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Composition and Genesis of Precambrian Metalliferous Conglomerates

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Abstract—Precambrian metalliferous conglomerates are the most important source of gold, uranium, and other metals. They concentrate no less than 30% of world gold reserves and provide 30–50% of world gold production. The metalliferous conglomerates are known at various chronological levels of the Early Precambrian: the Neoarchean (Witwatersrand Supergroup, South Africa), the Neoarchean–Paleoproterozoic (Huronian Supergroup, Canada), and the Paleoproterozoic (Tarkwaian Group, West Africa; Roraima Group, the Guiana Shield; Jacobina and Sierra de Carrego groups, the Brazil Shield; Mount Bruce Group, West Australian Shield). They are related to different stages of the tectonic evolution: preorogenic stage (Huronian Supergroup), orogenic stage (Tarkwaian Group), and postorogenic or protoplatformal stage (Witwatersrand). Long-term stabilization of the Earth's crust and deposition of thick sedimentary sequences were the most favorable conditions for the formation of metalliferous conglomerates.

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INTRODUCTION

The Precambrian metalliferous, first of all, gold-bearing conglomerates are the major geological–economic type of gold deposits. They concentrate about 30% of world gold reserves (32 kt versus 100 kt) and provide a significant share (30–50%) of gold production. They also contain significant uranium reserves and platinum and diamond occurrences. The Witwatersrand conglomerates are the most important source in South Africa. However, rocks of this type are also known in other regions: the Tarkwaian Group in West Africa, the Huronian Supergroup in Canada, the Tortue Conglomerate in Guiana, Jacobina and Moeda conglomerates in Brazil, the Nullagine Group in Western Australia, and so on (Krendelev, 1974; Konstantinovskii, 2000). Their correlation, composition, structures, genesis, and relationships with under- and overlying sequences, the origin of gold mineralization, and many other problems have attracted great interest and wide discussion. Regularities in the localization of gold mineralization depending on the type and origin of host conglomerates, the composition of provenances, and specific features of section have applied significance. Resolution of these problems may be helpful for forecasting paleoplacer deposits of gold and other metals. Deposits of this type are so far unknown in the Ukraine. However, some prerequisites for their discovery are present (Shcherbak et al., 2002). In this regard, it would be topical to compare metalliferous conglomerates in the world.

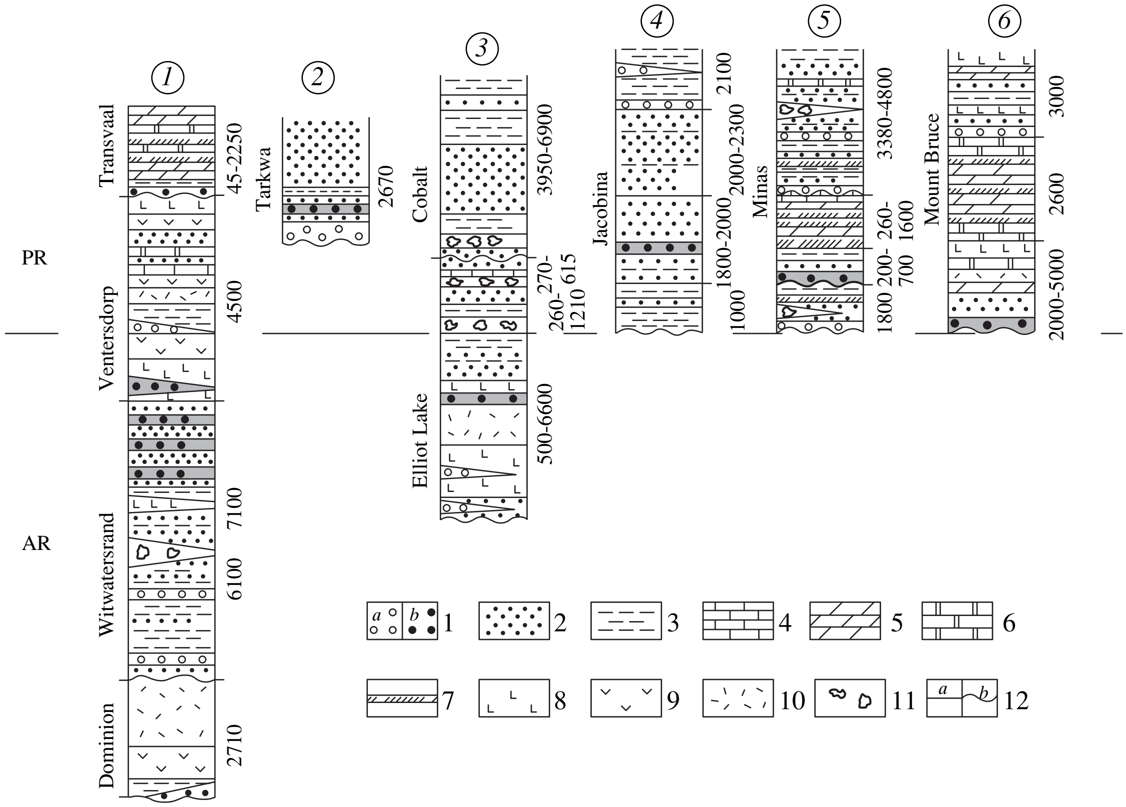
COMPARATIVE ANALYSIS

South Africa. About 40 kt Au and more than 125 kt U_2O_3 have been mined during the mining of metalliferous conglomerates in the Rand Basin. Osmium and iridium were mined as byproducts (Konstantinovskii, 2000; Malich et al., 2000; Roscoe, 1996).

