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The Correlation of Mesozoic Gold Ore Districts at the Sino–Korean and Aldan–Stanovoi Shields

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Abstract—The geological structure and gold ore potential of the activized Aldan–Stanovoi and Sino–Korean shields of East Asia are compared. These two regions show similar tendencies in their geological evolution during the Archean, Proterozoic, and Phanerozoic epochs but differ in types of tectonic structure and associations of ore deposits. According to recent studies by Russian and Chinese geologists, the Mesozoic complexes of these shields possess higher gold ore potential than was suggested before. As a result of these studies, the amount of conditions favoring the formation of large gold districts and deposits in the activized shields has strongly increased. Some of these deposits are polychronic and polygenetic (the Bam deposit), others are associated with J–K alkaline magmatism (the Central Aldan district), a third group of deposits are related to granites of the same age (the East Shandong district), and a fourth group includes stratiform deposits in the lower part of the udokan series (Ugui district). The various Mesozoic hydrothermal ore deposits of the northern framework of the Sino–Korean Shield are especially interesting. The study of problems of gold metallogeny was initiated in Russian geological science by Yu.A. Bilibin (1935–1940) in the central part of the Aldan Shield. Some new data concerning the gold ore potential of the Sino–Korean Shield extend our knowledge of gold ore districts in East Asia and make clear the necessity of more careful and systematic study of the gold ore potential of the Aldan–Stanovoi Shield.

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INTRODUCTION

Interest in large and superlarge mineral deposits is increasing year by year (Rundquist *et al.*, 2004). The key objects of study commonly are the ore deposits, discriminated by the reserves of the main economic metal. However, some of the deposits relate to regions containing other types of ore deposits with the same age. An example of such a region is the Central Aldan Au–U ore district, including the polygenetic Kuranakh Au deposits, hydrothermal gold deposits of the Lebedinsk and Ryabinovsk types, Au–U deposits of the El'kon type, gold-bearing placers, and some other types of ore mineralization.

Various terms are used for large and superlarge ore deposits. The authors use Laznicka's (1989) definition, which includes in this category deposits with unique reserves and genesis. Correspondingly, with this definition, not only deposits but also unique ore districts can be distinguished.

The study of the geological position and structure of large and superlarge deposits as components of ore districts enables a better understanding of their relation to the geotectonic units of the Earth's crust: cratons, ancient platforms, shields, orogenic belts, and so on. Such the study provides additional data concerning the conditions of deposit genesis and spatial distribution as well.

Many publications are devoted to the geological structure of old shields and related Precambrian gold deposits, so it is not necessary to cite them. The Mesozoic tectonic, magmatic, and ore-forming processes in old shields are less studied. This can be explained by more local manifestation of the Mesozoic tectonic activization, mainly restricted to the Aldan–Stanovoi and Sino–Korean shields, which relate to the outer zone of the Pacific ore belt (*Tectonics of* …, 1966; Chen Guo-Da, 1992).

Data concerning the gold metallogeny of East Asia in Russian publications were based for a long time on comparison between Mesozoic gold ore belts and deposits of the Russian Northeast, the Okhotsk–Chukotsk volcanic–plutonic belt, the Mongol–Okhotsk fold belt, activized regions of the Transbaikal region, and the Aldan Shield. Results of these studies are included in many publications and are well known, so they are not listed here. However, one point should be emphasised. It relates to the discovery and study of many hydrothermal gold deposits in Eastern and Central China with total reserves 4500 t of gold. A half of these reserves are concentrated at the Sino–Korean

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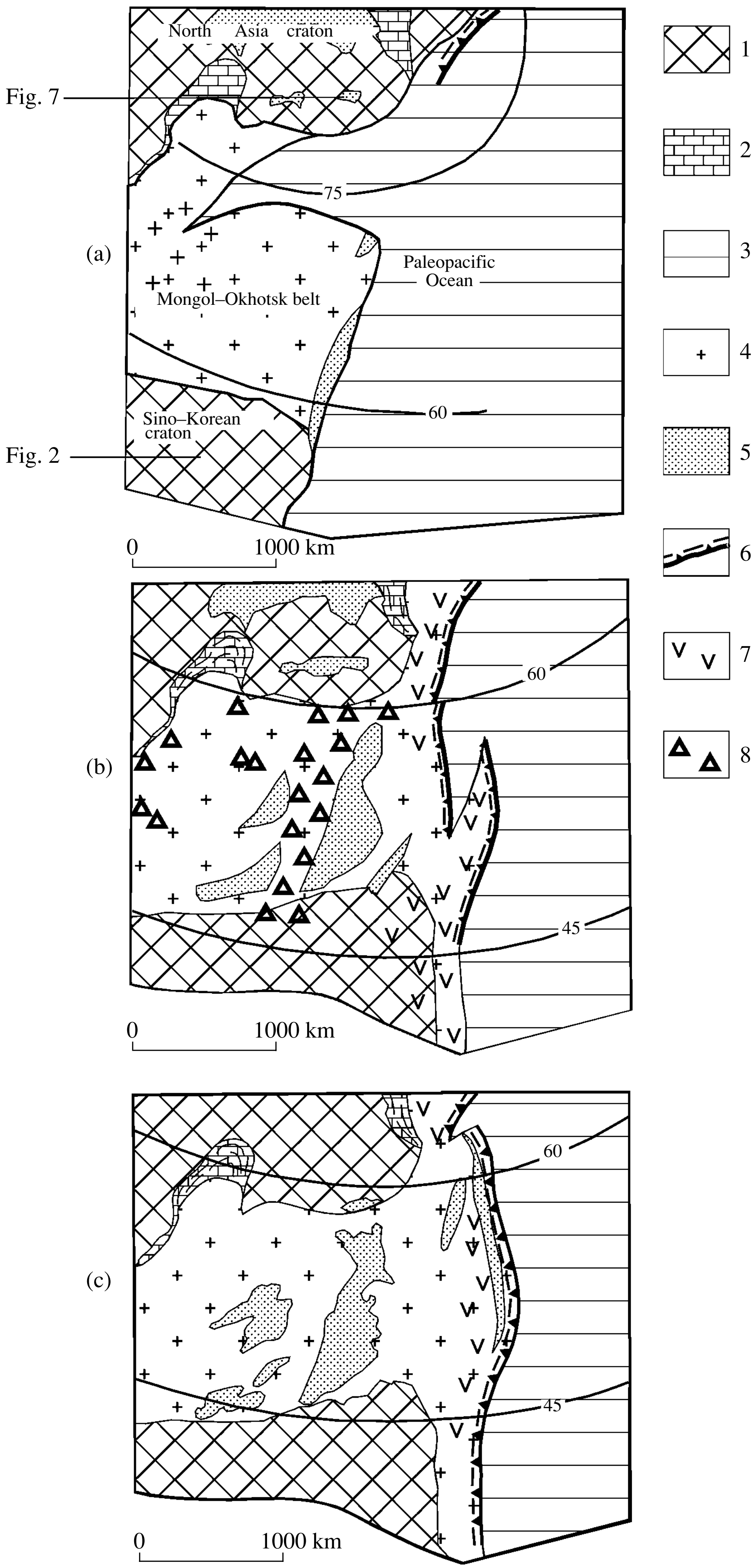

North Asia craton
Fig. 7
75
(a)
Paleopacific
Ocean
Mongol–Okhotsk belt
60
Sino–Korean
craton
Fig. 2
0 1000 km
1
2
3
4
5
6
7
8
60
(b)
45
0 1000 km
60
(c)
45
0 1000 km

Shield and in the fold belts of its framework. It can be suggested, taking into account the fundamental paper of Smirnov (1946) concerning the metallogeny of the Pacific ore belt, that the region with the highest concentration of Mesozoic hydrothermal gold deposits occurs in the central part of the outer zone of this belt and not in the northeast of Asia.

POSITION OF THE ALDAN–STANOVOI AND SINO–KOREAN SHIELDS IN THE STRUCTURES OF EAST ASIA

The concept of the East Asia geotectonics has strongly changed during the last 10–15 years as compared with the tectonic map of Eurasia (1965). The most important changes relate to the development of plate-tectonic models of the formation of the late Riphean, Paleozoic, and early Mesozoic orogenic belts bordering the North Asia and Sino–Korean cratons and the Mesozoic and Cenozoic orogenic belts at the northwestern border of the Pacific Ocean (Parfenov *et al.*, 2003). Within this systematics, cratons are considered as big continental blocks—the cores of the recent continents. There continental cores formed in the late Precambrian as a result of the destruction of Rodinia and included the ancient platforms with their lifted parts and lowered pericraton margins, which consist of fold belts lying on the metamorphic basement. The orogenic belts include deformation structures that were formed at the place of the oceanic basin and (or) of its borders as a result of the terrane accretions to the cratons or of continental block collisions. However, these belts do not contain collision granites or conjugated marginal depressions. The orogenic belts differ in age and rock composition, but all of them contain accretionary wedges and oversubduction magmatic bodies and island arcs and are accompanied by adjacent belts of the active continental margins.

Paleotectonic reconstructions for the T–K_2 of the discussed territory are shown in Fig. 1a. The territory includes the southern part of the North Asia Craton (with the Aldan–Stanovoi Shield), the northern part of the Sino–Korean Craton (Shield), and the Mongol–Okhotsk belt dividing these shields.

The western part of the late Paleozoic–early Mesozoic Mongol–Okhotsk orogenic belt completed its activity 320–280 Ma. The activity in the East Transbaikal region was completed in the early to middle Jurassic, and at the eastern part of the belt, in the middle Jurassic. The time of the beginning of the belt formation is not known. It is also not clear if the North Asia and Sino–Korean cratons formed a unit block in the early Precambrian.

It is important that intensive rifting, intrusive, and volcanic activity began in the Mongol–Okhotsk belt and in the eastern parts of both cratons in the middle Jurassic–early Cretaceous (Fig. 1b). The magmatism was commonly intraplate subalkaline related to epicontinental grabens. At the Aldan Shield, the alkaline magmatism predominated at that time, but at the boundary with the Paleopacific Ocean oversubduction acid volcanic and plutonic belts formed. The intraplate rifting and magmatic activity were completed at the Cenomanion–Campanian (Fig. 1d). It is these brief events that were named the Mesozoic tectono–magmatic activization of the gold-bearing shields in East Asia (Kazansky, 1972; Yanovsky *et al.*, 1995; Safonov, 2003).

