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Alternative gold prospecting methods used by artisanal and small scale miners: A review

Alternativne metode iskanja zlata, ki jih uporabljajo obrtniki in rudarji v majhnem obsegu: pregled

Fredrick Martin MANGASINI[1,3*], Michael MSABI[1], Athanas MACHEYEKI[1] & Alex KIRA[2]

[1]Department of Geology, College of Earth Sciences and Engineering, University of Dodoma, Tanzania; (*) corresponding author: mangatz@yahoo.co.uk, e-mail: mmsabi@yahoo.com, asmacheyeki@yahoo.com

[2]Department of Accounting and Finance, College of Business and Economics, University of Dodoma, Tanzania, e-mail: alexkira10@gmail.com

[3]State Mining Corporation, P. O. Box 981, Dodoma, Tanzania

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Abstract

Artisanal and Small Scale Mining (ASM) is distinctive to Industrial Mining (IM) upon minimal applications of scientific methods and inadequate funding of its geological exploration activities. Revision of scholarly sources indicate that for ASM, gold prospecting is done using visual features that signify zones of mineralization. Such features comprise soil and lithological indicators, geo-biotic indicators, indicator minerals, pathfinder elements and associate minerals. Others include physical features and mine vestiges. Imminent research on ASM rests upon studying scientific inter-relationships of such techniques and suitable mechanisms of financing activities related to geological exploration, an inordinate barrier to smart productivity of ASM.

Izvleček

Obrtniško rudarjenje in rudarjenje v majhnem obsegu (ASM) se od industrijskega rudarjenja (IM) razlikuje po minimalni uporabi znanstvenih metod in nezadostnem financiranju potrebnih geoloških raziskav. Pregled znanstvenih virov kaže, da se pri ASM iskanje zlata izvaja z uporabo vizualnih značilnosti, ki označujejo območja mineralizacije. Takšne značilnosti obsegajo talne in litološke indikatorje, geobiotske indikatorje, indikatorske minerale, sledilne elemente in povezane minerale. Druge vključujejo fizične značilnosti in ostanke rudarjenja. Bližnje raziskave ASM temeljijo na preučevanju znanstvenih medsebojnih odnosov takšnih tehnik in ustreznih mehanizmov financiranja dejavnosti, povezanih z geološkimi raziskavami, kar je pretirana ovira za pametno produktivnost ASM.

Introduction

Artisanal and Small Scale Mining is distinguished from Industrial Mining owing to its low levels of production, lower degree of mechanization and technological applications (ASM often use picks, chisels, sluices and pans), high degree of labour intensity and little capital investment. Other factors include lack of long-term planning, informality, poor occupational health, safety and environment conditions (Chaparro Ávila, 2003; Hinton et al., 2003; Lahiri-Dutt, 2004; Hinton, 2006; Adler et al., 2013).

Financing of geological exploration operations is yet another key difference between two modes of mining. IM finance exploration through debt, equity or own funding (Myers & Majluf, 1984) whereas ASM own funding is the foremost financing alternative. Nonetheless, ASM are financially constrained, so they do not carry out geological exploration to a stage of reserve and resource classification prior to operating their mines (Hentschel et al., 2003). Limited to using simple prospecting techniques (indicators), they work only to discover availability of the mineralization, and start mining instantaneously.

Indicators, in principle entail visual features that signify areas where mineral commodity, such as gold may be found. Skills and abilities involved to identify such features comprise activity, observation, knowledge, insight, opportunism, lateral thinking and luck (Marjoribanks, 1997). Little has been written about simple prospecting methods applied by ASM in gold exploration. It is very timely to report these methods and provide basic scientific explanations to enable an ever more realistic mineral localization predictions in future.

Apprehension of these techniques by the public is vital based on the fact that they are inexpensive, quick and simple, centered on field experience and minimal professional training, therefore they can be widely applied particularly in low income societies. The methods do not readily follow procedures of traditional geochemical prospecting yet they provide physical evidence of the presence of gold mineralization or alteration (McClenaghan, 2005).

Methodology

This work involved desk review of various documents including books, book chapters, academic journals and articles, conference papers and scientific reports. These documents were filtered using Google search engine on different platforms mainly Google scholar, ResearchGate and ScienceDirect.

The keyword terms for this search were designed to identify any study on gold prospecting related to ASM. Studies related to IM contexts were deliberately not included. The search keyword terms used include: gold exploration, controls of gold mineralization, indicators of gold mineralization, gold prospecting techniques, and geological prospecting methods.

A total of seventy eight (78) references based on different gold prospecting techniques were selected for the review. Amongst are 6 books and 8 book chapters, 3 conference papers, 54 journal articles, and 7 scientific reports. Therefore, this work is confined to secondary sources of information that have provided qualitative data that support different techniques employed by ASM to discover zones of gold mineralization.

Results and discussion

We begin with soils and rocks to discuss how they are applied by ASM to prospect for gold mineralization. Next we show how the biota is expedient for auriferous prospecting, pointing specifically to how some plants bolster sighting of mineralized zones. We also discuss uses of indicator minerals and surface features to point out potentials of gold locations. We conclude with the discussion of how historical features including reports and old infrastructures ease ASM prospecting for gold mineralization.

Soil indicators

Whereas local geology and surface conditions sustain, soils make the simplest way of discovering gold deposits. Soil texture, color and profiles have been extensively used by ASM to identify zones of mineralization.

Insitu weathered soils

Soils in tropical environments evolved from gold bearing greenstones for example, become slowly enriched in gold as the bedrock weathers. In the Tapajós region in the Brazilian Amazon, ASM are reported panning this type of soil to locate and define the size of deposits (Veiga et al., 2006). Quartz fragments and/or flaky grains of hematite (an iron oxide mineral) together with gold particles are checked to determine if the gold particles originate from a vein, or is supergenic. Primary gold is usually angular and dendritic (tree-shape) containing more impurities, such as copper and silver than the recrystallized gold (Sarala, 2015). Large (over 1m) gold bearing quartz veins have been detected using this method.

Lateritic soils

Lateritic soils develop essentially from long term exposure of cratonal rocks to the atmosphere and hydrosphere in equatorial and tropical climates (Colin et al., 1997). If they have for example developed from Archean to lower Proterozoic gold-rich formations, their profiles usually show an increasing gold concentration towards the bed rock. This is due to progressive weathering and leaching (Colin et al., 1997). Therefore, once discovered, they make good indicator of potential gold mineralization.

Rocks and ore bodies oxidized to depths of 30 to 100 meters in Geita, northern Tanzania (Cowley, 2001) exemplify this mode of mineralization. Other reported localities consisting similar form of gold mineralization include the Dondo Mobi gold deposit in Gabon (Colin & Vieillard, 1991), Amani gold deposit in southwest Tanzania (Dunn & von der Heyden, 2021); and Abim district gold deposit in northeastern Uganda (Voormeij, 2021).