The fanlike Witwatersrand gold ore field is composed of thin sandstone beds with pebbles at their base (Roscoe, 1996). Mining is confined to the enriched bands (reefs) that radiate in each sector. They are more than 10 km long in some places. The average Au grade was 9.2 g/t in 1972. The highest Au grade (19.4 g/t) is characteristic of the Carletonville gold ore field. The highest U grade is typical of the Krugersdorp (West Rand) field, where the Au grade is 6.3 g/t. In 1953–1972, the average U grade was 213 g/t (0.021%) in the Witwatersrand ore as a whole, 188 g/t in the Carletonville ore, and 477 g/t in the Krugersdorp ore. The Au-bearing quartz conglomerates are mainly confined to the Witwatersrand Supergroup that fills a basin 200 × 350 km^2 in size.

The oldest gold paleoplacers are known in the Pongola Supergroup that completes the Mesoarchean section of South Africa. The placers are related to the basal conglomerate of the Insuzi Formation, which unconformably overlaps the gneissic plagiogranites with the Rb–Sr age of 3230 ± 80 Ma. The overlying Mozaan Formation is intruded by the Usushwana gabbro–granite complex, including the granophyre granite dated at 2875 Ma (Rb–Sr).

Pretorius (1981) recognized the following major stratigraphic subdivisions in the Rand Basin (figure):



Correlation of Precambrian metalliferous conglomerates. (1) Conglomerates: (*a*) barren, (*b*) Au-bearing; (2) sandstone and quartzite; (3) mudstone and shale; (4) limestone; (5) dolomite; (6) chert, (7) jaspilite and itabirite; (8–10) volcanic rocks: (8) basic, (9) intermediate, (10) moderately silicic; (11) tillite; (12) stratigraphic boundaries: (a) conformable, (b) unconformable. Stratigraphic columns (numerals in circles): (*1*) South Africa, Witwatersrand; (*2*) West Africa, Tarkwa, (*3*) Canada, Elliot Lake; (*4*) Brazil, Jacobina; (*5*) Brazil, Moeda; (*6*) Australia, Nullagine.

the Dominion Group of volcanics (2710 m, 3.07 Ga); the Witwatersrand Supergroup, which includes the West Rand Group (5000 m) of marine sedimentary rocks and the Central Rand Group (2100 m) with prevalent fluvial clastic rocks; and the substantially volcanic Ventersdorp Supergroup dated at 2.71 Ga (U–Pb zircon age).

Paleoplacers in the Dominion Group occur locally in basal sandstones (60 m) of the Rhenosterhoek Formation (figure). They are overlain by volcanic rocks (1100 m) with paleocrusts of weathering. The uppermost sequence is composed of intermediate and moderately silicic volcanics (1550 m) with the U–Pb zircon age of 3.07 Ga.

The West Rand Group mainly consists of shales and sandstones formed in fluvial and coastal-marine environments. The basal Hospital Hill Formation (up to 2000 m) includes jaspilite at the base of the section and a few small conglomerate beds near the roof. The overlying Government Formation (1800 m) contains basal conglomerate with decreasing upsection pebble size. The Coronation Formation in the middle part of the group includes tillites overlain by ferruginous shales. The Jeppestown Formation (up to 1200 m) is composed of thin flows of the Crown amygdaloidal basalts and the Roodepoort Shale (600 m) in the upper part of the group.

The most productive paleoplacers are confined to the Central Rand Group. The lower portion of the section is represented by the Johannesburg Formation (up to 1200 m) with lavas of the Bird Formation at the base overlain by well-sorted sediments of the St. Helena, Welcome, Harmony, and Dagbreek formations. The Turffontein Formation (900 m) occupies the upper portion of the group. The Carbon Leader, Middleway, Main, and Main Leader reefs are localized in the lower part of the Johannesburg Formation, while the Stain, Basal, Vaal, and Bird reefs are located in its upper part. The Turffontein Formation consists of isolated conglomerate beds and separate massifs of conglomerate layers. Their thickness and pebble size increase upsection. The uppermost part of the section includes thin Kristalkop, Gold Estates, Orkney, and Kimberly reefs.

The Witwatersrand Supergroup is overlain by volcanosedimentary rocks of the Ventersdorp Supergroup (4500 m). Its lower part (Klipriviersberg Group) consists of continental tholeiitic basalts (1530 m) overlapped by sedimentary rocks, including the Ventersdorp reef. This Au-bearing conglomerate unit is distinguished from other reefs by the occurrence of metabasalts and intense secondary alteration dated at 2020 Ma (Gartz and Frimmel, 1999), which is close to the age of the Bushveld Complex (2054 ± 2 Ma). The overlying rocks include alluvial sediments, andesites, and rhyolites of the Maquassi Formation (360 m) with the U–Pb zircon age of 2714 ± 8 Ma.

The youngest Au-bearing conglomerates are known in the Black Reef Formation at the base of the Transvaal Supergroup (up to 6000 m). This supergroup largely consists of dolomites, shales, and jaspilites that unconformably overlie the Ventersdorp Supergroup and are, in turn, overlain by the Pretoria Group. The Rb–Sr age of volcanic rocks of the Hekpoort Formation is 2.2 Ga.

The clastic material of the Witwatersrand conglomerates is composed of well-rounded and subrounded pebbles (as large as 2.5 cm, occasionally up to 10 cm along the long axis) of quartz, quartzite, chert (often replaced by pyrite), jasper, and rhyolite. The pebbles are cemented by quartz sandstone (*Uran* …, 1963; Heimstra, 1976). Heavy minerals are represented by chromite, zircon, leucoxene (after ilmenite), native gold, uraninite, pyrite, rare osmiridium, and others. Muscovite, pyrophyllite, chlorite, and other minerals occur in cement. The carbonaceous matter (thucholite) is noted in some varieties. Clastic grains are often recrystallized. The secondary quartz often fills up fractures and veinlets or partly replaces many minerals (pyrite, chlorite, and others). No less than 70 minerals are present in ores of Witwatersrand (Roscoe, 1996).

