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Jabiluka-type Gold Deposits: Text and slides for a talk presented at the International Workshop on Gold Deposit Modeling in Exploration

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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Introduction

The purpose of this talk was to review the geology of Jabiluka gold deposit and provide data that would be useful in building either a genetic or exploration model for this type of deposit. The talk was presented by Grauch at the September 1986 International Workshop on Gold Deposit Modeling in Exploration hosted by the Colorado School of Mines in Golden, Colorado. Because of time constraints, most of the researchers responsible for collecting the data were not specifically mentioned in the talk. They are, however, for the most part acknowledged on the slides. Our USGS coworkers on the Australian unconformity-related uranium project are, likewise, not acknowledged enough in the text; Dave Frishman, Ken Ludwig, and Tom Nash have all made significant contributions to this work. A selected reference list is included in this report to acknowledge those references cited on the slides and to provide sources of additional information to the reader.

The slides (see appendix) are numbered consecutively for two projectors. Projector 1 has slides numbered 1-1, 1-2, etc., and similarly slides 2-1, 2-2, etc., are associated with projector 2. References in the text are to projector (or screen) 1 or 2.

Text

Good morning ladies and gentlemen. It is indeed a pleasure for me to be here talking to you today. I'd like to thank Sam Adams and Dick Hutchinson for asking me to participate in this workshop. I'm especially thankful for their direct charge not to present a coherent, well-reasoned model for the formation of the Jabiluka type of gold deposit. Rather, my purpose this morning is to set the scene and provide the data that will allow you to draw your own conclusions. I'll quickly review the regional geology, then the setting of the Jabiluka deposit, its characteristics (mineralogical and chemical), the theories related to the genesis of this kind of uranium deposit and indirectly to the geneis of the gold deposit, and finally I'll mention some possibly analogous deposits.

The first slide on each projector (1-1, 2-1), please. This is what it's all about at Jabiluka. The next slide in projector 2 (2-2). Of course, there are some by-products associated with the gold. Actually, this uraninite is from the South Alligator Valley Uranium Field--not from Jabiluka. The next slide in projector 2 (2-3). These are the reserves released by Pancontinental back in the late 70's. You can see that the Jabiluka 2 orebody contains at least a half million tonnes of ore with an average gold grade of 15.3 gm/tonne. There is also a minimum of 204,000 tonnes of U_3O_8.

The next slide on screen 2 (2-4) is an outline of Australia showing the location of the Pine Creek Geosyncline, which contains one of the world's largest uranium reserves. The next slide in each projector (1-2, 2-5), please. On screen 1 is a sketch map of the Pine Creek Geosyncline. The red shows the current distribution of Archean rocks, the colorless areas are underlain by Early Proterozoic metamorphites, the pink represents Early to Middle Proterozic postorogenic granites, and the brown represents Middle Proterozoic and younger sediments and volcanics. These small mine symbols show the location of the major uranium mines or districts in the geosyncline, Nabarlek, Jabiluka, Ranger, Koongarra, South Alligator Valley Uranium Field, and the Rum Jungle Uranium Field. On screen 2 is the latest in a series of stratigraphic interpretations of the geosyncline. The diagram is arranged normally along the vertical axis, going from Archean at the bottom to the Middle Proterozoic at the top. Horizontally, it portrays the stratigraphy from west (on the left) to east (on the right) across the geosyncline. Don't worry about formation names at this point. The idea is to note that the Archean basement is unconformably overlain by a "geosynclinal" sequence of sediments and volcanics. There are, of course, local unconformities in the sequence but nothing that has been recognized across the entire region. These rocks were intruded by the Zamu dolerite (the first of two major continental tholeiite sequences), metamorphosed, and then eroded. They are overlain by two sequences, the El Sherana and Edith River Groups, that are noted for their volcanic components. All these units were then intruded by Olenpelli dolerite, the second of the continental tholeiite sequences. The Middle Proterozoic Kombolgie Formation sandstones and minor volcanics (including the Nungbalgarri Member) overlie everything.