Soil color change

Related to that is soil color change. It usually signifies change in elemental content or oxidation states of elements and mineralogy of the soil; and can help to locate zones of gold mineralization (Rigobert et al., 2013). Goethite (α-FeOOH) and Haematite (α-Fe_2O_3), the most widespread Fe oxide and oxyhydroxide minerals in soils, particularly in well-drained tropical soils, greatly influence soil color (Allen & Hajek 1989; Schwertmann, 1988).

These minerals are formed by weathering of primary Fe-bearing minerals, such as pyrite, pyroxene, olivine, augite, hornblende and biotite. Mafic intrusive rocks (for example Dolerite dykes), where these minerals originate, are mostly host of auriferous quartz–carbonate–sulfide veins (Fielding et al., 2018). Therefore, ASM though unfamiliar to chemical relations between gold localization and presence of Fe-rich soils, have been curious in identifying soil color changes considering them as important pointers to sources of gold mineralization.

Soil color change may also be characteristic to lithological contacts (Graham et al., 1994; Wysocki et al., 2005). Formed through deposition, magma intrusion, and /or deformation of rock units, lithological contacts create weak zones through which hydrothermal fluids penetrate and precipitate mineralized veins (Zhu et al., 2011). Therefore, contiguous color changes in soil makes another important indicator to ASM of a probable gold setting. Buhemba and Nyasanero mines in Tanzania (Henckel et al., 2016) are example of places where ASM are mining quartz veins at lithological contacts.

Light colored soils

Furthermore, soils in lighter colors may be due to acidic mineral solutions bleaching lode deposits underground (Kontak & Kerrich, 1995). Both pre and syn-ore alteration, alters the physicochemical properties of the mineralizing fluids and thus promotes gold precipitation (Hastie et al., 2020; Williams-Jones et al., 2009). For example, in the vicinity of an oxidizing sulfide deposit, large quantities of both sulfate and metals go into solution in the ground water, creating extremely acidic condition by the free sulfuric acid resulting from the oxidation of pyrite and marcasite.

As a result, the mobility of elements in these areas will be higher than that in normal areas. Acidic solutions bleach host rocks to commonly exhibit yellow to pale grey coloration (Xu et al., 2017). Youthful soils developed from such bleached (light-colored) parent rocks will usually be lighter (Finkl, 1988). This feature has been used as an important indicator of gold mineralization in the deposits of Geita (Kwelwa et al., 2018) and Nyasirori (Yuan et al., 2019) in Tanzania; and Hira-Buddini in India (Sahoo et al., 2018).

Lithological indicators

Rocks are main hosts to primary gold mineralization. However, a handful rock types have been found to be useful to ASM as indicators for possible gold mineralization settings.

Quartz veins and reefs

On a global scale, ubiquitous orogenic quartz veins and reefs have been a focus of ASM in their prospecting for gold mineralization (Goldfarb, 2001; Vishiti et al., 2019). Being limited on exploration and metallurgical technology, ASM generally have less interest on low grade ores of wall rocks; rather they are focused onto highest-grade portions of the lodes. Logically, owing to their low production capacities, high grade veins seem necessary to ASM for two reasons. First, to minimize metallurgical costs; and secondly to earn more profit. Bismark reefs in the Lake Victoria Goldfield of Tanzania; and quartz veins mining in the Nazca-Ocoña belt in Peru are examples of gold discoveries in quartz veins by ASM (Hester et al., 1995; Alfonso et al., 2019).

Occurrence of gold mineralization in quartz veins can be explained using Bowen's reaction series, which posits that quartz (silica) precipitates last from the magma thus filling fissures and cavities of the host rock (Bowen, 1922). Since gold is chemically inert and does not react with most elements, it precipitates within or along fractures of these veins. This is why quartz veins mostly associate with primary gold mineralization.

Also, although gold is relatively soft (ductile and malleable), both quartz and gold also display relative resistance to physical weathering (Colin et al., 1997; Itamia et al., 2019). Their ability to sustain immediate physical and chemical changes help them to occur together, a fact that prompts ASM to look for quartz veins in their search for gold.

Lamprophyres

Another gold indicating rock is lamprophyre, a porphyritic igneous rock consisting of a fine-grained feldspathic groundmass with phenocrysts chiefly of biotite (McLennan, 1915). Gold enrichment of the lamprophyres is supported by their exceptionally deep origins in presumed Au-rich regions of the earth (>150 km), high F, K, Ba, and Rb and moderate S contents. $H_2O/(H_2O + CO_2)$ ratios and fluidized condition together make them uniquely similar to auriferous ore fluids in their element abundances and possibly in their physical state. These features brand them well suited to transporting gold into the crust (McNeil & Kerrich, 1986; Rock et al., 1989). Golden Pride intrusions in Nzega Greenstone Belt of northern Tanzania are examples of the ASM mined lamprophyres (Kwelwa et al., 2013).

Porphyries

Porphyry, an igneous rock containing conspicuous crystals (phenocrysts) surrounded by a matrix of finer-grained minerals is another rock unit indicator of gold mineralization if it is associated with quartz veinlets. Similar to the lamprophyres, gold in porphyries occurs in a stockwork of quartz veinlets within host rock units and their ores display remarkably consistent grade (Vila et al., 1991). Porphyries are commonly classified based on their main mineral contents. The carrier unit of gold is the Cu-Au porphyry. Amani and Mpanga Hills in southwest Tanzania where Cu-Au mineralization is hosted within impure micaceous marbles are the known ASM worked Cu-Au porphyry deposits (Dunn et al., 2021).

Breccia

Breccia, a rock composed of large angular broken fragments of minerals or rocks cemented together by a fine-grained matrix associated with either in situ deformation of rock, cataclastic deformation in tectonic shear zones, or mass flow deposits such as landslides or rock falls (Gibson et al., 1996), is another rock type considered in the search of gold mineralization. They may be mineralized within clasts and /or networks of epithermal quartz veins and veinlets (Sutarto et al., 2015; Rottier et al., 2018). The well-known breccia deposit mined by ASM is the Mananila deposit in Morogoro, Tanzania. This is the 400 to 450 meters long, and from 60 to 80 meters thick gold mineralized zone with echelon systems of quartz veins and veinlets, steeply dipping bodies of quartz breccia ranging from 1.0 to 1.5 meters thick. It is localized within tectonically sheared zones of Early Precambrian granitic-gneisses (Mykhailov et al., 2020).

Conglomerates

We note that auriferous conglomerates have also been a focus in the search for places of gold mineralization. These are clastic sedimentary rocks made up of rounded gravel and boulder sized clasts cemented or in a matrix support (Migoń, 2020). Generally, they mark periods of deep secular weathering that is favorable for the production of gold placers. Their gold grains may be of detrital origin, but they may also be in crystallized forms indicating hydrothermal emplacement caused by localized remobilization (Taylor and Anderson, 2018). Surface indications of auriferous conglomerates have been found to include manifestation of large amount of pyrite in the rocks, excess quantities of quartz pebbles or sands in streams or soil, large concentration of SO_4 in ground and surface waters due to the oxidation of pyrites, abundant iron staining and occurrence of gossans both residual and transported.

