol-Khingan collage) was separated from the continent by a large back-arc basin comparable in size to the modern Philippine sea. The arc contains Silurian, Devonian, and Mississippian units. Both terminations of the arc, that now occur in the Rudnyi Altay and northeast China (including the adjacent part of the left bank of the Amur River), are under Proterozoic and Cambrian metamorphic rocks and Ordovician sedimentary and island-arc volcanic and sedimentary rocks. The central sector of the South Mongol-Khingan arc consists of the Edrengin and Gurvansaikhan terranes with volcanic units that rest on oceanic crustal rocks and that are geochemically similar to those from the Lesser Antilles arc (Lamb and Badarch, 1997, 2001). The arc was reconstructed through mutual rotation of the terranes making up the South Mongol-Khingan collage belt along the separating left-lateral strike-slip faults.

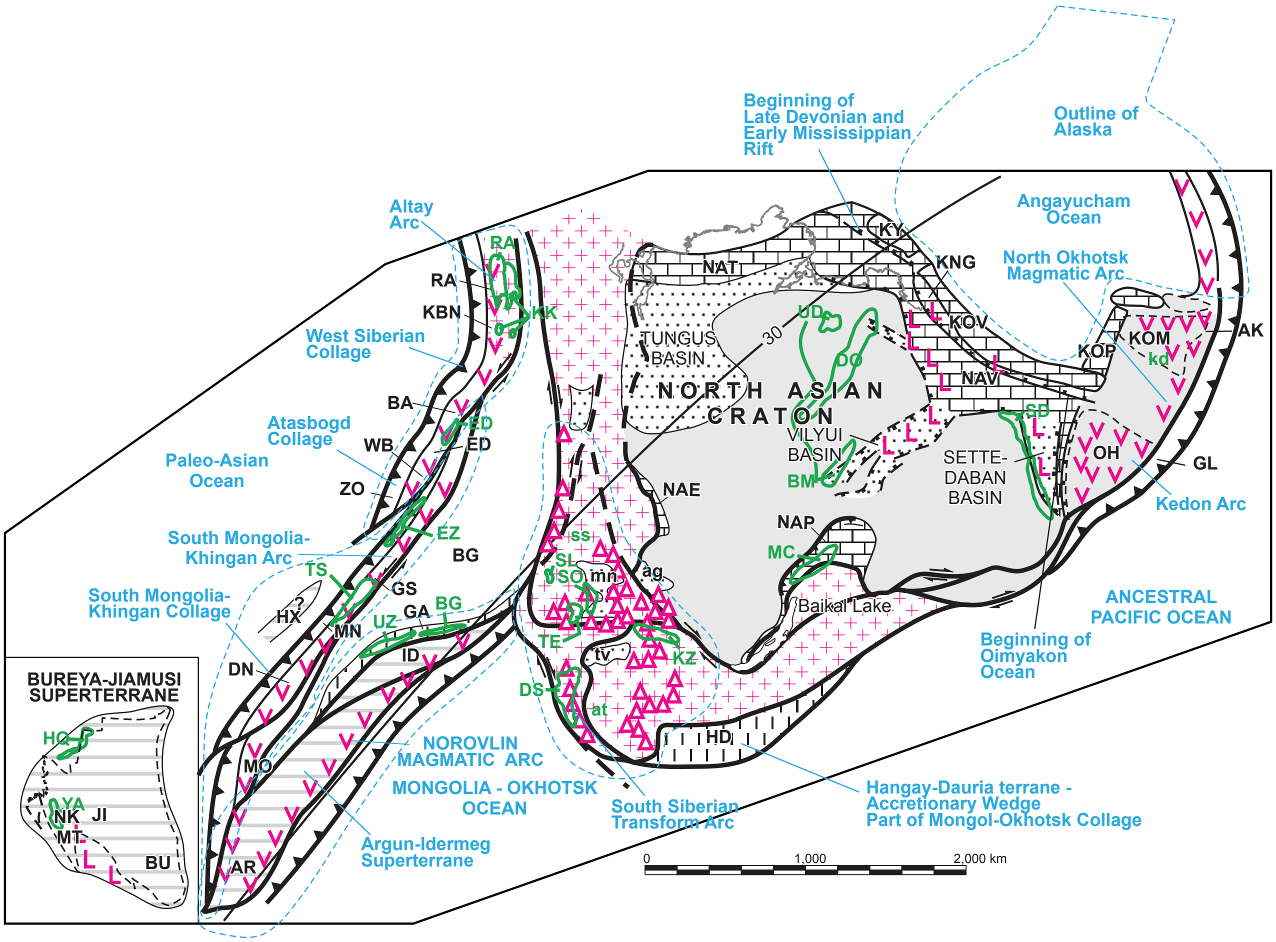
The subduction-zone complex that is tectonically-related to the arc (and the other major part of the South Mongol-Khingan collage) consists of the Dzolen terrane that extends for 700 km along the southern (present-day coordinates) margin of the arc (fig. 8). The complex consists of greenschist melange with fragments of tholeiitic basalt, andesite, tuff, volcaniclastic rock and chert of Silurian and Devonian and, presumably, Ordovician age, and also fragments of ophiolite and serpentinite melange (Zonenshain and others, 1975; Ruzhentsev and others, 1985, 1992).

Formations of the related back-arc basin include Silurian-Mississippian volcanic and sedimentary units of the Govi-Altai terrane and the melange of the Mandakh terrane that contains fragments of metavolcanic and metasedimentary rock, coral limestone, amphibolite, and gabbro in a serpentinite and aleurolite matrix (Suetenko, 1967; Tomurtogoo, 1989; Ruzhentsev and others, 1985, 1987).

(2) Formation of the South Mongol-Khingan collage was preceded by rifting and associated volcanism occuring to the northwest in the Altai-Sayan region along the continental margin. Rrifting probably occurred along systems of conjugate strike-slip faults (Şengör and others, 1994; Berzin, 1995, 1998, 2001).

(3) The Norovlin continental-margin arc formed along the margin of the Mongol-Okhotsk Ocean and consists of Early and Middle Devonian calc-alkaline volcanic rocks and Middle and Late Devonian volcanoclastic rock, chert, and mudstone (Marinov, 1973). The arc units overlie the northern part of the Argun superterrane and are associated with granites and syenites of the Tsagaanunder complex. The tectonically-related subduction zone of the arc consists of the Ononsky terrane containing blueschist facies metamorphic rocks and Devonian and Early Carboniferous volcanic and sedimentary rocks (Gordienko, 1987). An ophiolite fragment in the western part of the terrane has an U-Pb zircon age of 325 Ma (Windley and others, 2003).

(4) In the middle Paleozoic, the Mongol-Okhotsk Ocean reached its maximum size.



GEOLOGIC UNITS

North Asian Craton Margin

NAE - East Angara
NAP - Patom-Baikal
NAT - South-Taimyr
NAV - Verkhoyansk

Intracontinental sedimentary basin

ag - Agul (Rybinsk) molasse basin (Middle Devonian to Early Carboniferous)
mn - Minusa molasse basin (Middle Devonian through Early Permian)
tv - Tuva molasse basin (Middle Devonian through Late Carboniferous)

Terranes

AK - Avekov terrane
AR - Argunsky terrane
BU - Bureya terrane (Metamorphic)
DN - Dongwuzhumuqin-Nuhetdavaa terrane (Island arc) (Cambrian through Middle Devonian)
ED - Edren terrane (Island arc) (Devonian and Early Carboniferous)GA - Govi Altai terrane (Continental-margin turbidite) (Cambrian through Devonian)
GL - Galam terrane (Subduction zone) (Cambrian through Early Carboniferous)
GS - Gurvansayhan terrane (Island arc) (Silurian through Early Carboniferous)
HD - Hangay-Dauria terrane (Subduction zone) (Silurian through Late Carboniferous)
HX - Hutaguul-Xilinhot terrane
ID - Idermeg terrane
JI - Jiamusi terrane
KBN - Kalba-Narim terrane (Subduction zone) (Ordovician through Early Carboniferous)
KNG - Nagondzha terrane (Continental margin) (Carboniferous through Late Triassic)
KOM - Kolyma-Omolon superterrane
KOP - Prikolyma terrane
KOV - Omulevka terrane (Passive continental margin) (late Neoproterozoic through Triassic)
KY - Kotel'nyi terrane (Passive continental margin) (Late Neoproterozoic through Late Triassic)
MN - Mandah terrane (Subduction zone) (Devonian)
MO - Mandalovoo-Onor terrane (Island arc) (Middle Ordovician through Early Carboniferous)
MT - Matveevka terrane (Metamorphic)
NK - Nakhimovka terrane (Metamorphic)
OH - Okhotsk terrane
RA - Rudny Altai terrane (Island arc) (Late Silurian through Early Carboniferous)
WB - Waizunger-Baaran terrane (Island arc) (Ordovician through Permian)
ZO - Zoolen terrane (Subduction zone) (Ordovician(?) and Devonian)

Overlap Continental-Margin Arcs and Granite Belts

at - Altai volcanic-plutonic belt (Devonian and Early Carboniferous)
kd - Kedon volcanic-plutonic belt (Devonian and Early Carboniferous)
ss - South Siberian volcanic-plutonic belt (Early Devonian)

METALLOGENIC BELTS

BG - Bayangovi
BM - Botuobiya -Markha
DO - Daldyn-Olenyok
DS - Deluun-Sagsai
ED - Edrengiin
EZ - Edren-Zoolon
HQ - Hongqiling 331 to 350 Ma.
KK - Korgon-Kholzun
KZ - Kizhi-Khem
MC - Mamsko-Chuiskiy
RA - Rudny Altai
SL - Salair
SD - Sette-Daban
SO - Sorsk
TE - Teisk
TS - Tsagaan-suvarga
UD - Udzha
UZ - Ulziit
YA - Yaroslavka

Figure 8. Late Devonian (370 Ma) time stage of tectonic and metallogenic model. See text for explanation of tectonic events and origins of major metallogenic belts and figure 3 for explanation of symbols and patterns.

(5) On the eastern and northern sides of the North Asian craton and cratonal margin, the Verkhoyansk and South Taimyr passive continental margins continued to form. On the northern (present-day coordinates) margin, the Tunguska Basin continued forming in a small, flat depression conjugate to the South Taimyr passive continental margin. The depression contains Devonian and Mississippian sulfate-carbonate rock and variegated clay-carbonate rock with salt horizons (Matukhin, 1989; Vaag and Matukhin, 1989).

(6) Rifting was widespread in the Verkhoyansk passive continental margin and the adjacent part of the North Asian craton in the Middle to Late Devonian and the Mississippian (Gaiduk, 1988). Several, three-branch rift systems are recognized. The failed branches of the systems die out within the North Asian craton and are recognized as aulacogens. Most of the rift basins occur in the Verkhoyansk passive continental margin and are filled with thick Middle to Late Devonian and Mississippian units, including highly alkaline basalt, red beds, coarse-clastics, evaporite, and basalt dike swarms that extend for hundreds of kilometers parallel to the rift basins.

(7) At the boundary of the North Asian craton and cratonal margin with the Paleo-Pacific Ocean the North Okhotsk continental-margin arc formed for which fragments are preserved as overlap assemblages in the Okhotsk, Avekova, and Omolon cratonal terranes. The arc units consist of Middle to Late Devonian and Mississippian calc-alkaline volcanic rocks and granodiorite plutons. The active continental margin changes along strike into an island arc that is preserved in the Oloy and Yarakvaam island-arc terranes.

(8) The North Okhotsk continental-margin is connected with the Norovlin continental-margin arc by a transform fault along which the Hangay-Daurian subduction- zone terrane occurs. The wedge contains Silurian through Pennsylvanian flysch with lenses of chert and mafic and intermediate volcanic rock (Geological structure of Chita oblast, 1991). The Devonian and Mississippian occurrence of volcanic rocks indicates that oblique subduction occurred along the continent margin.

(9) In the Late Mississippian, the South Mongol-Khingan collage was duplexed along the strike-slip faults and collided with the Bureya-Jiamusi superterrane and possibly with the Sino-Korean craton. The collision terminated the South Mongol-Khingan collage.

Metallogenesis

Metallogenic Belts Related to Island Arcs

Four metallogenic belts (the Edrengiin, Rudny Altai, Salair, and Tsagaan-suvarga belts) possess geologic units favorable for a wide variety of island-arc-magmatism-related deposits (fig. 8). The deposits types are volcanogenic Cu-Zn massive sulfide (Urals type), volcanogenic Zn-Pb-Cu massive sulfide, volcanogenic-sedimentary Mn, volcanogenic-sedimentary Fe, barite-vein, volcanic-hosted metasomatite, polymetallic (Pb, Zn±Cu, Ba, Ag, Au) volcanic-hosted metasomatite, porphyry Cu-Mo (±Au, Ag), porphyry Cu (±Au), porphyry Cu-Au, and granitoid-related Au-vein. The fossil or isotopic ages of the deposits or hosting units range from Early Devonian through Early Carboniferous. The favorable geologic units are the Edren island-arc terrane, part of the South Mongolia-Khingan collage; the Rudny Altai island-arc terrane, part of the West Siberian collage; the Altai volcanic-plutonic belt, part of the South Mongolia-Khingan island arc; and the Gurvansayhan island-arc terrane, part of South Mongolia-Khingan collage.

