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Metallogeny of Hg, Sb, and Au-Hg deposits in the Pacific active continental margins

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ABSTRACT

The Circum-Pacific metallogenic map of Hg, Sb, and Au-Hg deposits (at a scale 1:50 M) compiled by the authors shows that Mesozoic and Cenozoic deposits are located at active continental margins. They occur along active continental margins, ensialic island arcs, accretionary complexes of subduction zones, overlying continental volcanic belts, and in the back-arc and intraplate rifting structures. There is a close relationship between Hg and Au-Hg deposits in this geodynamic environment, with common ore-forming epithermal and volcanogenic-hydrothermal systems. Seven model types of Hg, Sb, and Au-Hg deposits were described. A review of the spatial and temporal distribution of large Hg and Au-Hg deposits along the circum-Pacific Metallogenic Belt identifies the influence of mantle-plume magmatic activity in the metallogenic belts that were produced in complex geodynamic environments.

INTRODUCTION

The Circum-Pacific orogenic belt, along with the Alpine-Himalayan orogenic belt, is a great tectonic structure in the global context (Dickinson, 2007, 2008). It is also a large global metallogenic belt that is favorable for the occurrence and formation of various types of ore deposits, such as porphyry Cu-Mo/Au; epithermal Au-Ag, Au-Hg and Hg; pluton-related, sediment-hosted, and orogenic Au; Fe oxide-Cu-Au; VMS; carbonate-hosted Zn-Pb-Ag; and granitoid-related Sn, W, and Sb deposits.

The origin of mercury deposits was first described by Becker (1888). Later, Smirnov (1946) recognized the global metallogenic framework of both the western and eastern margins of the Pacific Ocean. And subsequently more than a century of studies have been conducted by the U.S. Geological Survey, numerous mining companies, and universities in the USA, and by similar organizations in Canada, Russia, Japan, Korea, China, Malaysia, and Australia. Ore deposits and metallogenesis of the Circum-Pacific Orogenic Belt were described in numerous basic works and collected articles (Lindgren, 1933; Ridge, 1968; Tatsumi, 1970; Warren, 1972; Radkevich, 1984).

Of special note are the results of recent researches on special multidisciplinary projects begun by the USGS on the Mineral Resource Program in 1996 to investigate the origin of Au-Hg deposits in northern Nevada and SE China (John et al., 2003; Hofstra et. al., 2003), as well as on the International Project on Tectonics and Metallogenisis of Russian Far East, Alaska, and the Canadian Cordillera (Nokleberg et al., 2005).

Bailey et al. (1973), for the first time, showed the relationship between Hg deposits and post-Jurassic subduction zones, as did the monograph by Russian geologists titled *Metallogeny of Mercury* (Smirnov et al., 1976) that summarized the results of a study of mercury deposits worldwide and described their geologic structure and genesis. These works provide insight into understanding the occurrence and formation conditions of Hg and Au-Hg deposits. Other essential monographs on the main types of mercury deposits are by Bailey and Everhart (1964), Sainsbury and McKevett (1965), Yates et al. (1951), and Yates and Thompson (1959); and major papers on metallogeny by Shilo et al. (1978), Khomich (1995), and Rytuba (1996).

The accumulated knowledge on the genesis of Hg and Au-Hg deposits, conditions of occurrence, specific features of

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ore-magmatic systems, and manifestations in time and space in relation to the geodynamic development of tectonic structures, enable us to perform a global assessment of the metallogeny of Hg and Au-Hg deposits in the active Pacific continental margins.

The Circum Pacific metallogenic map of Hg, Sb, and Au-Hg deposits (at a scale 1:50M) compiled by the authors shows that such deposits occur in the following five geodynamic settings on active continental margins (Obolenskiy and Naumov, 2003):

(1) Above subduction-related thrust-fault zones in obducted oceanic crust of the frontal parts of accreted terrane (Californian type). This type includes the New Almaden (Hg) and New Idria listwaenite type of Au-Hg deposits in the California Coast Ranges, the Tamvatnei (Hg, Sb, W) deposit on the Chukchi Peninsula, and others.

(2) In subaerial settings above subduction volcanism (Toscana type). Typical ore provinces are Toscana in Italy, Peru, Bolivia, etc.

(3) In back-arc rifting zones (Nevada type). An example is the ore belt in the Basin and Range Province in the western USA with the Opalite, Cordero, Carlin, and other large Au-Hg deposits.

(4) In areas of within-plate rifting related to mantle plumes. Such Hg, Sb, and Au-Hg deposits occur in the SE China (Yunan, Guinzhou, and Hunan) province.

(5) In ensialic island-arc systems predominantly in the western Pacific Ocean segment of the circum-Pacific orogenic belt (Japan, Oceanic, New Zealand) there occur small Hg and Au-Hg deposits.