In Tanzania, ASM are mining gold nuggets in the conglomeratic horizons within the braided river channels of the Amani River (Dunn et al., 2019).

Banded iron formations

Incongruent to clastic sediments are the chemically precipitated banded iron formations (BIFs). They are used in localization of gold places because gold in these rocks is found in cross-cutting quartz veins and veinlets, or as fine disseminations associated with pyrite, pyrrhotite and arsenopyrite. Gold-bearing BIFs may also include native gold, magnetite, chalcopyrite, sphalerite, galena and stibnite. BIF make excellent prospecting targets because of their scalability, often being found in clusters. A good example of BIF gold deposit exploited by ASM is the Mwamola gold deposit in northern Tanzania (Yuan et al., 2019).

Geo-biotic indicators

Scientific observations involving plant-soil relations on natural plant communities show that certain species can be used for the detection of elemental enrichments arising from mineralization in the underlying bedrock (Timperley et al., 1972). An urge of using plants in the search of economic deposits is based on either the ability of plants to absorb or to be affected by high concentrations of metals from considerable depths and/or from a mineralized halo surrounding the ore (Cannon, 1960).

Botany provide evidence that plants can be used in geological prospecting in three ways: (a) through mapping distribution of particular species (indicator plants) most affected by the mineral sought, (b) by the physiological and morphological changes in plants growing in mineralized grounds (appearance), and (c) via the differences in chemical composition, that is plant analysis (Hawkes, 1957). Here (i-vi), we use category (a) and present species mostly used by ASM to ascertain the presence of gold mineralization. The discussed species are shown in figure 1.

Ocimum centraliafricanum (Copper plant)

It is a subshrub and grows primarily in the seasonally dry tropical biome. It is a perennial herb found in Africa (especially in Tanzania, the Democratic Republic of Congo, Zambia and Zimbabwe). It is well known for its tolerance of high levels of copper in the soil (Paton et al., 2009). Since Cu sometimes occur with Au, the plant has been looked after by ASM to prospect for gold.

Acacia mellifera (Black thorn)

Known to up-take gold (Taylor, 2009), black thorn is an african shrub that grows to a height of about 9 m having an extensive root system that penetrates through large volumes of soils, allowing its survival in dry areas. It grows better on sandy, clayey or stony-rocky soils but it is tolerant of a wide range of soils, including black cotton soils (vertisols). The black thorn is found in regions with 400-800 mm annual rainfall but it can grow in areas with a minimum of 100 mm rainfall; and along seasonal watercourses or drainage networks (Heuzé & Tran, 2015). For ASM, its ability to occur along watercourses, attracts them to locate Au placers along paleostreams.

Eriogonum caespitosum (Wild Buckwheat)

Occurs in areas highly mineralized with Cu, Pb, Au, Ag and U; the secondary mineral dispersion zones due to mechanical and /or chemical weathering (Smee, 1998). The *Eriogonum caespitosum* genus is tolerant of metals in the dispersion zones and accumulates them, making it a focus to metal prospectors (Cannon et al., 1986).

Monardella odoratissima
(Alpine Mountainbalm or Coyote Mint)

A grayish, aromatic plant with erect, bunched, leafy stems bearing opposite leaves and topped by small, whitish to pale purple or pink flowers in a dense head; grows in sandy soils in Au-Ag, Cu mineralized grounds in the secondary dispersion halos. Like *Eriogonum caespitosum,* it has been used by prospectors to identify areas of gold mineralization (Cannon et al., 1986).

Debarked trees

Unlike specific flora species discussed above, ASM have also been looking for "sign trees" during gold prospecting. These are debarked trees to indicate presence and direction of the gold mineralized veins. Early explorers in Tropical areas (especially along the Proterozoic Ubendian belt in the southwestern Tanzania) prior to the wider applications of the Global Positioning System (GPS), debarked tree trunks to mark gold locations. In Africa, apart from locating gold, debarking was also done for other purposes such as trail making, ground water location and cultural activities (Atindehou et al., 2022).

However, the scars for gold were made in a special way to point to the direction of the mineralization. Depth and width of the mineralized veins are indicated by the length and width of the scars. Where longer and wider scar is made, it means the vein is buried at depth and is thick (over 5 m). Nevertheless, narrow and shallower veins are represented by narrow and short scars. In the Lupa Goldfield, SW Tanzania debarked trunks are currently followed by ASM to identify locations of gold mineralized veins (Bryceson et al., 2012).

Termitaria

Mounds made by termites are fauna-related features useful for mineral exploration. Termites move large amounts of soil material, and thereby bring up anomalous materials from depth to the surface through bioturbation process.

For insitu soils, the moved up material is usually representative of the underlying bed rock. Therefore, termite mound allows observation and/or sampling of geochemical materials from the interior without need for drilling and with much better certainty than surface soil sampling enabling locating of gold anomalous zones (Arhin et al. 2010; Petts et al., 2009).

Indicator minerals

Whereas indicator minerals can indicate the presence of a specific mineral deposit, alteration or rock lithology, their physical and chemical characteristics, including visual distinctiveness, moderate to high density, silt or sand size, and ability to survive weathering and/or clastic transport, allow them to be readily recovered from exploration sample media. In addition, their abundance, grain morphology, and surface textures help prospectors to determine their relative distance from the source (McClenaghan, 2005).

There is overwhelming evidence that indicator minerals: (1) offer an ability to detect haloes much larger than the mineralized target including associated alteration; (2) provide physical evidence of the presence of mineralization or alteration; (3) have the ability to provide information about the source (that traditional geochemical methods cannot), including nature of the ore, alteration, and proximity to source (Brundin & Bergstrom, 1977). Gold grains, pathfinder minerals and black sands help to support this conclusion.