Metallogenic Belts Related to Terrane Accretion

Five metallogenic belts possess geologic units favorable for a wide variety of major collisional granite-hosted deposits and related vein deposits (fig. 8)--the Bayangovi, Edren-Zoolon, Muiskiy, Ulziit, and Yaroslavka belts with granitoid-related Au-vein; Au in shear zone and quartz-vein; fluorite greisen; Sn-W greisen, stockwork, and quartz-vein; and carbonate-hosted Hg-Sb deposits. The fossil or isotopic ages of the deposits or hosting units range from Devonian through Early Carboniferous, or 440 to 396 Ma. The favorable geologic units and deposits are the Edren island arc and Zoolen subduction-zone terrane, both part of the South Mongolia-Khingan collage, granitoids and veins of the Barguzin-Vitim granitoid belt intruding the Baikal-Muya island arc and Muya metamorphic terrane, both part of the Tuva-Mongolia superterrane; granitoids intruding the Bureya-Jiamusi supterterrane, and 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 Transpressive Continental-Margin Arcs

Five metallogenic belts (the Deluun-Sagsai, Kizhi-Khem, and Korgon-Kholzun, Sorsk, and Teisk belts) possess geologic units favorable for a wide variety of major granite-hosted deposits (fig. 8). The major deposit types are polymetallic (Pb, Zn±Cu, Ba, Ag, Au) volcanic-hosted metasomatite; polymetallic (Pb, Zn, Ag) carbonate-hosted metasomatite; polymetallic Pb-Zn ± Cu (±Ag, Au)-vein and stockwork; volcanogenic Zn-Pb-Cu massive sulfide (Kuroko, Altai type); sediment-hosted Cu; volcanogenic-sedimentary Fe; porphyry Cu-Mo (±Au, Ag); Ag-Pb epithermal-vein; granitoid related Au-vein; W-Mo-Be greisen, stockwork, and quartz-vein; granitoid-related Au-vein; mafic-ultramafic related Ti-Fe (+V); porphyry Mo (±W, Bi); polymetallic (Pb, Zn, Ag); carbonate-hosted metasomatite; Fe-skarn; Zn-Pb (±Ag, Cu) skarn; and Ta-Nb-REE alkaline metasomatite. The host geologic units are the Deluun sedimentary-volcanic-plutonic belt (part of the transpressive South Siberian and Altai continental-margin arcs), replacements and granitoids related to the South Siberian volcanic-plutonic belt, and the Altai volcanic-plutonic belt. The isotopic ages of the deposits or hosting units range from Devonian through Early Carboniferous. The favorable geologic units and deposits are the South Siberian and Altai transpressive continental-margin arcs.

Metallogenic Belts Related to Transpressional Faulting

Two metallogenic belts (the Hongqiling and Mamsko-Chuisky belts) possess geologic units favorable for major vein deposits or plutonic-hosted deposits (fig. 8). The major deposit types are mafic-ultramafic related Cu-Ni-PGE, polymetallic (Pb, Zn±Cu, Ba, Ag, Au) volcanic-hosted metasomatite, and muscovite pegmatite. The fossil ages of the deposits or hosting units are Devonian and Early Carboniferous and the isotopic ages range from 330 to 416 Ma. The favorable geologic units that host the tracts and deposits are: (1) mafic and ultramafic plutons intruding and overlapping the Zhangguangcailing superterrane and the Laoling terrane, part of the Bureya-Jiamusi supterterrane; and (2) veins and dikes in the Mamsky and Konkudero-Mamakansky complexes intruding the Chuja paragneiss terrane that is included in the Baikal-Patom cratonal margin. These units and deposits are interpreted as having formed during transpressional faulting and associated interplate rifting.

Metallogenic Belts Related to Rifting

Two metallogenic belts (the Sette-Daban and Udzha belts) possess geologic units favorable for a wide variety of rift-related deposits (fig. 8). The major mineral deposit types are sediment-hosted Cu, Basaltic native Cu (Lake Superior type), REE carbonatite, and carbonate-hosted Pb-Zn (Mississippi valley type). The fossil ages of the deposits or host units are Devonian and Early Carboniferous. The favorable geologic units and deposits are interpreted as having formed during rifting of the North Asian craton or cratonal margin.

Unique Metallogenic Belts

Two unique metallogenic belts (the Botuobiya-Markha and Daldyn-Olenyok belts) are hosted in Devonian diamond-bearing kimberlite intruding the North Asian craton (fig. 8). The origin of the diamond-bearing kimberlite deposits is not well known. The unique Edrengiin belt (fig. 8) (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.

Late Carboniferous through Middle Triassic (320 to 230 Ma) Stage of Tectonic and Metallogenic Model

Major Tectonic Events

The major tectonic events in the Late Carboniferous through Middle Triassic (fig. 9) were as follows.

(1) In the northern North Asian craton, formation of the Tungus Plateau igneous province with widespread intrusive traps consisting of extensive belts of sills and rare dikes that intruded major fault zones.

(2) Starting of accretion of the Argun-Idermeg superterrane (Amur microcontinent composed of the Agun and Idermeg passive continental-margin terranes).

(3) Formation of the Gobi-Khankaisk-Daxing'anling continental-margin arc along the outboard edge of the accreted South Mongolia-Khingan collage and the Argun-Idermeg superterrane.

(4) Formation of the North Margin continental-margin arc along the edge of the Sino-Korean craton.

(5) Formation of the transform-continental-margin Hangay arc along the southern margin of the North Asian craton and accreted terranes.

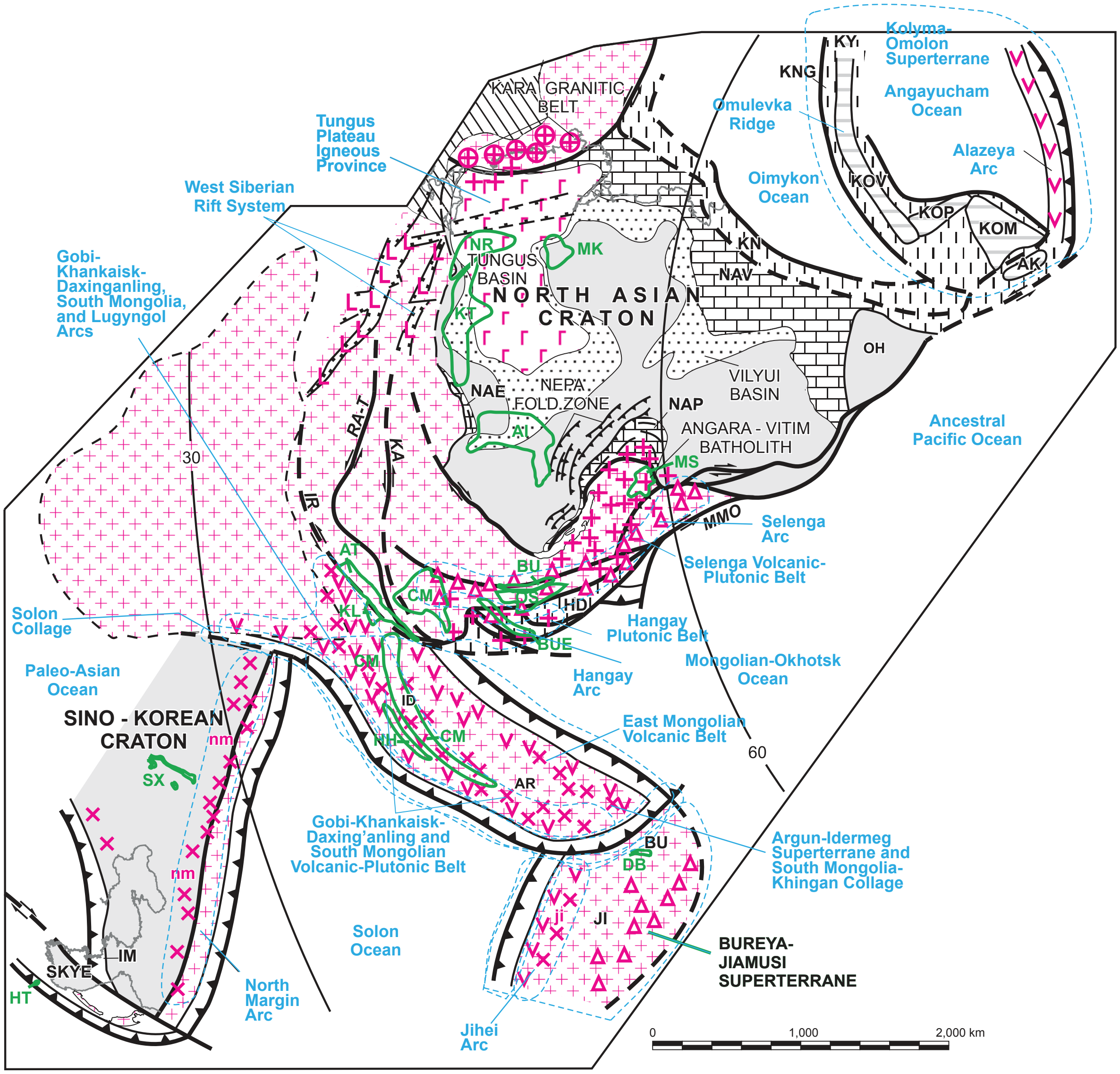
(6) Beginning of closure of the Mongol-Okhotsk Ocean and inception of an extensive, mainly right-lateral series of transform faults.

(7) Formation of the Jihei continental-margin arc along the margin of the Bureya-Jiamusi superterrane.

(8) Inception of the Alazeya island arc.

Important Geologic Details

(1) The Mongol-Okhotsk collage started to form with progressive eastward (present-day coordinates) accretion of the Argun-Idermeg superterrane (Zonenshain and others, 1990, including the Argun superterrane and the South Mongol-Khingan collage. Most of the displacement associated with accretion occurred along the Major Mongol-Okhotsk fault (MMP). Along with the Argun-Idermeg superterrane, the Solon collage commenced to form with left-lateral strike-slip displacement along the Kuznetsk-Altai and Kobdinsk faults, the Irtysh crush zone, and companion faults that are part of the Major Mongol-Okhotsk fault. In the West Siberian Lowlands these strike-slip faults are conjugate to Triassic longitudinal



GEOLOGIC UNITS

North Asian Craton Margin

NAE - East Angara
NAP - Patom-Baikal
NAV - Verkhoyansk

Terranes and Superterranes

AK - Avekov terrane
AR - Argunsky terrane
BU - Bureya terrane (Metamorphic)
ID - Idermeg terrane
IM - Imjingang terrane (Accretionary wedge, type B) (Devonian)
JI - Jiamusi terrane
KN - Kular-Nera terrane (Continental-margin turbidite) (Permian through Early Jurassic)
KNG - Nagondzha terrane (Continental margin) (Carboniferous through Late Triassic)
KOM - Kolyma-Omolon superterrane
KOP - Prikolyma terrane
KOV - Omulevka terrane (Passive continental margin) (late Neoproterozoic through Triassic)
KY - Kotel'nyi terrane (Passive continental margin) (Late Neoproterozoic through Late Triassic)
ND - Nora-Sukhotin-Duobaoshan terrane (Island arc) (Neoproterozoic through Early Carboniferous)
OH - Okhotsk terrane
SKYE - Yeongnam terrane (Granulite-paragneiss) (Late Archean to Paleoproterozoic)

Overlap Continental-Margin Arcs and Granite Belts

ji -Jihei plutonic belt (Permian)
nm - North marginal plutonic belt Carboniferous and Permian)

Strike-Slip Fault and Shear Zone

IR - Irtysh shear zone
KA - Kuznetsk-Altai
MMO - Main Mongol-Okhotsk
RA-T - Rudny Altai - Taimyr

METALLOGENIC BELTS

AI - Angara-Ilim
AT - Altay
BU - Buteeliin nuruu
BUE - Battsengel-Uyanga-Erdenedalai
CM - Central Mongolia
DB - Duobaoshan
HH - Harmagtai-Hongoot-Oyut
HT - Hitachi
KL - Kalatongke
KT - Kureisko-Tungsk
MK - Maimecha-Kotuisk
MS - Muiskiy
NR - Norilsk
OS - Orhon-Selenge (185-240, 250)
SX - Shanxi

Figure 9. Early Permian (275 Ma) time stage of tectonic and metallogenic model. See text for explanation of tectonic events and origins of major metallogenic belts and figure 3 for explanation of symbols and patterns.

rifts. The progressive wes to teastward closing of the Mongol-Okhotsk Ocean starting in the Late Permian is supported by paleomagnetic data (Zhao and others, 1990).

(2) A subduction zone formed along the northern margin of the Argun-Idermeg superterrane and is tectonically linked to the Permian East Mongolian volcanic belt (Mossakovskiy, 1975; Yarmolyuk, 1983; Zonenshain and others, 1990; Kovalenko and Yarmolyuk, 1990). The belt is conjugate to the more northerly North Gobi forearc basin that contains Mississippian and Pennsylvanian flysch and Permian and Early Triassic shallow marine sedimentary units with volcanic horizons (Mossakovskiy and Tomurtogoo, 1976). In the Argun region are widespread Undinsk granitoids (with Rb-Sr ages of 250 to 276 Ma; Dril' and others, 2000) that formed along an active continental margins (Efremov and others, 1998). The Undinsk granitoids are interpreted as being a continuation of the East Mongolian volcanic-plutonic belt. The Borzja Basin in the East Transbaikal region contains Late Permian marine sandstone, siltstone, and conglomerate, with bands of siliceous tuff, and is probably a forearc basin.