The next slide on screen 2 (2-6) is an enlarged version of the Early Proterozoic portion of the stratigraphic diagram. We'll now quickly go through a sequence of slides showing the known spatial and temporal distribution of lithologies within the Pine Creek Geosyncline. The next slide on screen 1 (1-3) shows the configuration of the basin during Namoona time. The Archean basement highs are shown in red. They are surrounded by fluvial and tidal systems. The central part of the basin received deeper water carbonates and pelites. In the vicinity of the South Alligator Valley, subaqueous mafic volcanism occurred. It was during this time period that the host sediments for Jabiluka were deposited. The next slide on screen 1 (1-4) shows that the basin expanded and deepened during early Mount Partridge time. After development of a widespread alluvial fan system, carbonates and evaporites became more extensive and submarine volcanism changed to intermediate to felsic composition and shifted its locus of activity to the north. The basin continued to enlarge and subside during South Alligator and Finnis's River time as shown on the next slide on screen 1 (1-5). Subareal acidic volcanism was centered in the South Alligator Valley area close to an area in which a carbonate reef developed. The hosts for many of the South Alligator Valley Uranium Field U-Au deposits were formed at this time as were exhalitive base-metal deposits and aurifereous iron formations. This depositional period was followed by metamorphism, deformation, and intrusion. The next slide on screen 1 (1-6) shows the distribution of metamorphic facies. In general, the central part of the basin is greenschist facies and the margins are amphibolite facies. Minor granulites and anatectic complexes occur on the eastern flank. Karsting may have occurred locally prior to the deposition of El Sherana and Edith River sediments and volcanics. The next slide on screen 1 (1-7) shows the known distribution of sediments and volcanics during that time. The volcanics are apparently bimodal with both basalts and rhyolites being fairly common.

A great deal of regional, as well as detailed geophysical work, has been done in the area. The next slide in both projectors (1-8, 2-7). On screen 1 is a summary of the landsat and aeromagnetic lineaments that have been recognized in the region. The other screen shows the bouguer gravity map. There has been no significant correlation recognized between lineaments defined by any of these parameters and ore deposits. Even where more detailed studies have been conducted, no real correlation has been found. Air-borne radiometric studies have been the most useful geophysical tool in exploration. The gravity and magnetic studies have, however, been helpful in outlining the granitic rocks.

The next two slides (1-9, 2-8). On screen 1 is a summary of many of the geochronological data that are available to help tie down the absolute timing of events in the Pine Creek Geosyncline. Please direct your attention to the middle horizontal region of the slide, it's a summary of geological events set on the horizontal time axis. You can see that the Archean age of the basement is supported by a U/Pb zircon age. Similarly, the age of metamorphism is indicated by U/Pb zircon ages. The ages of volcanic episodes are documented by Rb/Sr isochrons, and the age of the Ranger and Jabiluka deposits are defined by U/Pb whole rock isochrons. And those are, in brief, the data that are used, in conjunction with field relationships, to constrain the sequence of events in the geosyncline.

Here on screen 2 again is the sketch map of the geosyncline. You can see the distribution of the major metal fields in relationship to the generalized geology. Starting over here in the east is the Alligator River Uranium Field. Gold and uranium occur in economic concentrations at Jabiluka and possibly at the 7J prospect south of Jabiluka. The other deposits are devoid of gold--Ranger has up to 6 ppm gold in selected samples, but this is considered to be an unusual occurrence. To the west and south is the South Alligator Valley Uranium Field that hosts several small uranium-gold deposits. Further to the west is a mineral field dominated by small polymetallic deposits related to the post-orogenic granites. However, there are also exhalitive-type base-metal deposits and gold-bearing iron formations. The last major deposit field is the Rum Jungle Uranium Field in the western portion of the geosyncline. Most of these deposits are dominated by uranium but there are some deposits with by-product base metals. The gold occurrences seem to be related to intrusive rocks.