Pyrite is divided into three major types: rounded (as large as 2 mm), euhedral, and anhedral. Pyrrhotite, chalcopyrite, pentlandite, sphalerite, and other sulfides are commonly associated with pyrite. The well-rounded chromite and poorly rounded zircon grains often occur together. Uraninite is represented by subrounded grains (as large as 0.08 mm) often as botryoidal segregations (*Uran* …, 1963). The degree of roundness increases upsection. The uraninite grains are often corroded. The secondary uraninite surrounds and replaces primary uraninite grains. The uraninite grains contain fine dissemination and veinlets of galena. Gold occurs as subrounded, irregular, foliate, branching, and porous grains 0.005–0.5 mm in size (Konstantinovskii, 2000). Its content in thin flamelike laminas correlates with contents of uranium and other heavy metals. The average Ag and Cu contents are 10% and ~0.3%, respectively. The subordinate iridosmine and osmiridium occur as botryoidal sinters and irregular grains. Small greenish diamonds are also found.

The Witwatersrand sediments with Au- and U-bearing reefs were deposited in a closed intracratonic basin with a fluvial fan at the mouth of a large NW-flowing river (Antrobus, 1976). The river flowed into a shallow-water intermontane lake isolated by the fan base. Gold mineralization is maximal in the middle section of the fan, while the uranium mineralization is related to its base. The area incorporates six major fluvial fans that correspond to the Orange Free States, Klerksdorp, West Whites, West Rand, East Rand, and Evander gold ore fields. The Central Rand is an intersection of the eastern West Rand fan and the western East Rand fan.

Thus, the Au- and U-bearing Main Reef, Basal Reef, South Reef, and other conglomerates in the Witwatersrand are confined to the thick molassoid sequence (10 000 m) that transgressively overlaps older rocks of the granite gneiss complex and Mesoarchean greenstone belts (GB) of the Swaziland Supergroup. This sequence fills an oval basin (650×350 km^2) of simple syneclise type and is divided into three major lithostratigraphic subdivisions of variable thickness (Pongola, Dominion, and Witwatersrand supergroups) that are locally overlapped by volcanosedimentary rocks of the Ventersdorp Supergroup. The Au-bearing conglomerate units are largely confined to the Witwatersrand Supergroup, although separate reefs occur in both overlying and underlying units (Gartz et al., 1999). The age of supergroups is as follows (Ga): Pongola (3.2–2.9), Dominion (3.1–2.8), Witwatersrand (3.0–2.7), and Ventersdorp (2.7–2.1). They are overlapped by the subplatformal Transvaal Supergroup and intruded by granites (2.6–2.5 Ga) and the Bushveld Complex (2050 Ma) that hosts Cr, Ti, Ni, and Pt deposits.

West Africa. The Au-bearing Tarkwaian Group of the West African Craton belongs to the same type. Its ore potential amounts to 30–35 Mt of ore with 1.37–3.6 g/t Au. The total Au reserve is estimated at 250 t, while the Au resource is 450 t. These values are comparable with those in the world's largest gold deposits, although they are inferior to the Witwatersrand. Approximately 250 t of gold was recovered during the mining of conglomerate deposits in Ghana.

The Tarkwaian Group (figure) occurs in the NE-trending elongated grabenlike troughs commonly localized in axial zones of NE-striking GBs composed of volcanic and volcanosedimentary rocks of the Birimian Group with an age of 2.2–1.9 Ga (Mykhailov and Shcherbak, 2000). The most representative sections of the Tarkwaian Group are known in southwestern Ghana in the axial zone Ashanti GB, which incorporates the Tarkwa, Ntronang, and other paleoplacers (Junner et al., 1942). Here, the Tarkwaian Group (2670 m) includes quartz sandstones alternating with polymictic and oligomictic conglomerates. The section is divided into four groups (Ainoo, 1990; Stronger, 1996). The Kavere Group (550 m) is composed of polymictic conglomerates with pebbles of quartz, quartzite, basalt, andesite, dacite, mudstone, graywacke, and chert incorporated into the well-sorted medium- and coarse-grained sandstone matrix. The Banket Group (600 m) includes quartz sandstone with a unit (40–60 m) of Au-bearing oligomictic conglomerate. The Tarkwaian Group (150 m) is composed of greenish gray chlorite–sericite phyllites and shales. The Huni Sequence (1370 m) includes sandstone, gritstone, quartzite, and mudstone interbeds.

The Banket Group is subdivided into three units. The lower unit consists of quartz sandstone up to 420 m thick (Lower Quartzite). The middle (Au-bearing) unit is composed of oligomictic conglomerates (40–60 m). The upper unit, like the lower one, is composed of quartz sandstones (Upper Quartzite). The Au-bearing unit consists of four rhythms. Their basal conglomerate beds (2–9 m) represent Au-bearing reefs with economic Au grade (1.6–4.7 g/t). The highest grade is confined to the base of beds with the coarsest and least sorted conglomerates. Upward the section of rhythms, the amount and size of pebbles decrease, and conglomerate beds are separated by medium- and coarse-grained sandstone beds (6–12 m) with occasional "floating" pebbles and low Au grade (0.1–0.5 g/t).

The Au-bearing unit contains four Au-bearing conglomerate beds. The major economic ore is confined to the second (5–9 m) and the third (4–7 m) beds. The oligomictic conglomerates contain up to 90% of rounded pebbles of white, milky white, and gray quartz (1–6 cm) in the sandy matrix. The matrix contains hematite and less abundant ilmenite, rutile, magnetite, Au-bearing chromite, as well as sericite, chlorite, chloritoid, epidote, tourmaline, zircon, and garnet. Gold mainly occurs in the sandy matrix as rounded grains and fine dusty dissemination (up to 0.04 mm in size). In some places, gold occurs as very thin gold veinlets in the newly formed carbonate and quartz, as well as microcaverns in magnetite that replaces the primary ilmenite (Milesi et al., 1991).