(3) Triassic granitoids and fragments of a Pennsylvanian-Permian magmatic arc occur along the eastern margin of the Bureya-Jiamusi superterrane and are probably tectonically linked to an outboard subduction zone (Khanchuk and others, 1989; Sun Jiapeng and others, 2000) that is also a continuation of the active continental margin.

(4) Paleomagnetic data indicate that the width of the Mongol-Okhotsk Ocean was greater than 4,000 km in the Late Permian (Ziegler and others, 1996; Şengör and Natal'in, 1996; Kravchinskiy and others, 2002a). Paleomagnetic data also indicate that the Argun-Idermeg superterrane, that forms the southern margin of the Mongol-Okhotsk collage, was located at approximately 20^{o} N. latitude in the Late Permian (Kravchinskiy and others, 2002a,b). The superterrane contains numerous remains of Late Permian boreal brachiopods, bivalves, crinoids, and bryozoans. (Amantov and others, 1966; Durante, 1976; Meyen, 1970).

(5) Zonenshain and others (1976, 1985, 1990) interpret that the Mongol-Okhotsk collage formed progressively from west to east towards the Paleo-Pacific Ocean, from the Pennsylvanian through Jurassic (Zonenshain and others, 1990). The ocean was bordered by the giant Altai orocline that consisted of a sharp bend in the strike of the early Paleozoic orogenic belts. At the core of the orocline occurs a western or so-called blind termination of the Mongol-Okhotsk orogenic belt. Confined to the core of the Altai orocline are Pennsylvanian-Early Permian granitoids that intrude older, deformed rocks in the western Mongol-Okhotsk collage and the older units of the western and northern rims of the belt.

(6) The Mongol-Okhotsk collage contains a typical boreal late Paleozoic and early Mesozoic fauna. However, puzzling inclusions of carbonate rocks with Early Permian fusulinids are reported from subduction- zone terranes in the Dzhagdy Range (Kirillova and Turbin, 1979) and the East Transbaikal region (Amantov, 1963).

(7) The Pennsylvanian through Early Triassic Selenga volcanic-plutonic belt formed along the northern margin of the Mongol-Okhotsk collage and extends for 2,000 km in northern Mongolia and the Transbaikal region (Mossakovskiy, 1975; Mossakovskiy, Tomurtogoo, 1976; Kozubova and others, 1982; Yarmolyuk, 1983; Gordienko, 1987; Derbeko, 1998; Yarmolyuk and others, 2001). The belt consists of calc-alkaline rocks in the lower part of the section grading upward into bimodal alkaline rocks (Mossakovskiy, 1975; Kozubova and others, 1982; Kovalenko and others, 1983; Gordienko, 1987). The Selenga igneous belt formed along a transform fault along the continent-ocean boundary at the early stage of its development and graded into subduction beneath the continental margin.

(8) To the north of the Selenga volcanic-plutonic belt is the giant Late Pennsylvanian and Early Permian (290 to 320 Ma) Angara-Vitim batholith (Yarmolyuk and others, 1997) that formed synchronously with the Selenga belt (according to recent, extensive U-Pb zircons ages). To the northwest of the Angara-Vitim batholith, on the margin of the Siberian platform, is the late Paleozoic Nepa folded zone (Malykh, 1997).

(9) Also in the late Paleozoic, the Solon Ocean existed to the south of the Argun-Idermeg superterrane as indicated by Mississippian ophiolites with Tethyan fauna and Permian island-arc formations in the Solonker collage (Wang and Liou, 1986; Ruzhentsev and others, 1989; Badarch and others, 2002). The Solon Ocean was wide because paleomagnetic and paleobiogeographic data indicate that the Sino-Korean craton occurred in subtropical latitudes in the late Paleozoic, whereas in the areas to the north (present-day coordinates), the Solon Ocean was in a boreal paleobiogeographic province (Pavlova and others, 1986; Popeko and others, 1993; Xu Guirong and Yang Weiping, 1994; Popeko, 1996). The closure of the Solon Ocean and formation of the Solon collage occurred during subduction beneath bounding continental blocks (Chen and others, 2000).

(10) Along the northern margin of the Solon Ocean was the South Mongolian arc that contained Pennsylvanian calc-alkaline basalt, andesite, dacite, rhyolite, and Permian subalkaline and alkaline basalt, trachyrhyolite, comendite, and pantellerite (Kovalenko, Yarmolyuk, 1990; Kovalenko and others, 1995; Munkhtsengel and Iizumi, 1999). Southward the South Mongolian belt changes into a Permian forearc flysch basin. In Northeast China, the South Mongolian arc merged into the Permian Djikhey plutonic belt with granodiorite, monzogranite, and diorite with isotopic ages of 244 Ma (K-Ar) and 241 Ma (U-Pb) (Li and Zhao, 1989; Zhao and others, 1996).

(11) To the south of the Solon Ocean was the Pennsylvanian-Permian North marginal plutonic belt that formed along the margin of the Sino-Korean craton and the associated Wenduermiao collage (Cheng and others, 1994). The Solon Ocean closed in the Late Permian through Early Triassic, as indicated by paleomagnetic data showing that terranes in southern Mongolia and in the Sino-Korean craton had a single paleomagnetic pole in the Late Permian (Zhao and others, 1990). The

position of the pole significantly differs from that for the North Asian craton, Kazakhstan, and Europe.

(12) In the late Mississippian, after Devonian rifting, a large block, including the Okhotsk and Omolon cratonal and the Prikolyma and Omulevka passive continental-margin terranes, was detached from the eastern margin of the North Asian craton with clockwise rotation. As a result, the minor Oimyakon Ocean was formed, and that was separated from the Angayucham Ocean by the Omulevka ridge (Nokleberg and others, 2000). Also as a result of thermal subsidence following rifting, the Pennsylvanian Vilyui and Tunguska Basins formed on the North Asian craton, ending in the Permian.

(13) In the Verkhoyansk passive continental margin, thick grey clastic units accumulated and graded towards the adjacent ocean basin into turbidite and hemipelagic continental slope and rise deposits.

(14) In the Late Permian, the Kara terrane accreted to the northern margin of the North Asian craton with boundary diagonally cut by the Kara granitoid belt with isotopic ages of 264 Ma (U-Pb) and 258 to 252 Ma (Rb-Sr and Ar-Ar) (Vernikovskiy, 1996; Vernikovskiy and others, 1995, 1998).

(15) A huge and unique basalt eruption ($2x10^6$ to $3x10^6$ km^3) (Campbell and others, 1992) occurred on the northwestern North Asian craton at the Permian-Triassic boundary. The basalts are known as Siberian traps and are widespread in the Tungus Basin. The total thickness of lava sheets and tuffs locally reaches 3,000 m. The eastern, western and southern margins of the Tungus Basin are dominated by intrusive traps represented by extensive sills and rare dikes that mark a huge superplume.

Metallogenesis

Metallogenic Belts Related to Superplume

Four metallogenic belts (the Angara-Ilim, Kureisko-Tungsk, Maimecha-Kotuisk, and Norilsk belts) possess geologic units favorable for a wide variety of major trapp-magmatism-related deposits. The major mineral deposit types are 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. The isotopic ages of the deposits or hosting units range from Devonian through Early Carboniferous. The favorable geologic units and deposits are interpreted as having formed in a continental-margin or island-arc, or in associated arc-margin terranes. 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 hosting units range from Permian through Triassic (260 to 200 Ma). The belts are interpreted as related to widespread development of trapp magmatism on the North Asian craton that occurred during intrusion of a superplume. The Norilsk belt contains the famous mafic-ultramafic related Cu-Ni-PGE deposits in the Norilsk district in northern Siberia.

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

Four metallogenic belts (the Battsengel-Uyanga-Erdenedalai, Buteeliin nuruu, Central Mongolia and Orhon-Selenge belts) possess geologic units favorable for a wide variety of granitic magmatism-related deposits. The major mineral deposit types are 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 (Lake Superior type) 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 Tuva-Mongolia collages. The isotopic ages of the deposits or hosting units range from 240 to 285 Ma. The belts are interpreted as having formed during transform-faulting and 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 margin (present-day coordinates) of the Mongol-Okhotsk Ocean.

Metallogenic Belts Related to Island Arcs

Three metallogenic belts (the Duobaoshan, Hitachi, and Kalatongke belts) possess geologic units favorable for a wide variety of granite- and mafic- plutonic-related deposits, and volcanogenic massive sulfide deposits. The major deposit types are porphyry Cu-Mo; granitoid-related Au-vein; mafic-ultramafic related Cu-Ni-PGE; and volcanogenic Zn-Pb-Cu massive sulfide deposits. The isotopic ages of the igneous rocks that host the deposits range from Pennsylvanian through Permian. The belts are interpreted as having formed in a chain of island arcs that formed 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 supterterrane), and the Waizunger-Baaran terrane (part of the Atasbogd collage).

Metallogenic Belt Related to Collision of Cratons

The Altai 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 that intrudes the Altai continental-margin turbidite terrane. The belt is interpreted as having formed during intrusion of collisional granite that formed 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. The belt is interpreted as having formed during weathering of metamorphic rocks of the Northern China Platform. Bauxite deposits are hosted in karst and lagoonal basins in a littoral-shallow sea.

Late Triassic through Middle Jurassic (230 to 154 Ma) Stage of Tectonic and Metallogenic Model

Major Tectonic Events

The major tectonic events in the Late Triassic through Middle Jurassic (fig. 10) were as follows.

(1) Accretion of the Argun-Idermeg superterrane (Amur microcontinent composed of Agun and Idermeg passive continental-margin terranes), the Bureya-Jiamusi supterterrane, and the Sino-Korean craton.

(2) Continuation of closure of the Mongol-Okhotsk Ocean and continuation of an extensive, mainly right-lateral series of transform faults along the western, closed part of the ocean.

(3) Inception of the Uda-Murgal continental-margin and island-arc system.

(4) Continuation of the Alazeya island arc.

(5) Collision between the North Asian craton and the Kara superterrane with formation of post-collisional granitoid intrusions (with isotopic ages of about 223 to 233 Ma).

Important Geologic Details

(1) The Mongol-Okhotsk collage continued to form and was accompanied by left-lateral strike-slip faulting along the Major Mongol-Okhotsk and the Kuznetsk-Altai faults, Irtysh crush zone, and associated faults. In the late Middle Jurassic, the last part of the ocean closed in the east part of the collage, as indicated by paleomagnetic data (Zhao and others, 1990). However, recent paleomagnetic data indicate that the width of the Mongol-Okhotsk Ocean was about 3,000 km until the late Late Jurassic (Kravchinskiy and others, 2002a). The data contradict geological observations.

(2) In the Late Triassic, to the east of the eastern margin of the North Asian craton and cratonal margin, the Ancestral Pacific Ocean plate began migrating toward the margins of the North Asian craton and cratonal margin. As a result, a new system of subduction-related magmatic arcs formed along the continental margin (Parfenov and others, 1999a; Nokleberg and others, 2000).

(3) As a result of the migration of the Ancestral Pacific Ocean Plate, on the eastern margin of the the North Asian craton and cratonal margin, the Uda-Murgal arc and the Alazeya island arc formed. In the late Middle Jurassic, collision and amalgamation of the Alazeya island arc with the Omulevka Ridge and the Prikolyma and Omolon terranes produced the Kolyma-Omolon superterrane (Parfenov, 1991). From 180 to 135 Ma, convergence occurred between the northeastern margin of Asia and the northeastward moving Farallon plate (Engebretson and others, 1985), thereby resulting in oblique subduction beneath the active continental margin.