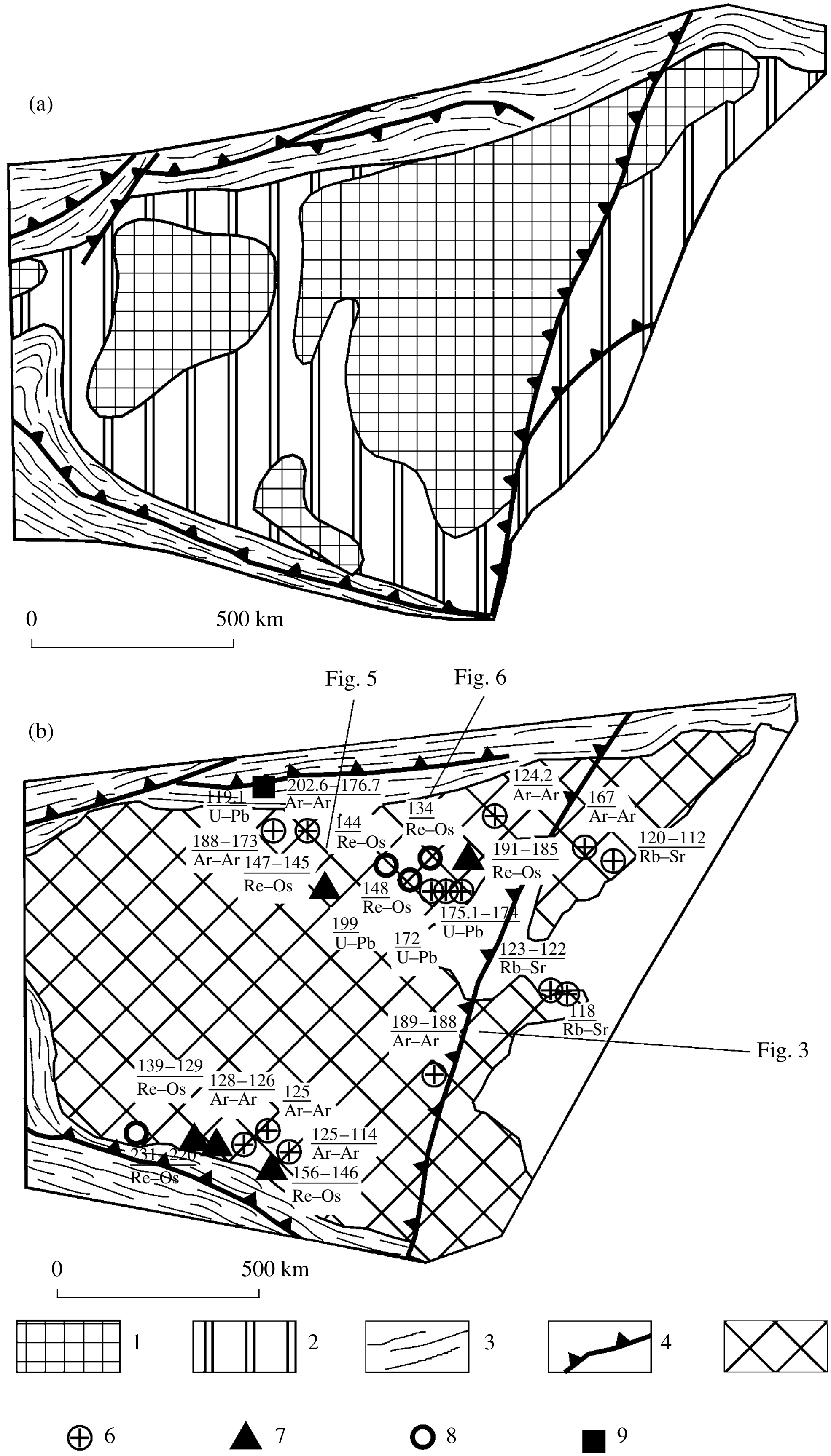
THE SINO–KOREAN SHIELD

The Sino–Korean Shield is also known as the North China Craton and by some other names. Archean and early Proterozoic metamorphic complexes form the crystal basement of this shield, as at the Aldan Shield. However, these complexes are overlain by myogeosynclinal or paraplatform sedimentary series (2.0–1.4 Ga), which form the second structural stage of the basement (Fig. 2a). The Sino–Korean Shield has no thick sedimentary cover, in contrast with the Siberian Platform. The cover there has a triangle morphology, joins with the Pacific Ocean plate at the East, and is bordered at the SW and NW with Paleozoic and early Mesozoic orogenic belts: the Tien Shan and the marginal part of the Mongol–Okhotsk belt, respectively. The internal structure of the Sino–Korean Shield is dominated by a combination of Archean cores, protoplatform blocks, and large faults with various strike (Wang and Mo, 1995).

The marginal zones of the Sino–Korean Shield underwent intensive tectonic deformations in the late Paleozoic and especially in the Mesozoic. They were caused by collision of the shield with the Yangtse craton at the SW, by subduction of the Pacific plate under the shield at the east, and by the influence of the Mongol–Okhotsk belt in the north.

All these geological events form the three stages of the metallogenic evolution of the Sino–Korean Shield. The formation of iron ores (Anshan region) and massive sulfide Pb–Zn deposits (Hongtoushan) relate is to the first, Archean stage. At the next, early Proterozoic stage, the stratiform boron-bearing and Pb–Zn bodies, the biggest magnesite deposits, and small uranium deposits in Na metasomatites (Lianshanguan) were formed (Shaokang, 1996). The Archean cores of the Sino–Korean Shield have no granite–greenstone complexes typical for other old shields, and the protoplat-

Fig. 1. Paleotectonic reconstructions in East Asia for the Mesozoic (after Parfenov *et al.*, 2003; simplified); (a) late Triassic–early Jurassic (210 Ma); (b) middle Jurassic–early Cretaceous (145 Ma); (c) Cenomanian–campanian (87 Ma). 1—Cratons; 2—passive continental margins of cratons; 3—oceanic crust; 4—collage of accretional terraines; 5—sedimentary basins; 6—subduction zones; 7—oversubduction magmatic rocks; 8—intraplate magmatic rocks.


(a)
0
500 km
Fig. 5
Fig. 6
(b)
202.6–176.7
Ar–Ar
119.1
U–Pb
124.2
Ar–Ar
167
Ar–Ar
134
Re–Os
144
Re–Os
188–173
Ar–Ar
147–145
Re–Os
191–185
Re–Os
120–112
Rb–Sr
148
Re–Os
175.1–174
U–Pb
199
U–Pb
172
U–Pb
123–122
Rb–Sr
118
Rb–Sr
189–188
Ar–Ar
Fig. 3
139–129
Re–Os
128–126
Ar–Ar
125
Ar–Ar
125–114
Ar–Ar
231–220
Re–Os
156–146
Re–Os
0
500 km
1
2
3
4
5
6
7
8
9

form rocks of the early Proterozoic were metamorphosed in low amphibolite to (rare) greenschist facies. The last metamorphic event has an age of 1.9 Ga and was accompanied by intrusion of potassic granites and pegmatites. The so-called Liaojitile suite, containing mainly tourmaline–feldspathic leptinites with underlying granites, occupies a specific position in the early Proterozoic. It forms rimmed cupolas and is overlain by the turbidite series with stratiform Pb–Zn deposits. The Rb–Sr age of the albitic leptinite is 2047 ± 72 Ma. The Liaojitite suite contains ludwigite bodies and phlogopite and phlogopite–diopside veins. Probably, it was formed in an aulacogen on the Archean basement (Chang Quisheng, 1983). It seems possible to conventionally correlate the Liaojitite suite with the Fedorovsk suite at the Aldan Shield, but in the latter ludwigite and phlogopite associate with magnesian skarns.

There are no fold belts on the basement in the Sino–Korean Shield, in contrast with the Siberian pericraton margins. Nonmetamorphosed sedimentary cover occurs discretely and consists of near-shore and shallow sea sediments of late Proterozoic, Vendian, Cambrian, and Ordovician age. The upper Carboniferous and Permian sediments are continental detrital and carbonate rocks, and Triassic ones are alluvium and lake sediments.

The strong change in the tectonic and magmatic activity and in ore formation in the early Jurassic is called by some Chinese geologists a "metallogenic explosion." It is clearly marked by the Re–Os, Ar–Ar, Rb–Sr, and U–Pb isotope dating of the hydrothermal Au, Cu–Mo, and Pb–Zn deposits (Fig. 2b). These Mesozoic deposits occur in the eastern part of the shield adjacent to the Pacific plate and were formed during three stages or three metallogenic events: 200–160, around 140, and 130–110 Ma (Mao *et al.*, 2003). The intensive gold ore formation at the Sino–Korean Shield and adjacent Pz–Mz orogenic belts relates to exactly this "metallogenic explosion."

Three-quarters of the gold deposits in China occur within the marginal structures of the Sino–Korean Shield (Zhou *et al.*, 2002). Half of them relate to the lifted blocks of the early Precambrian metamorphic rocks, and the other half relate to the phanerozoic granites. Such a distribution distinguishes this shield from other old shields, including the Aldan Shield. Three main gold ore provinces are distinguished in the Sino–Korean Shield today: Shandong, North China, and Syao–Tsinlin. The occurrence conditions of gold deposits are discussed below for the East Shandong ore district and three ore districts in the northern part of the Sino–Korean Shield (Zhangjiakou, Yanshan, and Chifeng).

THE EAST SHANDONG GOLD DISTRICT

The basement of the East Shandong district consists of granulites, gneisses, amphibolites, and biotite gneisses having an age of 2.94–2.67 Ga (Fig. 3). They are overlain by early Proterozoic metavolcanics, amphibolites, and crystal schists. Late Proterozoic rocks are phyllites and carbonate ones. The Precambrian basement is overlain by nonmetamorphosed Mesozoic sedimentary and volcanogenic rocks. The Yanshanian granitic plutons intrude all above-mentioned rocks (Fan *et al.*, 2003). The total gold reserves exceed 900 t, and 55 t of gold were mined in 2000.