The pebbles occur as well-rounded fragments of milky white quartz and less frequent quartzite (1–6 cm in size) in the sandy matrix or as thin (2–9 m) beds with chaotic distribution of fragments. No gold was detected in pebbles, and this casts doubt on its Birimian source.

The overlying Tarkwaian and Huni sequences are composed of greenish chloritized and sericitized mudstones and shales (up to 150 m). Intercalating sandstones, gritstones, and quartzites with phyllite interlayers are up to 1370 m thick. No gold was detected in these sequences.

It was deemed previously that the Tarkwaian Group overlies the Birimian Group with angular and structural unconformity. However, recent data testify to the absence of substantial hiatus and unconformity between these groups (Eisenlohr and Hirdes, 1992). The age of the Tarkwaian Group ranges from 2081 ± 25 to 1968 ± 49 Ma (Hirdes et al., 1991), which is virtually undistinguishable from the age of the Birimian. In the northwestern sector of the ore field, the Tarkwaian Group is intruded by doleritic and basaltic bodies (dikes and stocks) with the Rb–Sr age of 1968 ± 49 Ma. It has been proved that gold mineralization in the major vein gold deposits of West Africa (Obuasi, Bibiani, Pura, Kalana, and others) are younger than the Tarkwaian Group (*West* …, 1989; Marcoux and Milesi, 1993). The matrix of Au-bearing conglomerates contain neoforms of quartz, tourmaline, muscovite, Fe–Mn carbonates, and magnetite, which includes thin veinlets of the "secondary" gold in some places. Finally, in addition to the paleoplacers, quartz-vein gold deposits (e.g., the Damang deposit) were recently discovered in the Tarkwaian Group. Thus, the source of clastic gold in the Tarkwaian conglomerates has become an important issue, because gold could not be provided by the erosion of relatively small stratiform gold deposits (Lulo, Yaore, Wassa, Samira, and others) localized in the underlying Birimian Sequence. Therefore, it is logical to suggest the existence of so far unknown pre-Birimian sources of gold in West Africa. The Iti deposit may be among the ancient gold ore occurrences. Orebodies at this deposit are located in laterites that overlie presumably Archean amphibolites and calcareous metasedimentary rocks.

In northern Ghana (Bole–Navrongo GB), quartz sandstones of the Tarkwaian Group (500–600 m) with sporadic quartz pebbles overlies the Birimian fine-grained flysch without signs of angular unconformity and erosion (Kulish and Mikhailov, 2000). The sandstones fill the NNE-trending trough (16.5×1.5–$2.5\ km^2$) that extends along a regional strike-slip fault. On the one hand, the sandstones overlie the weathered Dixcove Granodiorite. On the other hand, they conformably grade in the overturned state into the underlying Birimian Flysch. Rocks of both subdivisions make up an overturned and tight asymmetric syncline with the NW-overturned southeastern limb. Their structural elements are similar. Hence, the major phase of tectonic deformation postdated the Tarkwa sandstones. The sandstones were deposited in an asymmetric graben bounded in the southeast by a synsedimentary strike-fault zone in an environment of permanent SE- to NW-oriented tectonic stress. Only sporadic gold mineralization was found in the Tarkwa sandstones, and Au-bearing conglomerates are absent here. However, the local prospectors mine gold from alluvium of streams, and the region has a certain gold potential.

Sequences similar to those in Ghana, probably, occur in other regions of West Africa. However, in some cases (e.g., in Burkina Faso), polymictic intraformational conglomerates of the Birimian Flysch were erroneously described as analogs of the Tarkwa conglomerates. In the Sirba GB (southwestern Niger), we found conglomerates similar to those in Tarkwaian Group in the narrow NNE-trending fault-line depressions. These conglomerates include rounded pebbles (1–2 to 10–15 cm) composed of quartz and quartzite (20–25%) and cemented by pale quartz sandstone. They unconformably overlie the Birimian volcanosedimentary rocks as nearly vertical sequences confined to the fault-line depression. Oligomictic conglomerates were also found in Côte d'Ivoire (Boduku), Mali (Lingekoto), and Senegal (Attak). However, gold mineralization is insignificant in these conglomerates.

Canada. The U-bearing quartz conglomerates of the Huronian Supergroup in Canada are the most important source of uranium, but they contain only insignificant gold concentrations. About 150 kt of U_3O_8 have been mined here. The ores also contain Th, Y, and REE.

The Huronian Supergroup comprises four groups with a total thickness of up to 15 km (figure): Elliot Lake (up to 6600 m), Hug Lake (up to 1100 m), Kirk Lake (up to 615 m), and Cobalt (up to 6900 m) (Pienaar, 1963; Robertson, 1974; Heimstra, 1976; Roscoe, 1996). They are characterized by rhythmic structure: the groups begin with coarse-clastic facies (Matinenda, Ramsay Lake, Bruce, and Guganda formations of the respective groups) that give way to the fine-grained sedimentary rocks (McKimm, Peckors, Espanola, and Gordon Lake formations) and thick quartz sandstones (Mississagi, Serpent, Lorraine, and Bar River formations). Quartz conglomerates occur only in the Elliot Lake Group.