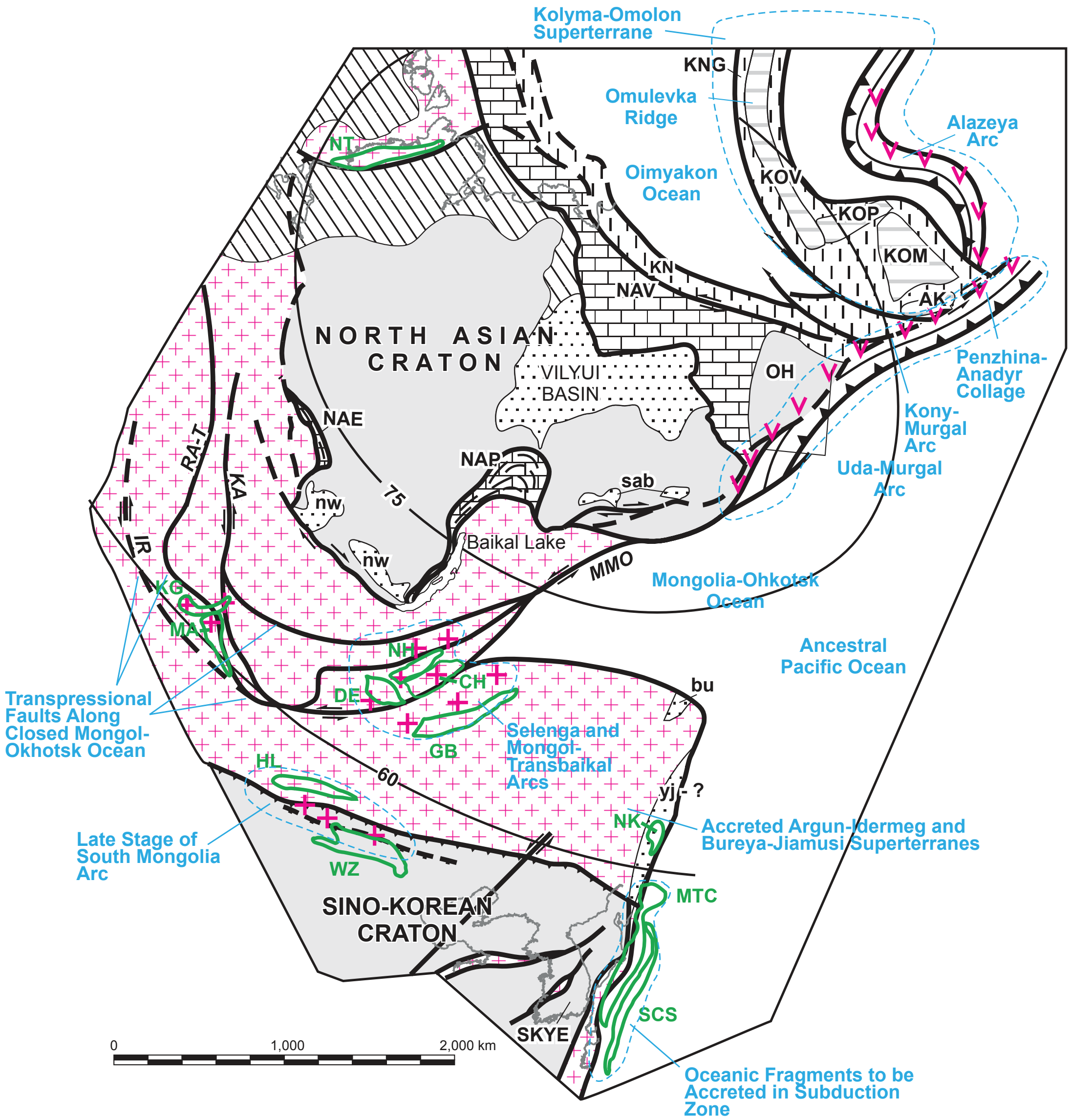
Major Late Triassic through Middle Jurassic Metallogenic Belts

Metallogenic Belts Related to Transpressional Arc and Faults Caused by Closure of Mongol-Okhotsk Ocean

Collision caused by the closure of the Mongol-Okhotsk Ocean resulted in the formation of the Late Triassic through Early Jurassic Mongol-Transbaikal volcanic-plutonic belt along with formation of numerous intraplate strike-slip fault zones and related transpression and transtension zones and related metallogenic belts.

In this area, (figs. 4, 10), five metallogenic belts (the Central Henti, Delgerhaan, Govi-Ugtaal-Baruun-Urt, Harmorit-Hanbogd-Lugiingol, and North Hentii belts) possess geologic units favorable for a wide variety of granite-related deposits. The major deposit types are porphyry Cu; granitoid-related Au; Au in shear zone and quartz-vein; Fe-Zn-skarn; Cu-skarn; Zn-Pb skarn; Sn-skarn; Sn-W greisen, stockwork, and quartz-vein; W-skarn; Ta-Nb-REE akaline metasomatite; REE carbonatite;peralkaline granitoid-related Nb-Zr-REE; and REE-Li pegmatite. The isotopic ages of the igneous rocks that host the deposits range from 199 to 242 Ma. The belts are hosted in the Late Triassic through Early Jurassic Mongol-Transbaikalia volcanic-plutonic belt that constitutes a major part 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 the final closure of the Mongol-Okhotsk Ocean.

Two more metallogenic belts (the Kalgutinsk and Mongol Altai belts) possess geologic units favorable for a wide variety



GEOLOGIC UNITS

North Asian Craton Margin

NAE - East Angara
NAP - Patom-Baikal
NAV - Verkhoyansk

Intracontinental Sedimentary Basin

bu - Bureya sedimentary basin (Early Jurassic to Early Cretaceous)
nw - Western Siberia sedimentary basins (Mesozoic and Cenozoic)
sab - South Aldan sedimentary basin (Jurassic)
yj - Yanji-Jixi-Raohe overlap sedimentary assemblage (Mesozoic and Cenozoic)

Terranes and Superterranes

AK - Avekov terrane
KN - Kular-Nera terrane (Continental-margin turbidite) (Permian through Early Jurassic)
KNG - Nagondzha terrane (Continental margin) (Carboniferous through Late Triassic)
KOM - Kolyma-Omolon superterrane
KOP - Prikolyma terrane
KOV - Omulevka terrane (Passive continental margin) (late Neoproterozoic through Triassic)
OH - Okhotsk terrane
SKYE - Yeongnam terrane (Granulite-paragneiss) (Late Archean to Paleoproterozoic)

Strike-slip Fault and Shear Zone

IR - Irtysh shear zone
KA - Kuznetsk-Altai
MMO - Main Mongol-Okhotsk
RA-T - Rudny Altai - Taimyr

METALLOGENIC BELTS

CH - Central Hentii
DE - Delgerhaan
GB - Govi-Ugtaal-Baruun-Urt
HL - Harmorit-Hanbogd-Lugiingol
KG - Kalgutinsk
MTC - Mino-Tamba-Chugoku
MA - Mongol Altai
NH - North Hentii
NK - North Kitakami
NT - North Taimyr
SCS - Sambagawa-Chichibu-Shimanto
WZ - Wulashan-Zhangbei

Figure 10. Late Triassic (210 Ma) time stage of tectonic and metallogenic model. See text for explanation of tectonic events and origins of major metallogenic belts and figure 3 for explanation of symbols and patterns.

of granite-related deposits. The major mineral deposit types are W-Mo-Be greisen, stockwork, and quartz-vein; Ta-Nb-REE alkaline metasomatite; and Sn-W greisen, stockwork, and quartz-vein deposits). The isotopic ages of the igneous rocks that host the deposits range from 183 to 204 Ma. The 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).

Metallogenic Belt Related to Superterrane Accretion

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). The isotopic ages of the host granitoids range from 223 to 233 Ma (Vernikovskiy, 1996). The belt is interpreted as having formed during generation of granitoids during and after accretion of the Kara superterrane with the North Asian craton.

Metallogenic Belts Related to Oceanic Crust

The Sambagawa-Chichibu metallogenic belt possesses geologic units favorable for stratiform sediment-hosted deposits (Besshi Cu-Zn-Ag massive sulfide, volcanogenic-sedimentary Mn, Cyprus Cu-Zn massive sulfide) that are now preserved in younger subduction-zone terranes. These terranes are the Shimanto subduction-zone terrane (part of the Sakhalin-Hokkaido collage), the Mino Tamba Chichibu subduction-zone terrane (part of the Honshu-Sikhote-Alin collage), and the Sambagawa metamorphic terrane (part of the Honshu-Sikhote-Alin collage. The age of the host rocks for the deposits is interpreted as beinig Early Jurassic and younger. The Mn deposits are interpreted as having formed in a syngenetic setting on the ocean floor, and the Besshi (fig. 5) and Cyprus 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 massive sulfide, volcanogenic-sedimentary Mn, and Cyprus Cu-Zn massive sulfide deposits. The belt and deposits are hosted in the Mino Tamba Chichibu subduction-zone terrane, part of the Honshu-Sikhote-Alin collage. The Mn deposits are interpreted as having formed in a syngenetic setting on the ocean floor. The kuroko deposits formed in an island arc. The deposits were subsequently incorporated into the subduction zone.

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 the Honshu-Sikhote-Alin collage, that contains fragments of late Paleozoic and early Mesozoic oceanic crust in which these deposits originally formed.

Late Jurassic through Early Cretaceous (154 to 105 Ma) Stage of Tectonic and Metallogenic Model

Major Tectonic Events

The major tectonic events in the Late Jurassic through Early Cretaceous (fig. 11) were as follows.

(1) Final closure of the Mongol-Okhotsk Ocean with resultant displacement of collisional processes eastward.

(2) Formation of the collisional Stanovoy granite belt, composed predominantly of granodiorite, granite, and granosyenite along the southern margin of the Aldan-Stanovoy shield of the North Asian craton and westward into the eastern Transbaikalia region.

(3) Continued formation of the Transbaikal volcanic-plutonic belt along the axis of the closed Mongol-Okhotsk Ocean in a transpressional-fault setting.

(4) Continued formation of transpressional fault zones along the axis of the closed Mongol-Okhotsk Ocean.

(5) Postcollisional transform faulting along within-plate transpression zones in northeast China.

(6) Accretion of the Kolyma superterrane and Okhotsk cratonal terrane against the Verkhoyansk (North Asian) cratonal margin and formation of collision-related granitoids and volcanic units.

(7) Formation of the Oloy continental-margin arc along the outboard edge of the accreted Kolyma-Omolon superterrane.

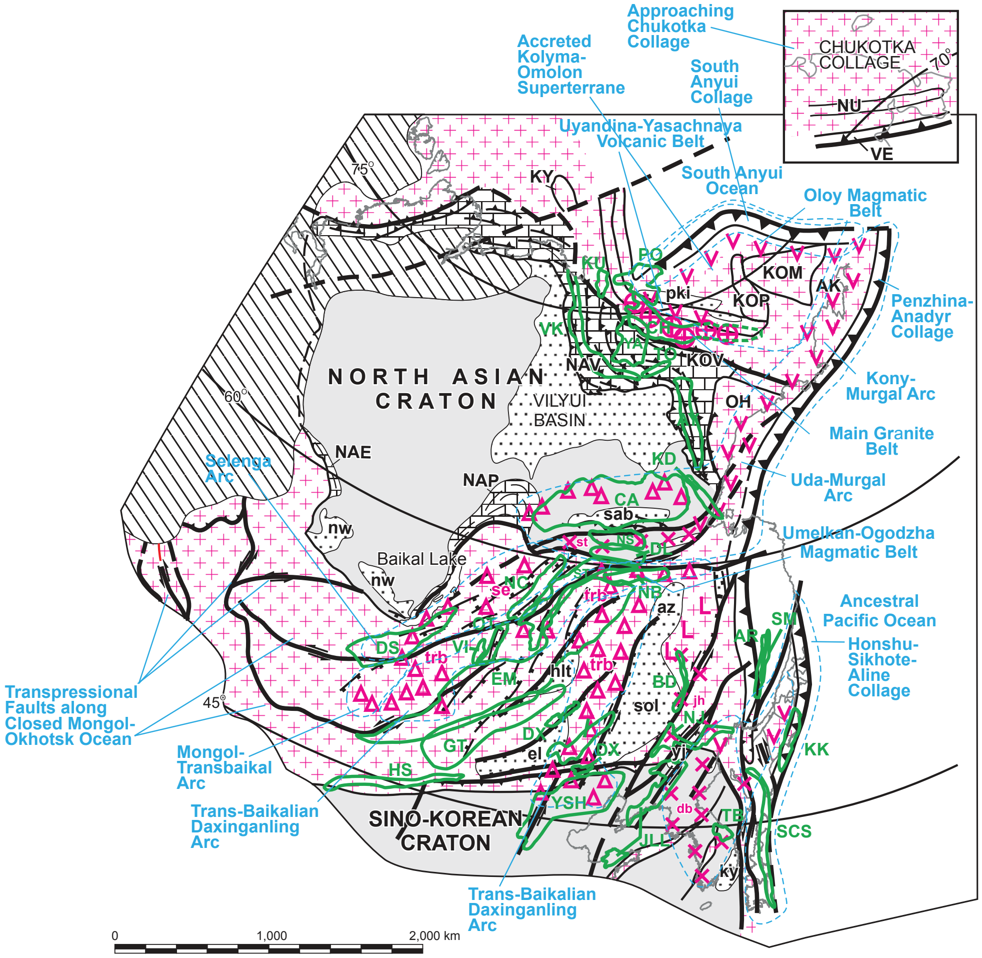
(8) Continued formation of the Uda-Murgal continental-margin arc and associated metallogenic belts.

(9) Beginning of underthrusting of the Kula oceanic ridge and formation of bimodal igneous rocks along the Khingan transform continental margin in the Russian Far East.

(10) Formation of oceanic lithosphere that is now preserved as tectonic fragments in subduction-zone terranes.