Well, we've developed a picture of an evolving basin, the boundaries of which we can not define. Before continuing, I should add a word of caution regarding the stratigraphy. The people responsible for its definition have done an admirable job under very difficult conditions--that is there is very little outcrop of the Lower Proterozoic units and correlations over large distances are very difficult. In fact, much of the stratigraphy in the east is based on shallow stratigraphic drilling. Ok, the basin appears to be symmetrical about an N-S axis, which runs more or less down the center of the currently exposed geosyncline. Early Proterozoic sedimentation seems to have occurred in two major cycles of interest, starting with shallow marine pelites, carbonates, and evaporates lapping on Archean highs (this is the Namoona Group of sediments). This was accompanied by subaqueous volcanism in the South Alligator River Valley area and by the deposition of some iron formation. An unconformity separates this sequence from the Mt. Partridge Group, the lower member of which is an alluvial fan sequence that covered most of the geosyncline. The basin deepened again and intra- to inter-tidal and deep water carbonates and pelites were deposited. Deposition of the second sequence of interest (the South Alligator and Finniss River Groups) followed what appears to be a brief period of erosion. This sequence appears similar to the Namoona Group except that these sediments do not contain Archean age detritus. The other major differences are the presence of exhalitive-type base-metal deposits and auriferous iron formation. The entire sequence was then intruded by the Zamu dolerite (a continental tholeiitic suite). Regional metamorphism was followed by deposition of two volcanic and clastic sequences, which are intruded by a second group of continental tholeiites (the Oenpelli dolerite). The entire metamorphic and sedimentary-volcanic package is overlain by the Middle Proterozoic Kombolgie Formation. The later does contain some volcanic units, which have been dated at about 1650 Ma. Base-metal exhalitive-type deposits and auriferous iron-formation formed essentially contemporaneously with deposition of the South Alligator and Finniss River Groups. Some uranium deposits formed at about the same time as the regional metamorphism, but many formed after the deposition of the Kombolgie Formation.

We're now going to quickly review some of these late U-Au deposits and then focus on the Jabiluka deposit. The next slide in project 1 (1-10), please. This is a list of U-Au deposits in the Pine Creek Geosyncline. Jabiluka has drilled reserves of 8.1 tonnes of gold; we don't know what is at the 7J occurrence other than native gold in surface samples of chloritic schist. The rest of the deposits listed are in the South Alligator Valley Uranium Field. All the gold production and reserves are listed under El Sherana. You can see that it is insignificant (a total of 330 kg) compared to Jabiluka.

The next slide in each projector (1-11, 2-9). Don't worry about the details of the stratigraphic column. The main thing to note here is that Jabiluka is hosted in the Cahill Formation (indicated in blue). All the other deposits and prospects are also hosted in that unit, except Nabarlek, which is hosted in the Myra Falls metamorphics, which are considered to be higher-grade metamorphic equivalents of the sequence that contains the Cahill Formation. The symbol 7 on the map is meant to indicate the 7J prospect not the 75 prospect.

The next slide on screen 1 (1-12) shows the surface expression of the Jabiluka 1 and 2 orebodies, the position of major faults, and the line of a longitudinal section that we'll see later. The next slide on screen 2 (2-10) is a lithologic column for a portion of the Cahill Formation at Jabiluka. It's colored mostly green to indicate the presence of chlorite throughout the section. Hole-to-hole correlation is in large part dependent on a few graphite schist marker units. The lower schist series 2 bottoms in amphibolite, which also generally was used as a marker to cease drilling. As can be seen on the longitudinal section (next slide in projector 1, 1-13), the Jabiluka 2 orebody is not exposed. The original discovery was made by drilling a radiometric anomaly over the number 1 orebody. Jabiluka 2 was found by drilling along the trend of ore body 1. It should be noted that between the two orebodies, intervals of carbonate up to 20 meters thick have been drilled. On strike both east and west, only minor carbonates and breccias appear in the section. If the stratigraphic column is accepted as real and if the drill-hole correlations are also accepted, the long-section shows a relatively flat-lying structure in the west that rolls over to being vertical in the east. The orebody is open to the east and with depth in that area. The next slide on screen 2 (2-11) is a north-south section at grid line 162 on the long section. The structure is steeply dipping to the south. Uranium ore is marked in red on both sections. Gold ore is shown on the long section as a lined pattern. A second gold orebody not shown on the section is located east of the Hegge Fault in the lower portion of the section. Both uranium and gold appear to be stratiform. However, the high-grade intersects are controlled by the presence of breccias. Therefore, the stratiform geometry of the ore may be a function of lithologic control on the formation of breccias. Structurally, this portion of the geosyncline is very complex. Needham and coworkers have defined at least four periods of isoclinal folding and several generations of faults. The next two slides (1-14, 2-12), please. In core, we have recognized at least two periods of penetrative deformation. On screen 2 is an example of transposed bedding. The "true" compositional layering dips to the left side of the screen and is highlighted by solid orange lines. It is being transposed into the metamorphic fabric that dips to the right side of the screen and is marked by dashed orange lines. Metamorphic fabric that has been isoclinally folded is shown on screen