Uranium ores hosted in pyrite-bearing quartz conglomerates are related to the Matinenda Formation of the Elliot Lake Group (figure). The lower part of this formation is composed of feldspathic and micaceous quartzites, gritstones, and conglomerates that unconformably overlap the Archean rocks. The upper part consists of metavolcanics (2.7 Ga) intruded by granites (>2.65 Ga, U–Pb zircon age). The formation is overlain by tholeiitic basalts (up to 300 m) of the Dolliberry Formation. The major ore zones (Nordyke, Kirk, and Keeler) correspond to the Ryan, Manfred, and Keeler members separated by barren intervals (Stinson, Ramsay Lake, and others). The Ryan Member (170 m) hosts the Nordyke, Lucknor, and Purdie orebodies (up to 30 m). The Manfred Member (100 m) hosts the Kirk Lake and Denison ore zones at its base. The ore zones are composed of pyrite-bearing conglomerates with arkose sandstone lenses (up to 10 m). The Kirk reef occurs 30 m above the Denison reef. The eroded surface of this member is overlapped by glacial sediments of the Ramsay Lake Formation that lies at the base of the Hug Lake Group. The Keeler Member also contains orebodies.

Uranium occurrences are also known in other fields of the Huronian Supergroup, e.g., intercalation of U-bearing conglomerate beds (more than 1–2 m) with thin flows of amygdaloidal basalts at the base of the Thessalon Formation and in the upper part of quartzites of the Livingstone Creek Formation. Subeconomic uranium mineralization was found in the following areas: Lake Sakami (Quebec); Ayapamicama, Benyah, and Tucky Jug lakes (northwestern Ontario); and Yellowknife and Montgomery Lake groups in the Northwestern Territories. Prospects with nearly economic grades were discovered in Deep Lake, Phantom Lake, Medecine Bow, and Sierra Madre groups, in Wyoming and Nemo Mountains, and the Black Hills in South Dakota.

Heavy minerals are represented by pyrite (up to 9–10%), uraninite, garnet, chromite, titanite, rutile, monazite, and xenotime (*Uran* ..., 1963; *Metallogeniya* ..., 1980). Along with fibrous sepiolite and crystals of calcite, pyrrhotite, pyrite, sphalerite, and galena, inclusions of organic matter (kerogen) fill fractures and occur as irregular segregations within uraninite grains.

Other occurrences. Cross-bedded red sandstones with interlayers and members of arkose, shale, and conglomerate of the Roraima Group (Guiana Shield) dated at 2.0–1.7 Ga (Read and Watson, 1975) are the nearest counterparts of the Au-bearing Tarkwaian Group. Outcrops of the Tortue Au-bearing conglomerate are known in the sandstones (Marcoux and Milesi, 1993). In the Brazil Shield, this interval includes the Proterozoic Jacobina Au-bearing conglomerates (Canavieiras, Morro Venta, Sierra Branco, and João Belo deposits) and Bahia conglomerates, as well as the Belo Horizonte pyrite-bearing quartz conglomerate previously mined for uranium (Konstantinovskii, 2000; Roscoe, 1996). The Jacobina Group includes the following formations (from bottom to top): Bananeira (1000 m)—massive pelitic rocks and intercalation of quartz–muscovite schists and micaceous quartzites; Sierra da Carrego (1800–2000 m)—intercalation of quartzites and Au-bearing conglomerates with interlayers of quartz–muscovite schists at the base; Rio de Oro (2000–2300 m)—pale bedded quartzites and sporadic shales; and Cruz das Almas (2100 m)—shales and conglomerate interlayers (Krendelev, 1974; Robertson, 1974; *Uran* ..., 1963).

The Au-bearing conglomerate units (1.8–2.4 m) of the Maneiro, Hollandez, Libertino, and Piritozo reefs belong to the Sierra da Carrego Formation. In addition to gold, they contain elevated concentrations of uranium (0.001–0.006%). The pebbles (up to 60%, 2.5–4.0 cm in size) are mainly composed of quartz and quartzite incorporated into the chlorite–sericite sandstone matrix with finely disseminated pyrite.

In the Minas Supergroup, the Au-bearing conglomerates are related to the lower part of a thick (up to 8000 m) substantially sedimentary sequence that unconformably overlaps the Proterozoic GB with a specific iron formation (itabirites) in the middle part of the section.

In Australia, the metalliferous conglomerates are located in the Nullagine Basin of the Proterozoic Hamersley GB, where the following groups are recognized from bottom to top (Konstantinovskii, 2000; Read and Watson, 1975):

(1) Mount Bruce Group including the following formations: Fortescue (2–5 km)—basalt, pyroclastic rocks, sandstone, conglomerate, chert, and dolomite (2.2 Ga); Hamersley (2600 m)—chemogenic sedimentary rocks, jaspilite, chert, dolomite, and banded iron formation (~2 Ga); and Willow (3000 m)—conglomerate, sandstone, siltstone, dolomite, and basalt (~2 Ga);

(2) Bresnaan Group (up to 13 km)—conglomerate and sandstone; and

(3) Benjamoll Group (up to 6 km)—stromatolitic dolomite and sandstone with rare conglomerate interlayers and rhyolitic flows (1.1 Ga).

Gold occurrences mined in the early 20th century are confined to lower units of the Fortescue Formation. Metalliferous conglomerates also occur in the Queensland Province in the Mesoproterozoic Westmoreland Formation (1200 m) composed of sandstones with conglomerate interlayers. The uranium ore is confined to coarse-grained cross-bedded sandstones, where the U grade in conglomerate interlayers amounts to 0.02–8.2% (0.765%, on average). Ore minerals are represented by carnotite, torbernite and less abundant renardite, soddyite, and phosphouranylite (Krendelev, 1974).

Au-bearing pyritiferous and radioactive quartz conglomerates were also found in the Karnataka State (South India) and the Singhbhum Block near Calcutta (Roscoe, 1996). Uranium occurrences are known in the Precambrian conglomerates of South Sweden and in the Eno and Koli deposits located at the base of the Jatulian section, Finland (Krendelev, 1974).