Granitic plutons formed in two phases. The early phase (160–156 Ma) consists of fine-grained granites with somewhat increased alumina content. Porphyric biotite–hornblende granodiorites (130–126 Ma) compose the second phase. The ^{40}Ar–^{39}Ar and Rb–Sr age of gold mineralization is 120 ± 10 Ma (Zhang *et al.*, 2003). It is considered that the Mesozoic volcanism, granitic intrusions, and formation of gold deposits relate to the subsidence of the Pacific plate under the shield. In the Yellow Sea, the M boundary occurs at a depth of 18–24 km, which corresponds to the transition between the oceanic and the continental crusts.

The gold deposits of the East Shandong district can be separated into two types: Linglong and Jiaojia. The Linglong-type deposits are veins hosted by Mesozoic granites and localized within second- and third-order faults. These can be separate veins or vein systems. The Jiaojia-type deposits occur within first-order faults at the contact of granites with Archean metamorphic rocks. These deposits contain disseminated and veinlet-disseminated ores and are surrounded by a wide halo of hydrothermally altered rocks. The orebodies of the linglong type occur at the intersections of NNE- and ENE-striking faults. The quartz veins vary in length from 100 to 5800 m, have a thickness of 1–10 m, and extend to a depth of 700 m. The gold occurs as a native metal impregnated in pyrite and quartz, and the gold content in ores varies from 3 to 32 g/t. In addition, the ore contains pyrrhotite, chalcopyrite, galena, and sphalerite. Metasomatic wall rocks consist of sericite, pyrite, and quartz with an admixture of carbonate, chlorite, albite, and K-feldspar. The rocks relate to the berezite family.

The main ore structures at the Jiaojia-type deposits are zones of brittle–ductile deformations and rock schistosity striking NNE. The main orebodies have a length of up to 1.2 km and a thickness of 2–4 m and extend to a depth of 850 m. The gold content varies from 3 to 50 g/t (average content 10 g/t). The ores contain pyrite, pyrrhotite, muscovite, K-feldspar, magne-

Fig. 2. Simplified geological structure of the Sino–Korean Shield and its framework (a) after (Wang and Mo, 1995; changed) and the Age of Mesozoic Hydrothermal Deposits at the same Region (b) after (Mo *et al.*, 2003; changed). Numerator, age in Ma; denominator, method of age determination. 1–5—Sino–Korean Shield: 1—archean cores, 2—protoplatform structures, 3—orogenic belts, 4—faults, 5—Archean and early Proterozoic rocks undivided; 6–9—ore deposits: 6—Au, 7—Mo and W, 8—Cu and Mo, 9—Pb and Zn.

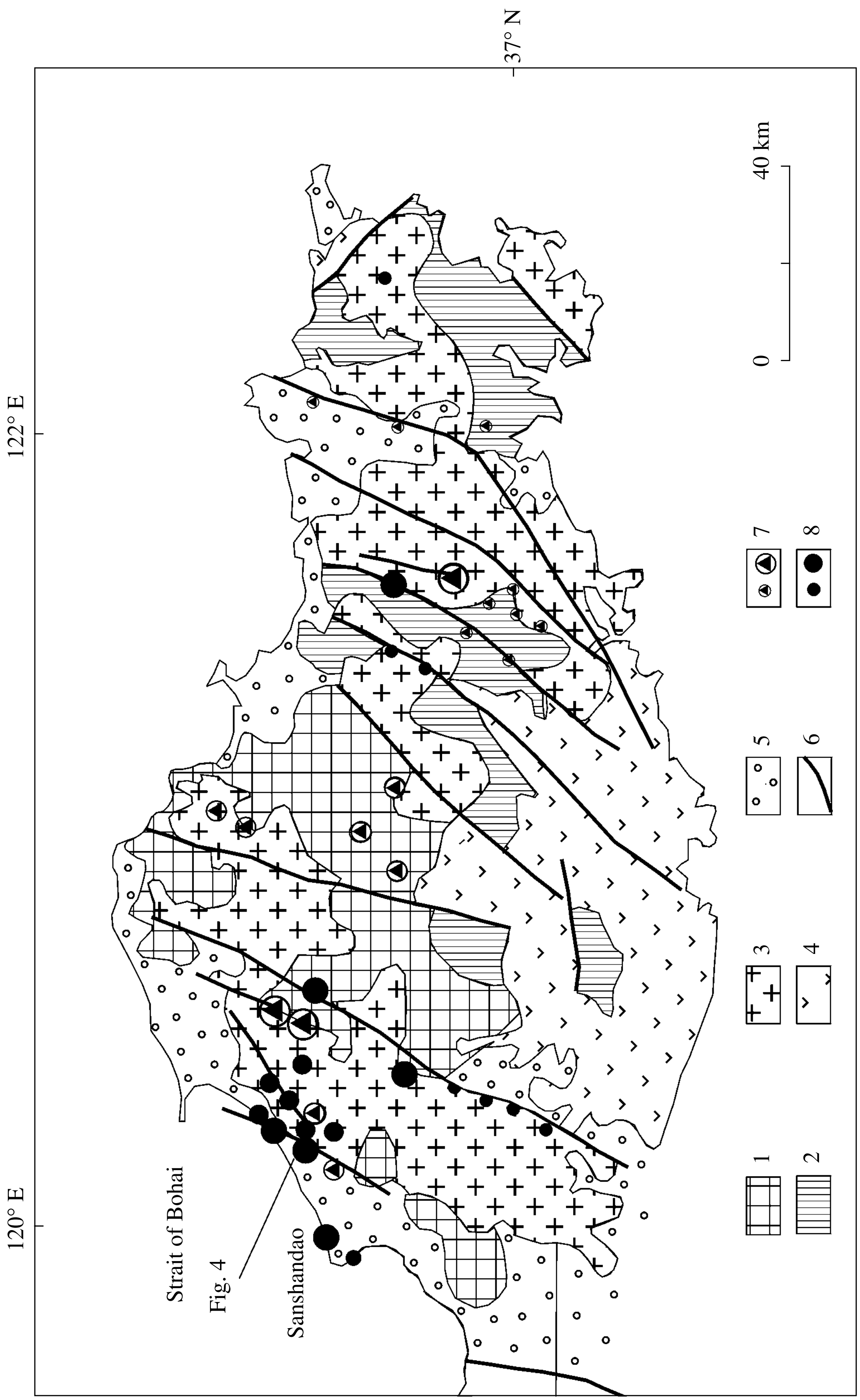


Fig. 3. Simplified geological structure of the East Shandong gold ore district after (Fan *et al.*, 2003; changed). 1—Archean metamorphic rocks; 2—Proterozoic metamorphic rocks; 3—Mesozoic granites; 4—Mesozoic volcanics; 5—Quaternary deposits; 6—faults; 7, 8—gold ore deposits and ore occurrences: 7—linglong-type, 8—jiaoyao-type (large symbols: deposits with reserves not less than 100 t).

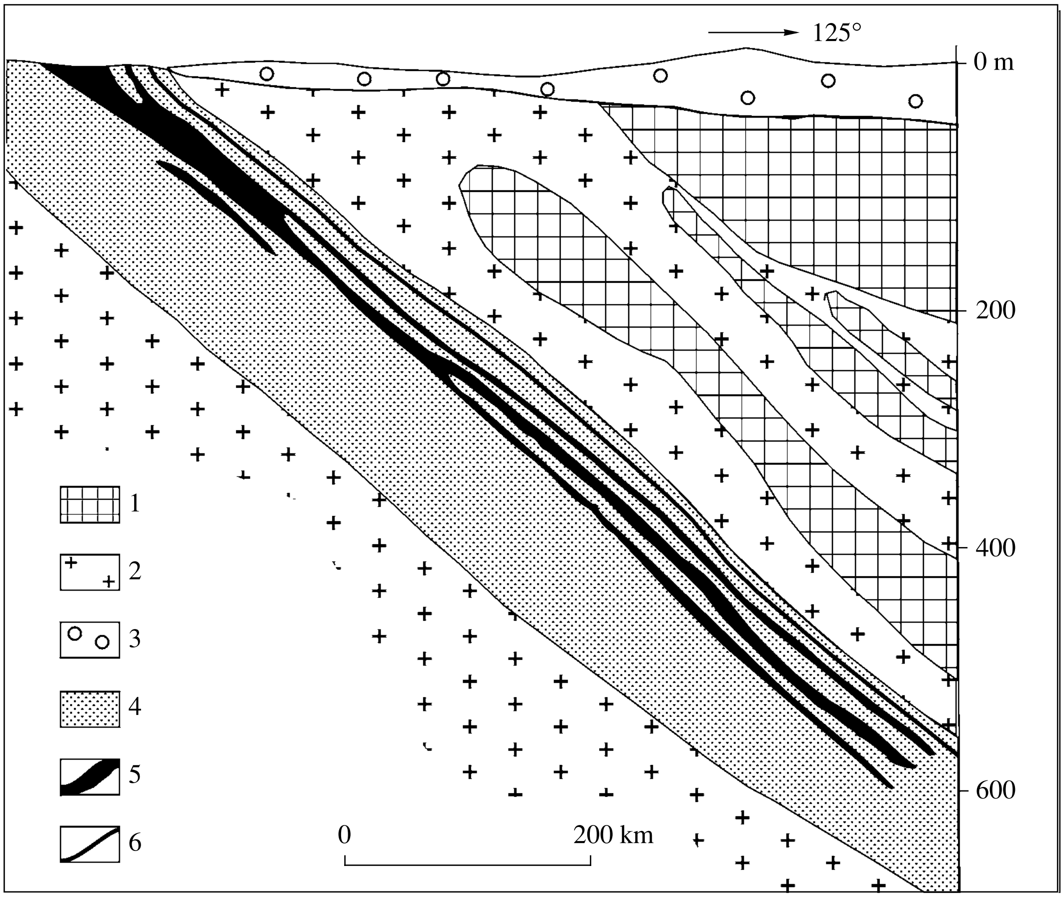


Fig. 4. Geological section across the Sanshandao gold deposit after (Fan *et al.*, 2003; changed). 1—Archean gneisses; 2—Mesozoic granites; 3—quaternary deposits; 4—hydrothermally altered sericite–quartz–pyrite rocks; 5—orebodies; 6—fractures.

tite, native gold and silver, electrum, chalcopyrite, galena, sphalerite, chlorite, siderite, ankerite, and arsenopyrite.