1. This penetrative-type deformation was followed by several episodes of brittle deformation. The next slide on projector 2 (2-13) shows an example of the early quartz cemented breccia. I'll elaborate later on some of the other breccias. I should point out that many authors believe that at least some breccias have been caused by solution collapse. The lack of thick carbonates such as those observed separating the two orebodies and the presence of breccia and chert--interpreted by some to represent the replacement of carbonate--at the "carbonate horizon" have been cited as evidence supporting the solution breccia hypothesis. Other workers and I have not seen any direct evidence to support that contention.

I'm now going to briefly show you a few typical examples of rock types and textures from the core. The next slide on screen 1 (1-15) is the Cahill section again. Remember that these rocks all contain quartz. Any primary feldspar and biotite has been replaced by white mica and/or chlorite, and pseudomorphs of chlorite after garnet are common in some parts of the section. The next slide on screen 2 (2-14) represents the most abundant rock type--quartz-muscovite-chlorite schist. You can also see an early metamorphic quartz segregation. The next slide (projector 2, 2-15) shows typical graphite schist. These schists contain significant amounts of sulfide, both disseminated and podiform. The sulfide is almost invariably pyrite. A typical, coarse-grained dolomite-magnesite marble is shown on the next slide (projector 2, 2-16). A couple periods of igneous activity are recorded in core samples. The next slide on screen 2 (2-17) shows the earliest event. You can see on the left a sort of basic igneous material that intruded the schist on the right, prior to metamorphism. This relationship is demonstrated by the metamorphic foliation that dips to the left and cuts across the near-vertical contact. I don't know if the reaction zone between the two rock types is a result of the intrusion, the metamorphism, or, most likely, both processes. The next slide on screen 2 (2-18) shows a late pegmatite vein cutting across the foliation of a quartz-muscovite-chlorite schist. The feldspars in the pegmatite are chloritized and the pegmatitie is cut by later veins of quartz and chlorite.

