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Analytical Tools to Constrain the Origin of Gold from Conflict-affected and High-Risk Areas

Scoping Study Based on the DR Congo

Imprint

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About this Report

International efforts to promote responsible sourcing from the Democratic Republic of the Congo (DRC) recognize both the significant development potential as well as the particular challenges associated with artisanal and small-scale gold mining. This sub-sector represents the dominant source of employment for artisanal miners in the eastern DRC while also showing the highest risks to contribute to conflict financing. Most supply chains are informal and lack transparency. Mineral traceability and supply chain due diligence efforts in ASM (Artisanal and Small-scale Mining) gold in the DRC are in their infancy. Artisanal gold leaves the country without adequate registration at the national export level.

Gold analysis is employed in different scenarios. Gold refiners analyze incoming gold to control its quality. Analyses performed in the context of archeometry attempt to evaluate the origin of certain artefacts. Regulatory and law enforcement authorities may analyze gold in order to differentiate legal from illegal sources. These different analytical efforts may contribute to constraining the origin of gold through "fingerprinting" of its composition. This study presents the state of the art knowledge on different methods and research approaches to analyze gold and interpret its compositional features. It then describes the impacts on gold composition resulting from the geological background in the DRC and transformations taking place along the gold supply chain. It further explores the practical framework and feasibility for employing certain analytical tools to support or verify the chain of custody along industrial and artisanal gold supply chains.

About the BGR Module of the German Program with the DRC Ministry of Mines

The bilateral German-Congolese cooperation program "Strengthening the transparency and control of the natural resource sector" was launched in 2009. BGR supports the DRC Ministry of Mines and its associated technical services as well as other selected mining sector stakeholders both at the national and province level. The project focuses on supporting the DRC in establishing a national mineral certification scheme for tin, tantalum, tungsten and gold. Project activities focus on mine sites but also include support to formalizing artisanal supply chains. The current second phase of the project runs until 2017. Online resources for the project are available at https://www.bgr.bund.de/mineral-certification.

Disclaimer

Abbreviations

Abbreviation	Descriptive text
3T	Tin, tantalum and tungsten
ASM	Artisanal and Small-scale Mining
ARM	Alliance for Responsible Mining
BGR	German Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe)
BMZ	Federal Ministry for Economic Cooperation and Development
BRGM	Bureau de Recherches Géologiques et Minières
CEG	Chair of Geology and Economic Geology
CEZ	Curt Engelhorn Zentrum
CEEC	Centre d'Expertise d'Evaluation et de Certification des substances minérales précieuses et semi-précieuses
CIL	Carbon in leach (cyanide leaching method)
CIP	Carbon in pulp (cyanide leaching method)
COSOC	Coalition of Civil society Organizations in the Great Lakes Region against illegal Exploitation of Natural Resources
CPSC	Closed pipe supply chain
CSR	Corporate Social Responsibility
DGDA	Direction Générale des Douanes et Accises
DRC	Democratic Republic of the Congo
EDS	Energy-dispersive spectrometry
EI	Extractive Industries
EPMA	Electron Probe Micro Analysis
FARDC	Forces Armées de la République Démocratique du Congo
FE-EPMA	Field Emission Electron Probe Micro Analysis
GD-MS	Glow Discharge Mass Spectrometry
GLR	Great Lakes Region
GoE	United Nations Group of Experts on the Democratic Republic of the Congo (also UN GoE)
GPA	Gold Provenance Analysis
ICGLR	International Conference on the Great Lakes Region
ICP-MS	Inductively Coupled Plasma-Mass Spectrometry
ICP-OES	Inductively Coupled Plasma-Optical Emission Spectrometry
IFF	Illicit financial flows
IPIS	International Peace Information Service
LA-ICP-MS	Laser-Ablation Inductively Coupled Plasma-Mass Spectrometry
LIBS	Laser Induced Breakdown Spectroscopy
LMBA	London Bullion Market Association
LSM	Large-scale Mining

MC-ICP-MS	Multi-Collector Inductively Coupled Plasma-Mass Spectrometry
MGL	Minière des Grands Lacs
Mt	Million Tons
Moz	Million ounces
MUL	Montanuniversitaet Leoben
NGO	Non-Governmental Organization
OCC	Office Congolais de Controle
OECD	Organisation for Economic Cooperation and Development
PDG	Président Directeur Général
PIXE	Proton-induced X-ray Emission
PIGE	Particle Induced Gamma-ray Emission
pLIBS	Portable Laser Induced Breakdown Spectroscopy
pXRF	Portable X-Ray Fluorescence
PGM	Platinum-group minerals
PGE	Platinum-group elements
REE	Rare earth elements
RMCA	Royal Museum for Central Africa (Tervuren)
SAESSCAM	Service d'Assistance et d'Encadrement du Small Scale Mining
SARS	South African Revenue Services
SEM	Scanning Electron Microscope
Spark OES	Spark optical emission spectrometry
SR-XRF	Synchrotron Radiation X-ray Fluorescence
TBD	To be defined
TIMS	Thermal ionization mass spectrometry
UAE	United Arab Emirates
UN GoE	United Nations Group of Experts on the Democratic Republic of the Congo
WDS	Wavelength-dispersive spectrometry
WFP	World Food Program
XRF	X-ray Fluorescence

Executive Summary

Recent years saw the emergence of frameworks, tools and standards applicable to gold mining, trading and sourcing from Conflict-affected and High Risks Areas such as the Democratic Republic of the Congo (DRC). Information on the chain of custody of gold has become of increasing interest to a broad range of stakeholders. International consumers are concerned about the conditions of mineral extraction, gold traders and refiners seek to demonstrate supply chain due diligence, and gold producing countries as well as international organizations aim to ensure a formalized, legal base for gold supply chains and associated financial flows.

