Views columns are the opinions of the authors and do not necessarily reflect the opinions of the SEG

VIEWS

URANIFEROUS CONGLOMERATES: THOUGHTS ON THEIR ORIGINS

Ronald E. Seavoy *(SEG 2001 HF)*

Ronald E. Seavoy

This essay is a commentary on two important articles published by the Society of Economic Geologists. The first is William Kerr and Roger Wallis' "'Real-World' Economics of the Uranium Deposits of the Athabasca Basin, Northern Saskatchewan: Why Grade is Not Always King," published in *SEG Newsletter* no. 99 (October 2014). It is a stunning success—a tightly written summary of the types of mineralization in the Athabasca uranium province by long-term participants, as up-to-date as possible. But what makes it so effective is that it has a high degree of generality (big picture) without being clogged by details. The problems and potential of the province are clearly defined.

The second article, Hartwig E. Frimmel's "A Giant Mesoarchean Crustal Gold-Enrichment Episode: Possible Causes and Consequences for Exploration," came out last year in SEG *Special Publication 18*. Frimmel (2014) presents conclusive evidence for the placer origin of gold in Witwatersrand quartz-pebble conglomerates, but in my view not for accompanying uranium mineralization, and this is the nexus of this discussion.

The best interpretations of scientific phenomena are those that have the fewest assumptions. The assumptions that guide this discussion are as follows:

- Gold and other heavy minerals in quartz-pebble conglomerates have a placer origin.
- Uranium (as uraninite), nodular pyrite, and graphite/bitumen in quartz-pebble conglomerates must have a non-placer origin because they are friable minerals that cannot survive the high-energy environment of placer deposition.
- The association of uraninite, pyrite, and graphite/bitumen in quartz-pebble conglomerates was a simultaneous event that occurred after conglomerates ceased receiving sediments.
- Microbial metabolism is the only process capable of explaining the presence of uraninite, pyrite, and graphite/bitumen together in quartz-pebble conglomerates.

Ronald Seavoy is Professor Emeritus in history at Bowling Green State University, Ohio. He was originally trained in geology, and is most familiar with Archean rocks. Ron worked many summers on the Canadian Shield, centered on the Abitibi greenstone belt and the Slave craton, north of Yellowknife. He did all of the initial sampling on the Lupin gold mine in the Northwest Territories in 1961, after its discovery in 1960. He is the author of 10 books and numerous scholarly articles.

The physical evidence is that only quartz pebbles and extremely small quantities of abrasion- and solution-resistant minerals (zircons, chromite, gold) can survive long-distance transportation to deposition in quartz-pebble conglomerates. This heavy mineral assemblage (with or without gold) is found in the quartz-pebble conglomerates in the Witwatersrand, the Elliot Lake quartz-pebble conglomerates, several quartz-pebble conglomerates in Australia, and Mesoarchean quartz-pebble conglomerates elsewhere.

By comparison, magnetite did not survive as a detrital mineral in Witwatersrand and Elliot Lake quartz pebble conglomerates. If detrital magnetite did not survive long-distance transportation in high-energy sediments, it is inconceivable to me that nodular pyrite (commonly porous) and sooty uraninite could survive and be of placer origin, even though mineral chemical data are interpreted to indicate that the rounded uraninite grains are detrital (Frimmel et al., 2014). Although recent evidence suggests that the porous, concentrically laminated pyrite is of synsedimentary or very early diagenetic age (Agangi et al., 2015), as I interpret it, the nodular pyrite would fragment and be washed out to sea, along with the sooty uraninite.

Uraninite, pyrite, and graphite/bitumen must have been deposited in a different environment. That environment was conglomerates that were no longer receiving sediments because they were buried. Burial was shallow so that they retained their permeability, and during burial they received aquifer water containing dilute solutions of iron sulfate and trace amounts of dissolved uranium (UO_2 uranyl). Although gold, uraninite, pyrite, and graphite/bitumen form a mineral assemblage in Witwatersrand conglomerates, uranium mineralization is not genetically related to the placer origin of gold.