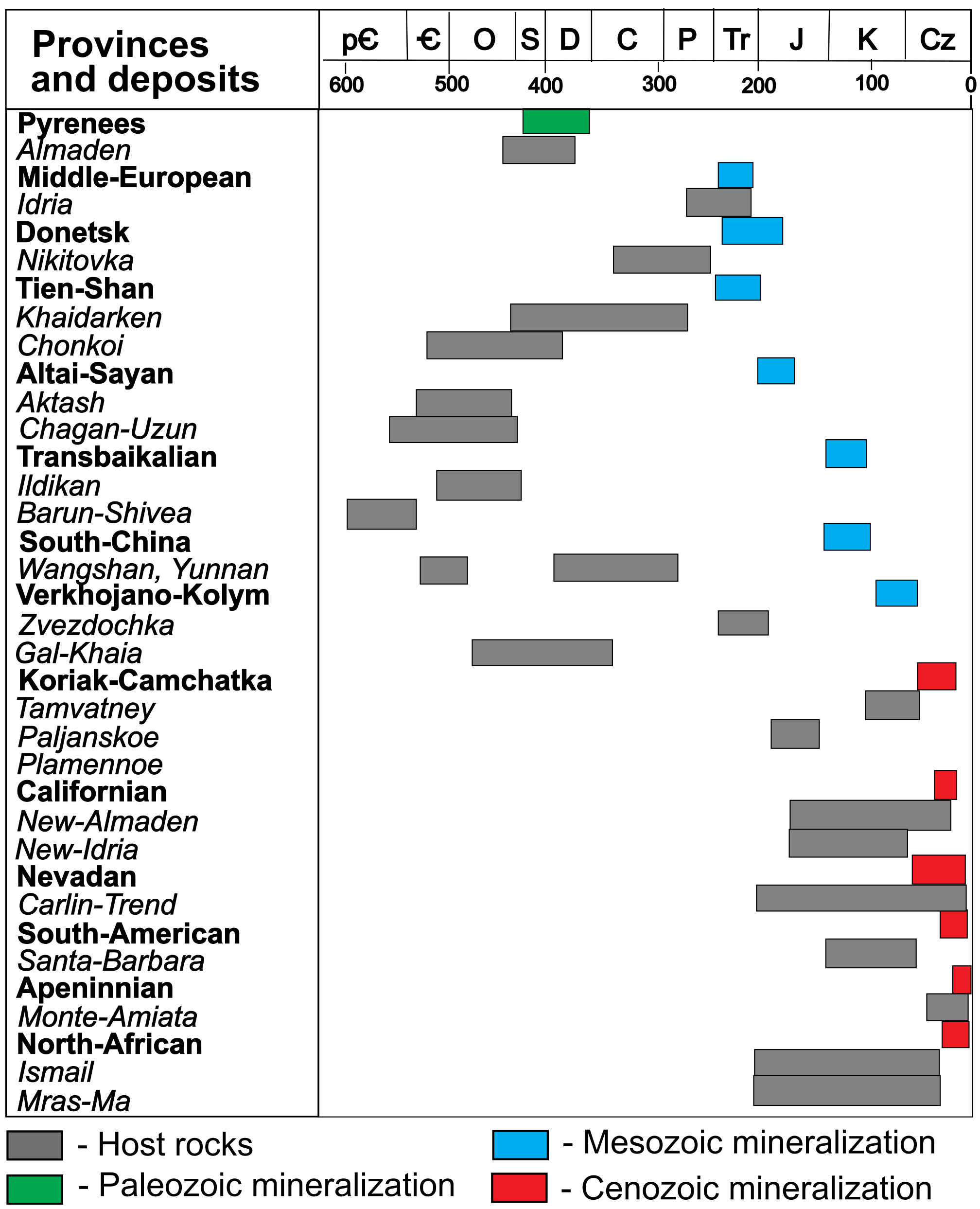

Fig. 1. Epochs of formation of Hg and Au-Hg mineralization.

TABLE 1. Metallogenic belts, major tectonic events, and ore deposits of western North American and Andean parts of the circum-Pacific global metallogenic belt.

Metallogenic belt	Tectonic events	Deposits
Southwestern Alaska (SWA)	Accretion, overlying volcanic belt	Red Devil, Hg Elis, Hg Bessie, Hg Barometer and others, Hg
Canadian Cordillera (CC)	Accretion, transform continental margin faulting	Pinchy, Hg Tackla, Hg Bralorn, Hg
Nevada (NV)	Back arc rifting, mantle plume activity	Carlin Trend, Au-Hg Getchell Trend, Au-Hg Battle Mountain – Eureka Trend, Au-Hg Jerritt Canyon Trend, Au-Hg MacDermott, Opalite, Hg Cordero, Hg and other
California Costal Ranges (CCR)	Accretion, transform continental margin faulting, overlying volcanic belt	New Almaden, Hg New Idria, Au, Hg Knoxville, Au, Hg Staton, Hg Sulfur Bank, Hg Sulfur Springs, Hg Wilburn Springs, Hg Altuna, Hg and other
Mexican and Texan (MX)	Rifting, overlying volcanic belt	Terlingua, Hg Mariposa, Hg Guaitsuko, Hg
Peru (PR)	Accretion, back arc rifting, overlying volcanic belt	Santa Barbara, Hg
Bolivian (BL)	Accretion, back arc rifting, overlying volcanic belt	Yalagna, Hg, Sb, W Oruro, Hg, Sb, W Potose, Hg, Sb, W Emily, Hg
Chile (CL)	Rifting, overlying volcanic belt	Alianza, Ag, Au, Hg Negra, Ag, Au, Hg Punitaki, Au, Hg Huanielo, Cu, Hg Illapel, Cu, Hg

The geodynamic settings of occurrence of Hg and Au-Hg mineralization are defined as metallogenic epochs of formation of these deposits (Fig. 1) as well as their location in particular tectonic units and metallogenic belts (Tables 1, 2). To generalize the metallogeny of Hg, Sb, and Au-Hg deposits in the Pacific active continental margins, the methodology of combined regional metallogenic and tectonic analysis was used that requires: (1) use of modern concepts and mineral-deposit databases, (2) formulation of mineral-deposit models, (3) construction of regional geologic and metallogenic belt maps, (4) interpretation of major geologic units and contained mineral deposits according to latest tectonic methods, and (5) synthesis of an integrated metallogenic and tectonic model (Nokleberg et al., 2007).