In this context, BGR commissioned this Scoping Study to evaluate if – and to what extent – existing methods for the analysis of chemical gold composition might serve as scientifically robust and practically feasible tools to increase the transparency of gold supply chains.

Natural gold occurrences originate from a diverse variety of geologic processes. Despite similarities, every gold deposit is unique as native gold may contain different elements in solid solution as well as different minerals as inclusions. Both attributes are considered as characteristic for certain types of gold deposits. Along the supply chain, from "vein to vault", the precious metal is transformed in various ways. With a broad diversity of gold processing techniques in use by industrial and artisanal supply chain actors, the mineralogical, chemical, and metallurgic properties of the metal are modified with every processing step. Chapter 1 of this study analyzes these transformations with the purpose of determining which geologic and processing characteristics might be retained in the intermediate gold products at each stage of the supply chain.

Gold Provenance Analysis (GPA) employed to help constraining the origin of gold at the various processing and trading stages can be facilitated based on different parameters. Chapter 2 compiles the present knowledge on gold composition in primary and secondary gold deposits. Natural gold (^{197}Au) is mono-isotopic; therefore, no isotopic variation of the major element may be used for GPA. As gold is a multi-component alloy, its chemical composition is the most useful parameter for GPA. The minor and trace element composition of gold will provide the most promising results for evaluating the origin of primary and secondary gold. Some mobile elements are removed whereas others are additionally introduced through applying different gold processing methods. Gold from different sources may become physically and chemically homogenized through trading, processing and refining. The chemical composition of processed gold reflects the mix of different sources from where the gold originated as well as the processing methods.

The composition of gold can be analyzed in bulk samples or as single spot measurement. Depending on the specific field of application (type of material) different techniques are applied for gold analysis. Chapter 3 screens all currently available analytical methods[1] and their usefulness for GPA. Various parameters influence the selection of the most appropriate method. While some methods are widely used in the industry, other methods serve specific research purposes. Findings are summarized in a matrix that allows selecting the most appropriate analytical method(s) for different intermediate and final gold products and for different purposes of gold provenance analysis.

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[1] Grouped as 1: Emission and mass spectrometric techniques, 2: Electron beam methods, 3: Ion beam methods, 4: X-ray methods, and 5: Others

Based on the generic principles laid out in the previous chapters, chapters 4 and 5 of this study focus on the specific factors related to potential provenance analysis of gold from the DRC. The DRC case is used as an exemplary illustration; it is anticipated that similar evaluations can be performed for other countries. The relevant factors are related to the types of gold deposits and the structure of different supply chains. 99% of the official gold exports (31.8 t in 2015) of the DRC originate from three large-scale industrial mines (Kibali, Namoya and Twangiza). Additionally, more than 176,000 people are engaged in artisanal and small scale mining (ASM), extracting 8 to 12 t of gold per year (onshore; dredging along rivers produces additional ASM gold), mostly unregistered. This gold stems from a huge number of variably-sized mine sites in the eastern DRC; up to now, >1,500 ASM gold mines with 16,000 pits have been described.

Geologically, four different areas, termed “gold provinces”, can be distinguished in the DRC. The “Northern gold province” in (former) Orientale, with a focus around Kilo-Moto in Ituri, comprises greenstone belts formed ca. 2.6-2.7 billion years ago. The “Lubero gold province” in North Kivu was formed ca. 2.1-1.8 billion years ago; it is characterized by rivers carrying gold and platinum-group minerals. The “Kibaran gold province” comprises North Kivu (around Walikale), Maniema in the area around Punia and Pangi, and South Kivu (around Shabunda). It was formed ca. 1 billion years ago. The “Panafrican gold province” in North and South Kivu is the youngest major gold-forming event, ca. 500 million years ago. These “gold provinces” have different geological histories, with gold formed due to different processes. Therefore, trace elements and associated minerals differ according to deposit type and may thus form the basis of a regional gold provenance indicator. However, local variations and overlapping compositions are expected to add a layer of complexity on differentiating gold provenance.

Gold supply chains from industrial producers represent straightforward closed pipes from three mines delivering to a single destination (Rand Refinery) in South Africa. In contrast, the ASM gold supply chain consists of highly complex trade relations described in chapter 5. A large network of supply chain actors is involved, with the number of stakeholders increasing exponentially with every step towards the upstream end of the supply chain. Small batches of gold (nuggets, dust or sponge from amalgamation) traded at the upstream end of the supply chain (i.e., gold sold by miners to local traders) retain most mine site-specific chemical information in their composition. However, the number of involved stakeholders (i.e. possible sampling points for GPA) at this stage of the supply chain is too high to perform efficient sampling at a broad scale. Larger batches of gold (typically doré), aggregated by formal or informal traders and exporters, may still retain some characteristics indicating the origin from one of the DRC geologic gold provinces. These larger batches of doré gold represent the most realistic sampling target for potential GPA. Almost all ASM gold leaving the DRC is transported to and sold in Dubai, usually through one or more transit countries, mostly without adequate documentation. Once the gold has been refined, it is unreasonable to expect any conclusive results from gold provenance analysis using currently available analytical technology.