Shallow burial of conglomerates provided stratigraphic traps (closed systems) where microbial metabolism could thrive in a passive environment. The water that entered buried conglomerates drained granitic rocks and derivative arkose sandstones where prolonged weathering released trace elements from the crystal lattices of silicate minerals that formed these rocks. Uranium was one of these trace elements. Uranium was present in a few parts per billion in aquifer water, and was accompanied by much higher concentrations of iron and sulfate that were derived from the oxidation of pyrite. Within this closed system, microbes metabolized soluble uranium and iron minerals to produce uraninite and pyrite (Horscroft et al., 2011), as well as lesser amounts of soluble thorium and REE minerals that were concentrated in uraninite crystals or were adsorbed onto their surfaces. Microbial metabolism of uranium and REE ceased after conglomerates were deeply buried and were no longer aquifers.

Mesoarchean quartz-pebble conglomerates were deposited in deltas on the shelves of cratons or deltas in epeiric seas. It is likely that gold deposited in Witwatersrand conglomerates originated a long distance from the continental shelf, which can be assumed because the quartz pebbles are well rounded from being transported from the same source as the gold. Quartz-pebble conglomerates were deposited in a stable

to page 10 . . .

...from page 9 VIEWS *(continued)*

geologic environment, which can be deduced from the thick sequences of siliceous quartzites and sandstones that host the quartz-pebble conglomerates. The thick piles of these sediments indicate that pervasive weathering produced clean quartz sand from basement granites and other crystalline rocks, and this weathering was an ongoing process for long periods, measured in millions of years.

Frimmel emphasizes that gold mineralization in quartz-pebble conglomerates on the Kaapvaal craton were ongoing events for tens of millions of years. Thirty or more conglomerate strata in the pile of quartz have been mined for gold. According to Frimmel and Hennigh (2015), "a syngenetic model for Witwatersrand deposits requires a mega-gold depositional event during the Mesoarchean" (p. 7). The protracted length of gold mineralization in quartz-pebble conglomerates and the slow accumulation of quartz arenites on the shelf of the Kaapvaal craton greatly favored microbial metabolism of uranium from aquifer waters. A favorable environment for microbial metabolism of uranium was at the base of conglomerate beds where algal growths formed on impervious shale members. These growths surrounded placer gold particles that were already there.

Frimmel et al. (2014) also document that uraninite crystals in different conglomerates have different ratios of REE, and that variable amounts of REE occurred at different locations in the same conglomerate. They further document that gold particles in Witwatersrand conglomerates have elevated trace amounts of osmium and that this signature persisted during the Mesoarchean mega-gold event on the Kaapvaal craton. This event was on a much larger scale than at any other time and place in the Neoarchean, Proterozoic, Mesozoic, and Tertiary. This is good detective work. The best interpretation for the variable ratios of trace elements associated with uraninite, as well as the osmium content of gold particles, is that they measure a prolonged process of microbial metabolism from different source rocks that supplied uranium.

Many investigators of gold and uranium mineralization in Witwatersrand conglomerates reject the separate origin of uranium mineralization because the atmosphere lacked free O_2 to produce uranyl (UO_2) necessary to put uranium into solution after it weathered from the lattices of silicate minerals in crystalline rocks, or from derivative arkoses. Free O_2 did not become available until the global oxidation event (GOE), which began about 2.4 billion years ago and produced banded iron formations worldwide. Until the GOE, these investigators argue that uraninite and pyrite crystals accumulated in the bottom sands of inland streams, and gold accumulated in the channels of inland rivers, where both were simultaneously deposited whenever surges of flood water added quartz pebbles to river channels and deltas.

These investigators also assume that uraninite and pyrite crystals could survive the high-energy environment of conglomerate deposition because, like gold, both had enough internal strength to survive as heavy minerals. This assumption does not agree with physical evidence. Sooty uraninite does not have this internal strength. During floods, only gold and other heavy mineral crystals with strong internal strength would survive. The extreme difference in the internal strengths of uraninite crystals and gold precludes their simultaneous accumulation as placer minerals.

Photosynthesizing bacteria were abundant in the surface waters of Mesoarchean oceans, but they used a purple enzyme to metabolize CO_2 and water. They did not produce free oxygen; however, these microbes contributed carbon to the formation of black shale. Nonphotosynthetic bacteria were also hugely abundant at black smoker vents, where they have been fossilized into graphite lenses that now contribute to EM anomalies that have been drilled in exploration for volcanic-hosted massive sulfide (VHMS) deposits. The assumption of these investigators was that the Mesoarchean atmosphere was without free O_2 and uranium released by weathering could not become UO_2 (uranyl) and go into solution. Uraninite would form a detrital mineral.