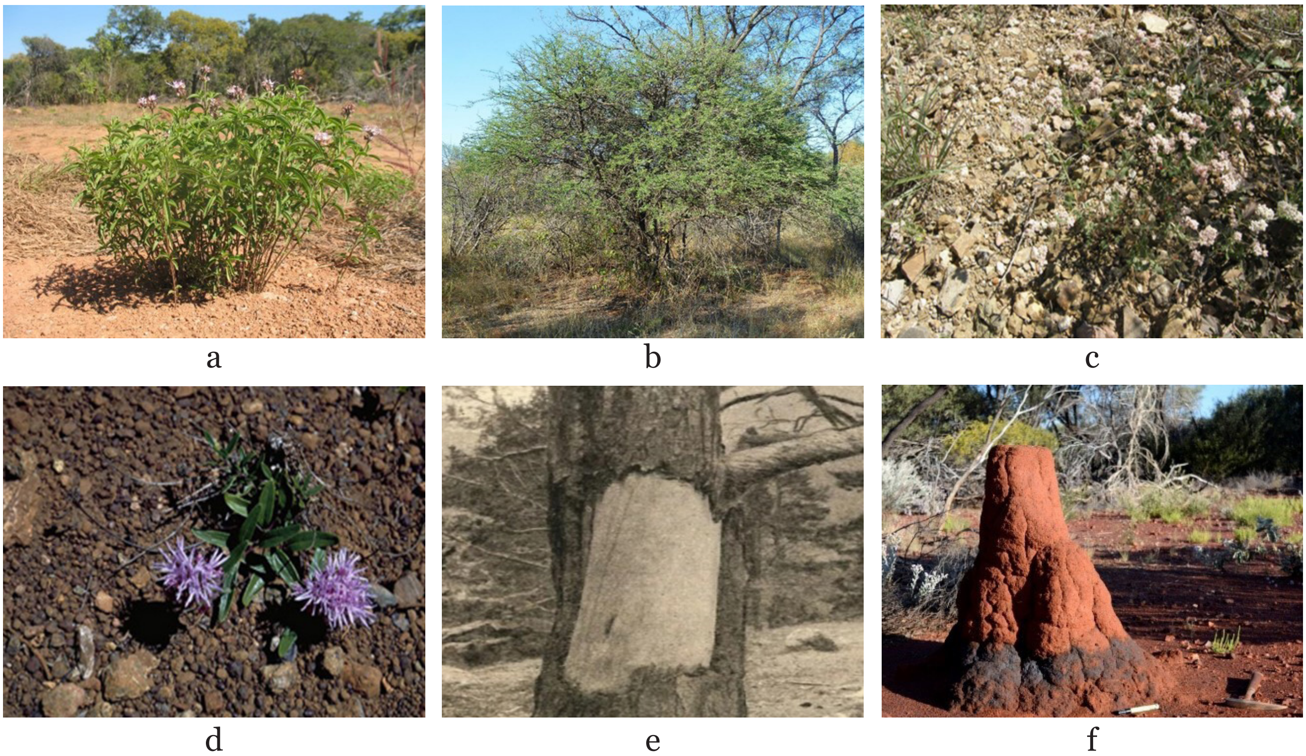

Fig. 1. Geobiotic indicators (a) *Ocimum centraliafricanum* a plant tolerant to high levels of Cu in the soil used to search for Au, (b) *Acacia mellifera* up-taker and tracer of Au, (c) *Eriogonum caespitosum* grows in Cu, Pb, Au, Ag and U dispersion zones, (d) *Monardella odoratissima* grows in sandy rich in Au-Ag, Cu halos, (e) Debarked tree trunk indicate direction, size and depth of mineralized vein (f) Termitaria showing >30 cm of haematitic oxidation at base an indication of Fe enrichment from the underlying bed rock. Rocks rich in Fe-containing minerals are mostly host to Au mineralization.

Gold grains

Gold grain condition including grain abundance, size, shape, flatness and fineness is useful in the determination of availability of gold mineralization and its proximity to the source. Based on gold grain characteristics, mineralogists have rated them as pristine, modified or reshaped (McClenaghan, 2005). They are briefly discussed below and figure 2 indicates their appearance.

(i) Pristine gold grains

They maintain their primary shapes and surface textures; and appear to be undamaged during transport. They often occur as angular wires, rods and delicate leaves being casts of fractures they once in-filled. Two possibilities help to interpret transport history of pristine grains: (1) gold grains were eroded from a bedrock source nearby and transported to the site with little or no surface modification; and (2) gold grains were liberated from rock fragments during in situ weathering of transported sulphide grains containing gold. However, discovery of pristine grains indicate that the sample is less than 500 meters from the source (McClenaghan, 2005; Sarala, 2015).

(ii) Modified gold grains

Comparable to pristine samples, the primary surface textures in modified gold grains are retained. However, all edges and protrusions are damaged because of transportation. They are striated and the protrusions are crumpled, folded and curled; grain moulds and primary surface textures are preserved only on protected faces of grains. Samples that contain elevated concentrations of modified grains are generally proximal to the bedrock source (Kelley et al., 2011). Experience shows that the discovery of modified gold grains indicate that the sample is less than 1,000 meters away from the source.

(iii) Reshaped gold grains

Important aspect of reshaped grains is that all primary surface textures have been destroyed mostly loosing the original grain shapes. They are flattened to rounded as a result of repeated folding of leaves, wires and rods (Marquez-Zavalia et al., 2004). Grain surfaces may be pitted from impact marks from other grains. Although these grains can have a complex transport history, the presence of large numbers of reshaped grains is significant to prospectors. It shows that the grains have been transported more than a kilometer from the source (Averill, 1988). Reshaped gold grains are best indicators of placer deposits.

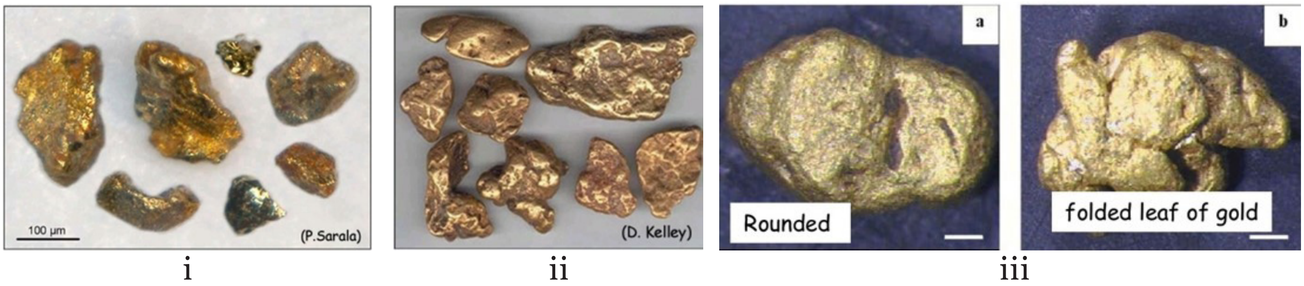

Fig. 2. Gold grains: (i) Pristine gold grains, (ii) Modified gold grains, and (iii) Reshaped gold grains (After Sarala, 2015; Kelley et al., 2011; McClenaghan, 2005).