Based on these findings, three scenarios for the practical application of GPA have been developed as described in chapter 6: (I) product confirmation along local (closed pipe) supply chains from mine to refiner, notably for LSM or well-controlled ASM supply chains; (II) verification of gold origin with regards to production regions in the DRC, to the extent that such regions reflect different geological gold provinces correlating with fixed “catchment areas” where *comptoirs* and exporters source their gold from; and (III) assessment of the claimed origin (country) of gold at international airports, either during export from the Great Lakes Region or import at international gold destinations such as Dubai.

The main gold product recommended for performing GPA along the supply chain corresponds to gold doré smelted at the trader or exporter level as well as at some larger mines. Broad-scale sampling of disaggregated ASM mine gold does not represent a feasible implementation option; mine gold sampling may be reasonable for product confirmation along LSM or ASM closed pipe gold supply chains, however. Due to the chemically relatively homogenized nature of doré bars, analysis of their major and minor element composition does not require a sophisticated laboratory setup. Instead, traded batches of doré may be analyzed using portable equipment providing immediate results and operating non-destructively (not consuming significant quantities of sample material).

The above scenarios provide different potential starting points for enhancing transparency and supporting due diligence along different segments of the upstream gold supply chain. Implementing any single GPA scenario would reinforce potential implementation of other scenarios. In this sense, Scenarios I and II are seen as possible entry points and Scenario III as part of an upscaling strategy. We recommend conducting further research into development of suitable analytical methods, including methods using portable equipment, which represent a new application of known and available appliances. In addition, we recommend piloting these methods and GPA scenarios in the DRC or another country with a similar ASM gold setting in order to validate the underlying scientific and practical assumptions.

Contents

Preface

This study investigates the background of different analytical methods employed to constrain and interpret the composition of gold. This evaluation is motivated by the question whether the analysis of gold could contribute to supply chain due diligence at a practical level as outlined in the following.

Gold forms one of the most important mining products with an annual global production value well above US$ 100 billion. Most gold is produced through large-scale mining (LSM) while >10% of primary gold is produced through artisanal and small-scale mining (ASM) in a large number of developing countries. The Democratic Republic of the Congo (DRC) is among the countries that host significant gold deposits, some of which are amenable to LSM while others are exploited through ASM. In fact, gold mining dominates today's ASM sector in the Eastern DRC with four out of five miners active in gold. It represents a fundamentally important livelihood base for local communities with more than 180,000 "diggers" directly involved. However, these gold mining and trading activities are largely informal and lack transparency; local ASM gold supply chains are mostly untraceable. There are significant risks for the sector to contribute to the financing of illegal armed groups, organized crime and conflict in the DRC.

In order to manage such risks, recent years have seen the emergence of frameworks, tools and standards applicable to gold mining, trading and sourcing from Conflict-affected and High Risks Areas such as the DRC. These include overarching international frameworks such as the OECD Due Diligence Guidance for Responsible Supply Chains, legal instruments of producer countries such as the Regional Certification Mechanism endorsed by the member states of the East-Central African ICGLR (International Conference on the Great Lakes Region), and legal instruments of consumer countries such as the US Dodd Frank Act ("conflict mineral" section 1502) and an upcoming EU regulation on due diligence. Self-regulation of the industry complements these regulatory efforts, e.g., the London Bullion Market Association's (LBMA) Responsible Gold Guidance, the Conflict-free Sourcing Initiative's Conflict-free Smelter Program, and the Responsible Jewelry Council's Code of Practices and Chain of Custody certification. Voluntary CSR-, traceability- and sustainability standards, as well as premium-based certification schemes for fair gold supply chains such as Fairmined (developed by the Alliance for Responsible Mining) or Fairtrade, additionally support and strengthen the framework. These different instruments allow stakeholders to better understand their gold supply chains, to develop procedures to trace and track them, and to implement adequate risk management.

Information on the chain of custody of gold is of increasing interest to a broad range of stakeholders. International consumers are concerned about the conditions of mineral extraction, gold traders and refiners seek to demonstrate supply chain due diligence, and gold producing countries as well as international organizations aim to ensure a formalized, legal base for gold supply chains and associated financial flows. Information and assurance on the origin and integrity of LSM gold in formalized supply chains is commonly generated through a paper trail of documents, sealed shipments and additional security measures. In most informal ASM gold supply chains, on the other hand, either such information and assurance is of questionable quality or it may be altogether lacking. In such cases, responsible buyers and consumers may seek additional assurances, e.g. through auditing, or else prefer not to engage at all. This can potentially result in less responsible supply chains, vulnerable to be controlled by illicit actors.