There is evidence, however, that the ocean had an ephemeral content of O_2 that came from biofilms of cyanobacteria on stromatolites near beaches. Most investigators assume that this O_2 was used immediately to oxidize detrital particles of sooty uraninite and pyrite when they reached marine water, where they were dispersed; therefore, the only way that uraninite and pyrite could accumulate was as detrital minerals before they reached marine water.

Donald E. Canfield (2014) and other researchers suggest that as early as 2.6 billion years ago, and possibly earlier, there was enough O_2 in paleosols that the pyrite associated with primary gold mineralization was oxidized, went into solution as a sulfate, and entered groundwater (Canfield, 2014; Knoll, 2003). Canfield cites Ariel Anbar, who called the trace amounts of O_2 in the biosphere by 2.6 Ga "a whiff of oxygen," and Andrew H. Knoll cites Hiroshi Ohmoto, who also found evidence that O_2 was being produced in small amounts on land in protected environments. Ohmoto called these places "local oxygen oases within cyanobacterial mats" (Knoll, 2003, p. 99; Canfield, 2014, p. 95; Frimmel and Hennigh, 2015).

Canfield's research indicates that before 2.4 Ga and possibly as early as 2.65 Ga, anoxygenic photosynthetic bacteria (using a purple enzyme for metabolism) were in the process of evolving to oxygenic photosynthetic bacteria (using green chlorophyll as an enzyme for metabolism). It was these microbes that produced trace amounts of O_2 that oxidized pyrite to sulfate and trace amounts of uranium to uranyl so that they could enter groundwater (Canfield, 2014).

There is one more piece of evidence for the existence of oxygenic cyanobacteria producing trace amounts of O_2 on land as early as 2.6 Ga. Analysis of paleosols in South Africa, ranging in age from 2.67 to 2.46 Ga, found biomarker molecules for cyanobacteria synthesis, including steranes. Since steranes require O_2 for synthesis, their presence means that there were oxygenic cyanobacteria (chlorophyll bacteria) or an evolutionary predecessor that produced the O_2. This was the source of the O_2 that was used by microbes to produce uranyl and iron sulfate on land (Knoll, 2003; Canfield, 2014).

Microbial metabolism during long periods of time in the stratigraphic traps of shallow buried quartz-pebble conglomerates is the most likely process that explains the presence of sooty uraninite, nodular pyrite, and fossil microbes (graphite/bitumen) in quartz-pebble conglomerates. The metabolizing process that concentrated uranium in quartz-pebble conglomerates is similar to the biogenic origin of radiolarian chert and chalk, except that concentration of uranium took place in the closed confines of buried porous conglomerates instead of in marine water.

A process of uranium concentration similar to the process in Mesoarchean

conglomerates may have also operated during the Mesozoic on the Colorado Plateau in the United States, where microbes metabolized uranium (± vanadium and copper) from solutions in aquifers. The Colorado Plateau uranium deposits are on a stable craton that is similar to the Kaapvaal craton in South Africa, the Superior craton in Canada, and the Pilbara craton in Australia. Like the numerous uranium-hosting conglomerates on the Kaapvaal craton that are separated by tens of millions of years, all of the uranium-hosting conglomerates on the Colorado Plateau are of Mesozoic age (252–65 Ma) and also separated by tens of millions of years.

The uranium ores on the Colorado Plateau formed in river channels and deltas where they entered epeiric seas. The host rocks are small-pebble conglomerates and coarse sand that are porous and friable, and can be crumbled by hand. They occur within a thick pile of bright red sandstones deposited in a fully oxygenated atmosphere. The red sandstones are as bright today as when the conglomerate beds in them were receiving uranium mineralization. This extraordinarily visible oxidation did not affect uranium mineralization. Uranium was delivered to the Mesozoic conglomerates in the same way it was delivered to the quartz-pebble conglomerates on the Kaapvaal craton—in an oxidized state in aquifer water.

The uraniferous conglomerates of the Colorado Plateau have a high content of organic debris, up to the size of tree trunks, which sustained a diverse microbial community. Microbe species in this aquifer community metabolized uranium, vanadium, and copper from aquifer water. Like the Witwatersrand and Elliot Lake conglomerates, the Colorado Plateau conglomerates were never deeply buried while they were receiving aquifer water with trace amounts of uranium in solution. Where beds of small-pebble conglomerate and coarse sand have been down-warped by tectonic activity, they subsequently became methane reservoirs.