MODEL TYPES OF Hg AND Au-Hg DEPOSITS

According to J. Rytuba (*in* Cox and Singer, 1986; Rytuba, 1996, 2005) three distinct model types of Hg deposits occur in the Hg mineral belts on the Earth: Almaden type Hg deposit well known in Iberian belt in central Spain (Hernandez et al., 1999; Higueras and Munha, 1993). Silica-carbonate and hot-spring type deposits are commonly present in most of the Hg mineral belts but do not occur in association with Almaden type deposits. The Hg sulfide cinnabar and more rarely its high temperature polymorph metacinnabar are the main ore minerals in the three Hg deposit types. Elemental Hg is abundant in some Hg ores, and Hg sulfates, chlorides, and oxides are present in minor amounts in silica-carbonate and hot-spring type deposits (Rytuba, 2005; Table 1).

In analyzing the model types of Hg the three main types can be supplemented with at least three more types: (1) silica-carbonate (listwaenite), Au-Hg (New Idria), and As-Hg-W (Tamvatney); (2) volcanic- and carbonate-hosted Hg and Au-As-Hg; and (3) carbonate-jasperoid-hosted Sb-Hg and Au-Sb-Hg types. These three types are briefly described, as follows.

(1) Silica-carbonate (listwaenite) Au-Hg (New Idria, Knoxville in California) and Sb (±As)-Hg-W deposits (Obolenskiy, 1985; Obolenskiy et al., 2003) consist of cinnabar and associated minerals along contacts of serpentinite and

TABLE 2. Metallogenic belts, major tectonic events, and ore deposits of the eastern Asian branch of the circum-Pacific global metallogenic belt.

Metallogenic belt	Tectonic events	Deposits
Chukotka (CHK)	Transform continental margin and associated overlying volcanic-plutonic belt	Palyan, Hg Plamennoe, Hg Matachingay, Hg
Koryak-Kamchatka (KK)	Accretion; overlying volcanic belt	Tamvatney, Hg, Sb, W Olutorskoe, Hg Anavgay, Hg Apapel, Au, Hg
Sakhalin (SHK)	Accretion, overlying volcanic belt	Svetloe, Hg Nadezhda, Hg Mereiskoe, Hg Biruza, Hg Yn'skoe, Hg
Sikhote-Alin (SA)	Overlying subaerial volcanic belt	Boguchanskoe, Hg Severnoe, Hg, Netka, Hg
Japanese (JPN)	Ensialic island arc, overlying volcanic belt	Ytomuka, Hg Kitano, Ag, Au, Hg Ykotovara, Ag, Au, Hg Ebisutate, Au, Sb, Hg
Southeast Chinese (SEC)	Rifting, mantle plume activity	Wangshan, Hg Danjay, Hg Suntao, Hg Dongbaishan, Au, Hg Quioluo, Au, Hg Zimudang, Au, Hg
East Australian (EA)	Rifting	Kilkivan, Hg Spring-Creek, Hg Little River, Hg
North New Zealand (NNZ)	Ensialic island arc, overlying volcanic belt	Ngawha, Pui Pui, Taupo VZ

siltstone-graywacke, and limestone, that occur in major thrust zones. The deposit minerals are mainly cinnabar, along with stibnite, pyrite, realgar, orpiment, arsenopyrite, sometimes Au, Ni, and Co minerals, and scheelite. Gangue minerals are mainly dolomite, breunnerite, and ankerite in association with quartz, calcite, dickite, fuchsite, and talc. The deposits occur in masses, veins and disseminations in irregular lenses, in veins in crush breccia and mylonite zones, and in adjacent sedimentary rocks. Cinnabar is closely associated with silica-carbonate (listwaenite) and argillic alteration. The depositional environment consists of zones of thrust faults containing lenses of serpentinite, ultramafic rock, and greywacke. Deposits generally occur in accretionary-wedge and subduction zone terranes in association with subduction-related thrust faults, and are often reactivated by younger intraplate movement.

(2) Volcanic- and carbonate-hosted Au-As-Hg deposits (Carlin type) (Hofstra and Cline, 2000; Borisenko et al., 2006) occur in areas of volcanogenic-hydrothermal Au-Pb-Zn, Au-Ag, and Sb-Hg types of mineralization, and are genetically associated with basalt-andesite-rhyolite volcanism (Carlin, Cortez, and Bell deposits in Nevada) of rare rifting settings. The most famous deposits of this hydrothermal mineralization are in the Nevadan gold-ore belts, USA. Beginning in the Eocene (40.3 Ma), Au-Ag and Sb-Hg deposits as well as Carlin-type Au-As-Hg mineralization formed in several stages. The period 40.3-36.2 Ma was the most producing: At that time, large Carlin-type Au-As-Hg deposits (Carlin, Cortez, Getchell, Betze, and others) formed; their total gold reserves are estimated at several thousands of tons (Emsbo et al., 2006; Ressel and Henry, 2006).

Gold mineralization in ore clusters and districts with Carlin-type Au-As-Hg deposits is produced at two levels: (1) surface (travertines and lacustrine sediments of the Waiotapu, Broadlands, and Rotokawa thermal springs in New Zealand and Steamboat Springs in Nevada, El Tatio geyser in Chile), and (2) subsurface (mineralized crush zones and sheet-like bodies - Carlin, Getchell, and Betze deposits in Nevada). In some ore clusters, there is a distinct vertical change in mineralization of different depth levels up to mesothermal (Borisenko et al., 2006).

(3) Deposits of carbonate-jasperoid-hosted Sb-Hg and Au-Sb-Hg model types occur beyond volcanic areas, but are intimately associated with intrusive calc-alkalic and potassic calc-alkalic rock complexes. They are spatially and genetically associated with plutonic-hydrothermal gold-sulfide (gold-arsenopyrite), and, likely, Au-Sb types of mineralization, as confirmed by the fact that they are localized in the same geologic settings and are formed by ores of the same age and

mineral and geochemical compositions. Such deposits occur in the South Chinese Platform, upper Yana region in Yakut (Kyuchyus deposit, Levaya Sakyndzha ore cluster).