The chemical composition of minerals may hold clues to their geological origin or to the processing steps they might have been subject to. Such information is commonly used in a scientific context, e.g., in order to constrain the origin of gold artefacts in archeometry, or to understand ore-forming processes in mineral deposits. In this context, one may ask the question if – and to what extent – existing methods for the analysis of gold composition might become relevant to better understand ASM and LSM gold supply chains, e.g., through identifying the mine of origin or a specific processing step. BGR commissioned this Scoping Study on "Analytical Tools to Constrain the Origin of Gold from Conflict-affected and High-Risk Areas" in March 2016 in order to evaluate this question in more detail, both at the scientific and practical level. This evaluation is considered as a contribution to efforts of formalizing ASM gold supply chains in the DRC where BGR, in concert with a range of donors and partners, supports the Congolese Ministry of Mines in creating an enabling formalization framework. It is anticipated that study findings with regards to the DRC context may provide information that will also be applicable elsewhere in the global gold sourcing framework.

The study was conducted in two steps:

(1) During a "screening phase", current state of the art research approaches and methods to analyze gold were summarized and impacts on gold composition associated with the DRC supply chain were explored. The results were compiled in a report representing Part I of this study[2].

(2) Subsequently, during a "design phase", the potential to develop some of these approaches and methods as practical tools contributing to gold supply chain risk management and chain-of-custody monitoring were evaluated, using the DRC context as a reference scenario. The tight interlinkages and interdependencies between appropriate analytical methods and approaches, relevant supply chain aspects and feasible scenarios for gold provenance analysis led to the decision to combine the results from the screening and design phases into a single comprehensive report.

The present report, integrating both study phases, starts with a global overview of the steps and processes characterizing LSM and ASM gold supply chains, and their respective impact on gold composition. Subsequently, the different chemical parameters for gold provenance analysis are explained. Chapter 3 provides the reader with an illustration of analytical techniques employed to constrain and interpret the compositional features of gold. In chapter 4, an analysis of the geological and geochemical features of the DRC's gold deposits provides the background for resolving the origin of gold based on compositional characteristics. This evaluation is expanded further in chapter 5 where the compositional impact from trading, processing and mixing gold and gold products along the supply chain from the DRC's mines to the point of industrial refining or jewelry manufacturing, either in South Africa (LSM) or Dubai (ASM), is discussed. Based on the findings from the prior chapters, three scenarios for gold provenance analysis are presented in chapter 6. For each scenario the report investigates practical feasibility issues, due diligence questions and stakeholder involvement at specific segments in the upstream gold supply chain as further outlined in the Annex.

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[2] Hruschka et al. (2016)

1. The Gold Supply Chain “from Vein to Vault”

The composition of gold is key for the development of a method to trace or constrain its origin. There are different steps involved in the journey of *gold* along its supply chain. This chapter introduces the generic aspects of the gold supply chain from “vein to vault”, i.e. from the natural occurrence of native gold to the final refined bullion or consumer product, with a focus on mineralogical, chemical, and metallurgic properties of the metal and processes that influence its composition (Figure 1). Specific aspects of the link between the geology of the DRC and gold composition will be addressed in chapter 4, and effects of the gold supply chain will be elaborated on in chapter 5.