CIS countries. In the territory of the former Soviet Union, metalliferous conglomerates are known in various localities at different chronological levels (Konstantinovskii, 2000; *Problema* …, 1969). Sporadic gold occurrences were detected in Paleoproterozoic conglomerates (Stoilen Formation in the Voronezh Massif; Segozero, Onega, and Susar formations in Karelia; Kedrov Formation in the Muya Block; and Targai, Tuostai, Charodakan, and Stanakh formations in the Aldan Shield); Mesoproterozoic conglomerates (Khugda, Pognyazhek, and Davangra formations in the Aldan Shield; Bilyakcha Group in the eastern framework of the Siberian Craton; Oktyabrsk Formation in Taimyr; Purpol Formation in the Patoma Highland); Riphean conglomerates (Talyn and Bik formations in the Yudoma–Maya Trough); Vendian rocks (Moty Formation in the Sayan region, Khudzhir deposit); Lopatino and Vandadyn formations in the Yenisei Ridge; the Paleozoic rocks (Subpolar Urals, Rudny Altai, Anabar Anteclise, and Timan); and Mesozoic rocks (southern Tien Shan and Russian Plate).

In Ukraine, the major attention was paid to Paleoproterozoic conglomerates of the Krivoi Rog iron basin (Butyrin et al., 1999; Kobzar, 1981; Kuvshinov et al., 1979; Pisemskii et al., 1969). However, the geological exploration established a low resource potential of metaconglomerates of the Saksagan Formation. A polymictic conglomerate bed (up to 135 m) was found in the western exposure of gneisses of the Shpola Formation. Conglomerate–sandstone–shale sequences with insignificant gold occurrences overlie iron rocks, cherts, and slates of the Srednebelozersk Formation on limbs of the Belozersk structure. Of certain interest are the following metasedimentary sequences of the Ukrainian Shield formed at the orogenic and postorogenic (protoplatformal) stages of its evolution: Gorodskaya Formation (Teterev Group) in the framing of the Korosten pluton with occasional conglomerate at its base; Klesov Group in the northwestern Ukrainian Shield with leptites and other metavolcanic rocks (this group can be correlated with the Venterdorp Supergroup of South Africa in formation conditions); Osipenko Formation with quartz conglomerates in the Azov region (Soroki structure); and Belokorovichi Formation in the eponymous graben-syncline with conglomerate interlayers in the lower part of the section (*Stratigraficheskie* …, 1985). Small gold paleoplacers were found here.

According to Shcherbak et al. (2002), the following three types of metasedimentary sequences in the Ukrainian Shield can contain gold paleoplacers:

(1) Metasedimentary sequences of the initial stage of the evolution of GBs. These sequences are integral parts of greenstone sequences (Sura Formation of the Belozersk GB).

(2) Metasedimentary sequences of the final stage of the evolution of GBs. These sequences occur at the top of their sections and are closely related to the evolution of these belts (Belozersk Formation of the Verkhovtsevo GB; Osipenko Formation of the Soroki GB; and others);

(3) Sediments of intracratonic basins that correspond to the protoplatformal stage of the evolution of the Ukrainian Shield (Gulyai-Pole Formation in the eponymous brachysyncline; Gorodskaya Formation in the Radomyshl Trough; Belokorovichi Formation in the eponymous structure, and Zbran'kovo Formation in the Vil'shanka structure).

DISCUSSION: GENESIS OF CONGLOMERATES

Witwatersrand. The origin of gold mineralization in Witwatersrand is a matter of hot debates. In recent years, the idea of superimposed nature of this mineralization was emphasized in the Russian literature. It was suggested that the gold in conglomerates was transported from below by hydrothermal solutions or was actively redeposited in the substrate, while the conglomerates only served as a favorable ore-localizing medium (Shcheglov, 1997). Shcheglov (1994) stated that the combination of gold mineralization and conglomerates is an accidental rather than universal phenomenon. Pyrite and quartz pseudopebbles are not alluvial products. Their origin may be diverse. This opinion is supported by Brodskaya and Shumskaya (1998) who adduced arguments in favor of the hydrothermal origin of pebbles in the Witwatersrand conglomerates (growth of quartz grains in the course of complex physicochemical processes). According to (Dolgushin, 2000), gold deposits of Witwatersrand are related to processes of intrusion and immiscibility, and the conglomerates are relicts of igneous globular structures of layered intrusions.

Other genetic models have also been proposed for the Witwatersrand conglomerates. For example, Kremenetskii and Yushko (2000) suggested that their formation is mainly governed by SEDEX processes similar to those in active black smokers. In some places, these processes created reducing conditions that were favorable for the deposition of Au-bearing massive sulfide ores. According to (Tsonda, 2001), the ores are products of multistage hydrothermal sedimentary processes.

However, the overwhelming majority of researchers cast no doubt on the primary sedimentary nature of both the clastic material of the Witwatersrand conglomerates and the gold mineralization. The available materials have undoubtedly proved the following facts: the alluvial origin of quartz pebbles; the presence of rounded pyrite grains and other placer minerals (osmiridium, diamond, chromite, rutile, zircon, and others); the distinct stratification of sediments, on the whole, and gold mineralization, in particular; the preferential concentration of gold in the basal portion of conglomerate units; the confinement of gold to oligomictic rock varieties; and the consistent Au grade along the strike of conglomerate units (Konstantinovskii, 2000). Minter et al. (1993) and Frimmel et al. (1993) have proved the occurrence of rounded gold grains and their short-range redeposition. Therefore, the primary sedimentary origin of the Witwatersrand can be considered a fact. This model assumes the concentration of gold in the Neoarchean fluviodeltaic environment during the deposition of thick quartzitic sandstone sequences (with oligomictic Au-bearing conglomerates). The gold was partially remobilized and redeposited in the Paleoproterozoic (2050 ± 100 Ma), probably, due to the emplacement of the Bushveld Complex into the central Rand Basin. According to the estimate made by Minter et al. (1993), the secondary (redeposited) gold represented by very fine dissemination and interstitial segregations accounts for 25% of the total reserves. Some primary gold grains could acquire a "ghost ore" appearance under the lithostatic pressure as a result of the burial of sedimentary rocks to a great depth, as in the case of the Devonian placer gold in the Timan Ridge (Nikiforova and Filippov, 1990). As was emphasized by Minter (1999), the eolian processes were important in the formation of the Rand placers.