Large deposits of Au-Sb-Hg model types are localized predominantly in carbonaceous terrigenous sediments (Kyuchyus, Gold Quarry, etc.) or carbonate rocks (deposits in SE China, Levaya Sakyndzha ore cluster, etc.). Ores occur as mineralized crush zones and substrate or cross-cutting orebodies.

The gold-antimony-mercury ore association is similar to the gold-arsenic-mercury association in geochemistry (Au-As-Sb-Hg-Tl (±Mo, ± W)) and mineral composition (fine gold, As-pyrite, minerals of As (arsenopyrite, realgar, orpiment), Hg (cinnabar, saukovite, Hg-fahlores), and Tl (carlinite, lorandite, routhierite, etc.), antimonite, scheelite, clay minerals, chalcedony-like quartz, etc.). In contrast to Au-As-Hg deposits, Au-Sb-Hg deposits have elevated contents of W (scheelite), Cs (galkhaite), and Rb (clay minerals) and somewhat lower contents of Tl. Gold of ores localized in aluminosilicate rocks has high contents of Hg – up to 26 wt.% (Kyuchyus, and other deposits), and gold of ores present in carbonate rocks is poor in Hg – usually <1-2 wt.% (Fig. 2).

In some ore districts, Au-Sb-Hg mineralization is spatially associated with other consanguineous types of mineralization – Au-As and Sb-Hg. The genetic relations between these types of mineralization were considered in detail by the example of ore deposits in NE Russia and Northern Nevada (John et al., 2003). They were also comprehensively studied in SE China (Qinling and Yunnan-Hunan belts) (Rui-Zhong et al., 2002; Mao et al., 2002) by the example of various deposits: Au-As (Shijiba, Mingshan, etc.); Au-As, with antimonite and scheelite (Manaoke, Jiaozio); Au-Sb-Hg (Lannigou, Zimudang, Dongbeizhai, Getang, etc.); and Sb-Hg (Wangshan, Wuchuan, etc.). There are vertical and lateral mutual transitions between these types of mineralization at some deposits. Gold-sulfide mineralization with scheelite is localized at lower levels; Au-Sb-Hg mineralization at the upper levels; and Au-As mineralization with antimonite (± cinnabar) occurs at middle levels. Mercury mineralization is usually localized along the periphery of gold-sulfide and Au-Sb-Hg ore clusters separately from the other type of mineralization.

EPOCHS OF FORMATION OF Hg AND Au-Hg MINERALIZATION

Analysis of the setting of Hg and Au-Hg deposits indicates their joint deposition sites in the well-known metallogenic belts: Pacific-Ocean, Mediterranean, and Central Asia (Smirnov et al., 1976; Obolenskiy and Naumov, 2003). Ancient Precambrian Au-Hg deposits of Canada, South America and Australia, which are localized in the separate ore districts and controlled by rifting structures of the ancient cratons, occur beyond the limits of the belts. Different ages and geodynamic environments are typical for the Hg and Au-Hg deposits in recognized global metallogenic belts, and particularly for the Pacific Ocean global metallogenic belt.

In the formation of Hg and Au-Hg deposits, two metallogenic epochs, Mesozoic (T-J) and Cenozoic (Cz), are recognized (Fig.1). Mercury and Au-Hg deposits of the Verkhoyano-Kolym, Okhotsk-Chukotka, and Primor'e provinces as well as the Mongol-Okhotsk mercury belt in Russia formed in the Late Jurassic to Early Cretaceous. The Late Mesozoic (J-K) is the most significant time span of Hg and Au-Hg mineralization with deposits forming in the central part and in the eastern margin of the Asian continent along an active transform continental margin. According to the available data, the deposits of southeastern China are about this age (Rui-Zhong et al., 2002) and related to Emeishan plume

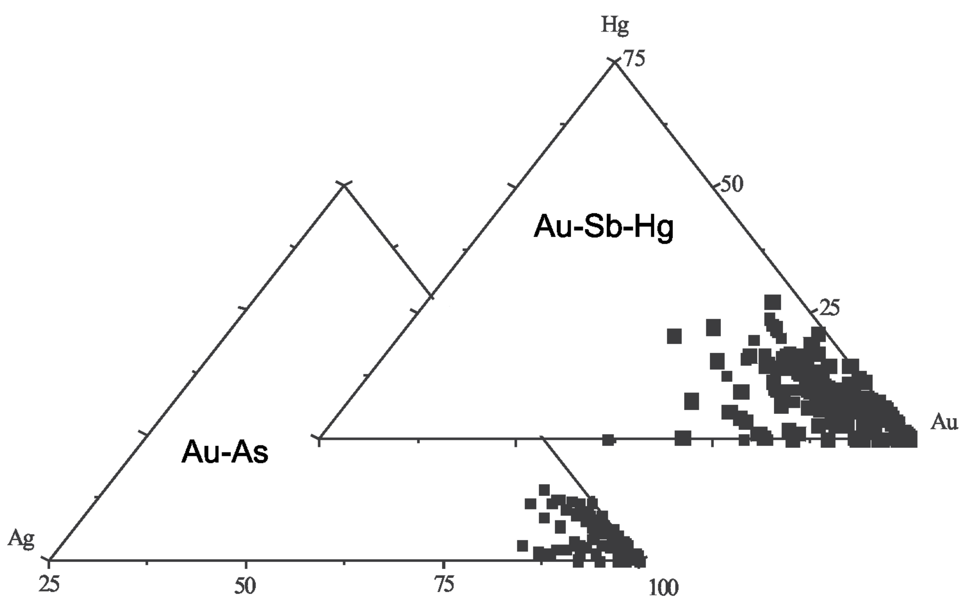

Fig. 2. Composition of native gold in Au-As and Au-Sb-Hg ore associations.

magmatic activity (Chung and Jahn, 1995; Borisenko et al., 2005, 2006).