Pathfinder elements

Owing to their ability to form broader halos and their relative ease of detection by analytical methods, pathfinder elements are relatively easily found. Ag, Cu, Pb, Zn, Co, Ni, As, Sb, Te, Se and Hg are geochemical indicators for gold. However, for ASM only Cu and Ag are the familiar elements, and are therefore used to trace associated gold mineralization. A good example of this discovery by ASM are the mines near Nyakona Hill in the Musoma-Mara greenstone belt in northern Tanzania (Taylor, 2009). Gold was discovered when artisanal miners were working for copper ore

Black sands

The widely accepted explanation for black sand is that it comes from eroded volcanic material such as basalt and other dark-colored rocks and minerals. It is enriched in heavy minerals, including ilmenite ($FeTiO_3$), rutile (TiO_2), zircon ($ZrSiO_4$), monazite (Ce, La, Nd, Th)PO_4 and xenotime (YPO_4), and a mix of other iron-group minerals such as hematite (Fe_2O_3) and magnetite (Fe_3O_4) (Peristeridou et al., 2022). Gold found in black sand comes in the form of small nuggets and flakes that are not attached to any of the minerals. Its abundance, shape and size helps ASM in the search of its source. ASM gold mines in the Mkuvia area along the Mbwemkuru river plateau, southern Tanzania is an example of a mineralization zone where gold is found in significant amounts in black sands (Hathout, 1983).

Associate (Sulphide) minerals

Pyrite, arsenopyrite, pyrrhotite and chalcopyrite (copper sulphide) minerals form the commonest host ore minerals of gold (Yang et al., 2020). Gold may associate with these minerals in a variety of ways. It may occur physically within the minerals in coarse to submicroscopic sizes, chemically as gold compounds and in solid-solutions. Some of the gold may also occur in fractures, along cleavages and at mineral grain boundaries (Schwartz, 1944).

Most of times it is uncommon to see sulphide minerals on the surface in tropical areas because of oxidation. However, Pseudomorphoses of pyrite and rarely pyrrhotite and chalcopyrite are common, which the prospectors focus on while looking for gold mineralization (Taylor, 2011).

Physical indicators

Reports indicate that ASM have been able to discover gold mineralization through prospecting certain geologic features. Simply stated they include extensions of known mineral areas, similar geologic areas nearby and consideration of the correct topography.

Extensions of known mineral areas

Most small scale gold deposits have a linear component. It is fairly common that new deposits can be found along this linear zone of deposition by looking for extensions along the line of deposition (see figure 4). ASM usually use the idea of

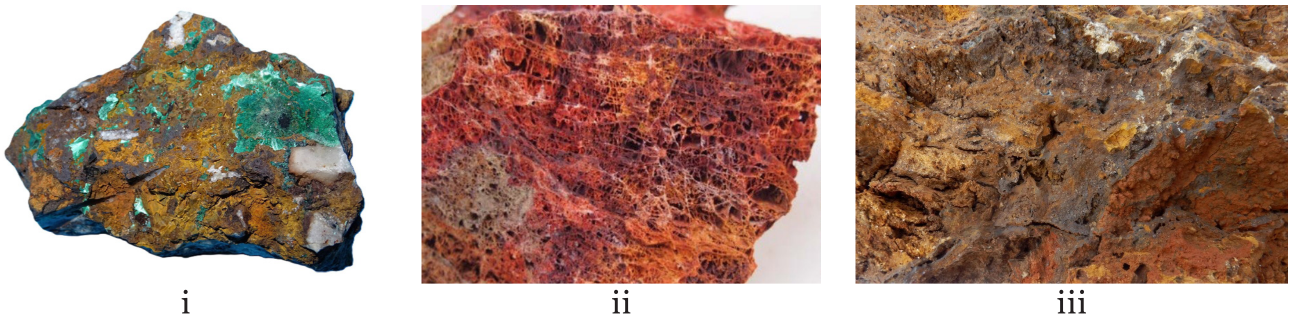

Fig. 3. Examples of boxwork textures after sulphides (i) Boxwork texture after chalcopyrite contains orange zones of limonite, green colored mineral is malachite, (ii) Spongy boxwork after coarse grained pyrite, and (iii) Sponge-style gossan with boxwork that has developed directly over a pyrrhotite zone (After Taylor, 2011).

Fig. 4. Linear ASM Gold Deposits (a) A photography displaying a WNW–ESE trending ASM hardrock mining indicated by blue tarps used to cover ASM shafts, (b) Topographical image showing ASM workings along NE-SW trend (After Voormeij, 2021).

extension of known zones of mineralization to discover new gold deposits,

Similar geologic areas nearby

If a certain rock type or geologic environment has been productive for gold in one area, and the same rock type or environment occurs a few kilometers away in the same mountain range, it is likely that mineralization of the first area can be found in the second. It is most likely that mineralization in these areas were caused by same regional geologic event (Kwelwa et al., 2018; Kuehn et al., 1990). This feature has locally been useful to ASM while looking for new gold deposits.

Correct topography

It is well known that most of the placers form in areas with moderate to flat slopes. For example, alluvial placers are formed by the deposition of gold particles at a site where water velocity remains below that required to transport them further. Typical locations for alluvial gold placer deposits are on the inside bends of rivers and creeks; in natural hollows; at the break of slope on a stream; the base of an escarpment, waterfall or other barrier. Stream placers are the most common types of placers prospected and mined by ASM in Tanzania (Shand & Jønsson, 2011; Dunn et al., 2019).

Anthropogenic indicators

These are indicators for places of gold mineralization based on previous human activities. They include old reports and mining remnants.

Old reports

In many places of the world, gold has been mined since ancient times. In Africa, the search for gold in the Sahara for example is reported beginning as early as 4000 BC (Klemm & Klemm, 2013; Miller et al., 2000). In northern Africa specifically, reports indicate that between 1480–1340 BC many important gold mining sites in the eastern Desert of Egypt and in the Nubian Desert were discovered and exploited (Klemm et al., 2001). Information in old reports, such as Olfert Dapper's description of Africa, first published in Amsterdam in 1668 (Habashi, 2009), has helped many explorers to locate places of gold mineralization.

Mining remnants

In addition to old reports are the relics of old mine workings being mostly the development excavations of old mines, especially adits and shafts; as well as preserved fragments of mining surface infrastructure consisting of buildings and machinery. Although these features whenever found are considered archaeological items, hence are protected by heritage laws (Kaźmierczak et al., 2019), to ASM they indicate proximity to areas of potential mineralization.

Conclusions

ASM, although employs simple technology in its operations; and is limited from accessing formal financing for its activities related to gold exploration, has devised some prospecting techniques capable of locating zones of gold mineralization.

The techniques are basically visual features of soil, rocks, biotic resources, mineralogical and elemental indicators as well as physical and human-based indicators. The techniques are inexpensive, quick and simple, centered on field experience and minimal professional training. They can be widely applied by gold prospectors in most regions, particularly in low income societies.

Interestingly, the techniques are supported by scientific explanations related to occurrences of gold mineralization. This implies that, detailed scientific research can be done to deduce theoretical principles behind them.

In addition, the techniques are in essence limited to surface observations, and they cannot be used to explore concealed sub-surface resources that require application of modern technologies and advanced scientific techniques. Therefore, to enable ASM acquire such tools necessary for systematic exploration, a study is being proposed on appropriate funding mechanisms beyond available traditional financing schemes to support ASM exploration activities.