Important Geologic Details

(1) The Kolyma-Omolon superterrane was accreted onto the Verkhoyansk cratonal margin. During convergence and accretion, the Uyandina-Yasachnaya arc was formed on the superterrane margin and was tectonically linked to the



GEOLOGIC UNITS

North Asian Craton Margin

NAE - East Angara
NAP - Patom-Baikal
NAV - Verkhoyansk

Intracontinental Sedimentary Basins

az - Amur-Zeya sedimentary basin (Late Jurassic to Quaternary)
el - Erlian sedimentary basin (Jurassic through Quaternary)
hlt - Hailar-Tamsag sedimentary basin (Late Jurassic and Cretaceous)
ky - Kyongsang sedimentary basin (Early Cretaceous)
nw - Western Siberia sedimentary basins (Mesozoic and Cenozoic)
pki - Ilin'-Tas back-arc basin (Late Jurassic)
sab - South Aldan sedimentary basin (Jurassic)
sol - Songliao sedimentary basin (Jurassic through early Tertiary)

Terranes and Superterranes

AK - Avekov terrane
KY - Kotel'nyi terrane (Passive continental margin) (Late Neoproterozoic through Late Triassic)
KOM - Kolyma-Omolon superterrane
KOP - Prikolyma terrane
KOV - Omulevka terrane (Passive continental margin) (late Neoproterozoic through Triassic)
NU - Nutesyn terrane
OH - Okhotsk terrane
VE - Velmay terrane

Overlap Continental-Margin Arcs and Granite Belts

db - Daebo granite belt (Early to Late Jurassic)
jh - Jihei volcanic and plutonic belt (Mesozoic)
se - Selenga sedimentary-volcanic plutonic belt (Permian through Jurassic)
st - Stanovoy granite belt (Jurassic and Early Cretaceous)
trb - Trans-Baikalian-Daxinganling sedimentary-volcanic-plutonic belt (Middle Jurassic through Early Cretaceous)

METALLOGENIC BELTS

AR - Ariadny
AY - Allakh-Yun'
BD - Bindong
CA - Chara-Aldan
CH - Chybagalakh
DL - Djeltulaksky
DS - Dzid-Selenginskiy
DX - Daxinganling
EM - East Mongolian-Priargunskiy-Deerbugan
GT - Govi-Tamsag
HS - Hartolgoi-Sulinheer
JLL - Jiliaolu
KD - Kondyor-Feklistov
KK - Kitakami
KU - Kular
NB - North Bureya
NC - Nerchinsky
NJ - North Jilin
NS - North Stanovoy
OT - Onon-Turinskiy
PO - Polousny
SCS - Sambagawa-Chichibu-Shimanto
SM - Samarka
ST - Shilkinsko-Tukuringrskiy
TB - Taebaegsan
TO - Tompo
VI - Verkhne-Ingodinsky
VK - Verkhoyansk
YA - Yana-Adycha
YSH - Yanshan

Figure 11. Late Jurassic (145 Ma) time stage of tectonic and metallogenic model. See text for explanation of tectonic events and origins of major metallogenic belts and figure 3 for explanation of symbols and patterns.

subduction of the Oimyakon Ocean Plate. Accretion of the Kolyma-Omolon superterrane ended in the latest Late Jurassic with formation of the Main granite belt that consists mainly of peraluminous collisional granitoids with $^{40}Ar/^{39}Ar$ isotopic ages of 135 to 145 Ma (Layer and others, 2001).

(2) After accretion of the superterrane, the northern margin of the North Asian craton and cratonal margin was defined by the Late Jurassic through Neocomian Oloy arc that was tectonically linked to subduction of the South Anyui Ocean Plate.

(3) The Uda-Murgal arc contined to form along the eastern margin of the Northeast Asia and was tectonically linked to subduction of the Ancestral Pacific Ocean Plate. This arc extended southwestward into the continent into the Stanovoy plutonic belt. In the back arc area, the South Aldan coal basin formed during the Jurassic-Early Neocomian. Also in this area, Jurassic-Neocomian subalkaline and alkaline magmatism occurred in the Aldan shield and Omolon cratonal terrane (Terekhov and others, 1984).

(4) From 145 to 135 Ma, the western Ancestral Pacific Ocean and Farallon Ocean Plates continued northeastward migration, and from 135 to 100 Ma, the Izanagi Plate migrated at an oblique angle to the continental margin (Engebretson and others, 1985; Maruyama and Seno, 1986). Consequently, the extensive Kema transform continental margin arc formed south and was tectonically linked to a Late Jurassic-Early Neocomian subduction zone that consisted of schistose turbidites with fragments of Pennsylvanian and Permian limestone with Tethyan fauna, Permian-Middle Jurassic jasper, and ophiolites (Shevelev and Kuzmin, 1990; Natal'in, 1991; Kemkin and Khanchuk, 1993; Kirillova and others, 1996; Isozaki, 1997; Kemkin and Filippov, 2002). In the Late Jurassic-Berriasian, a zone of mixing of Boreal and Tethyan faunas existed here (Zakharov and others, 1996, Kirillova, 2000).

(5) Also in the Late Jurassic-Early Cretaceous, left-lateral strike-slip faulting continued along the eastern segment of the Major Mongol-Okhotsk fault. Farther west in the Transbaikal region and Mongolia, the faulting graded into a zone of crustal extension. As a result, a series of one-sided and two-sided grabens, with east-west to northeast strikes, formed and were filled with Late Jurassic-Early Cretaceous bimodal volcanic and continental clastic units.

(6) Farther south, in the Mongol-Okhotsk collage, a system of large grabens formed and extended northeastward for 1500 km, roughly parallel to the continent-ocean boundary. The grabens contain Late Jurassic continental volcanic and sedimentary units and Cretaceous sedimentary rocks up to 3-10 km thick (Liu Li and others, 1994; Liu and others, 1996, Sun and others, 1997; Tian and Zhong, 1997). To the west, the Late-Jurassic-Early Cretaceous Bolshoy Khingan volcanic belt extended parallel to the grabens. This belt contains basalt, trachyandesite, trachydacite, and dacite with K-Ar isotopic ages of about 150 Ma (Xu Wenliang and others, 1994; Hung and others, 2000). This large zone of crustal extension, that grades into graben systems in the Transbaikal region and Mongolia is analogus to the late Cenozoic Basin and Range Province of the western USA. The extension zone is probably the result of subduction of a "slab window" that formed during subduction of an oceanic ridge beneath the eastern margin of Asia in the late Paleozoic through early Mesozoic. The detachment probably occurred in the Late Triassic through Middle Jurassic during the changing kinematics of the plate motions in the western Ancestral Pacific Ocean.

Metallogenesis

Metallogenic Belts Related to Trans-Baikalian-Daxinganling Transpressional Arc

Eleven metallogenic belts (the Daxinganling, Dzid-Selenginski, East Mongolian-Priargunskiy-Deerbugan, Govi-Tamsag, Hartolgoi-Sulinheer, Nerchinsky, Onon-Turinskiy, Shilkinsko-Tukuringrskiy, and Verkhne-Ingodinsky belts) possess geologic units favorable for a wide variety of siliceous igneous-rock related deposits. The major types of deposits are Au-skarn; Zn-Pb (±Ag, Cu) skarn; W±Mo±Be-skarn; Au-Ag epithermal; 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; sediment-hosted U; Sn-skarn; 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; W-Mo-Be greisen, stockwork, and quartz-vein; W-skarn; and Zn-Pb-skarn. The isotopic ages of the igneous rocks that host the deposits range from 125 to 190 Ma. The belts are hosted in the major Trans-Baikalian-Daxinganling sedimentary-volcanic-plutonic belt that overlaps terranes that were previously accreted to the southern (present-day coordinates) North Asian craton and cratonal margin. The host rocks and metallogenic belts are interpreted as having formed along the major Trans-Baikalian-Daxinganling transpressional arc that formed along the major Mongol-Okhotsk suture that cuts previously accreted terranes south of the southern margin (present-day coordinates) of the North Asian craton and cratonal margin. Displacement along the suture and arc formation occurred after the closing of the Mongol-Okhotsk Ocean

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

Eight metallogenic belts (the Allakh-Yun, Chybagalakh, Kular, Polousny, South Verkhoyansk, Tompo, Verkhoyansk, and Yana-Adycha belts) possess geologic units favorable for a wide variety of Au-vein deposits and collisional granite-related deposits. The major mineral deposit types are Au in shear zone and quartz-vein; granitoid-related Au-vein; Cu-skarn; Au in black shale; W-skarn; polymetallic Pb-Zn-vein and stockwork;

cassiterite-sulfide-silicate-vein and stockwork; Sn-W greisen, stockwork, and quartz-vein; W-Mo-Be greisen, stockwork, and quartz-vein; and Au-Ag epithermal-vein. The ages of the veins and associated granites range from Late Jurassic through Aptian. The belts and deposits are hosted in veins and granitoids (such as the South Verkhoyansk, Main, and Northern 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 that 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 the accretion of the Okhotsk terrane to the North Asian cratonal margin.

Metallogenic Belts Related to Uda-Stanovoy Continental-Margin Arc

Three metallogenic belts (the Chara-Aldan, Djeltulaksky, and North Stanovoy belts) possess geologic units favorable for granitoid-related deposits. The major mineral deposit types are granitoid-related Au-vein; Au-Ag epithermal-vein; Au-skarn; Au in shear zone and quartz-vein; Au potassium metasomatite; and charoite metasomatite. The isotopic ages for the granitoids hosting or related to the deposits 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. The arc 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 Transpression

Four metallogenic belts (the Jiliaolu, North Jilin, Samarka, and Yanshan belts) possess geologic units favorable for a wide variety of transpressional granitoid-related deposits. The major mineral deposit types are Au-Ag epithermal-vein; Cu-skarn; W-skarn; fluorspar-vein; granitoid-related Au-vein;, polymetallic Pb-Zn-vein and stockwork; polymetallic volcanic-hosted metasomatite; porphyry Cu and Cu-Mo; W-skarn; and Zn-Pb-skarn. The isotopic ages for the granitoids hosting the deposits range from 110 to 186 Ma. The granitoids and veins intrude either overlap assemblages on the Sino-Korean craton or the Samarka subduction-zone terrane (part of Honshu-Sikhote-Alin collage). The metallogenic belts are interpreted as having formed during intrusion of granitoids along transpressional zones along microplate boundaries, underthrusting of the Kula oceanic ridge, and formation of bimodal igneous rocks along a transform continental margin, or during interplate magmatism associated with extensional tectonism related to oblique subduction of the Pacific Oceanic Plate beneath the Eurasian Plate.

Unique Metallogenic Belts

Six unique metallogenic belts formed during this time span. (1) The Kondyor-Feklistov belt, with zoned mafic-ultramafic Cr-PGE deposits, is hosted in mafic-ultramafic intrusions and is interpreted as having formed during intrusion of mafic-ultramafic plutons along a deep-seated fault that formed along the North Asian cratonal margin during collision and accretion of outboard terranes. (2) The North Bureya belt, with Au-Ag epithermal-vein and granitoid-related Au-vein deposits, is hosted in the Umlekam-Ogodzhin volcanic-plutonic belt. The belt is interpreted as having formed during formation of the Umlekan-Ogodzhin continental-margin arc that formed during subduction of part of the Ancestral Pacific Ocean plate. (3) The Ariadny belt, with mafic-ultramafic rock-related deposits, is hosted in Middle Jurassic and Early Cretaceous plutons intruding the Samarka subduction-zone terrane, part of the Honshu-Sikhote-Alin collage. The belt is interpreted as having formed during generation of ultramafic and gabbroic plutons during underthrusting of the Kula oceanic ridge and formation of bimodal igneous rocks along a transform continental margin. (4) The Taebaegsan belt, with a wide assortment of granitoid-related deposits, is hosted in the Daebo granite and is interpreted as having formed during intrusion of granitoids associated with Late Jurassic through Early Cretaceous Daebo granite. The granitioid are interpreted as being part of a continental-margin arc that was linked to subduction of the Ancestral Pacific Ocean plate. (5) The Kitakami belt, with Cu-skarn and granitoid-related Au deposits, is hosted in the Early Cretaceous Hiroshima granite belt (with isotopic ages of 110 to 120 Ma) and is interpreted as having formed during intrusion of granitoids associated with a continental-margin arc and siliceous magmatism. (6) The Bindong belt, with Zn-Pb (±Ag, Cu) skarn and W±Mo±Be-skarn deposits, is hosted in small granitoids in the Mesozoic Jihei volcanic and plutonic belt and is interpreted as having formed during interplate extensional tectonism and generation of subalkaline to alkaline volcanism and related sedimentation along northeast and east-west regional faults.

Cenomanian through Campanian (97 to 74 Ma) Stage of Tectonic and Metallogenic Model

Major Tectonic Events

The major tectonic events in the Cenomanian through Campanian (fig. 12) were as follows.

(1) Formation of granitoids along the the Khingan transform continental-margin arc in response to oblique subduction of the Ancestral Pacific Ocean Plate in the Russian Far East.

(2) After accretion of the Kolyma-Omolon superterrane and the Okhotsk terrane, and accretion of the Koryak collage (composed of Late Jurassic and Early Cretaceous island-arc and tectonically-linked subduction-zone terranes) in the Late Jurassic and Early Cretaceous, outboard stepping of subduction and formation of the major Late Cretaceous and early Tertiary Okhotsk-Chukotka continental-margin arc.

(3) After accretion of the Bureya-Jiamusi supterterrane and the Sino-Korean craton in the Late Jurassic through Early Cretaceous, and accretion of outboard terranes, outboard stepping of subduction and formation of the East Sikote-Alin continental-margin arc (containing the East Sikote-Alin volcanic-plutonic belt).

(4) Formation of major back-arc basins in the Russian Northeast behind the Okhotsk-Chukotka continental-margin arc and in northern China behind the East Sikhote-Alin continental-margin arc.

(5) Late-stage continuation of transpressional-fault zones along the axis of the closed Mongol-Okhotsk Ocean.

(6) Postcollisional transform faulting along within-plate transpression zones in northeast China.