The formation of mercury metallogenic belts in the Cenozoic is related to the displacement of the Laurasia and Gondwana fragments because of the opening of the Atlantic Ocean, and coincides with the latest stages of formation of the Andean and Californian continental-margin structures. Most Hg and Au-Hg deposits in the western USA (New Almaden, New Idria, etc.) occur in the ocean crust fragments (Franciscan group) obducted on the ancient hard plate. The age of these deposits is Miocene - 10-12 Ma. (Bailey and Everhart, 1964).

According to H. De Boorder (De Boorder et al., 1999), slab subduction under western North America was more complex than in most other orogenic belts. Here, an opening through the subducted Farallon Plate into the asthenosphere was created during subduction of the Pacific Rise. Its position is imaged in tomography and is seen to underlie the epithermal volcanic-hosted and porphyry-related deposits in the Great Basin and in the Coast Ranges of California (Thorkelson and Taylor, 1989; Haeussler et al., 1995). An earlier phase of slab detachment is seen, which at the time of tearing would have underlain belts of porphyry and volcanic-hosted mercury and antimony deposits in northern Mexico.

A different tectonic process to explain the origin of tectonic structures of the Nevadan belt and evolution of Cenozoic (40 Ma) magmatism began around 20-15 Ma, when typical bimodal calc-alkaline magmatism gave way to alkaline-basalt magmatism, and at 5 Ma to basalt magmatism. This is most satisfactorily explained by the influence of Yellowstone mantle plume and influence of the volcanic arc geodynamic environment on riftogenesis. The most important ore-magmatic systems of porphyry-Cu-Mo and Au-Hg epithermal deposits were formed at the boundary of 45-35 Ma, and also at 26-22 and 9-5 Ma. The intensity and duration of ore-forming processes in the Nevadan belts may be explained by the consecutive influence of mantle plumes on tectonic structure formation, magmatism, and associated ore-forming process (Oppliger et al., 1997; Muntean et al., 2004).

METALLOGENIC BELTS OF Hg AND Au-Hg DEPOSITS

A review of the spatial and temporal distribution of the different styles of geodynamic settings along the east Asian and west American and Andes branches of Circum-Pacific metallogenic belt highlights the heterogeneous appearance of Sb-Hg and Au-Hg deposits in space and time (Fig. 3, 4).

In western North America and the Andes, eight Hg and Au-Hg metallogenic belts possess units favorable for occurrence of Hg, Hg-Sb, Hg-Sb-W, Ag-Au, Au-Hg deposits, including southwestern Alaska and Canadian Cordilleras, California Coastal Ranges, Nevadan (Basin and Ranges), Mexican, Peru, Bolivian and Chile belts (with Hg and Au-Hg volcanic and sediment-hosted, Au-Hg carbonate-jasperoid-hosted, and Hg and Au-Hg hot-springs model types).

The unique metallogenic belt in the Nevadan Basin and Ranges province contains large and super-large Au-Hg Carlin-type gold deposits, distal disseminated Ag-Au; epithermal-high-, intermediate-, and low-sulfidation Au, low-sulfide Au-quartz vein deposits, and some others (Table 1, Fig. 5).

A large number of Au model types, and especially Au-Hg deposits of the Basin and Range province, are localized mainly in the back-arc tectonic setting over the rifted North America paleocontinental margin (Emsbo et al., 2006). The intensity and duration of ore-forming processes in the Nevadan belt may be explained by the consecutive influence of mantle plumes on tectonic structure formation, magmatism, and associated ore-forming process (Oppliger et al., 1997; Ressel and Henry, 2006; Fig. 5).

In the East Asian branch, Hg and Au-Hg metallogenic belts possess units favorable for occurrence of Hg, Hg-Sb, Hg-Sb-W, and Au-Hg deposits, including Chukotka, Koryak-Kamchatka, Sakhalin, Sikhote-Alin, Japanese, East Australian, and North New Zealand belts (with Hg volcanic and sediment-hosted, Hg and Hg-Sb-W silica-carbonate (listwaenite), and Hg, Sb, and Hg, Sb, W, Au-hot springs model types). The southeast Chinese metallogenic belt is unique, with world class Au-Hg Carlin-type gold deposits; Hg and Sb-Hg carbonate-jasperoid-hosted, and Sedex-Ba deposits (Fig. 6, Table 2) that are related to intraplate rifting caused by Emeishan mantle plume activity (Chung and Jahn, 1995).

CONCLUSIONS

Mesozoic and Cenozoic Hg and Au-Hg deposits occur along active continental margins, ensialic island-arcs, accretionary complexes of subduction zones, overlying continental volcanic belts, and in the back-arc and intraplate rifting structures. There is a close relation between Hg and Au-Hg deposits in this geodynamic environment, with common ore-forming epithermal and volcanogenic-hydrothermal systems.

A review of spatial and temporal distributions of large Hg and Au-Hg deposits along the global Pacific Ocean Metallogenic Belt identified the leading influence of mantle plume magmatic activity in the metallogenic belts connected with complex geodynamic environments and superimposed heterogenous gold and mercury mineralization (Sedex, pluton related and epithermal).