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References

Adler, M. R., Bergquist, B.A., Adler, S.E., Guimarães, J.R.D., Lees, P.S.J., Niquen, W., Velasquez-López, P.C. & Veiga, M.M. 2013: Challenges to measuring, monitoring, and addressing the cumulative impacts of artisanal and small-scale gold mining in Ecuador, Resources Policy, 38/4: 713–722. https://doi.org/10.1016/j.resourpol.2013.03.007

Alfonso, P., Anticoi, H., Yubero, T., Bascompta, M., Henao, L., Garcia-Valles, M., Palacios, S. & Yáñez, J. 2019: The Importance of Mineralogical Knowledge in the Sustainability of Artisanal Gold Mining: A Mid-South Peru Case. Minerals, 9/6: 345. https://doi.org/10.390/min9060345

Allen, B.L. & Hajek, B.F. 1989: Mineral Occurrences in Soil Environments. In: Dixon, J.B. & Weed, S.B. (eds.): Minerals in Soil Environments, 2nd ed, Soil Science Society America, Madison.

Arhin, E. & Nude, P.M. 2010: Use of termitaria in surficial geochemical surveys: Evidence for >125-µm size fractions as the appropriate media for gold exploration in Northern Ghana, Geochemistry: Exploration, Environment, Analysis, 10: 401–406. https://doi.org/10.1144/1467-7873/09-004

Atindehou, M.M.L., Avakoudjo, H.G.G., Idohou, R., Azihou, F.A., Assogbadjo, A.E., Adomou, A.C. & Sinsin, B. 2022: Old Sacred Trees as Memories of the Cultural Landscapes of Southern Benin (West Africa). Land, 11/4: 478. https://doi.org/10.3390/land11040478

Averill, S.A. 1988: Regional variations in the gold content of till in Canada. In: Macdonald, D.R. & Mills, K.A. (eds.): Prospecting in Areas of Glaciated Terrain – 1988. Canadian Institute of Mining and Metallurgy: 271–284.

Bowen, N.L. 1922: The Reaction Principle in Petrogenesis. The Journal of Geology, 30/3: 177–198. https://doi.org/10.1086/622871

Brundin, N.H. & Bergstrom, J. 1977: Regional prospecting for ores based on heavy minerals in glacial till. Journal of Geochemical Exploration, 7: 1–19. https://doi.org/10.1016/0375-6742(77)90071-1

Bryceson, D., Jonsson, J., Kinabo, C. & Shand, M. 2012: Unearthing treasure and trouble: mining as an impetus to urbanisation in Tanzania. Journal of Contemporary African Studies, 30/4: 631–649. https://doi.org/10.1080/02589001.2012.724866

Cannon, H.L. 1960: Botanical Prospecting for Ore Deposits: How plant chemistry is being used to aid the geologist in his search for metals at home and abroad. Science, 132/3427: 591–598. https://doi.org/10.1126/science.132.3427.591

Cannon, H.L., Trimby, S., Harms, T.F. & Mosier, E.L. 1986: Some observations on plant assemblages and elemental content of plants in mineralized areas of the Walker Lake 1°×2° quadrangle, US Dept. of Inter. Geological Survey, California-Nevada.

Chaparro Ávila, E. 2003: Small-scale mining: a new entrepreneurial approach, Comisión Económica para América Latina (CEPAL), United Nations, Santiago, Chile: 82 p.

Colin, F. & Vieillard, P. 1991: Behavior of gold in the lateritic equatorial environment: weathering and surface dispersion of residual gold particles, at Dondo Mobi, Gabon. Applied Geochemistry, 6/3: 279–290. https://doi.org/10.1016/0883-2927(91)90005-A

Colin, F., Sanfo, Z., Faso, Brown, E., Bourlès, D. & Minko, A.E. 1997: Gold: A tracer of the dynamics of tropical laterites. Geology, 25/1: 81–84. https://doi.org/10.1130/0091-7613(1997)025<0081:GATOTD>2.3.CO;2

Cowley, P.N. 2001: The discovery and development of the Geita gold deposits, Northern Tanzania. New Gen Gold Conference 2001, Perth Australia: 123–135.

Dunn, S.C., von der Heyden, B.P., Rozendaal, A. & Taljaard, R. 2019: Secondary gold mineralization in the Amani Placer Gold Deposit, Tanzania. Ore Geology Reviews, 107: 87–107. https://doi.org/10.1016/j.oregeorev.2019.02.011

Dunn, S.C. & von der Heyden, B.P. 2021: Gold remobilization in gossans of the Amani area, southwestern Tanzania. Ore Geology Reviews, 131: 104033. https://doi.org/10.1016/j.oregeorev.2021.104033

Dunn, S.C., von der Heyden, B.P., Steele-MacInnis, M., Kramers, J.D., St. Pierre, B., Erasmus, R. & Harris, C. 2021: Neoproterozoic copper-gold mineralization in the Amani area, southwestern Tanzania. Ore Geology Reviews, 132: 104070. https://doi.org/10.1016/j.oregeorev.2021.104070

Fielding, I.O.H., Johnson, S.P., Zi, J., Sheppard, S. & Rasmussen, B. 2018: Neighboring orogenic gold deposits may be the products of unrelated mineralizing events. Ore Geology Reviews, 95: 593–603. https://doi.org/10.1016/j.oregeorev.2018.03.011

Finkl, C.W. 1988: Soils and weathered materials, field methods and survey. In: General Geology. Encyclopedia of Earth Science. Springer, Boston, MA. https://doi.org/10.1007/0-387-30844-X_107

Gibson, I.L., Milliken, K.L. & Morgan, J.K. 1996: Serpentinite-breccia landslide deposits generated during crustal extension at the Iberia margin. In: Whitmarsh, R.B., Sawyer, D.S., Klaus, A. & Masson, D.G. (eds.): Proceedings of the Ocean Drilling Program, Scientific Results, 149.

Goldfarb, R.J., Groves, D.I. & Gardoll, S. 2001: Orogenic gold and geologic time: A global synthesis. OreGeology Reviews, 18/1-2: 1–75. https://doi.org/10.1016/S0169-1368(01)00016-6

Graham, R.C., Tice, K.R. & Guertal, W.R. 1994: The pedologic nature of weathered rock. In: Whole Regolith Pedology, D. L. Cremeens, R. B. Brown & J. H. Huddleston (eds.): Special Publication, 34: 21–40. https://doi.org/10.2136/sssaspecpub34.c2

Habashi, F. 2009: Gold in the ancient African kingdoms. De Re Metallica, 12: 65–69.

Hastie, E.C.G., Kontak, D.J. & Lafrance, B. 2020: Gold Remobilization: Insights from Gold Deposits in the Archean Swayze Greenstone Belt, Abitibi Sub-province, Canada. Economic Geology, 115: 241–277. https://doi.org/10.5382/econgeo.4709

Hathout, S.A. 1983: Soil atlas of Tanzania. Tanzania Publishing House, Dar es Salaam, Tanzania.