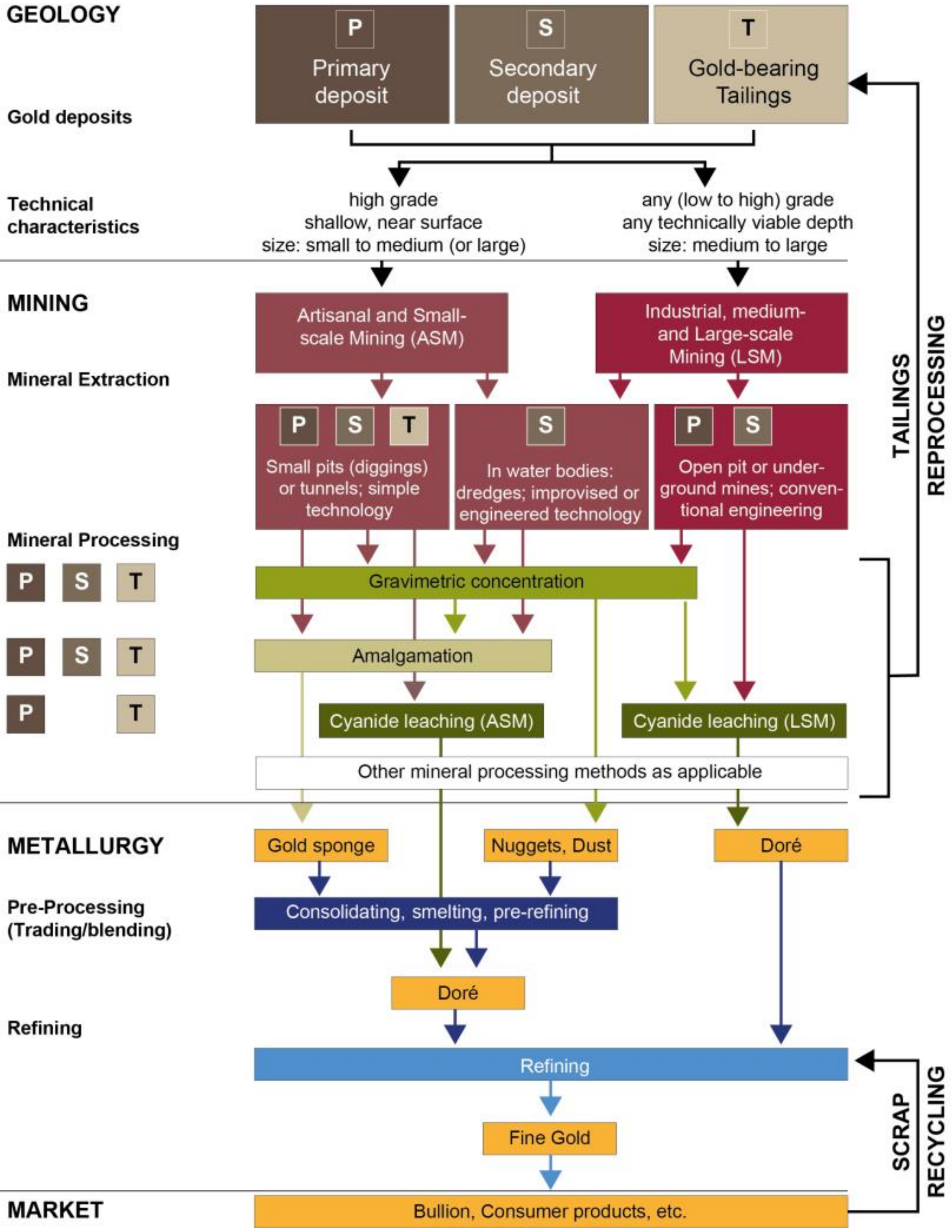

Figure 1: Simplified generic gold Flowchart “from Vein to Vault”.

1.1 Natural Occurrence of Gold

Gold is mobilized and concentrated into economic deposits by many geological processes, including igneous melting and crystallization, hydrothermal leaching and precipitation, weathering, fluvial hydraulic sorting and biogenic accumulation (Figure 2). In general gold deposits are grouped into primary and secondary deposits (Figure 2). Primary gold forms in situ deep in the Earth' crust or at shallower levels, where circulating hydrous fluids are heated up (Figure 3).

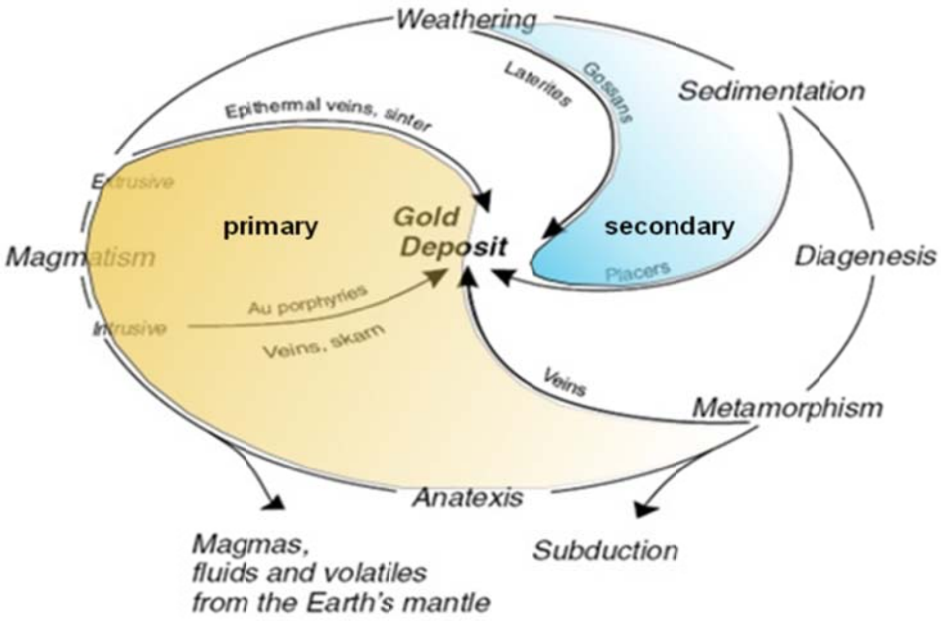

Figure 2: Processes forming gold deposits modified from Pohl (2011).