The use of principles of plate tectonics and deep-level geodynamics indicates areas to be explored for new Hg and Au-Hg deposits, and new ones will probably be formed along the favorable metallogenic belts. Most of the undiscovered resources of the past century have come from new ore bodies to be found in districts that were being exploited.

Origin and geologic occurrence of known deposits provide the best clues about where to look and the best data for predicting the potential of unexplored areas.

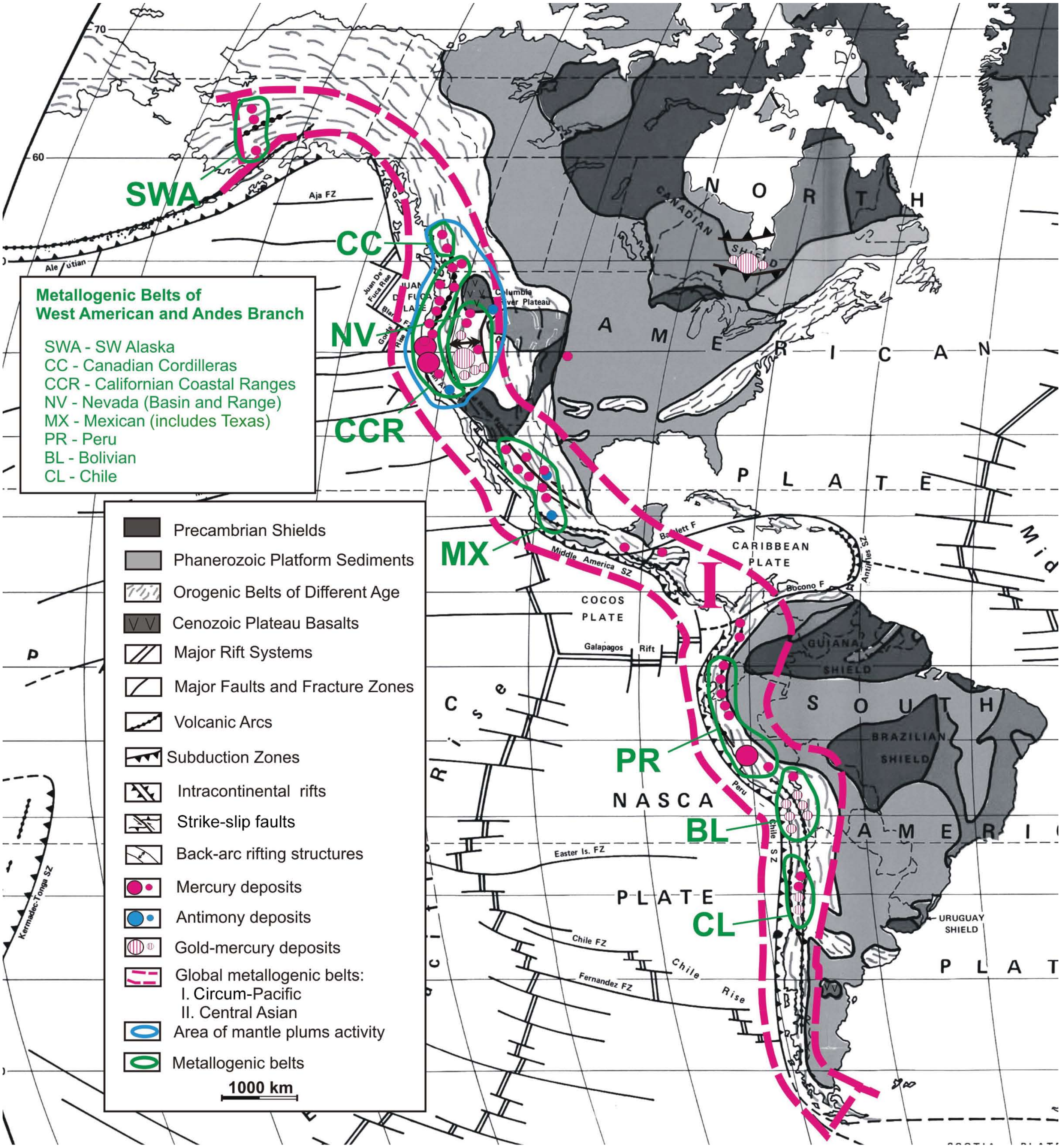

Fig. 3. Metallogenic belts of western North America and Andes branches of the circum-Pacific global metallogenic belt. See Table 2 for explanation of abbreviations.