(7) In the late part of this time span, in the area of the East Sikhote-Alin fault, formation of a major continental-margin transform-fault system in the Russian Southeast along with generation of granitic and volcanic rocks.

(8) Rifting and formation of the Eurasian Basin and formation of the Arctic Ocean.

(9) In the area to become Japan, accretion of the Honshu-Sikhote-Alin collage that is composed mainly of island-arc, continental-margin turbidite (flysch), and subduction-zone terranes.

Important Geologic Details

(1) After closure of the South Anyui Ocean, that led to the formation of the South Anyui and Penzhina-Anadyr orogenic belts, the large Eastern Asian active continental margin formed along the western margin of the Ancestral Pacific Ocean. This arc extended from South China through Korean peninsula and eastern Sikhote-Alin region to Chukotka and farther into western Alaska (Parfenov and others, 1999a; Nokleberg and others, 2000).

In eastern Northeast Asia, the East Asian active continental margin consists of the East Sikhote-Alin arc to the south and the Okhotsk-Chukotka arc to the north. Associated with the arcs are Late Cretaceous coal-bearing forearc basins--the Penzhina Basin to the north and the West Sakhalin-Ezo and Izumi Basins to the south.

(2) In the rear of the active continental margin, the Indigirka crust extension belt formed and extended from the Laptev Sea shelf southeastward to the Okhotsk-Chukotka arc. The belt contains a series of grabens that on the Laptev shelf and the adjacent area are filled with thick Aptian-Albian and the lowermost Late Cretaceous sedimentary units (Drachev and others, 1998; Drachev, 1999) and, to the south, contains linear and isometric magmatic zones with Aptian-Late Cretaceous and, presumably, Paleogene subalkaline and alkaline volcanic and plutonic rocks and anorogenic alkaline granitoids [Tectonics, geodynamics, and metallogeny of the territory of the Sakha Republic (Yakutia), 2001]. Formation of the Indigirka belt is related to crustal extension that predated the opening of the Eurasia Ocean in the Arctic.

(3) In the Late Cretaceous, onto the northern margin of this arc was accreted the Koryak collage (containing the Mainitskiy island arc, Alkatvaam turbidite, and Ekonay subduction-zone terranes). Similar accreted terranes may occur in the Sea of Okhotsk (Maruyama and others, 1997; Fujita and others, 1983).

(4) Opening of the Eurasian Basin along the margin of the North American cratonal margin (not shown in fig. 12) (Nokleberg and others, 2000).

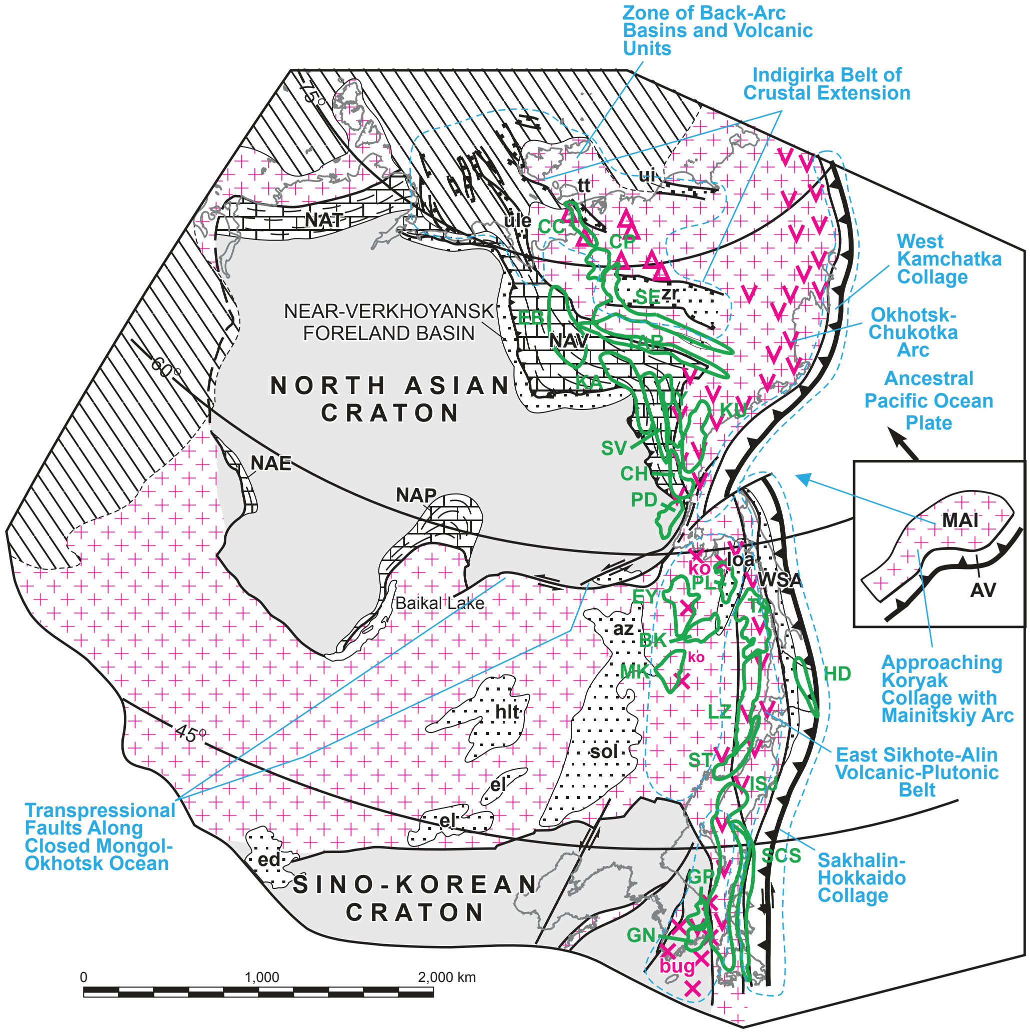
Metallogenesis

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

Seven metallogenic belts (the Chelasin, Kukhtuy-Uliya, Luzhkinsky, Preddzhugdzhursky, Sergeevka-Taukha, Tumnin-Anyuy, and Upper Uydoma belts) possess geologic units favorable for a wide variety of granitoid-related deposits. The major mineral deposit types are 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-skarn; porphyry Sn; Sn-W greisen, stockwork, and quartz-vein; Sn-B-skarn; W-Mo-Be greisen, stockwork, and quartz-vein; and Zn-Pb-skarn. The ages of the associated granites range from mid-Cretaceous through Paleocene. The belts and deposits are hosted in granitoids in the Okhotsk-Chukotka volcanic-plutonic belt, or in the East Sikhote-Alin volcanic-plutonic belt. Both units are major overlap assemblages in the Russian Far East and are interpreted as part of the extensive, nearly coeval, and colinear continental-margin Okhotsk-Chukotka and East Sikhote-Alin arcs that 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 Eurasin Basin

Four metallogenic belts (the Central Polousny, Chokhchur-Chekurdakh, Eckyuchu-Billyakh, Khandyga, and



GEOLOGIC UNITS

North Asian Craton Margin

NAE - East Angara
NAP - Patom-Baikal
NAT - South-Taimyr
NAV - Verkhoyansk

Intracontinental Sedimentary Basins

az - Amur-Zeya sedimentary basin (Late Jurassic to Quaternary)
ed - Erduosi sedimentary basin (Triassic through Cretaceous)
el - Erlian sedimentary basin (Jurassic through Quaternary)
hlt - Hailar-Tamsag sedimentary basin (Late Jurassic and Cretaceous)
loa - Lower Amur overlap assemblage (Late early and early Late Cretaceous)
sol - Songliao sedimentary basin (Jurassic through early Tertiary)
tt - Tastakh Basin
ui -Ust-Indigirka Basin
ule - Ust-Lena Basin
zr - Zyryanka sedimentary basin (Late Jurassic through Cenozoic)

Terranes

AV - Alkatvaam terrane
MAI - Mainitskiy terrane
WSA - West Sakhalin terrane (Accretionary wedge, type A) (Cretaceous)

Overlap Continental-Margin Arcs and Granite Belts

ko - Khingan-Okhotsk volcanic-plutonic belt (Cretaceous)
bug - Bulgugsa granite (Late Cretaceous

METALLOGENIC BELTS

BK - Badzhal-Komsomolsk
CC - Chokhchur-Chekurdakh
CH - Chelasin
CP - Central Polousny
EB - Eckyuchu-Billyakh
EY - Ezop-Yam-Alin
GN - Gyeongnam
GP - Gyeongpuk
HD - Hidaka
ISJ - Inner Zone Southwest Japan
KA - Khandyga
KU - Kukhtuy-Uliya
LZ - Luzhkinsky
MK - Malo-Khingan
PD - Preddzhugdzhursky
PL - Pilda-Limuri
SCS - Sambagawa-Chichibu-Shimanto
SE - Selennyakh
ST - Sergeevka-Taukha
SV - South Verkhoyansk
TA - Tumnin-Anyuy
TAR - Taryn
UY - Upper Uydoma

Figure 12. Santonian (87 Ma) time stage of tectonic and metallogenic model. See text for explanation of tectonic events and origins of major metallogenic belts and figure 3 for explanation of symbols and patterns.

Selennyakh belts) possess geologic units favorable for a wide variety of vein and replacement and granitoid-related deposits. The major mineral deposit types are 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. The isotopic ages for the vein deposits range from 97 to 120 Ma and the interpreted ages for the deposits range from Aptian through Late Cretaceous. The belts and deposits are hosted in units that intrude 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. The 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 (the Badzhal-Komsomolsk, Ezop-Yam-Alin, Malo-Khingan, and Pilda-Limuri belts) possess geologic units favorable for a wide variety of vein and replacement and granitoid-related deposits. The major mineral deposit types are Cu-skarn; porphyry Mo; granitoid-related Au-vein; polymetallic Pb-Zn; porphyry Sn; rhyolite-hosted Sn; Sn-W greisen, stockwork, and quartz-vein; cassiterite-sulfide-silicate-vein and stockwork; and W-Mo-Be greisen, stockwork, and quartz-vein. The isotopic ages for the granitoids hosting or associated with the deposits range from 75 to 100 Ma. The belts and deposits are hosted in granitoids related to the Khingan-Okhotsk volcanic-plutonic belt that is interpreted as having formed during the generation of granitoids along the Khingan continental-margin arc. The arc is related to oblique subduction of the Ancestral Pacific Ocean Plate and formation of the Early Cretaceous Zhuravlevsk-Amur River and Kiselevka-Manoma subduction-zone terranes, part of the Honshu-Sikhote-Alin collage.

Unique Metallogenic Belts

Four unique metallogenic belts formed during this time span.

(1) The Gyeongpuk and Gyeongnam belts (with granitoid-related deposits) have isotopic ages of Cenomanian through Campanian and are hosted in the Cretaceous Bulgugsa granite that intrudes the Sino-Korean craton.

(2) The Hidaka belt (with Cyprus Cu-Zn massive sulfide deposits) is hosted in Middle Cretaceous through Eocene stratiform units that occur in tectonic fragments in the Shimanto subduction-zone terrane, part of the East Sakhalin collage.

(3) The Inner Zone Southwest Japan belt (with a wide variety of vein and replacement and granitoid-related deposits) is hosted in the Nohi rhyolite volcanic belt and coeval Hiroshima granitic belt that overlie previously-accreted terranes. The host rocks and deposits have isotopic ages of Cretaceous through Paleogene.

Maastrichtian through Eocene (72 to 33.7 Ma) Stage of Tectonic and Metallogenic Model

Major Tectonic Events

The major tectonic events in the Maastrichtian through Eocene (fig. 13) were as follows.

(1) Migration of the Olyutorka-Kamchatka collage (and contained Olyutorka-Kamchatka island arc and subduction zone) toward the northeast margin of Northeast Asia.

(2) Slightly later, accretion of the Olyutorka-Kamchatka collage.

(3) Migration of the East-Sakhalin collage (and contained Terprniya-Nemuro island arc and subduction zone) toward the eastern margin of Northeast Asia.

(4) Continuation of transpressional-fault zones along the axis of the closed Mongol-Okhotsk Ocean and formation of associated metallogenic belts.

(5) Postcollisional, transform faulting along within-plate transpression zones in northeast China.