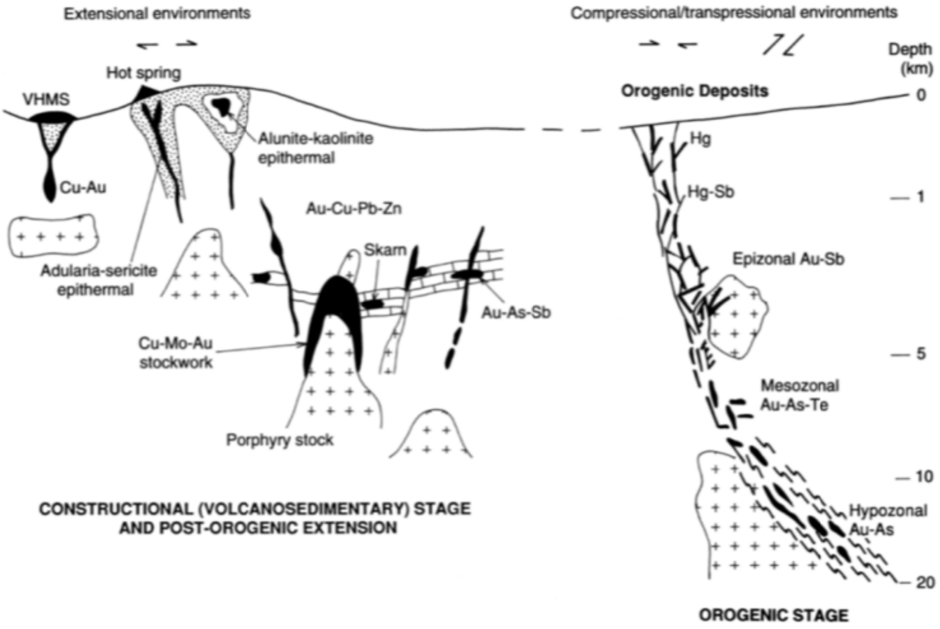

Figure 3: Schematic representation of crustal environments of hydrothermal gold deposits (Groves et al. 1998).

Native gold in primary deposits (Figure 4) is commonly hosted by quartz and quartz-carbonate veins, and is often associated with sulfide minerals, mostly with pyrite [FeS_2] and arsenopyrite [FeAsS]. These minerals may also carry gold as tiny inclusions (<5 µm in size) or even bound in their crystal structures – such gold is not easily recoverable and therefore termed "refractory gold". Refractory gold, along with fine-grained free gold particles, may also occur as by-products of base metal (copper, zinc) ores in porphyry copper or volcanogenic massive sulfide deposits. Secondary deposits are formed afterwards during weathering, mechanical erosion and transport. Such "placer gold" is found as flakes, grains and nuggets in stream sediments, beach sands and soils (Figure 5 and Figure 6). Primary gold deposits rich in sulfides weather under atmospheric conditions to form "gossans", iron oxide-rich weathering zones where gold may become enriched during secondary processes.

About 40 gold minerals occur in nature. Native gold is by far the most abundant forming solid solutions with silver (electrum) and a number of other elements. Gold telluride minerals (e.g., calaverite [$AuTe_2$]) are second in abundance and are often associated with native gold and sulfide minerals. The densities of the tellurides are lower than those of native gold. Rare minerals include gold antimonides (aurostibite [$AuSb_2$]), gold selenides (fischesserite [Ag_3AuSe_2]), gold sulfides (uytenbogaardite [Ag_3AuS_2]), yet unnamed gold oxysulfides (Kucha & Raith 2009) and rare gold-silicate compounds.

Native gold is often alloyed with silver (Ag), copper (Cu), mercury (Hg) and, less frequently, with platinum group elements (PGE; including ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir,) and platinum (Pt)). Gold and silver alloy to form a complete solid solution series, with a mineral phase termed "electrum" containing between 20 and 80 wt.%[3] of Ag (and more commonly, between 30 and 55 wt.% Ag). Cu concentrations are usually low (<2 wt.%; Dube 2006), but may range up to 20 wt.% (cuprian gold). The solubility of Hg in gold is slight, only 0.13 at.%[4] Hg at 20°C, but Au-Hg compounds may carry up to 35 at.% Hg (Boyle 1979). Natural gold from the Witwatersrand deposits in South Africa contains up to 6 wt.% Hg (Oberthür & Saager 1986), and even higher values have been reported from the Otago Schist Belt in New Zealand (Youngson et al. 2002).

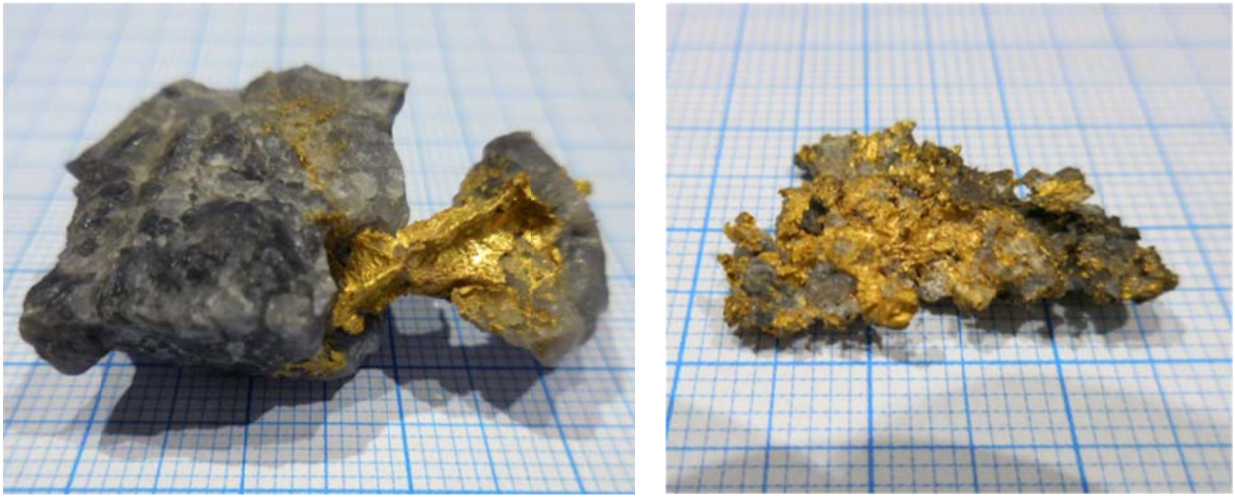

Figure 4: Native gold from primary hard rock deposits, source: F. Hruschka.