The Sanshandao deposit is typical for the Jiaojia-type type deposits and is the largest among them (Fan *et al.*, 2003). It occurs in a granodiorite intrusive body that is intruded into Archean gneisses. The deposit is enclosed by a thick (200 m) zone of sericite–quartz–pyrite hydrothermal rocks with intensive silicification (Fig. 4). The zone relates to the large NE-striking Sanshandao fault, with an explored length of 5 km. The rocks within the fault underwent ductile deformations and then were crossed by fissure enclosing gold mineralization. Gold associates with pyrite, arsenopyrite, chalcopyrite, siderite, and some other minerals. Four mineralization stages are distinguished at the deposit: I, quartz–K-feldspar–sericite; II, quartz–pyrite–arsenopyrite; III, quartz–sulfide; and IV, carbonate. The gold was deposited mainly at stages II and III. According to the stable isotope inclusion data, the ore fluids are of magmatic origin and the source of the fluids was probably dikes of basic and intermediate composition age 126–120 Ma. The hydrothermal process developed at 375–204°C and 3.0–1.2 kbar according to the fluid inclusion data.

THE GOLD DISTRICTS AT THE NORTHERN MARGIN OF THE SINO–KOREAN SHIELD

The northern margin of the Sino–Korean shield forms a gold-bearing belt 1500 km long extending from the city of Baotou to the boundary with North Korea and up to 200 km wide. The total gold reserves of the belt are around 900 t. The belt includes 12 gold deposits with reserves from 20 to 100 t (Hart *et al.*, 2002). Most of them occur in the lifted blocks of Precambrian metamorphic rocks, and 30%, in granite plutons of Paleozoic (?) and Mesozoic age. The orebodies are quartz veins with low sulfide content and with accompanying hydromica rock alterations. K-feldspathization is found at some of the deposits and is considered as a Paleozoic or even more ancient event. This belt occurs on the continental crust 32–42 km thick and outside of the Pacific Ocean plate. There are no data concerning the subduction of the Mongol–Okhotsk belt under the Sino–Korean Shield.

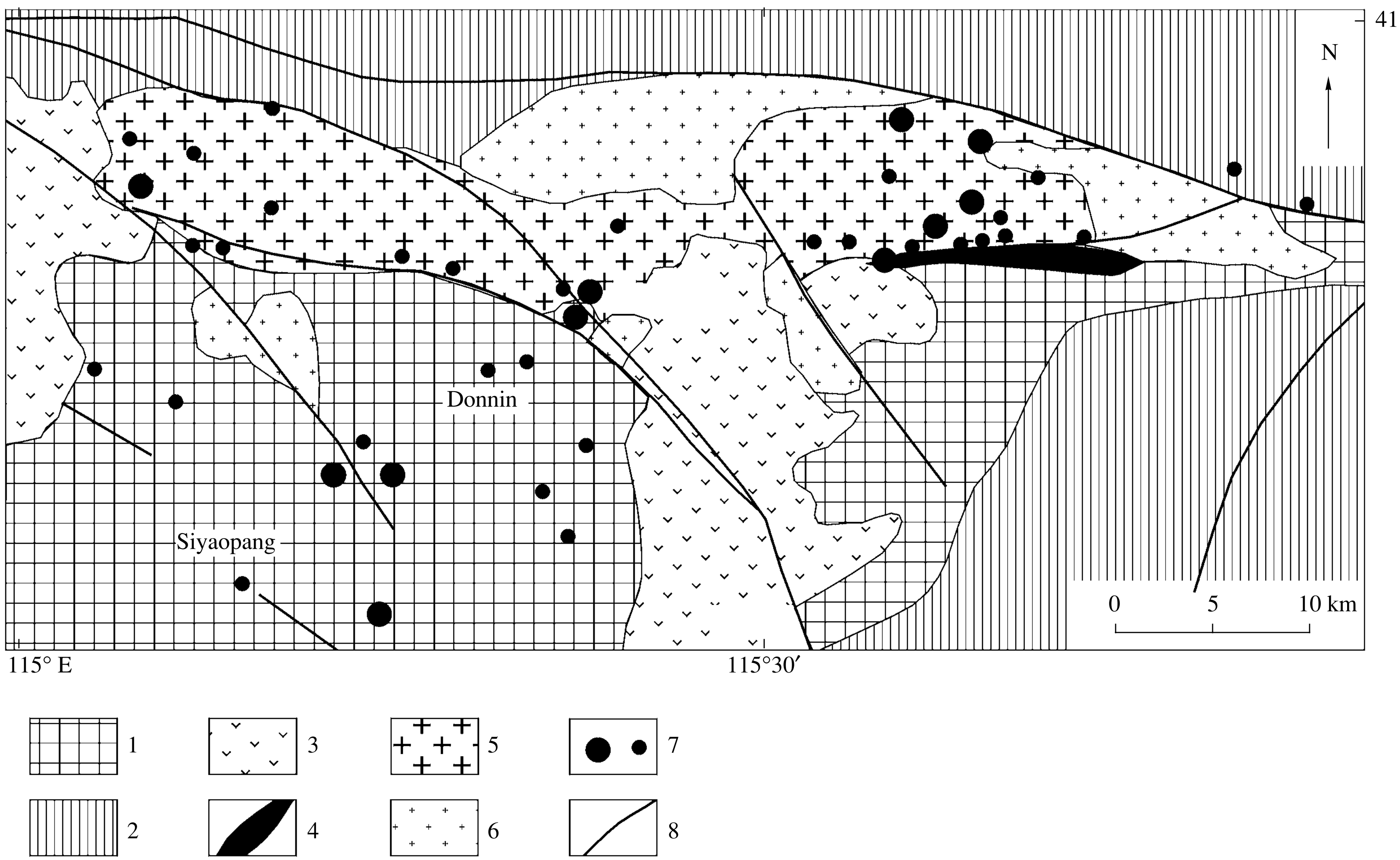


Fig. 5. Simplified geological structure of the Dzanyankou ore district after (Hart *et al.*, 2002; changed). 1—Archean rocks; 2—late Proterozoic rocks; 3—late Jurassic volcanics; 4—pyroxenites; 5—Shuiguankou intrusive complex; 6—Yanshanian granites; 7—gold ore deposits and occurrences (large and small symbols); 8—faults.

The Yan–Liao province occupies the central position in the belt. It includes three ore districts (Zhangjiakou, Yanshan, and Chifeng) with 400 gold deposits and occurrences and total gold reserves of around 280 t (Hart *et al.*, 2002). The gold ores occur in lifted blocks of Archean and early Proterozoic gneisses, amphibolites, and granulites. These rocks are overlapped by slightly metamorphosed volcanic and sedimentary rocks of the late Proterozoic and Phanerozoic. Rather large parts of the belt area are occupied by thick Mesozoic series of subaerial volcanics.

The most important *ore district Zhangjiakou* occurs around 100 km from the boundary with the Mongol–Okhotsk belt. A system of steeply dipping latitudinal faults marks this boundary. Some smaller faults striking NW conjugate with this fault system. The Shuiguankou intrusive complex associates with this district and consists of a batholith occupying an area of 55×8 km. Its northern border is crossed by a latitudinal fault, and the western and central parts are unconformably overlain by late Jurassic volcanics (Fig. 5). The batholith consists of pyroxene diorites, aegirine–augite syenites, and quartz syenites. The age of these rocks is not clear despite numerous isotope datings (data vary from 390 to 150 Ma). However, some small intrusive bodies at the batholith periphery show Mesozoic age according to the U–Pb SHRIMP method (188–165 Ma and even 143 ± 3 Ma).

The largest deposit in the ore district, Donping, has gold reserves of 90 t and consists of some tens low sulfide of quartz veins that relate to the NW-trending faults. The veins occur either in the Shuiguankou complex or in the Archean rocks and are accompanied by quartz–feldspathic metasomatism. The ores, with an average gold content of 6–8 g/t, contain sphalerite, pyrrhotite, magnetite, specularite, kalaverite, tellurides, and electrum. The Xiaoyipang deposit, hosted by Archean amphibolites and metabasic and metasedimentary rocks metamorphosed in the granulite facies, has a similar ore composition.

The Yanshan ore district occurs in the lifted blocks of the basement too, but it contains many Mesozoic (190–130 Ma) granite and granodiorite intrusives.

The relation of gold ores to the Mesozoic tectonics and magmatism is the clearest in the *Chifeng ore district*. The district occurs 80 km to the south of the Sino–Korean Shield boundary (Fig. 6). Its basement consists of Archean plagioclase–amphibole gneisses and amphibolites that are crossed by many granite bodies and are overlain by subaerial volcanics 129 Ma old. Thus, the Jinchangouliang deposit occurs around a small body of coarse-grained and porphyric granites (131–126 Ma) that cross a Paleozoic batholith composed of quartz monzonites. It is important that deposits there occur within Jurassic volcanics too. The gold is present in electrum and in native form in pyrite. The Chifeng district differs from the other ore districts at the northern margin of the Sino–Korean Shield by a higher Au/Ag ratio (3–5); by enrichment of ores with As, Hg, and Sb; and by low-temperature sericitization and chloritization of wall rocks.

Hart *et al.* (2002) summarized data concerning the gold deposits of the northern margin of the Sino–Korean Shield and came to the conclusion that they occur inside the craton without any relation to the accretional prisms, in contrast with typical orogenic gold deposits. Many deposits relate to granite intrusives with age varying from 350 to 120 Ma. The formation of the Jurassic–Cretaceous gold deposits relates in time to the subsidence of the Pacific plate under the continent of Asia. However, the gold deposits of the northern part of the Sino–Korean Shield occur rather far (up to 1500 km) from the transitional ocean–continent zone. Despite the relation of the gold ores to the Mesozoic magmatism, most important is the structural control of ores by the lifted blocks in the ancient basement. Extensive studies of the stable isotopes and fluid inclusions were carried out to clear up the genesis of the gold deposits, but they did not give a clear answer regarding the problem of the gold source and mechanisms of the gold ore deposition.