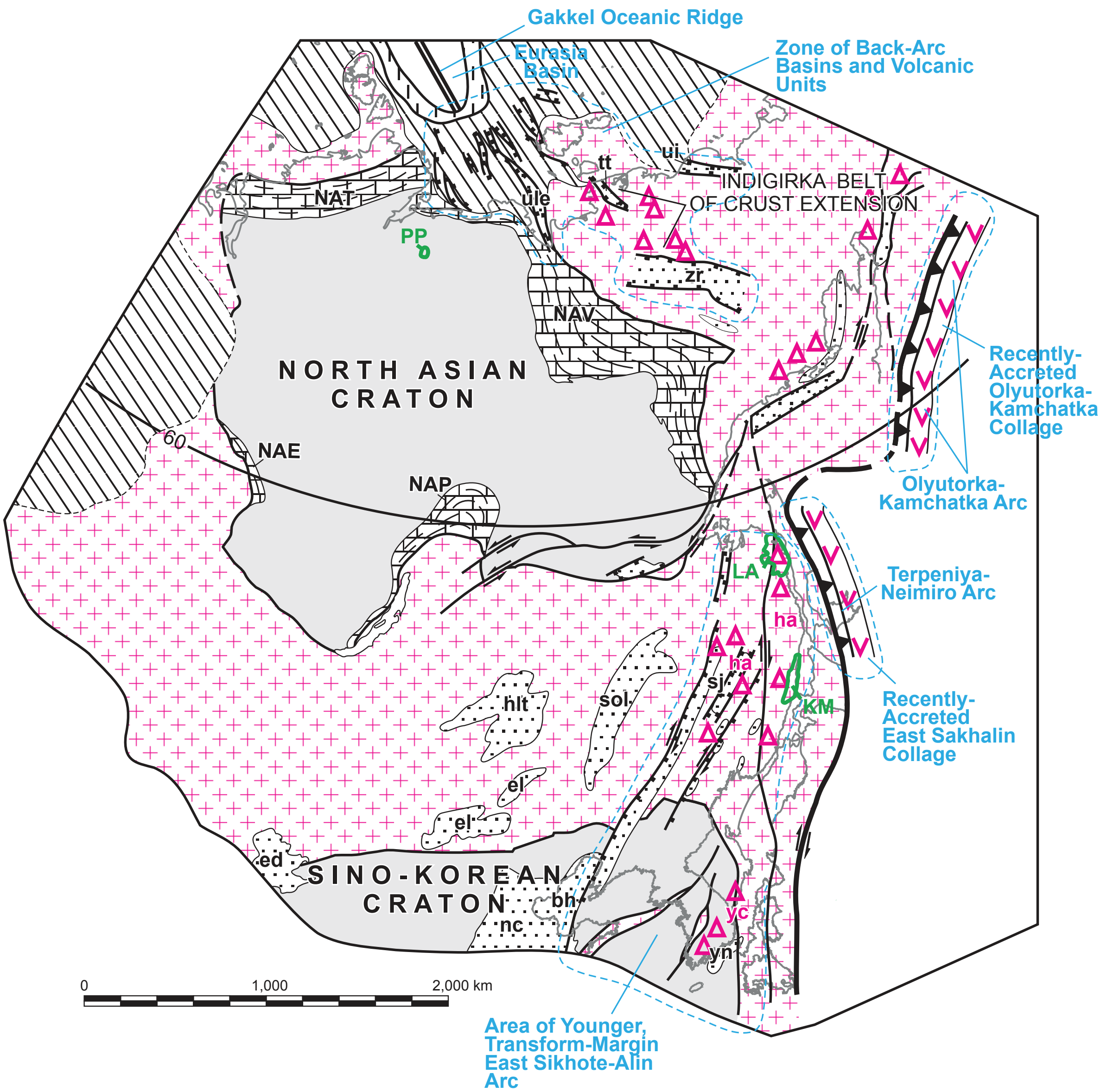
(6) Continued formation of a major continental-margin transform-fault system and generation of the younger part of the East Sikhote-Alin volcanic-plutonic belt (East Sikhote-Alin transform continental-margin arc) in the Russian Southeast and northeast China.

(7) Continued rifting and formation of the Eurasia Basin and opening of the Arctic Ocean.

Important Geologic Details

(1) Following the subduction of the Izanaga Plate, the Pacific Plate moved northward at a low angle to the continent margin and began plunging beneath it (Engebretson and others, 1985), thereby causing a transform boundary. This transform boundary is presently in the Sea of Okhotsk.

(2) At about 50 Ma, the Olyutorka-Kamchatka collage accreted to the continental margin (Zinkevich and Tsukanov, 1992), and subsequently, at about 40 Ma, the T East-Sakalin collage (and contained Terprniya-Nemuro island arc and subduction zone) accreted.



GEOLOGIC UNITS

North Asian Craton Margin

NAE - East Angara
NAP - Patom-Baikal
NAT - South-Taimyr
NAV - Verkhoyansk

Intracontinental Sedimentary Basin

bh - Bohai sedimentary basin (Cenozoic)
ed - Erduosi sedimentary basin (Triassic through Cretaceous)
el - Erlian sedimentary basin (Jurassic through Quaternary)
hlt - Hailar-Tamsag sedimentary basin (Late Jurassic and Cretaceous)
nc - North China sedimentary basin (Cenozoic)
sj - Sanjiang sedimentary basin and Yishu graben (Mesozoic and Cenozoic)
sol - Songliao sedimentary basin (Jurassic through early Tertiary)
tt - Tastakh Basin
ui -Ust-Indigirka Basin
ule - Ust-Lena Basin
yn - Yonil Group (Cenozoic)
zr - Zyryanka sedimentary basin (Late Jurassic through Cenozoic)

Overlap Continental-Margin Arcs and Granite Belts

yc -Yucheon volcanic belt
ha - Hasan-Amurian volcanic-plutonic belt (Paleocene to early Miocene)

METALLOGENIC BELTS

KM - Kema
LA - Lower Amur
PP - Popigay

Figure 13. Eocene (50 Ma) time stage of tectonic and metallogenic model. See text for explanation of tectonic events and origins of major metallogenic belts and figure 3 for explanation of symbols and patterns.

(3) Around the margin of the Circum-North Pacific, major, right-lateral strike-slip faults formed and extended for thousands of kilometers. These faults are well-studied in Alaska and the Canadian Cordillera (Frasier, Straight Creek, Denali, Kaltag, and Tintina faults), where motions on them are estimated at hundreds and 1,500 to 2,000 km (Plafker and Berg, 1994; Monger and Nokleberg, 1996).

(4) During the Eocene, along the East Asia margin, extensive graben systems (Bohai, I-Shu, Pereyaslavskiy, Yama-Tuya) formed and accumulated thick lacustrine-alluvial deposits (Kirillova and others, 1996; Maruyama and others, 1997).

(5) The Eurasia Basin continued to open with detachment of a narrow linear strip from the margin of the Barents Sea shelf and formation of the intraoceanic Lomonosov Ridge (not shown on fig. 13) (Karasik, 1974; Karasik and others, 1983). The boundary between the Eurasian and North American plates is the Gakkel oceanic ridge, and it can be traced in a series of grabens on the Laptev Sea shelf and the onshore Zyryanka Basin to the southeast [Tectonics, geodynamics, and metallogeny of the territory of the Sakha Republic (Yakutia), 2001]. In the early Paleogene, the pole of rotation of the plates occurred north of Japan.

(6) With extension along the Gakkel ridge, the Northeast Asia lithosphere was extended.

Metallogenesis

Two metallogenic belts (the Kema and Lower Amur belts) possess geologic units favorable for a wide variety of vein and replacement and granitoid-related deposits. The major mineral deposit types are Ag-Au epithermal-vein; porphyry Cu-Mo; porphyry Cu; porphyry Au; porphyry Mo; Au-Ag epithermal-vein; epithermal quartz-alunite; and Sn-W greisen, stockwork, and quartz-vein. The isotopic ages for the granitoids hosting or associated with the deposits range from Late Cretaceous through Paleocene. The belts and deposits are hosted in granitoids in the East Sikhote-Alin volcanic-plutonic belt that is a major overlap assemblage in the Russian Far East. The belt is interpreted to be part of an extensive continental-margin arc that formed along the eastern margin (present-day coordinates) of the North Asian craton and cratonal margin and previously-accreted terranes to the east. The arc is interpreted as having formed during subduction of the Ancestral Pacific Ocean Plate.

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

Oligocene through Miocene (33.7 to 5.3 Ma) Stage of Tectonic and Metallogenic Model

Major Tectonic Events

The major tectonic events in the Oligocene to Miocene (fig. 14) were as follows.

(1) Formation of the short-lived Central Kamchatka continental-margin arc along the outboard margin of northern Northeast Asia.

(2) Migration of the East Kamchatka collage (and contained Kronotskaya island arc and subduction zone) toward the northeast margin of Northeast Asia.

(3) Slightly later, accretion of the East Kamchatka collage outboard of the Central Kamchatka arc.

(4) Formation of the Japan continental-margin arc and back-arc spreading between the arc and the southern part of Northeast Asia.

(5) To the south, formation of the Izu Bonin continental-margin arc.

(6) Continued rifting and formation of the Eurasian Basin and formation of the Arctic Ocean.

Important Geologic Details

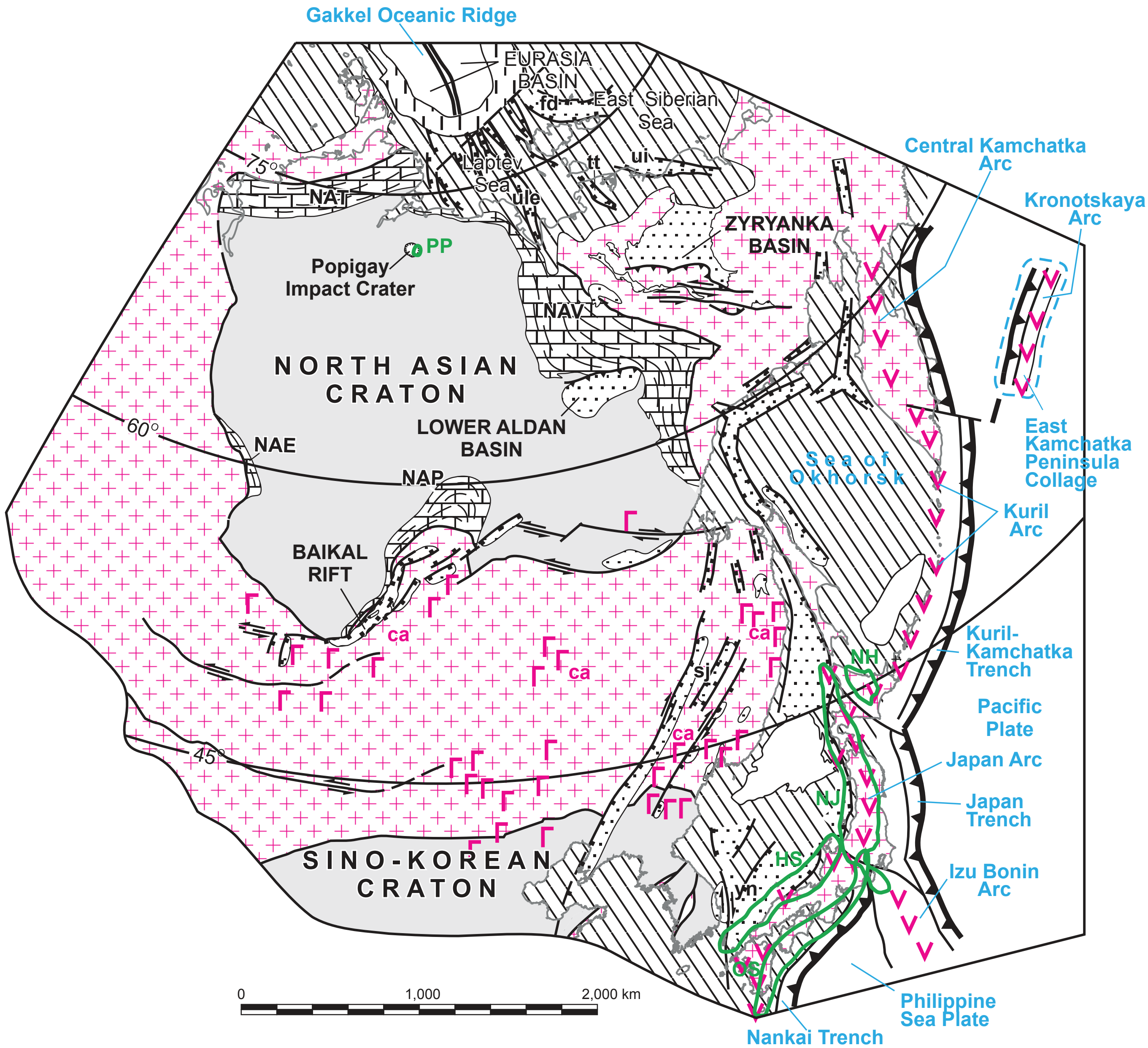
(1) The eastern margin of North Asia underwent a transition to the present-day shape. In the early Oligocene, the Pacific Plate moved northwestward at a high angle to the continental margin at a rate of about 10 cm/yr (Zonenshain and others, 1985; Engebretson and others, 1985).

(2) After accretion of the East Sakhalin collage, subduction stepped oceanward, and the Japan and Kuril island arcs formed. The Kuril and Central Kamchatka arcs, connected by a transform fault, were the northern continuation (Parfenov and others, 1979).

(3) The East Kamchatka collage (and contained Kronotskaya island arc and subduction zone) migrated towards Kamchatka as part of the Pacific Plate (Levashova and Bazhenov, 1997) and was accreted to the accreting continental margin in the late Miocene.

(4) After accretion of the East Kamchatka collage, subduction stepped oceanward, and in the Pliocene, the Kamchatka arc formed.