The occurrence of uraninite, which cannot exist as a clastic mineral at present-day conditions, is one of the arguments adduced by advocates of the hydrothermal origin of the Witwatersrand ore. However, the assumption of oxygen-deficient atmosphere in the Archean can explain the existence of uraninite as a placer mineral at that time (Heimstra, 1976). This assumption is supported by the coexistence of brannerite, a typical mineral of placer deposits, with uraninite in the Rand paleoplacers.

Developing the works by Ramdohr, Leibenberg, Shidlovski, Atter, and other scientists, Konstantinovskii (2000), Robertson (1976), Shuvalov (*Metallogeniya…*, 1980), and Holland (1984) proved the primary clastic character of not only gold, but also uranium ore in Witwatersrand on the basis of the following observations: the lithostratigraphic control of ore mineralization; the occurrence of rounded gold and uraninite grains; relationships between morphologies of uraninite grains and their internal zoning; specific features of their chemical composition, in particular, elevated contents of ThO_2 (1.6–6.5 wt %) and REE (1.0–3.4 wt %), which are much higher than those in the hydrothermal pitchblende; the stratified distribution of uranium in conglomerates; and the strong correlation between uranium in the ore and elements in clastic minerals. According to Randell and Spelling (Holland, 1984), the age of uraninite is 3050 Ma, which is older than clastic rocks of the Witwatersrand Group. Superimposed processed are reflected in the partial regeneration of gold, uraninite, and pyrite; the formation of two pyrite generations; and the formation of brannerite as a result of interaction between uraninite and titanates (*Metallogeniya …*, 1980).

The primary sedimentary nature of most minerals from the Evander ore field (pyrite, uraninite, zircon, chromite, cobaltite, gold, and Os–Is minerals) has been proved, although some other minerals (leucoxene, pyrrhotite, gersdorffite, chalcopyrite, galena, sphalerite, and a part of pyrite and gold) bear indications of remobilization and they could be deposited in hydrothermal ore systems (Malich et al., 2000).

Most of researchers refer the Witwatersrand Supergroup to the protoplatformal stage in the evolution of the Kaapvaal Craton. They believe that numerous vein, stringer–disseminated, and stratiform ore deposits (Barberton, Murchison, and others) hosted in the Mesoarchean GBs served as sources of placer gold.

Tarkwa. The primary sedimentary origin of the Au-bearing conglomerates of the Tarkwaian Group was never doubted. The Tarkwa deposit is localized in a tight asymmetric syncline with the NW-overturned southeastern limb. In plan view, the Au-bearing unit is traced over a few tens of kilometers, retaining its stratigraphic position and strictly repeating all bends of the host rocks. If the ore mineralization was superimposed, such a situation could hardly be possible (Kulish and Mikhailov, 2001). The primary sedimentary origin of gold mineralization at the Tarkwa deposit is also supported by rounded shape of the largest gold grains (0.04–0.06 mm). They often occur together with the prevalent fine dustlike dissemination in the sericitized and chloritized matrix in association with hematite and sporadic ilmenite, rutile, magnetite, and Au-bearing chromite. At the same time, the rocks subsequently underwent intense hydrothermal metasomatic reworking. This is evident from the fact that the matrix includes the newly formed quartz, tourmaline, muscovite, Fe–Mn carbonates, chloritoids, hematite, as well as threads and microcaverns of gold in carbonates, quartz, and magnetite (Milesi et al., 1991).

Thus, the Tarkwa Au-bearing conglomerates represent paleoplacers related to the following processes: (1) wash-out of gold deposits that are older than the leading quartz-vein type in Proterozoic GBs of West Africa; (2) repeated mechanical redeposition of gold by high-energy water streams and progressive concentration; and (3) accumulation of placers within a relatively narrow asymmetric grabenlike trough with a steep northeastern wall formed as a result of extension of the axial zone of the Ashanti GB. The trough inherited the shape of the GB, but predated the major phase of tectonic deformation. In paleogeographic terms, the trough probably represented a narrow marine gulf (or lagoon) periodically transformed into a chain of elongated intermontane lakes that resembled riftogenic depressions. The clastic material was mainly delivered from the southeast (Strongen, 1996). Origination, localization, and morphology of the trough were most likely governed by the same suture that controlled the location of the Ashanti GB. Permanent seismic activity in the fault zone promoted multiple redeposition of the sedimentary material and eventual concentration of gold in placers. Transition from the extensional to the compressional setting provoked the major phase of folding that affected both the Birimian and the overlying Tarkwa deposits. The consequent hydrothermal metasomatic alteration fostered the formation of secondary minerals in conglomerates, the remobilization and local redistribution of gold, and the formation of filiform gold veinlets and caverns in the newly formed minerals. The same processes with more active mobilization and migration of gold gave rise to the formation of Au-bearing quartz veins (Obuasi, Bibiani, and other deposits), including those in the Tarkwaian Group (Damang).