THE ALDAN–STANOVOI SHIELD

There are two points of view concerning the geotectonic position of the Aldan and Stanovoi terranes. The first one considers them as independent structural elements of the early Precambrian of the Siberian Platform. According to the other view, they form a common structural entity. A review of the extensive literature concerning this discussion is not a task of this paper, but its authors prefer the latter interpretation. The gold potential of the Aldan Shield is studied in most detail (Moiseenko and Eirish, 1996; Popov *et al.*, 1999).

Three large megablocks are distinguished in the western and central parts of the Aldan Shield: Olekminsk, Aldan–Timpton, and Timpton–Uchur. The first of them is considered now as an Archean granite–greenstone domain, and the two others, as an early Proterozoic granulite–greenstone region (Larin and Rundquist, 1999). Thick zones of brittle–ductile rock deformations divide these megablocks from each other (Kotov, 2003). The early precambrian metallogeny of the Aldan–Stanovoi Shield is in general similar to that of the Sino–Korean Shield.

The Olekminsk megablock is overlapped at its western margin by the early Proterozoic udokan series. The Aldan Shield remained stable during a time gap of 1.5 Ga, when its Precambrian basement was strongly eroded and the carbonate cover was deposited on its surface. These features differ the Aldan Shield from the Sino—Korean Shield (Fig. 7).

Important differences are characteristic of the Mesozoic history of both shields as well. A system of deep depressions filled with terrigenous rocks containing thick coal layers was formed in the southern part of the Aldan Shield in the Jurassic. The largest anthracite

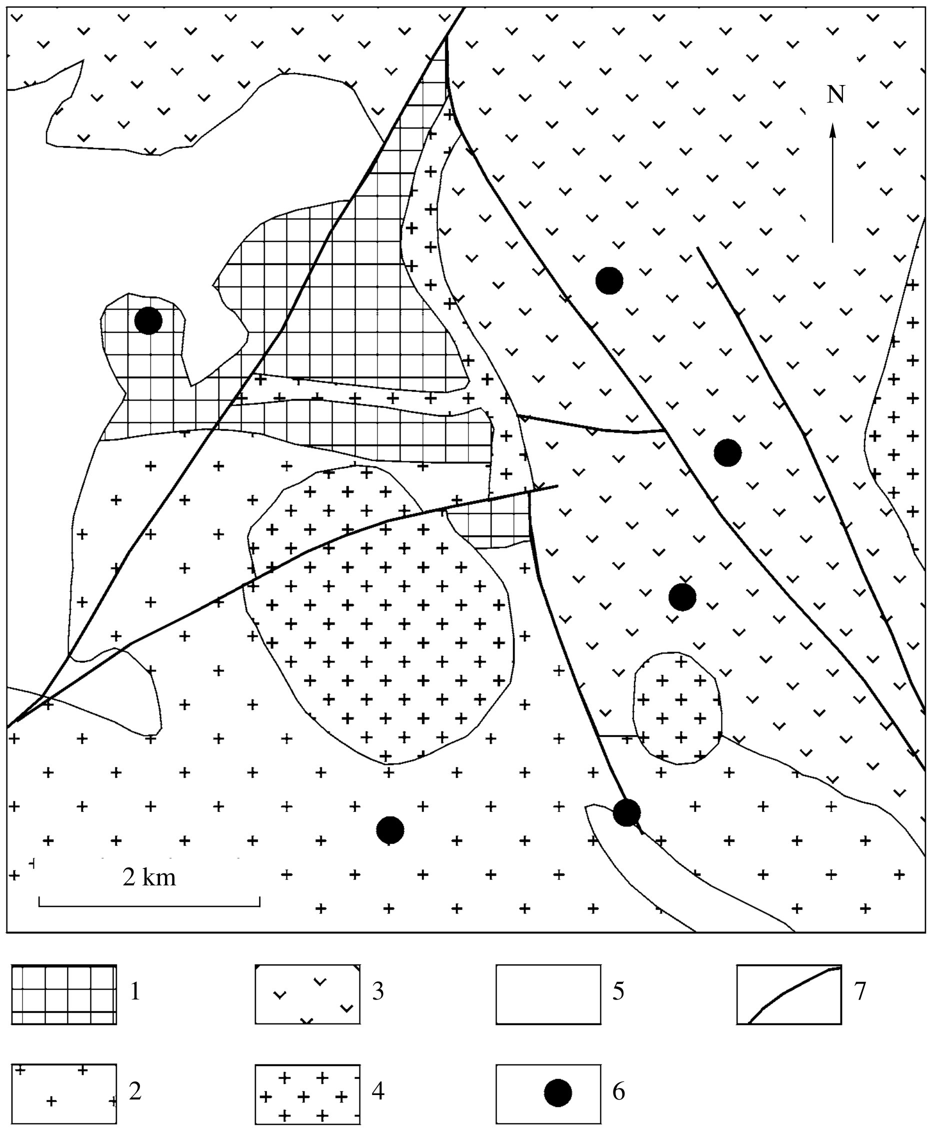


Fig. 6. Simplified geological structure of the central part of the Chifeng ore district after (Hart *et al.*, 2002; changed). 1—Archean gneisses; 2—Paleozoic granites; 3—Jurassic volcanics; 4—Mesozoic granites; 5—recent deposits; 6—gold deposits; 7—faults.

deposits occur in the Chullman depression. To the north, at the boundary with the platform cover of the Siberian plate, the Mesozoic tectonic movements formed gentle steplike uplifts and depressions and rare ringlike structures.

However, the most remarkable Mesozoic event at the Aldan Shield was the formation of an alkaline volcano-intrusive complex that consists of several clusters (groups) of magmatic bodies distributed closely to each other and strongly unconformable with the crystal basement structures (Bilibina *et al.*, 1967; Maksimov, 2003). Most of these bodies occur in the slightly metamorphosed rocks of the carbonate cover. The regularities of the spatial distribution and the age of the intrusives are debatable, though many schemes of their age and compositional systematics have been proposed. There is no doubt that the Aldan Shield was the region of the most intensive Mesozoic alkaline magmatism in East Asia.

The Central Aldan region concentrates the most igneous rocks and the most gold deposit varieties. Thus, the idea of "the gold Aldan" is associated first of all with the central part of the Aldan Shield.

THE CENTRAL ALDAN GOLD–URANIUM DISTRICT

This district is associated with a magmatogen superimposed on the platform cover and crystal basement, with a radius of about 120 km. The position of the district relative to the basement structures is characterized by the following: (1) localization on the early Archean

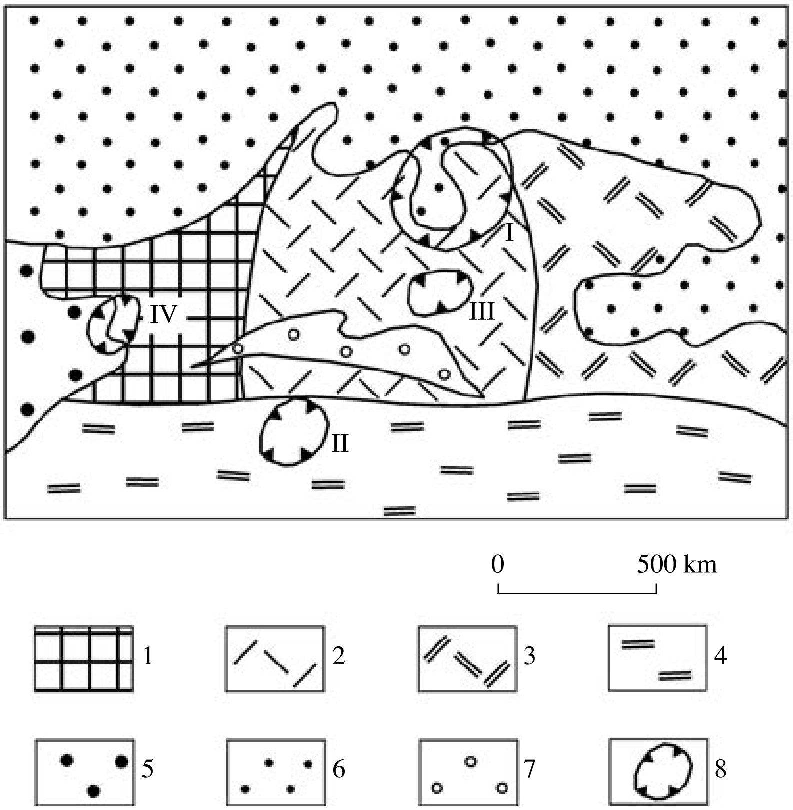


Fig. 7. Distribution of gold ore districts at the Aldan–Stanovoi Shield discussed in this paper. 1–4—Megablocks of the Aldan–Stanovoi Shield: 1—Olekminsk, 2—Aldan–Timpton, 3—Timpton–Uchursk, 4—Stanovoi; 5—early Proterozoic Udokan depression; 6—Vendian–Cambrian cover of the Siberian platform; 7—Jurassic terrigenous rocks of the Chulman depression; 8—ore districts: I—Central Aldan, II—Apsakan, III—Evotin, IV—Ugui.

crust (3.8–3.2 Ga) altered by endogenic processes in the late Archean (3.1–2.8 Ga) and early Proterozoic (2.5–2.0 Ga); (2) formation after granulite and amphibolite metamorphism and after granitization of the phlogopite-bearing Fedorovsk suite; and (3) spatial relations to the largest fault system amalgamating the Aldan–Timpton and Timpton–Uchur megablocks to form a united structure (Kazansky and Maksimov, 2002).