(5) Rifting and back-arc spreading occurred behind the island arcs. In the Sea of Okhotsk and the sea west of Japan, deep-water basins with oceanic crust as well as linear,



GEOLOGIC UNITS

North Asian Craton Margin

NAE - East Angara
NAP - Patom-Baikal
NAT - South-Taimyr
NAV - Verkhoyansk

Intracontinental Sedimentary Basins

fd - Faddeevskiy Basin
sj - Sanjiang sedimentary basin and Yishu graben (Mesozoic and Cenozoic)
tt - Tastakh Basin
ui -Ust'-Indigirka Basin
ule - Ust'-Lena Basin
yn - Yonil Group (Cenozoic)

Plateau Basalt Belt

ca - Central Asian plateau basalt belt (Neogene and Quaternary)

METALLOGENIC BELTS

HS - Hokuriku-Sanin
NH - Northeast Hokkaido
NJ - Northeast Japan
OS - Outer Zone Southwest Japan
PP - Popigay

Figure 14. Miocene (10 Ma) time stage of tectonic and metallogenic model. See text for explanation of tectonic events and origins of major metallogenic belts and figure 3 for explanation of symbols and patterns.

rift-related sedimentary basins formed and were filled with Oligocene-Pliocene basalt and sedimentary rock (Kharakhinov, 1998, Ingle and others, 1990; Jolivet, 1992; Tamaki and others, 1992; Maruyama and others, 1997; Tectonic map of the Sea of Okhotsk, 2000). West of Japan, back-arc spreading occurred from 32 to 23 Ma and was marked by crustal extension and thinning, intense basalt magmatism, marine-rifting sedimentation, and thermal sinking of the crust at a rate of 150 mm/yr. The main rifting event occurred in the early Miocene. During back-arc spreading, a right-lateral strike-slip fault system formed and extends for about 2,000 km from central Japan to North Sakhalin Island.

(6) The Eurasian Basin continued forming in the Arctic. In the Oligocene, the pole of rotation of the Eurasian and North American Plates migrated to the area north of the New Siberian Islands (Drachev and others, 1998) caused compression in an area to the south. The result was onset of general uplift, formation of the arches of the Verkhoyansk, Chersky, and Moma Ranges. In addition, piedmont basins (Lower Aldan, Zyryanka) formed along the periphery of the arched uplift. In the late Miocene to early Pliocene, thrust systems with horizontal displacements of up to 20 km, as well as conjugate folded folds and strike-slip faults, formed along the sides of the arched uplifts [Tectonics, geodynamics, and metallogeny of the territory of the Sakha Republic (Yakutia), 2001]. These tectonic events correlate well with increased spreading rate in the Eurasian Basin (up to 1.2-1.5 cm/yr) (Drachev and others, 1998) that was the result of an increased convergence rate between the Eurasian and North American Plates.

(7) In the Oligocene-Miocene, the Baikal rift formed (Mats and others, 2001).

(8) During the Miocene, the extensive plateau basalts were erupted in Central Asian, including both solitary lava sheets and fields up to 3,000 km^2. The plateau-basalts occur from East Sayan and the Stanovoy Range in the north to the northern margin of the Sino-Korean craton in the south, and from northern and central Mongolia in the west to the shores of the Tatar Strait in the east. The volcanic units include high alkalinie basalts (Rasskazov, 1993; Yarmolyuk and others, 1997, 2000). This volcanic activity was initially related to local mantle plumes and was associated with grabens, as in the South-Khangai area (Yarmolyuk and others, 1997, 2000).

Miocene to Present Metallogenesis

The five major Miocene through Present metallogenic belts (the Kyushu, Northeast Hokkaido, Hokuriku-Sanin, Northeast Japan, and Outer Zone Southwest Japan belts) possess geologic units favorable for a wide variety of volcanic-rock-related deposits. The major mineral deposit types are Au-Ag epithermal-vein; cassiterite-sulfide-silicate-vein and stockwork; chemical-sedimentary Fe-Mn; clastic sediment-hosted Hg±Sb; clastic-sediment-hosted Sb-Au; Ag-Sb and Hg-Sb-W-vein and stockwork; limonite from spring water; Mn-vein; polymetallic Pb-Zn-vein and stockwork;, polymetallic volcanic-hosted metasomatite; Sn-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; W-Mo-Be greisen, stockwork, and quartz-vein; and Zn-Pb-skarn. The isotopic ages of the igneous rocks hosting the deposits range from 0.3 to 15 Ma. The belts and deposits are hosted in the Quaternary Japan volcanic belt and the Neogene Japan sedimentary basin that are interpreted as part of the modern-day Japan continental-margin arc. This arc is tectonically related to subduction of the Pacific Ocean and Philippine Sea Plates beneath the East Asia continental margin.

Pliocene through Present (5.3 to 0 Ma) Stage of Tectonic and Metallogenic Model

Major Tectonic Events

The major tectonic events in the Pliocene through the Present (fig. 15) were as follows.

(1) Continued formation of the Kuril-Kamchatka continental-margin arc along the eastern margin of Northeast Asia.

(2) Continued formation of the Japan continental-margin arc and back-arc spreading between the arc and the southern part of Northeast Asia.

(3) To the south, continued formation of the Izu Bonin continental-margin arc.

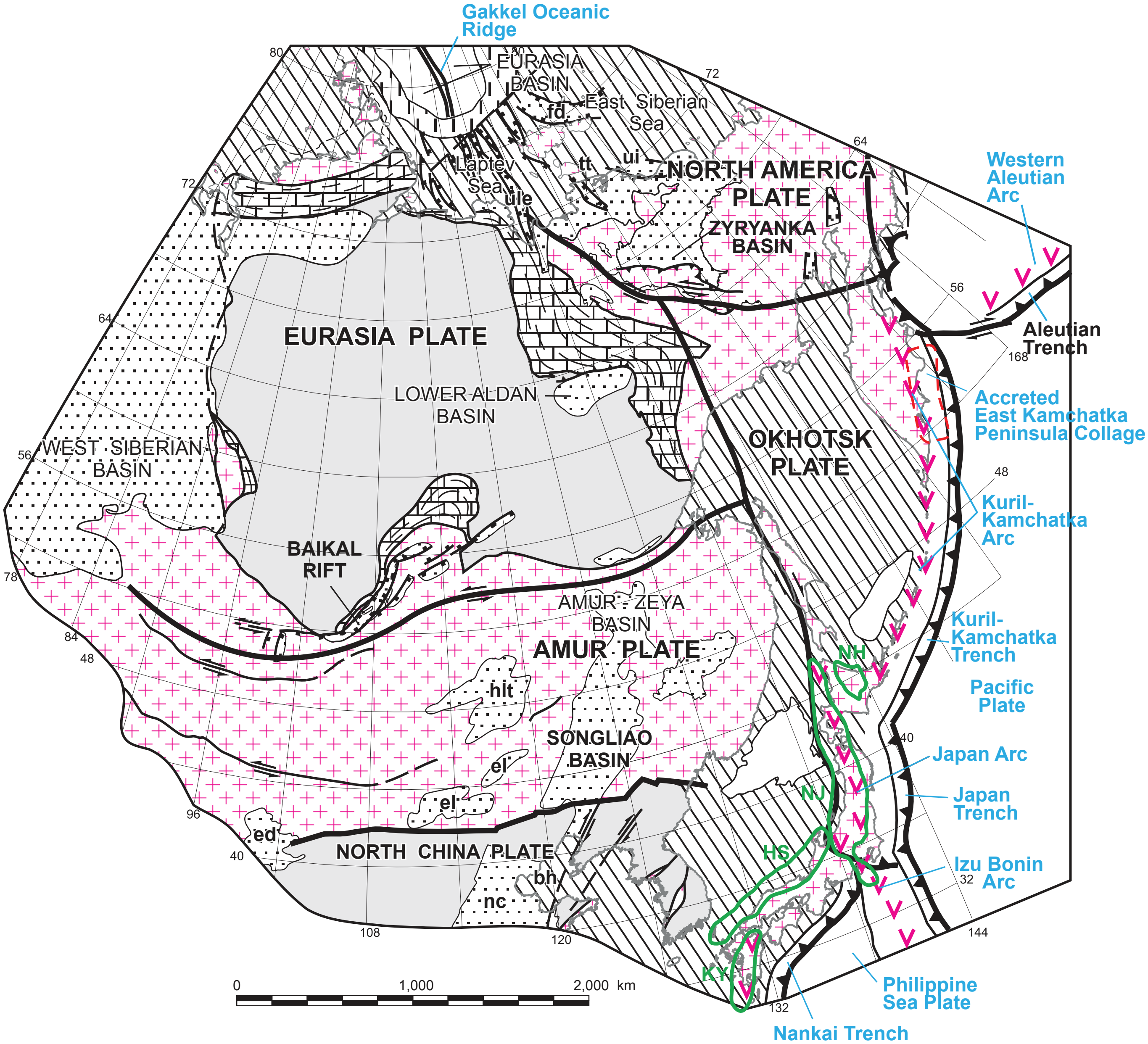
(4) Continued rifting and formation of the Eurasian Basin and formation of the Arctic Ocean; and on the basis of modern-day earthquake foci, formation of several new tectonic plates across the region (Nokleberg and others, 2000).

(5) Continued formation of the Baikal rift (Mats and others, 2001).

Conclusions

Major Tectonic Processes

New and fundamental processes in the tectonic evolution and formation of collages and orogenic belts are supported by this research. The major ancient ocean basins (Paleo-Asian, Mongol-Okhotsk, and Solon), that contain the major collages of Central and Northeast Asia, were major new units that



GEOLOGIC UNITS

Intracontinental Sedimentary Basins

bh - Bohai sedimentary basin (Cenozoic)
ed - Erduosi sedimentary basin (Triassic through Cretaceous)
el - Erlian sedimentary basin (Jurassic through Quaternary)
fd - Faddeevskiy Basin
hlt - Hailar-Tamsag sedimentary basin (Late Jurassic and Cretaceous)
nc - North China sedimentary basin (Cenozoic)
tt - Tastakh basin
ui -Ust'-Indigirka Basin
ule - Ust'-Lena Basin

METALLOGENIC BELTS

HS - Hokuriku-Sanin
KY - Kyushu
NH - Northeast Hokkaido
NJ - Northeast Japan

Figure 15. Present (0 Ma) time stage of tectonic and metallogenic model. See text for explanation of tectonic events and origins of major metallogenic belts and figure 3 for explanation of symbols and patterns.

exhibited common tectonic processes. Formation of variously aged collages (orogenic belts) along the margins of the North Asian and Sino-Korean cratons was controlled by the same processes that are still occurring along the periphery of the Pacific and Arctic Oceans.

In the northern, western, and southern margins of the North Asian craton, various independent, late Riphean, Vendian-Cambrian, and Silurian-Devonian island arcs formed and were separated from the cratons by large back-arc basins. The arcs are comparable to the modern-day island arcs offshore from Asia. Accretion of these ancient island arcs culminated in the formation of late Riphean, early Paleozoic, and middle Paleozoic collages. Formation of the late Paleozoic through early Mesozoic, Mongol-Okhotsk and Solon collages was also related to closure of major ocean basins.

The Mesozoic and Cenozoic collages along the eastern margin of Northeast Asia formed during convergence between the Paleo-Pacific and North Asian craton and cratonal margin. Convergence of the oceanic and continental plates was accompanied by rifting, opening, and subsequent closure of minor ocean basins behind active continental-margin and island arcs. In the Late Mississippian, after extensive Devonian rifting, a narrow linear strip of the shelf was detached from the eastern margin of the North Asian craton, and it became the intraoceanic Omulevka Range. The Omulevka Range and the Oimyakon Oceanic Basin are comparable to the present-day Lomonosov Ridge and the Eurasian Basin of the Arctic Ocean.

Formation of major orogenic belts was accompanied by large (hundreds and thousands of kilometers), longitudinal strike-slip motions that were subparallel to the continental margin. Large strike-slip motions were the result of oblique convergence between the oceanic plates and the continental margins.

Refinement of the Tectonic and Metallogenic Model

Our tectonic and metallogenic model is the first major interpretation for the region. The most important problems for future studies are (1) determining the age and nature of rifting events responsible for the break-up of the Proterozoic supercontinent Rodinia and formation of the North Asian craton; (2) establishing the nature of fragments of cratons and Riphean and early Paleozoic collages that occur in various, different-aged orogenic belts of Central Asia; and (3) clarifying the origin of late Paleozoic-early Mesozoic ocean basins that were eventually preserved in the Mongol-Okhotsk and Solon collages.

These problems can be solved with additonal isotopic-geochemical and geochronological data that will permit better understanding of the geodynamic nature of magmatic complexes, as well as the timing of geological events. For example, for the origin of the Mongol-Okhotsk collage, evidence needs to be found for magmatic units that formed during the early opening of the Mongol-Okhotsk Ocean. Such data will be very important for understanding the nature of the Mongol-Okhotsk Ocean. In addition, new isotopic and geochemical data on the formation of the early stages of the emplacement of the Selenga, East Mongolian, and South Mongolian volcanic-plutonic belts are needed. New data on the geodynamic nature and the age of Paleozoic granitoids of the Khangai-Daurian, West Stanovoy, and Argun terranes are also needed.

Finally, reliable reconstruction of the tectonic evolution of Northeast Asia is dependent on high-quality paleomagnetic data. The present data are limited and are available only for distinct stratigraphic horizons of various terranes. Paleomagnetic data for the entire stratigraphic section of each terrane are needed, as well as for overlap assemblages. In particular, new data are needed for the Argun-Idermeg superterrane. These data will assist solving major debates about the origin of the Mongol-Okhotsk region and are of prime importance for understanding the tectonic evolution of Northeast and East-Central Asia.

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