Heuzé, V. & Tran, G. 2015: Black thorn (Acacia mellifera). Feedipedia, a programme by INRAE, CIRAD, AFZ & FAO. https://www.feedipedia.org/node/347 (17.2.2023)

Hawkes, H.E. 1957: Principles of geochemical prospecting, U.S. Geol. Survey Bull. 1000-F: 225–355.

Henckel, J., Poulsen, K.H., Sharp, T. & Spora, P. 2016: Lake Victoria Goldfields. Episodes. 39/2: 135–154. https://doi.org/10.18814/epiiugs/2016/v39i2/95772

Hentschel, T., Hruschka, F. & Priester, M. 2003: Artisanal and Small-Scale Mining: Challenges and Opportunities. Mining, Minerals and Sustainable Development Project, International Institute for Environment and Development, London: 94 p.

Hester, B.W., Barnard, F. & Johnson, A. 1995: Opportunities for Mineral Resource Development: Tanzania. Ministry of Water, Energy and Minerals, United Republic of Tanzania, Knudsen Printing, Denver: 108 p.

Hinton, J.J., Veiga, M.M. & Veiga, A.T.C. 2003: Clean artisanal gold mining: a utopian approach? Journal of Cleaner Production, 11/2: 99–115. https://doi.org/10.1016/S0959-6526(02)00031-8

Hinton, J. 2006: Communities and small scale mining: an integrated review for development planning. Report to the World Bank, Communities and Small-Scale Mining (CASM) Initiative, Washington DC.

Itamiya, H., Sugita, R. & Sugai, T. 2019: Analysis of the surface microtextures and morphologies of beach quartz grains in Japan and implications for provenance research. Progress in Earth and Planetary Science, 6: 43. https://doi.org/10.1186/s40645-019-0287-9

Kaźmierczak, U., Strzałkowski, P. & Lorenc, M.W. 2019: Post-mining Remnants and Revitalization. Geoheritage, 11: 2025–2044. https://doi.org/10.1007/s12371-019-00408-8

Kelley, K.D., Eppinger, R.G., Lang, J., Smith, S.M. & Fey, D.L. 2011: Porphyry Cu indicator minerals in till as an exploration tool: Example from the giant Pebble porphyry Cu-Au-Mo deposit Alaska, USA. Geochemistry: Exploration, Environment, Analysis, 11: 321–334. https://doi.org/10.1144/1467-7873/10-IM-041

Kontak, D.J. & Kerrich, R. 1995: Geological and geochemical studies of a metaturbidite-hosted lode gold deposit; the Beaver Dam deposit, Nova Scotia: II. Isotopic studies. Economic Geology, 90: 885–901. https://doi.org/10.2113/gsecongeo.90.4.885

Klemm, D., Klemm, R. & Murr, A. 2001: Gold of the Pharaohs – 6000 years of gold mining in Egypt and Nubia. Journal of African Earth Sciences, 33/3–4: 643–659. https://doi.org/10.1016/S0899-5362(01)00094-X

Klemm, R. & Klemm, D. 2013: Gold and Gold Mining in Ancient Egypt and Nubia. Geoarchaeology of the Ancient Gold Mining Sites in the Egyptian and Sudanese Eastern Deserts. Springer, Berlin-Heidelberg: 649 p.

Kuehn, S. Ogola, J. & Sango, P. 1990: Regional setting and nature of gold mineralization in Tanzania and southwest Kenya. Precambrian Research, 46/1–2: 71–82. https://doi.org/10.1016/0301-9268(90)90067-Z

Kwelwa, S., Manya, S. & Vos, I.M.A. 2013: Geochemistry and petrogenesis of intrusions at the Golden Pride gold deposit in the Nzega greenstone belt, Tanzania. Journal of African Earth Sciences, 86: 53–64. https://doi.org/10.1016/j.jafrearsci.2013.06.012

Kwelwa, S.D., Dirks, P.H.G.M., Sanislav, I.V., Blenkinsop, T. & Kolling, S. 2018: Archaean Gold Mineralization in an Extensional Setting: The Structural History of the Kukuluma and Matandani Deposits, Geita Greenstone Belt, Tanzania. Minerals, 8/4: 171. https://doi.org/10.3390/min8040171

Lahiri-Dutt, K. 2004: Informality in mineral resource management in Asia: Raising questions relating to community economies and sustainable development. Natural Resources Forum, 28/2: 123–32. https://doi.org/10.1111/j.1477-8947.2004.00079.x

Marjoribanks, R.W. 1997: Prospecting and the Exploration Process. Geological Methods in Mineral Exploration and Mining, Springer, Dordrecht: https://doi.org/10.1007/978-94-011-5822-0_1.

Marquez-Zavalia, M.F., Southam, G., Craig, J.R. & Galliski, M.A. 2004: Morphological and chemical study of placer gold from the San Luis Range, Argentina. Canadian Mineralogist, 42: 169–182. https://doi.org/10.2113/gscanmin.42.1.169

McClenaghan, M.B. 2005: Indicator mineral methods in mineral exploration. In: Geochemistry: Exploration, Environment, Analysis, 5: 233–245. https://doi.org/10.1144/1467-7873/03-066

McLennan, J.F. 1915: Quartz veins in lamprophyre intrusions: Engineering Mining Journal, 99: 11–13.

McNeil, A.M. & Kerrich, R. 1986: Archean amprophyre dykes and gold mineralization, Matheson, Ontario: The conjunction of LILE enriched mafic magmas, deep crustal structures, and Au concentration: Canadian Journal of Earth Sciences, 23: 324–343.

Migoń, P. 2020: Geomorphology of conglomerate terrains – Global overview, Earth-Science Reviews, 208: 103302. https://doi.org/10.1016/j.earscirev.2020.103302

Miller, D., Desai, N. & Lee-Thorp, J. 2000: Indigenous gold mining in Southern Africa: A review. South African Archeological Society, Goodwin Series, 8: 91–99.

Myers, S.C. & Majluf, N.S. 1984: Corporate Financing and Investment Decisions when Firms Have Information that Investors Do Not Have. Journal of Financial Economics, 13: 187–221. https://doi.org/10.1016/0304-405X(84)90023-0

Mykhailov, V., Andreeva, O. & Omelchuk, O. 2020: Model of the new gold deposit Mananila (Tanzania). Geoinformatics: Theoretical and Applied Aspects 2020, European Association of Geoscientists and Engineers, 11–14 May 2020, Kyiv, Ukraine.

Paton, A.J., Bramley, G., Ryding, O., Polhill, R., Harvey, Y., Iwarsson, M., Willis, F., Phillipson, P., Balkwill, K., Lukhoba, C., Otiend, D. & Harley 2009: Lamiaceae (Labiatae). Flora of Tropical East Africa: 430 p.