The Central Aldan magmatogen consists of core and radial blocks displaced relative to each other according to the results of complex geological and geophysical studies (Maksimov, 2003). The faults displacing radial blocks abruptly pinch out in the basement. Mesozoic magmatic bodies form radial ringlike and knotlike systems. Most of them occur in the platform cover as laccoliths, beds, multilayer sills, stocks, dikes, and some larger intrusive bodies. Dikes and stocks predominate in the basement. It is proposed that an electric anomaly that reaches the mantle exists under the Central Aldan district. No subduction or riftogenic zones are known in the Central Aldan district, which belongs to intracontinental structures.

The metal association of the Central Aldan district contains silver, molybdenum, and PGM in addition to gold and uranium. The largest deposits are hydrothermal Au–U El'kon-type deposits with low-grade ores but large reserves. They are followed by gold Kuranakh-type deposits, hydrothermal gold Lebedinsk-type deposits, and gold-bearing placers. The El'kon-type deposits occur in the rejuvenated faults in the crystal basement, while the Kuranakh- and Lebedinsk-type deposits are situated in the platform cover. The Au–U and Au deposits of these three types form ore fields isolated from each other. The Cenozoic gold-bearing placers occurring within the Central Aldan district were formed by the erosion of the Lebedinsk- and Kuranakh-type deposits. The whole association of the above-mentioned deposits forms an endogenic–exogenic gold–uranium ore district with potential reserves of gold of 1000 t and of uranium of 600000 t. The uranium ores are low-grade and occur at deep levels, so they are regarded as unprofitable now. A comparative description of the ore deposits and ore fields of the Central Aldan district was published by Vetluzhskikh *et al.*, (2002) and Kazansky (2004).

The spatial and paragenetic relations of gold ores to the alkaline magmatic rocks for many years directed gold prospecting at the Aldan Shield. All groups of alkaline rocks were studied, but the results were not significant. New data were obtained for other types of deposits and ore districts (Popov *et al.*, 1999). Three representative gold-bearing districts of the Stanovoi megablock are characterized below: the Apsakan, Evotin, and Ugui districts.

THE APSAKAN GOLD DISTRICT

The Apsakan gold district occurs to the south of the Aldan Shield, in the central part of the Stanovoi belt. Gold placers, some hydrothermal deposits of gold and silver hosted by Precambrian and Mesozoic rocks (Bam, Ledyanoe, and Skalistoe), and gold ore occurrences (Des, Ernichnoe, Sivakan, and Klyun) occur in the district. The largest is the Bam deposit (Moiseenko, 1998).

The area of the Apsakan ore district is 400 km^2. The most ancient early Archean metamorphic rocks fill the depressions in the roof of a big granite pluton and occur inside granites as xenoliths. The early Archean ultrametamorphic rocks form plagiogranite and granite dikes. The early Archean intrusives include small bodies of metagabbro; the metamorphic complex consists of gneisses, plagiogneisses, amphibole crystalline schists, amphibolites, quartzites, and calciphyres. Their total thickness is around 2.4–2.5 km. The early Mesozoic sedimentary–volcanogenic series form a horizontal cover unconformably lying on the granites and gneisses. It consists of trachyandesites, their lavobreccias, and tuffs. Tuff–sandstones, tuff–aleurolites, and argillites occur in the base of the series. The age of the series estimated by flora dating in the argillites is Jurassic–early Cretaceous. The upper age limit of the volcanics is estimated with the age of the quartz monzodiorite–porphyry dikes (142–105 Ma according to K–Ar dating).

The subvolcanic intrusive complex in the district consists of monzodiorites, quartz monzodiorites, quartz syenites, and quartz syenite–porphyries. Data on their isotope age are inconsistent. A.M. Tugarinov and coauthors (1980) estimated the age of monazite (1790 ± 80 Ma) and zircon (1140 ± 65 Ma) from pegmatites (Far East of Institute Mineral Resources (DVIMS)). The Rb–Sr isochrone developed at the same institute for the quartz syenites of the first stage of the granite complex showed an age of 1924 Ma with an $^{87}Rb/^{86}Sr$ ratio of 0.7038 ± 0.0011.

In addition, an early Cretaceous intrusive complex is distinguished in the district. It is composed of biotite gabbro and biotite–pyroxene quartz monzodiorites (the first stage) and biotite–hornblende quartz monzodiorites and granodiorites (the second stage). The Rb–Sr isochrone for the monzodiorites of the first stage corresponds to an age of 142 Ma (DVIMS), and for the granites of the complex the isochrones correspond to an age varying from 159 to 122 Ma (Abramovich *et al.*, 1967; Glebovitskii, 1965). The Rb–Sr age of the intrusive rocks spatially related to the Bam deposit is estimated in the moderate-grained quartz monzodiorite xenoliths and is 142 Ma according to Moiseenko *et al.* (1998).

The younger dikes of diabases, lamprophyres, quartz syenite– porphyries, granite–porphyries, subalkaline granite–porphyries, quartz monzodiorite–porphyries, granodiorite–porphyries, and hornblende quartz monzodiorite–porphyries relate to the early Cretaceous according to the K–Ar age data for the first three rock types. The age of the granodiorite–porphyries is 138–105 Ma (Abramovich *et al.*, 1967) or 142 Ma (Tseimakh *et al.*, 1980), but K-feldspar phenocrysts show the age 114 ± 3 Ma (Kotov *et al.*, 1993). It is possible to conclude, summarizing all these age data, that the period 142–105 Ma was the time of intrusion of the early Cretaceous dikes and of the gold–quartz Bam deposit origin.

The ore-containing structures of the Bam deposit cross monoclinal Precambrian gneisses and crystal schists, which contain abundant granite bodies and dikes and were repeatedly dislocated both before the Mesozoic and during the Mesozoic tectono–magmatic activization (Fig. 8).

Three or four subparallel faults bordering lenses of the less distorted rocks occur in the zone of the ore-containing structures. The probable ore-screening fault and vein–impregnated zones conformable with it are accompanied by tectonic gouges, schistosity, brecciation, and milonitization of rocks. The thickness of tectonites varies from some meters to some tens of meters.

Fourteen large and several small orebodies are explored at the deposit. In some places, they consist of quartz–carbonate veins, but commonly they occur as linear zones of dislocation metamorphism, where the vein quartz composes only a part of the rock volume. These two types of orebodies alternate along the ore zone strike and dip. The orebodies have a length of 300–1100–1500 m, their thickness varying from 1.5 to 4.5–5.5 m, and contain 5.3–6.4 g/t Au and 10–20 g/t Ag.

The orebodies are ribbonlike or lenslike, complicated with flexurelike bends along the strike and dip. They plunge to the SSE parallel to the bends of the screening fault. An orebody commonly consists of separated echeloh-like veins and zones of veinlet–impregnated mineralization hosted by berezitized (quartz–sericite) rocks. The volume of the quartzitized rocks exceeds the volume of the orebodies. As a whole, the morphology of the ore "megastockwork" is similar to a curved plate under the screen of the Bam fault (the thickness of the plate is up to 300–400 m, and the length around 4 km). The deposit is mined to a depth of 750–800 m downward.

The following stages are distinguished in the formation of the orebodies: preore (quartz), early ore (quartz–scheelite–sulfide), middle ore (berezitic), late ore (gold–sulfide–sulfosalts), and postore.

The common ore minerals of the ore stages are galena; chalcopyrite; tetrahedrite; acantite; sulfobismuthites of Cu, Pb, and Ag; and tellurides of Au, Ag, and Bi. Rare minerals are sphalerite, cinnabar, and molybdenite. Dispersed gold with fineness 772–938 is