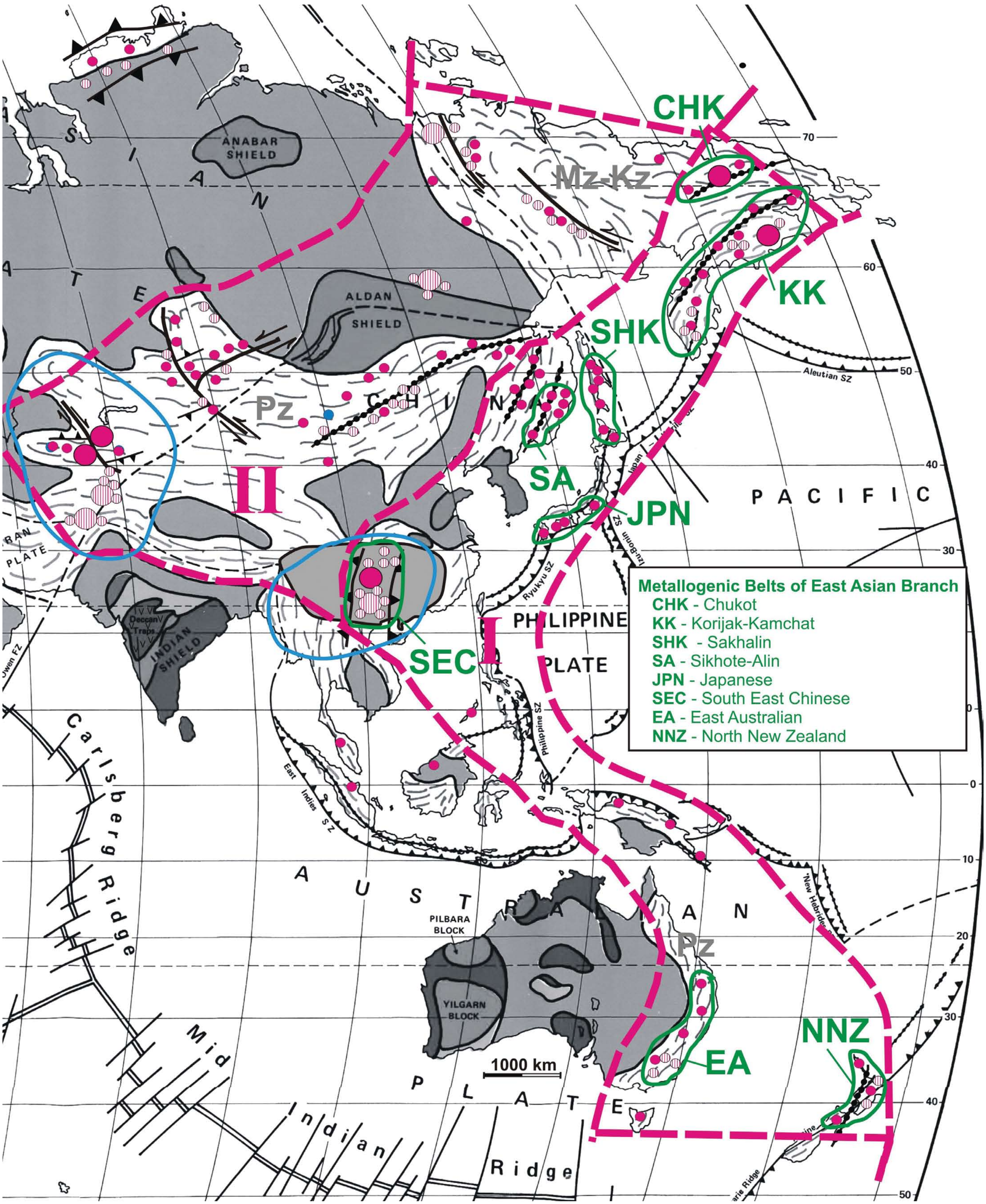

Fig. 4. Metallogenic belts of east Asian branch of circum-Pacific global metallogenic belt. See Table 2 for explanation of abbreviations.