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[3] wt.% - weight percent

[4] at.% - atomic percent

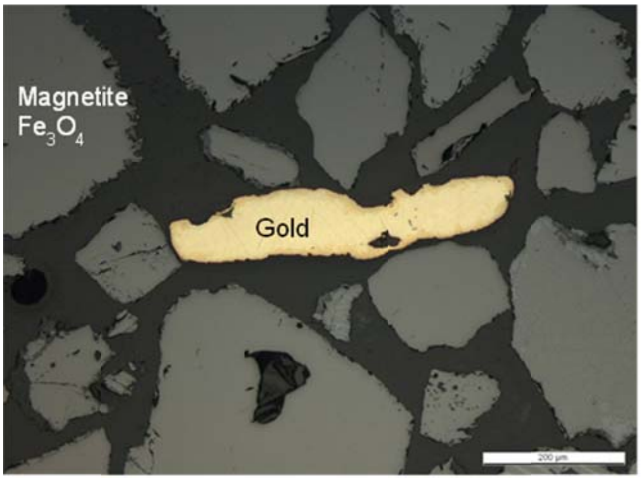

Figure 5: Native gold in alluvial placer (Mongolia), reflected light microscopy, source: F. Melcher.

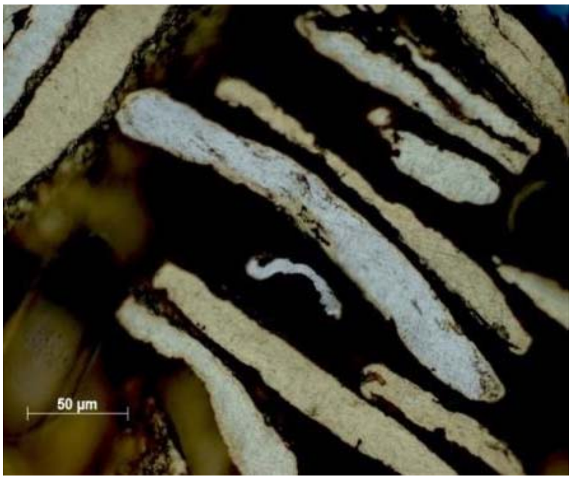

Figure 6: Native gold as flakes. Silver rich gold is whitish, whereas silver poor gold is yellowish, Rheinzabern, source: T. Oberthür.

Chemical composition of native gold

Despite the elements mentioned above, natural gold is usually very pure. However, traces (<0.001 wt.%[5]) to minor (0.001 - 1.0 wt.%) amounts of the following elements have been reported: Al, As, B, Ba, Be, Bi, Ca, Cd, Co, Cr, Ga, Ge, In, K, Li, Mn, Mo, Na, Ni, Pb, Sb, Sc, Se, Si, Sn, Sr, Te, Th, Ti, U, V, W, Y, Zn, Zr and rare earth elements (REE) (Boyle 1979). This list, comprising most of the periodic table of elements (Figure 7) is based on bulk analysis of gold, before the invention of in-situ analysis with high spatial resolution. Such methods have demonstrated that minor and trace elements in gold may be present (1) as substituting elements within the gold lattice, (2) as mineral and fluid inclusions hosted by the gold, or (3) as “impurities”, i.e. matrix minerals accidentally entrapped by gold during growth, weathering or transport.

Among group (1), Ag, Cu, Fe, Ni, Hg, As, Sb, Bi, Te, Pd and Pt are regarded as probable lattice constituents (Boyle 1979) (Figure 7). Group (2) elements also include S present as abundant sulfide inclusions within primary gold along with Fe, Cu, Zn, Pb, As, Sb, Te, Bi and Se. The presence of Cl, I and Br in gold has recently been confirmed by laser ablation-ICP-MS analysis (Schmiderer 2009; Altigani et al. 2016); this may be explained by fluid inclusions trapped by crystallizing gold crystals or by chalcogenide microinclusions[6]. Group (3) elements include many lithophile[7] elements that are highly unlikely to substitute into the gold lattice, but tend to form silicate and oxide minerals.

The trace and minor element signature of native gold may vary significantly both within a single grain and within a deposit and primarily depends on the deposit type (Figure 2, Figure 3). Intrusion-related gold deposits, for example, are characterized by elevated Bi (Baker et al. 2005), and large variations in Ag concentration are typical for epithermal deposits (Morrison et al. 1991) (Figure 3). Epithermal gold systems in Chile produce gold with 5 wt.% Ag and 0.1 wt.% Cu, whereas gold-rich porphyry systems have on average 8 wt.% Ag at similar Cu values; Cu-Au porphyry systems have elevated Cu (0.75 wt.%)

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[5] For the purpose of this report, traces are defined as element concentrations below 0.001 wt.% (<10 ppm; 1 ppm equals 1 g/t.). Minor elements range from 0.001 to 1 wt.%, and major elements are those exceeding 1 wt.%. This definition is chosen based on the detection limits of analytical methods discussed in chapter 3.