Peristeridou, E., Melfos, V., Papadopoulou, L., Kantiranis, N. & Voudouris, P. 2022: Mineralogy and Mineral Chemistry of the REE-Rich Black Sands in Beaches of the Kavala District, Northern Greece. Geosciences, 12: 277. https://doi.org/10.3390/geosciences12070277

Petts, A.E., Hill, S.M. & Worrall, L. 2009: Termite species variations and their importance for termitaria biogeochemistry: towards a robust media approach for mineral exploration. Geochemistry: Exploration, Environment, Analysis, 9/3: 257–266. https://doi.org/10.1144/1467-7873/09-190

Rigobert, T., Jean-Claude, D., Marambaye, D. & Yannick, B. 2013: On the occurrence of gold mineralization in the Pala Neoproterozoic formations, South-Western Chad. Journal of African Earth Sciences, 84: 36–46. https://doi.org/10.1016/j.jafrearsci.2013.03.002

Rock, N.M.S., Groves, D.I., Perring, C.S. & Golding, S.D. 1989: Gold, lamprophyres, and porphyries: What does their association mean? In: Keays, R.R. Ramsay, W.R.H. & Groves, D.I. (eds.): The geology of gold deposits. Economic Geology Monograph: 609–625. https://doi.org/10.5382/Mono.06.47

Rottier, B., Kouzmanov, K., Casanova, V., Bouvier, A., Baumgartner, L. P., Wälle, M. & Fontboté,

L. 2018: Mineralized breccia clasts: a window into hidden porphyry-type mineralization underlying the epithermal polymetallic deposit of Cerro de Pasco (Peru). Miner Deposita, 53: 919–946. https://doi.org/10.1007/s00126-017-0786-9

Sahoo, K.A., Krishnamurthi, R. & Sangurmath, P. 2018: Nature of ore forming fluids, wall rock alteration and P-T conditions of gold mineralization at Hira-Buddini, Hutti-Maski Greenstone Belt, Dharwar Craton, India. Ore Geology Reviews, 99: 195–216 https://doi.org/10.1016/j.oregeorev.2018.06.008

Sarala, P. ed. 2015: Novel technologies for greenfield exploration. Geological Survey of Finland, Special Paper, 57: 11–22

Schwartz, G.M. 1944: The host minerals of native gold, Economic Geology, 39/6: 371–411.

Schwertmann, U. 1988: Occurrence and Formation of Iron Oxides in Various Pedoenvironments. In: Stucki, J.W., Goodman, B.A. & Schwertmann, U. (eds.): Iron in Soils and Clay Minerals. NATO ASI Series, 217. Springer, Dordrecht. https://doi.org/10.1007/978-94-009-4007-9_11

Shand, M. & Jønsson, J.B. 2011: Tanzania gold mines and minerals map. University of Glasgow, UPIMA project.

Smee, B.W. 1998: A new theory to explain the formation of soil geochemical responses over deeply covered gold mineralization in arid environments, Journal of Geochemical Exploration, 61: 149–172. https://doi.org/10.1016/S0375-6742(98)00007-7

Sutarto, S., Idrus, A., Harijoko, A., Setijadji, L.D. & Meyer, F.M. 2015: Veins and hydrothermal breccias of the Randu Kuning porphyry Cu-Au and epithermal au deposits at Selogiri area, central Java Indonesia, Journal of Applied Geology, 7/2: 80–99. https://doi.org/10.22146/jag.26982

Timperley, M.H., Brooks, R.R. & Peterson, P.J. 1972: Trend analysis as an aid to the comparison and interpretation of biogeochemical and geochemical data: Econ. Geol., 67/5: 669–676.

Taylor, M.J. 2009: Report on the Kibara Mineral Exploration Property of Tanzanian Royalty Exploration Corporation in the Bunda District, Mara Region of the United Republic of Tanzania, East Africa, unpublished report.

Taylor, R. 2011: Boxworks and related features. In: Gossans and Leached Cappings: Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-22051-7_7

Taylor, R.D. & Anderson, E.D. 2018: Quartz-pebble-conglomerate gold deposits, U.S. Geological Survey Scientific Investigations Report 2010–5070–P, 34 p. https://doi.org/10.3133/sir20105070P

Veiga, M.M., Metcalf, S.M., Baker, R.F., Klein, B., Davis, G., Bamber, A., Siegel, S. & Singo, P. 2006: Manual for Training Artisanal and Small-Scale Gold Miners, GEF/UNDP/UNIDO, Vienna, Austria: 144 p.

Vila, T., Sillitoe, R.H., Betzhold, J. & Viteri, E. 1991: The porphyry gold deposit at Marte, northern Chile. Economic Geology, 86/6: 1271–1286. https://doi.org/10.2113/gsecongeo.86.6.1271

Vishiti, A., Etame, J. & Suh, C.E. 2019: Features of gold-bearing quartz veins in an artisanal mining-dominated terrain, Batouri gold district, Eastern region of Cameroon, Episodes, 42/3: 199–212. https://doi.org/10.18814/epiiugs/2019/019016

Voormeij, D. 2021: Gold exploration in tropical landscapes. Fifth Edition. Mynah Exploration Inc.

Williams-Jones, A.E., Bowell, R.J. & Migdisov, A.A. 2009: Gold in Solution. Elements 5/5: 281–287. https://doi.org/10.2113/gselements.5.5.281

Wysocki, D.A., Schoeneberger, P.J. & Lagarry, H.E. 2005: Soil surveys: a window to the subsurface. Geoderma, 126/1–2: 167–180. https://doi.org/10.1016/j.geoderma.2004.11.012

Xu, D., Deng, T., Chi, G., Wang, Z., Zou, F., Zhang, J. & Zou, S. 2017: Gold mineralization in the Jiangnan Orogenic Belt of South China: Geological, geochemical and geochronological characteristics, ore deposit-type and geodynamic setting. Ore Geology Reviews, 88: 565–618. https://doi.org/10.1016/j.oregeorev.2017.02.004

Yang, Y., Chen, J., Liu, W., Zhong, S., Ma, Y., Gao, X. & Chen, M. 2020: The impacts of pyrite/pyrrhotite on aqueous arsenic species in arsenopyrite pressure leaching: An XAS study, Minerals Engineering, 155: 106447. https://doi.org/10.1016/j.mineng.2020.106447

Yuan, Y., Li, S., Peng, J., Si, J., Cheng, H., Sun, J., Wei, J. & Shao, J. 2019: An integrated ore prospecting model for the Nyasirori gold deposit in Tanzania. China Geology, 2/4: 407–421. https://doi.org/10.31035/cg2018127

Zhu, Y., An, F. & Tan, J. 2011: Geochemistry of hydrothermal gold deposits: A review. Geoscience Frontiers, 2/3: 367–374. https://doi.org/10.1016/j.gsf.2011.05.006