In arkose sandstones that host stratiform uranium deposits (unconformity and roll front deposits), there are more metallic minerals than pyrite. The best description of this mineralization is from the Athabasca basin in Canada, where the arkose sandstones that host uranium deposits are at or near an unconformity with basement crystalline rocks. In addition to uraninite, the other metallic minerals are pyrite and arsenides of nickel, copper, and cobalt, commonly in large amounts. These stratiform deposits are in zones of intense alteration that often extend into basal crystalline rocks in a keel (basement hosted; Kerr and Wallis, 2014). They cannot have a detrital origin because the concentrating process was never exposed to the atmosphere. They are in physically closed traps, probably related to fracture zones in basement rocks that emitted small amounts of methane, which helped sustain microbial metabolism that stripped uranium and other metals from the circulation of basinal water.

We have much to learn about the involvement of microbes in forming stratabound and roll front uranium deposits, as well as metal deposits in other environments (e.g., banded iron formations, sedimentary copper deposits). Gordon Southam and James Saunders neatly summarized the ability of microbial metabolism to create ore deposits from dilute solutions (especially uranium): "Bacterial metabolism can aid in the release of ore metals from rocks and minerals, as well as their transport and precipitation. This process has the potential to play a significant role in ore formation, particularly in low-temperature systems" (Southam and Saunders 2005, p. 1068–1071); similar conclusions have been made by others (Stevenson et al., 1990; Mancuso et al., 1993; Bonnetti et al., 2015).

REFERENCES

Agangi, A., Hofmann, A., Rollion-Bard, C., Marin-Carbonne, J., Cavalazzi, B., Large, R., and Meffre, S., 2015, Gold accumulation in the Archaean Witwatersrand basin, South Africa—evidence from concentrically laminated pyrite: Earth Science Reviews, v. 140, p. 27–53.

Bonnetti, C., Cuney, M., Michels, R., Truche, L., Malartre, F., Liu, X., and Yang, J., 2015, The multiple roles of sulfate-reducing bacteria and Fe-Ti oxides in the genesis of the Bayinwula roll front-type uranium deposit, Erlian Basin, NE China: Economic Geology, v. 110, p. 1059–1081.

Canfield, D. E., 2014, Oxygen: A four billion year history: Princeton, Princeton University Press, 216 p.

Frimmel, H.E., 2014, A giant Mesoarchean crustal gold-enrichment episode: Possible causes and consequences for exploration: Society of Economic Geologists Special Publication 18, p. 209–234.

Frimmel, H.E., and Hennigh, Q., 2015, First whiff of atmospheric oxygen triggered onset of crustal gold cycle: Mineralium Deposita, v. 50, p. 5–23.

Frimmel, H.E., Schedel, S., and Bratz, H., 2014, Uraninite chemistry as forensic tool for provenance analysis: Applied Geochemistry, v. 48, p. 104–121.

Horscroft, F.D.M., Mossman, D.J., Reimer, T.O, and Hennigh, Q., 2011, Witwatersrand metallogenesis: The case for (modified) syngenesis: Society of Sedimentary Geology Special Publication 101, p. 75–95.

Kerr, W., and Wallis, R.H., 2014, "Real-world" economics of the uranium deposits of the Athabasca basin, northern Saskatchewan: Why grade is not always king: SEG Newsletter, No. 99, p. 1, 11–15.

Knoll, A.H., 2003, Life on a young planet: The first three billion years of evolution on Earth: Princeton, Princeton University Press, 288 p.

Mancuso, J.J., Frizado, J., Stevenson, J., Truskoski, P., and Kneller, W., 1993, Paragenetic relationships of vein pyrobitumen in the Elliot Lake uranium district, Ontario, *in* Parnell, J., Kucha, H., and Landeis, P., eds., Bitumen in ore deposits: Berlin, Heidelberg, New York, Springer-Verlag, p. 335–349.

Southam, G., and Saunders, J.A., 2005, The geomicrobiology of ore deposits: Economic Geology, v. 100, p. 1067–1084.

Stevenson, J., Mancuso, J.J., Frizado, J., Truskoski, P., and Kneller, W., 1990, Solid pyrobitumen in veins, Panel mine, Elliot Lake district, Ontario: Canadian Mineralogist, v. 28, p. 161–169.