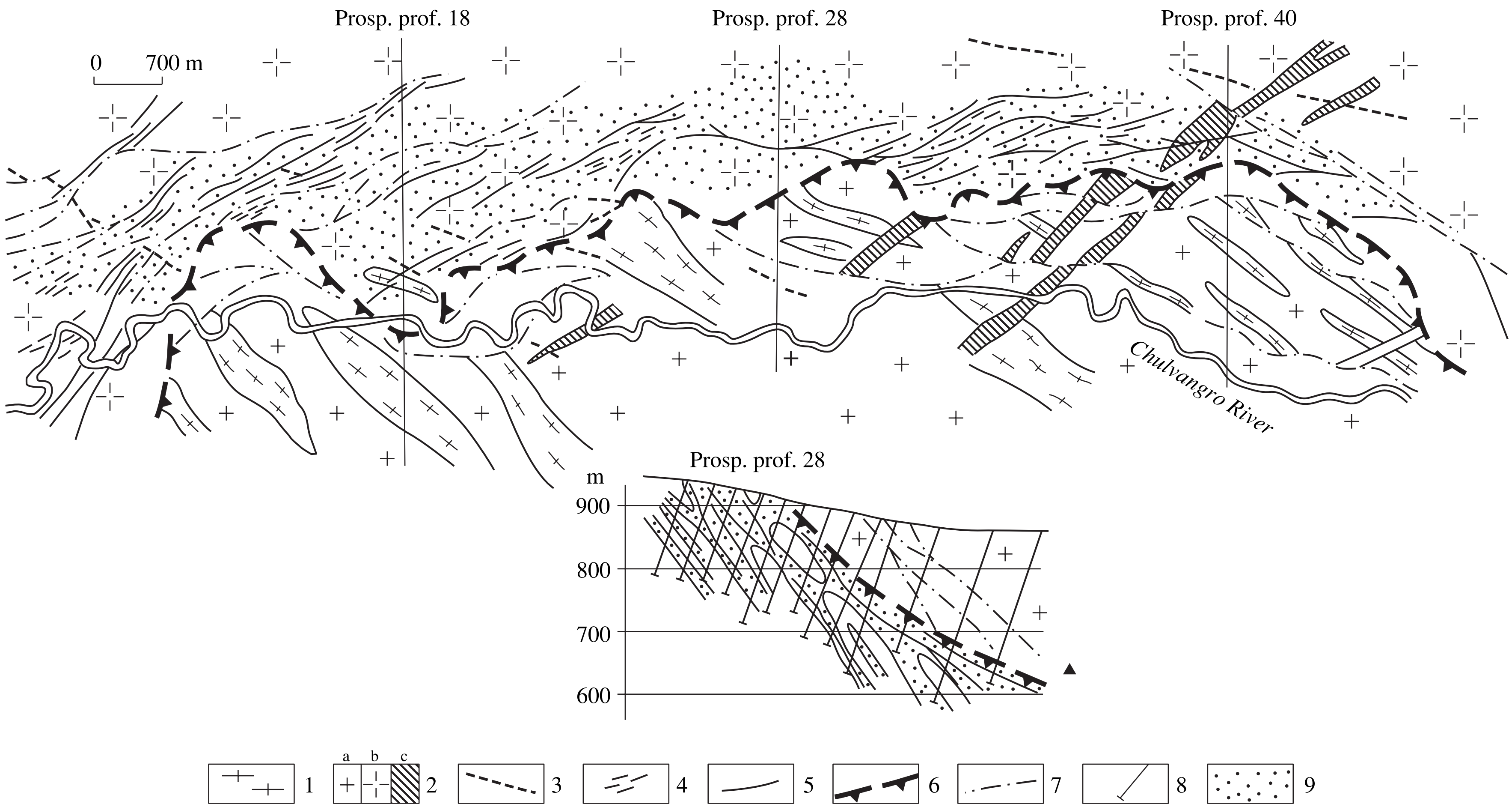


Fig. 8. Simplified geological structure of the Bam deposit (after the Amur Complex Research Institute, 1998; simplified). 1—Early Archean crystal schists, gneisses, and amphibolites; 2—early Proterozoic gneiss-like granites (a), porphyry granites (b), and pegmatoid leucogranites (c); 3—early Cretaceous dikes of granodiorite porphyries and lamprophyres; 4—zones of quartz veinlets; 5—veinlet–impregnated and vein gold orebodies; 6—fault that was a barrier for the ore deposition (screen); 7—other faults; 8—drilling holes along prospecting profile 28; 9—metasomatic zones with contour of veinlet–impregnated gold ores.

found in ores. At the late ore stage, the sulfosalts and tellurides were deposited together with dispersed gold and late galena.

The fluid inclusions in quartz of the deposit contain hydrocarbons. Inclusions containing 70 vol % of the gas phase show a homogenization temperature of 390°C, but some inclusions are homogenized at 280–300°C. The maximum on the variation curve occurs at 230°C with a subsequent decrease to 180–100°C.

The Bam gold deposit is regarded as an example of the long activity of the ore-forming process in the ancient continental crust according to Rundquist (1997). The early and late Proterozoic processes of crustal rejuvenation had a strong influence on the deposit, along with the subsequent granite intrusions under conditions of an active platform margin in the Jurassic–early Cretaceous and later (Cretaceous–Paleogene) under the conditions of intracontinental rifting. According to this interpretation, the general prehistory of the formation of this polychronic deposit embraced more than 2 Ga, including the formation of the Archean greenstone belt.

THE EVOTIN GOLD DISTRICT

Some gold deposits (Kur and Pritrassovoe) were found and evaluated at the Evotin district in the late 1990s. The deposits relate to the gold–sulfide veinlet–impregnated type and possess tens of tons of gold reserves. There are two points of view on the nature of the country rocks at the deposit: (1) they compose a basic–ultrabasic intrusive body crossing surrounding rocks and (2) they compose a horizon of metamorphic rocks at the base of the Fedorovsk suite. Phlogopitic bodies occur in these rocks in the immediate vicinity of the gold deposits. The ore-bearing horizon consists of gneisses, gabbro–norites, and granites (normal and subalkaline). These rocks form bedlike bodies with monoclinal layering along the strike and dip (Fig. 9). The composition of the gabbro–norites is related to the tholeiitic series, and composition of the crystal schists of the Fedorovsk suite at the Evotin district is similar to calc–alkaline metabasalts. The Sm–Nd age of the country rocks is early Proterozoic (around 1900–2300 Ma) (Popov *et al.*, 1999).

The central part of the orebodies consists of coarse-grained quartz aggregates with "floating" idiomorphic crystals of pyroxenes and andesine. Sulfide minerals are common pyrrhotite and less abundant chalcopyrite. In the thick orebodies, arsenopyrite, loellingite, and pyrite associate with quartz. Cobaltine, bismuthite, native Bi, molybdenite, fahlore, argentite, galena, and sphalerite are rare. Pyrrhotite and pyrite are commonly predominant minerals, with their content varying from 5–7 to 50–60 vol %; sometimes arsenides predominate. There is a direct correlation between the content of gold and arsenic, bismuth, and to a lesser degree copper (V.A. Amuzinskii and others).

The gold-bearing horizon extends latitudinally to more than 90 km and has a width at the surface of from 200 to 1200 m. Some secondary dispersion halos of Au, As, and Bi occur within the outcrops of gabbro–norites.

The gabbroic rocks form series of dikes localized near to each other (like packages) with lengths of 2.8–7.5 km and thicknesses from 20–30 to 110–150 m. Their composition is characterized by a predominance of andesine (45–60 vol %) and a somewhat heightened silica content (49–60 wt %). The sampled orebodies consist of series of polymineral sulfide–silicate lenses and zones of vein–impregnated sulfide mineralization. The orebodies are 200–1000 m long and vary in thickness from 0.5–0.8 to 2.4 m; the average gold content in ores is 4–6 g/t. The sulfide content is commonly 5–10 vol % but can reach 18–20 or even 50–60 vol %. The impregnated and veinlet–impregnated sulfide mineralization contains more than 20 vol % of ore minerals.

The sulfides are pyrrhotite, pyrite, and arsenopyrite; galena, sphalerite, bornite, and fahlore are rare. The gold is free and concentrates in intergrowths with sulfides and in quartz.

The impregnation, nests, and veinlets of ore minerals contain loellingite, pyrrhotite, pyrite, chalcopyrite, arsenopyrite, molybdenite, native Bi, cobaltine, native Fe (?), and Au. High-sulfur loellingite occurs in high-grade ores. Loellingite contains admixtures of Ni and Co. Ores with 80 g/t Au contain native Bi. Cobaltine was found in some samples as inclusions in pyrrhotite. The gold fineness depends on the admixture of Ag, Cu, and Hg and varies from 947 to 1000.

Zonal sulfide–pyroxene–quartz–plagioclase aggregates, ilmenite, arsenopyrite, loellingite, nickeline, rammelsbergite, pyrrhotite, chalcopyrite, burnonite, fahlore, linneite, pyrite, and marcasite were found at the Kur deposit. The condition, age, and the sequence of the mineral formation are unclear there.

THE UGUI GOLD DISTRICT

The new Ugui gold-bearing district occupies an isolated place in the Aldan Shield. It occurs at the western part of the shield, where the early Proterozoic series of the Udokan, Ugui, and some other depressions overlay the Charo–Olekminsk greenstone megablock.

Four tectonic events are distinguished in the early Proterozoic history of the Charo–Olekminsk region: 2.4–2.5, 2.18–2.05, 1.95–1.90, and 1.85–1.73 Ga. The first event was accompanied by formation of granites similar to the intraplate A-type ones at the conjugation of the Olekminsk and the Central Aldan blocks. Their U–Pb age estimated with zircon is 2487–2398 Ma (Sal'nikova *et al.*, 1993).

At the following stages, depressions were formed and filled with early Proterozoic sedimentary series: Udokan, Khanin, Oldongsin, Ugui, and some others.

The Udokan depression is the largest, and the thickness of its sedimentary filling reaches 9–12 km. The

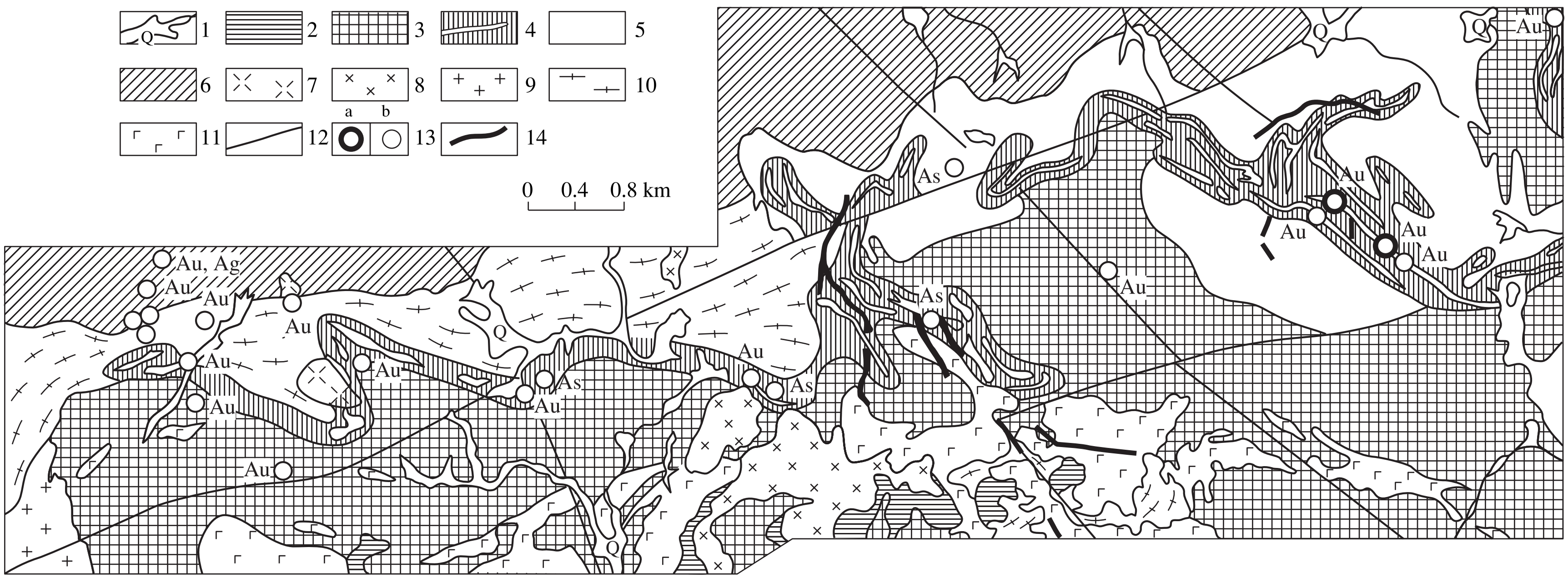


Fig. 9. Distribution of the gold deposits and occurrences within the Evotin district (after data of Aldangeologiya, 2004). 1—Quaternary deposits; 2—Vendian platform deposits; 3—Fedorovsk suite; 4—medvedevsk horizon: gabbro–norites, amphibole–hypersthene and amphibole–two-pyroxene orthoschists; 5—biotite and biotite–two-pyroxene plagiogneisses; 6—early Archean gneisses and plagiogneisses with quartzitic lenses; 7—Mesozoic quartz syenites; 8—Mesozoic hornblende syenites; 9—late Archean granites and plagiogranites; 10—late Archean granitogneisses and plagiogranitogneisses; 11—early Archean gabbro–syenites, gabbro–diorites, and gabbros; 12—main faults; 13—ore deposits (a) and ore occurrences (b) of Au and As; 14—gold placers.