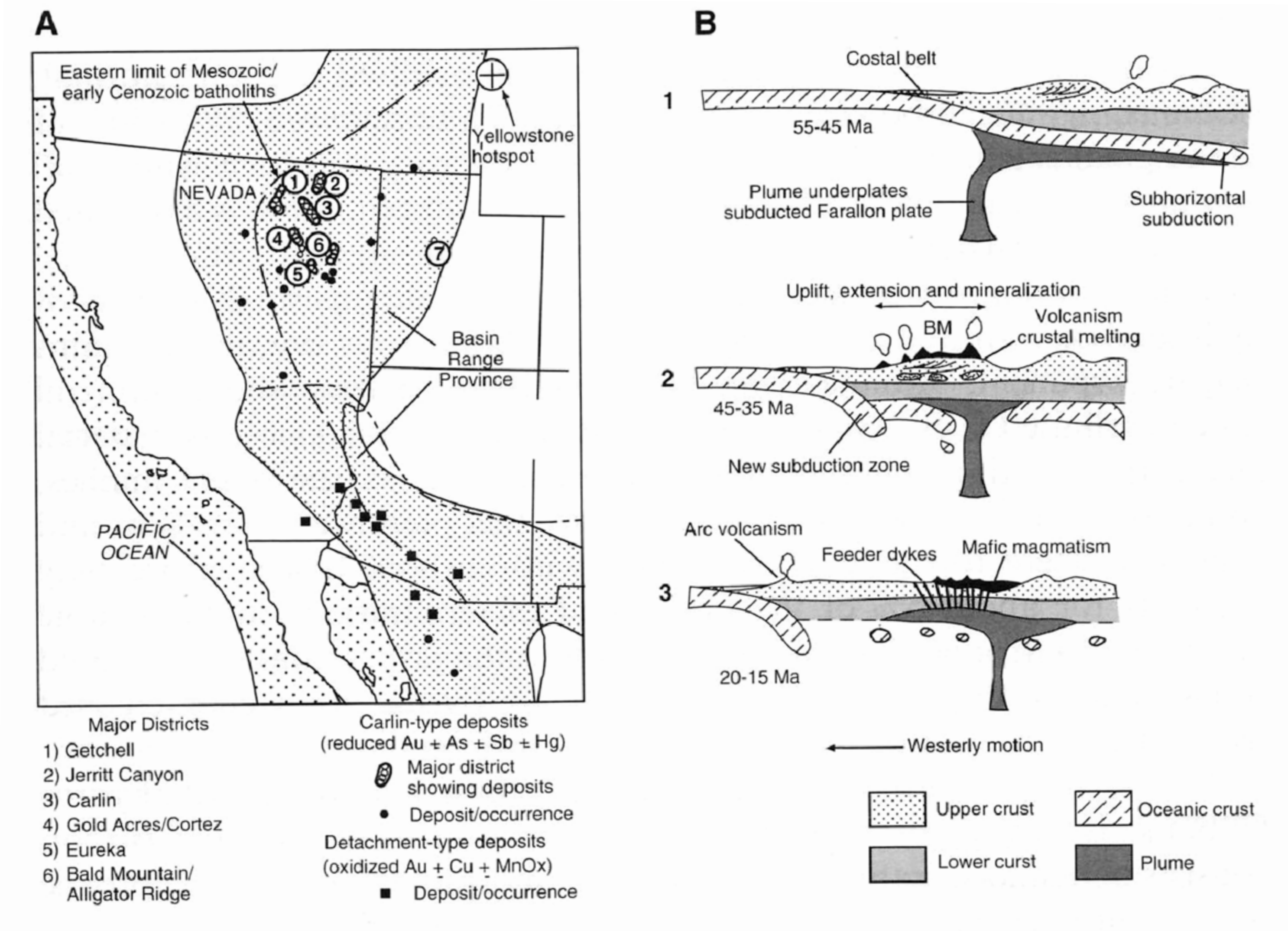

Fig. 5. Schematic model of Basin-and-Range province showing relation of Carlin-type deposits to plume magmatism (after Pirajno, 2000).

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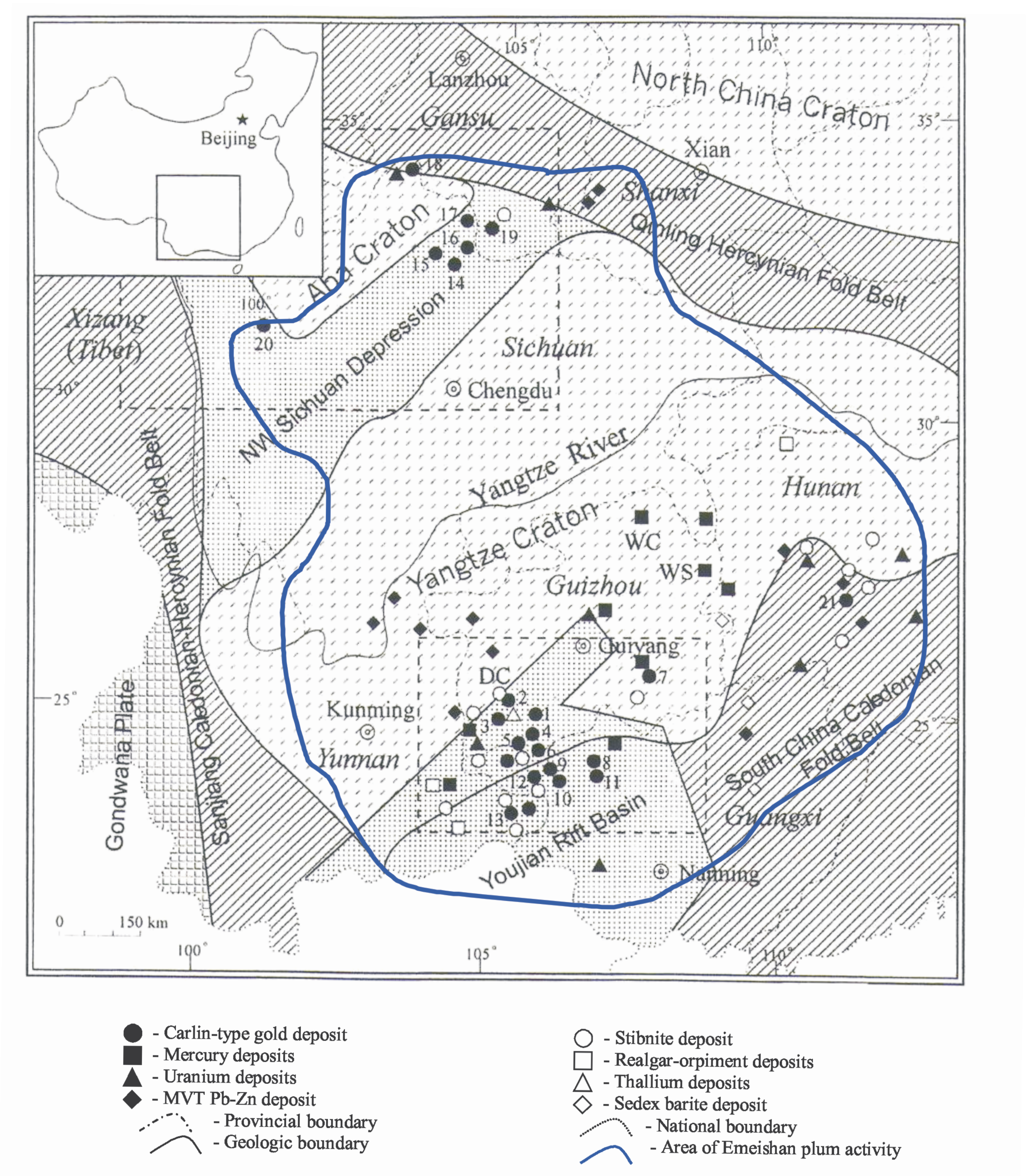

Fig. 6. Ore mineralization related to Emeishan plume activity (blue line) in the southeastern China metallogenic belt (after Rui-Zhong et al., 2002). Numbers of Carlin-type gold deposits: 1. Lannigou; 2. Zimudang; 3. Getang; 4. Yata; 5. Banqi; 6. Baidi; 7. Danzhai; 8. Jinya; 9. Longhe; 10. Sijia; 11. Mingshan; 12. Gaolong; 13. Gedang; 14. Qiaoqiao shang; 15. Dongbeizhai; 16. Lianhecun; 17. Manaoke; 18. Laerma; 19. Pingding; 20. Qiuluo; 21. Gaojiaao.

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