In contrast to the Archean Witwatersrand Supergroup, the Proterozoic Tarkwaian Group is characterized by a relatively short time of formation (no more than 100 Ma). The typical fanlike radiate pattern of gold-bearing deposits is absent in the Tarkwa Au-bearing rocks. Hence, the Tarkwa deposits can hardly be defined as typical deltaic facies. Probably, therefore, the Tarkwa Basin is significantly inferior to the Rand Basin in resources. Occurrence of hematite and low contents of pyrite and uranium are other distinctive features. The Tarkwaian Group is a typical lower molasse related to final stages of the evolution of Paleoproterozoic GBs in West Africa. This molasse fills narrow linear troughs within the GBs controlled by deep fault and suture zones. The latter zones have important implications for the localization of virtually all large endogenic deposits in the craton. It is not excluded that these zones incorporated not only Proterozoic deposits of various genetic types, but also so far undiscovered Archean deposits, which could serve as sources for the Tarkwa paleoplacers.

Huronian Supergroup. Researchers have suggested various tectonic models for the formation of the Huronian Supergroup: aulacogen, intercratonic graben, passive cratonic margin of the Superior province, rifting, sedimentary basin in the extension and breakup zone continent, and so on (*Metallogeniya…*, 1980; Pienaar, 1963; Roscoe, 1996). It is important to emphasize the complicate character of folding of these rocks involved in the Hudsonian orogeny (Read and Watson, 1975). In fact, they are preorogenic complexes.

Holland (1984) demonstrated that the Canadian uraninite grains are similar to those from Witwatersrand; i.e., they are largely clastic grains, although younger in age (~2.5 Ga).

It is notable that the Huronian and Snow Pass (Wyoming) supergroups contain pyrite-bearing conglomerates in the lower parts of sections, whereas hematite-bearing rocks and red beds occur in the upper part. Their formation depends on the degree of atmosphere oxidation, i.e., on the appearance of free oxygen 2.6–2.2 Ga ago.

The Huronian Supergroup is distinguished from the Witwatersrand Supergroup by younger age (2.70–2.45 and 3.07–2.71 Ga, respectively); immature character of quartz sandstones; low U/Th ratio in ores; lower degree of roundness of fragments and mineral grains; lesser amount of chromite and greater amount of monazite in heavy minerals; lower content of Ni and higher content of Co in pyrite; low abundance of organic matter; and relatively low contents of sulfoarsenides and sulfides in ores.

Similar sequences with both gold and high-grade uranium mineralization are known elsewhere in the world. They occur in molassoids deposited at final stages of the evolution of GBs and mark the onset of protoplatformal evolution of ancient cratons. Chronological boundaries of this stage are shifted from the Mesoarchean to the Paleo- and Mesoproterozoic boundary.

However, thin conglomerate beds are frequently found in the upper parts of typical Archean GB sections. For example, in the Yilgarn province of Western Australia, thin conglomerate units are known at the base of the Brown Lake Sequence. The Black Flag and Kurrawang metasedimentary sequences with conglomerate interbeds occur in the upper part of the Archean section. Thin conglomerate interbeds are noted in the lower part of the Penalonga Sequence (the middle part of the Tati GB section of Botswana), the upper part of the Yellowknife GB section (Canada), and elsewhere. However, they differ from metalliferous conglomerates by the polymictic composition, poor sorting, and rhythmic structure. The clastic material is commonly composed of acid, intermediate, and basic volcanics, gabbro, and amphibolites. Aplites, cherts, plutonic rocks, graywackes, and mudstones are less frequent. These conglomerates are not of practical interest. However, they occasionally host small gold deposits, e.g., the

Mount Robert deposit in the Witkin Sequence, Pietersburg GB, South Africa (Konstantinovskii, 2000).

CONCLUSIONS

(1) Metalliferous conglomerates are known at various chronological levels of the Early Precambrian: the Neoarchean (Witwatersrand Supergroup, South Africa), the Neoarchean–Paleoproterozoic (Huronian Supergroup in Canada), and the Paleoproterozoic (Tarkwaian Group, West Africa; Roraima Group in the Guiana Shield; Jacobina, Sierra de Carrego, and Moeda Groups in the Brazil Shield; and Mount Bruce Group in the West Australian Shield). They are also known at other Precambrian and Phanerozoic chronological levels up to the Recent Period.

(2) The metalliferous conglomerates could be formed at different stages of tectonic evolution: preorogenic stage (Huronian Supergroup), orogenic stage (Tarkwaian Group), and postorogenic or protoplatformal stage (Witwatersrand Supergroup). This factor was probably crucial for the estimation of quality and quantity of economic gold paleoplacers. The postorogenic conditions, which correspond to the highest maturity of the Earth's crust and the longest periods of its stable state, were most favorable in this respect.

(3) The primary sedimentary origin of gold mineralization has been proved for the world's largest paleoplacer deposits (Witwatersrand, Tarkwa, and others). Gold was concentrated in the fluviodeltaic setting in the process of deposition of thick sequences of polymictic conglomerates and quartzites with Au-bearing quartz and oligomictic conglomerate beds. As much as 25% of gold was remobilized and redeposited under the influence of younger hydrothermal solutions related to various tectonomagmatic processes (folding, intrusions, tectonic reactivation, and so on). However, the primary source of gold remains an unsettled issue. Irrespective of the mechanism of accumulation, it is especially difficult to imagine a source for the enormous quantity of gold deposited in Witwatersrand. This statement is also valid for large sources of the clastic uraninite, authigenic and allogenic sulfur, and pyrite.

(4) Specific attributes of the Archean pyritiferous ore conglomerates, in comparison with the Proterozoic hematite-bearing paleoplacers and recent unconsolidated placers, reflect the evolution of the primordial atmosphere, which was almost free of oxygen at the initial stage. Abrupt increase in the atmospheric oxygen concentration at the Archean/Proterozoic boundary provoked oxidation with the formation of hematite (instead of pyrite), brannerite (instead of uraninite), and so on.

(5) Geological features of the Ukrainian Shield (in particular, the presence of protoplatformal volcanosedimentary sequences) suggest the possibility of discovery of paleoplacer gold deposits. However, they will probably be subeconomic deposits that can hardly be compared with the known large deposits of this type.

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