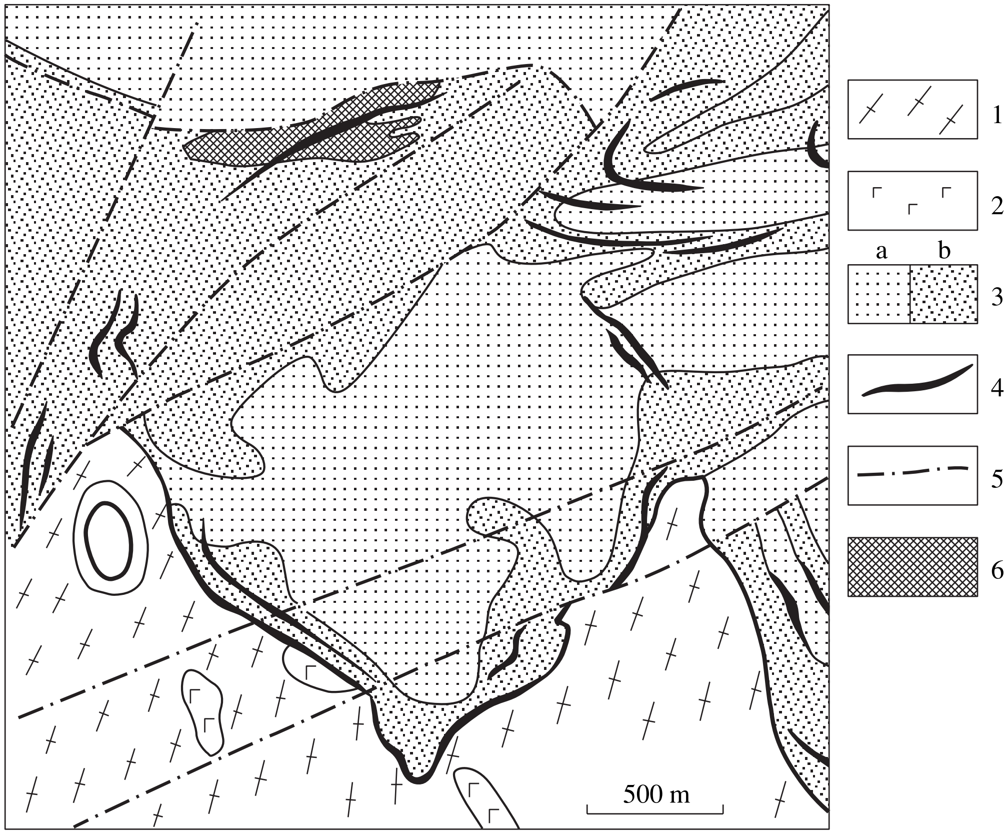


Fig. 10. Schematic geological map of the Ugui region with the location of the Tabornoe deposit (after S.A. Parshin, 2004). 1—Archean granitogneisses of the basement; 2—early Proterozoic gabbro massifs; 3—early Proterozoic arcose sandstones unaltered (a) and K-feldspathized (b) in the base of the sedimentary sequence; 4—sills and dikes of late Jurassic syenite–porphyries; 5—faults; 6—gold orebody.

terrigenous sediments of the lower part of the section (the kodar and chinei subseries) consist of carbonaceous sandstone–schist, flysch graystone, and carbonate–aleurolite–sandstone molassic variegated (mature arcose sandstones with heightened potassium content) formations. The sedimentary rocks underwent low-temperature metamorphism. The degree of metamorphism increases toward the depression borders to the amphibolite facies. Simple brachifolds are combined with complicate folds, especially in the depression borders.

The early Proterozoic was a period of intensive deposition of various metals. Most of the economic deposits occur exactly in the Olekminsk block. At the period 2.2–1.8 Ga, the epicraton Udokan-type depressions enclosed giant deposits of copper schists. The Chinei gabbro–anorthosite massif with V–Ti ores and the rare metal Katugin deposit were formed at nearly the same time.

Recently, some gold deposits forming the Ugui gold district were found in the sedimentary and magmatic rocks at the periphery of the Udokan and some other depressions (the Tabornoe deposit and some ore occurrences in the Lemochi–Oldongsinsk area).

The ores at the Tabornoe gold deposit occur in the contact zones of early Proterozoic sedimentary rocks with Archean gneisses. The stratiform ore zone is crossed by late Jurassic syenite–porphyries and contains extensive areas of potassic metasomatic rock alteration (Fig. 10).

The orebodies at the Tabornoe deposit occur along a reverse fault zone having a length of 30 km and a thickness of 5–6 km according to Sedenko (1991) and Dvurechenskaya and Kryazhev (2005). Syenite–porphyry and bostonite–porphyry dikes contain from 5–9 to 22 g/t Au at the territory of the Tabornoe deposit (several samples), while potassic feldspar metasomatites replacing dislocated sandstones contain 1.9–2.3 g/t Au and hypergenic ores contain up to 3.0–6.2 g/t Au.

The K-feldspar metasomatism of the sandstones and impregnated–veinlet mineralization in the syenite–porphyries and sandstones are considered as a result of the same ore-forming stage related to the Mesozoic tectono–magmatic activization. In the early pyrite–quartz–K-feldspar stage, K-feldspar, adular–quartz, gold–pyrite–quartz, and gold–sulfide–quartz associations were formed.

The gold–pyrite–quartz association consists of pyrite (3 vol %), needlelike arsenopyrite, and marcasite. The pyrite contains thin gold drops (up to 0.01 mm). The gold–sulfide–quartz association contains free gold and low barite, ankerite, late pyrite, chalcopyrite, galena, and sphalerite. The total sulfide content is less than 1 vol %. The sulfur isotope composition is near the meteoritic one ($\delta^{34}S$ is 0.2‰). The formation of postore quartz veinlets completes the stage. The galena–molybdenite–quartz association is gold-free but contains acantite and native silver. The silver content is around 10 g/t.

The ores that underwent hypergenic alterations contain hematite, goethite, their hydrated varieties, jarosite, cryptomelane, pyrolusite, kaolinite, minerals of the coronadite group, and hypergenic gold in addition to the primary minerals. The horizon of secondary ore enrichment occurs at a depth of 50–100 m. It contains from 1.1 to 3.3 g/t Au.

It is important that placers with rather low gold content are common within the large territory of the Stanovoi Ridge. One such area with gold-bearing placers occurs at the left bank of the Gilyui River within the Dzheltulinsk cupola-like structure. The rocks of the structure underwent metamorphism of the amphibolite and then the greenschist facies. High-fineness gold (850–950‰) is common in rocks of the Precambrian shear zones, and low-fineness gold (606–702‰) is typical for the blocks with preserved early Cretaceous volcanics according to Neronskii and Borodavkin (2005). These authors relate the formation of the low-fineness gold to the NE-striking faults that formed during the Mesozoic tectono–magmatic activization.

CONCLUSIONS

The high significance of the Archean greenstone belts for gold metallogeny is commonly recognized and is confirmed by the discovery of large gold deposits at the Canadian, West Australian, Indian, and some other ancient shields.

The data on the East Asia metallogeny show that a high gold potential of old shields can relate to superimposed younger, Mesozoic processes. These processes are called in Russian publications "tectono–magmatic activization" or "rejuvenation"; in plate tectonic terminology, "intraplate rifting"; and in the terminology of Chen Guo-da, "diwa."

The Mesozoic gold districts and deposits are extremely variable according to data of the activated Aldan–Stanovoi and Sino–Korean shields, so they cannot be interpreted within a single scheme. The gold deposits of the Apsakan (Bam) district (the Aldan–Stanovoi Shield) relate to the polygenetic and polychronic model of ore formation. However, the Central Aldan gold–uranium ore district, which occurs at the intracontinental region of East Asia and is accompanied by Mesozoic alkaline intrusives, has no genetic relations to the previous episodes of geological history. The East Shandong gold district is in a similar position. It occurs in the immediate vicinity of the conjugation of the Sino–Korean Shield and the Pacific oceanic plate and relates to the Mesozoic granites. For this second variant, most convenient is the term "metallogenic explosion," used by some Chinese geologists.

It is scarcely possible to develop a general classification for the gold districts and deposits of the activated shields and, what is more, to separate the most promising of them. However, one proposition concerning the southern part of the Aldan–Stanovoi Shield can be made. The gold prospectings at the Aldan Shield were mostly based on the metallogenic concepts worked out for the Central Aldan many years ago. The Stanovoi belt was less studied, though gold diggers mined gold from placers there from ancient times. A similar situation existed at the northern part of the Sino–Korean Shield. The gold occurrences of this district occur in Archean rocks and so were considered as Archean. However, the isotopic age of many of them estimated in the last 15 years appears to be Mesozoic. The geological structure of the gold-bearing belt at the northern border of the Sino–Korean Shield is similar to the Stanovoi belt. The first Mesozoic gold deposits of economic value have now been found in the Stanovoi belt. In our opinion, the southern part of the Aldan–Stanovoi Shield should be studied and prospected in more detail in order to turn this territory into one of the main gold mining provinces of Russia.

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Remarks by D.V. Rundquist and Yu.G. Safonov were taken into account in this paper.

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