The next slide on screen 2 (2-19) is a rather incomplete listing of the sequence of events that are documented at Jabiluka. The list starts by assuming the sedimentary episodes we've already discussed. The metamorphic event is mentioned. I should emphasize that we have no direct evidence that either the gold or uranium were present prior to metamorphism. In fact, the isotope data and paragenetic sequences indicate the contrary. A period of retrograde metamorphism is recorded by the regional alteration of biotite to chlorite and white mica. You've already seen the evidence for pegmatite emplacement and early brecciation. The next slide on screen 1 (1-16) shows an early uraninite vein that was more or less contempoanraeous with brecciation. You can see that some of the ore-forming fluid leaked out of the fracture along foliation planes. The next slide on screen 1 (1-17) shows one of the early dark-green chlorite veins. There have been several periods of chloritization that have been extensively studied by Connie Nutt of the USGS. She has been able to optically as well as chemically distinguish the chlorites belonging to major periods of chloritization and will be reporting on those at the forthcoming national GSA meeting. OK, another period of brittle deformation followed. The next slide on screen 1 (1-18) shows a later chlorite cemented breccia and push-apart chlorite-supported structures in a quartz-chlorite-muscovite schist. More or less accompanying this brecciation was the formation of uraninite-quartz veins. Shown on the next slide on screen 1 (1-19) is an example of cross-cutting quartz veins. Dissemenated uraninite was probably also formed at this time. You can see that this uraninite-quartz vein cross-cuts an earlier quartz vein. It is the observation and detailed description of cross-cutting relationships that has allowed us to build up a picture of the sequence of events that occurred at Jabiluka. The next event was the development of dark-green chlorite veins. The next slide on screen 1 (1-20) shows what has been called "injection chlorite." It looks in places as if it has been squeezed into the rock. Here it is "injected" into the Kombolgie sandstone. I should mention here, that the Kombolgie does not contain uranium or gold and that the only alterations we know of are extensive silicification; hematite alteration; two distinct periods of chlorite formation, one of which was accompanied by the growth of white mica; and a period of carbonate deposition. The latest set of veins contain carbonate (dolomite and magnesite), quartz, and both chalcopyrite and pyrite. One such vein, where it cuts an earlier quartz vein is shown on the next slide on screen 1 (1-21). Contemporaneous with this set of veins or slightly preceeding them, the gold-bearing veins and breccias were developed. The next slide in projector 1 (1-22), please. Here is an half section of core showing flakes of gold lying on shear planes. The gold was apparently originally emplaced in veins and breccias and later smeared out along the shears. The next series of slides will be photomicrographs magnified between 160 and 1450 times. The field of view varies between about 2.5 mm and 50 microns. The next slide (projector 1, 1-23) shows gold in a quartz-uraninite vein shown in the previous slide. The next slide (projector 1, 1-24) shows gold (slightly yellow colored) and euhedral uraninite (gray). The more silver colored material is a bismuth telluride. The next slide (projector 1, 1-25) is a close-up of a portion of this slide showing gold included in uraninite. Just about any textural relationship you can think of between gold and uraninite can be found in these samples, and those relationships can be explained in a variety of ways. For instance, this slide could show the preferential replacement of uraninite by gold or it could show that gold precipitation preceeded that of the uraninite. Good arguments can be mounted for either explanation. The next slide on screen 1 (1-26) shows intergrowths of bismuth telluride and uraninite. The next slide (projector 1, 1-27) shows gold, in this case containing detectable silver, intergrown with bismuth telluride. The next slide (projector 1, 1-28) is of a bismuth telluride grain contaning, near its center, a very difficult to see crystal of a harder mineral, which has been shown through microprobe analysis to be a Pd-Ni-Te phase. It's too small to x-ray and hence cannot be specifically identified. The next slide (projector 1, 1-29) shows a Pb-S grain that contains Se and hosts several grains of an Ni-Te phase. The next slide (projector 1, 1-30) has at its center another galena grain. It does not contain Se but does host a Fe-S (the smaller of the two) phase and a larger grain of a Co-Ni-Fe-S phase. The last photomicrograph (screen 1, 1-31) shows several uraninite crystals surrounded by small wiskers of a Re-Fe-S phase, all are in a matrix of quartz. The next slide on screen 1 (1-32) is a photograph (about 1 cm across) showing, again, the late stage carbonate-bearing veins. At the bottom of the slide are quartz crystals with their terminations pointing up. Organic matter, here a small black sphere, has formed on the terminations. Deposition of the organic material was followed by precipitation of carbonate and sulfides.

The next slide in projector 2 (2-20), please. What this sequence of slides has shown us is some of the evidence used to document some of the chemical changes that occurred along with the formation of the gold deposit. We have documented the concentration of gold, bismuth, tellurium, nickle, palladium, rehnium, and (not shown) selenium in the system. The uranium may have been recycled from preexisting veins or, less likely, may be "new" uranium introduced during this period of ore formation.

The next slide in projector 1 (1-33), please. There have been several studies that have investigated the chemical changes associated with the uranium mineralization. I'd like to digress for a minute and comment on my forthcoming comments. I'm going to very quickly expose you to a lot of data and a list of types of genetic models that have been published. By being brief, I am not trying to negate the work of the people involved. They have all done careful and well-documented work. It's just that we all are a bit like the three blind men who were asked to describe an elephant. The end result was an excellent description of a trunk, a leg, and a tail. I don't know if a major rift occurred between the three blind men involved. At Jabiluka, we all have had only drill core to examine and have all looked at different parts. And it's only recently that the paragenetic sequences based on cross-cutting relationships and detailed petrographic work that are required for a comprehensive story have been developed and we're still in the infancy of that work.

This slide summarizes the work of Ray Binns and colleagues at the C.S.I.R.O. (a division of the Australian Institute of Earth Resources) on chemical changes associated with uranium mineralization at Jabiluka. You should notice at first glance that some of the elements associated with uranium are those that I've associated with gold, which is paragenetically later than most of the uranium. So, one must look at this kind of data very carefully. What they've done here is to take a few samples, removed several kilometers from the deposit, and compared them to a suite of samples called the alteration halo--that is a suite of samples that are removed from ore-grade samples by a matter of meters. The next suite, which was separated from ore by a matter of a few centimeters, is compared to the alteration halo. And similarly, ore samples were compared to the immediate host rock. The next slide on screen 2 (2-21) is borrowed from Tom Nash and Dave Frishman, of the USGS, who have been working on the Ranger deposit. They show that during the various episodes of chloritization the net chemical change of the Cahill Formation was the addition of 145 percent Mg and 650 percent P and the loss of several 10's of percent Ca, Na, K, and F. Again, very useful information for exploration models but not detailed enough for genetic modelling.

The next four slides summarize a lot of isotope and fluid inclusion data that has many of the same limitations as the chemical data we've just seen. The next slide in both projectors (1-34, 2-22), please. On screen 1 is a summary of the carbon and oxygen isotope data. It is obvious from the carbon data that no simple mechanism can be invoked for the generation of vein carbonates from marble. It is also obvious that the two studies sampled different vein systems and different marbles--all from the same deposit. The oxygen isotope data do show some meteoric water component in the late veins. The sulphur isotope data again show that the different workers sampled paragenetically as well as isotopically different veins. They do show that the isotope systems reached a blocking condition between 360 and 227 ^{o}C. The next slide on screen 2 (2-23) summarizes the published fluid inclusion data. Both studies found metamorphic inclusions. The next generation of fluid inclusions in the Ypma and Fuzikawa study contained a concentrated brine with homogenization temperatures between 100 and 160 ^{o}C. Their next generation contained low-temperature, CO_2-rich, low-salinity inclusions. Durak restricted his work, other than noting the presence of metamorphic inclusions in the Cahill rocks, to studying inclusions related to silicification of the Kombolgie sandstone. The earliest inclusions were of moderate salinity with homogenization temperatures between 150 and 180 ^{o}C. The later inclusions were lower temperature but higher salinity.

The next side on screen 1 (1-35) is a listing of the types of genetic models that have been proposed for the Jabiluka uranium deposit. They range from syngenetic through supergene to epigenetic. They all have strengths and weaknesses, and may not be immediately applicable to the gold deposits, as no model has yet specifically addressed the gold problem. Centainly, uranium must be explained in any model of the gold deposit; but until we have a better understanding of the parageneses of both the uranium and gold, genetic modelling seems to be premature.

Looking at analogous deposits does not help the situation, because those deposits have the same problems with data that Jabiluka does. In fact, it's worse; we know less about the distribution of gold in the Canadian deposits than we do at Jabiluka. However, the analog deposits listed in the next slide on screen 1 (1-36) do serve the purpose of demonstrating that gold does occur elsewhere in settings similar to Jabiluka. We've already mentioned those deposits in the South Alligator Valley area. So let's look at Canada. The Athabasca region now exceeds the Pine Creek Geosyncline in drill indicated uranium reserves. Those deposits are very similar (in host lithologies and proximity to a major unconformity) to Jabiluka except that the uranium occurs both above and below the Middle Proterozoic unconformity. The next slide on screen 2 (2-24) shows the results of analyses performed on seven grab samples from the Collins Bay "A" deposit. That deposit is truely polymetallic with coproduct U and Ni and has the potential of producing Ag and Au. The Cluff D deposit has significant gold and the rest of the deposits listed are at least geochemically enriched in Au as well as many of the elements that accompanied gold mineralization at Jabiluka.

The next slide on screen 1 (1-37) summarizes the major characteristics of this type of deposit. They are contained in a chlorite alteration envelope. They are polymetallic with uranium, gold, and not listed nickle as primary products. They occur in breccia zones. They occur in close proximity to the Early/Middle Proterozoic unconformity. They are associated with the Middle Proterozoic cover rocks. And they occur within major uranium deposits.

Well, I've reviewed the setting of the Jabiluka gold deposit, some of the details of the deposit, some of the diverse data that is available for the deposit, and listed some possible analogs. It will now be up to the workshop team to decide what kind of model they want to build and what data--the details of which we can dig out of the literature--they want to use to build that model.

Even though I was specifically asked by Sam not to, I can't resist drawing at least one conslusion. The next slide on projector 2 (2-25) can be used as a model for that conclusion; which is, that all in all this gold deposit that has a drilled reserve of 8100 kilograms of gold is a very curious creature and warrants much more detailed examination.

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APPENDIX

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