[6] e.g. by Hg iodide (Roger Dixon, oral communication May 17, 2016)

[7] lithophile – elements that tend to combine readily with oxygen forming silicate and oxide minerals

and variable Ag contents (Townley et al. 2003). Antweiler & Sutton, Jr. (1970) reported that Pb, Pd, Bi, V, Ni and Co were higher in lode (vein) type samples than in placer samples, whereas Ti, Zr, La, Y and Cr occurred more frequently in secondary gold. Scanning electron microscopy in combination with laser ablation-ICP-MS proves that the latter elements are present as minute inclusions within pores in alluvial gold grains. In a study of detrital gold flakes recovered from the Rhine River, Brauns[8] showed that the concentrations of a number of elements (e.g. Cr, Ti, Zr, REE) decreased from rims to the cores of gold grains, corresponding to increased porosity along the rims. In addition to detrital heavy minerals such as zircon, monazite, ilmenite, magnetite and chromite, gold grains may also contain inclusions of silicate minerals.

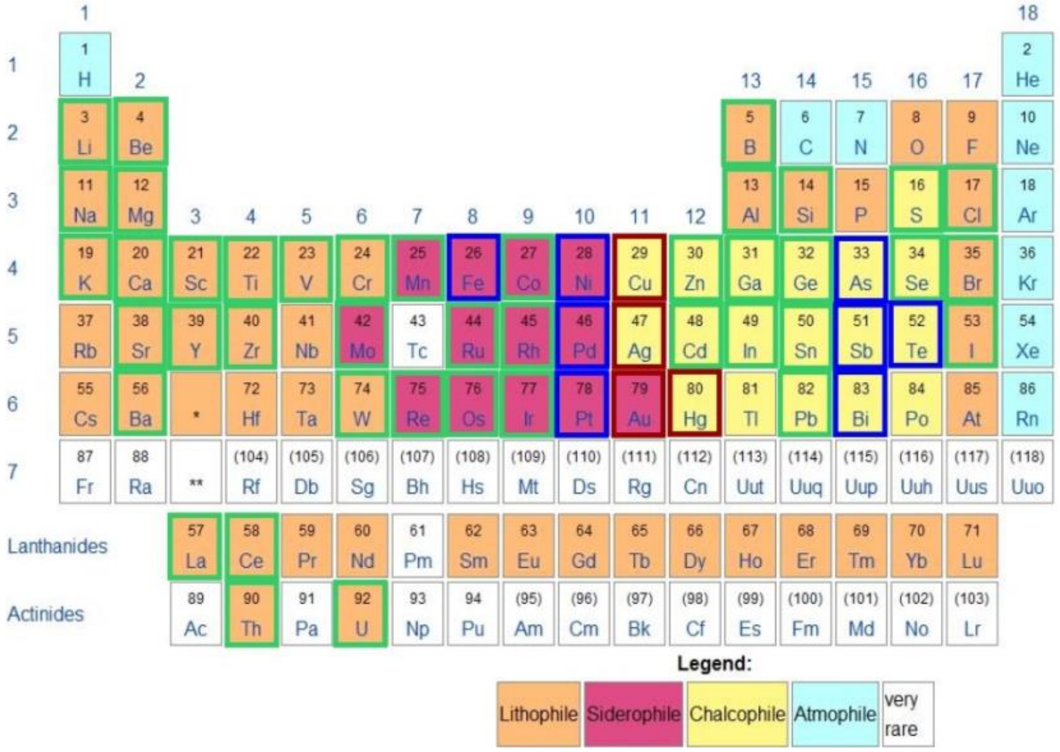

Figure 7: Periodic table after V. M. Goldschmidt. Elements present in the gold lattice are marked (as thick frame) in red (major elements) and in blue (minor elements). Elements marked in green are minor and trace elements in gold reported by Boyle (1979).

Numerous studies of gold grains from alluvial deposits addressed the link between gold morphology, composition and mineral inclusion assemblages in search for the primary lodes (Knight et al. 1999; Chapman et al. 2000; Mortensen et al. 2004; Mortensen et al. 2005; Chapman & Mortensen 2006, 2016). In general, such gold grains have a higher fineness compared to the primary source, due to partial leaching of silver and other trace elements during transport (Boyle 1979) (Figure 6). Although gold is insoluble except in aqua regia, mobilization as complexes with several organic and inorganic ligands in tropical soils (laterites, saprolites) has been proven (Freyssinet et al. 2005). Precipitation and in situ growth of secondary gold in soils and sediments as indicated by textural and chemical arguments, is heavily disputed in the literature (Hough et al. 2009; Chapman & Mortensen 2016).

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[8] Michael Brauns, CEZ Mannheim, contract 212-4500072679 for the BGR Hannover (2012)

Native gold may contain different elements in solid solution, as well as different mineral inclusions. Both attributes are considered as characteristic for certain types of gold deposits (see chapter 4 for more information).

1.2 Mining – Mineral Extraction and Processing

Depending on the characteristics of the gold deposit, **mineral extraction** may be economically feasible for industrial, medium to large-scale mining (LSM)[9], for artisanal and small-scale mining (ASM)[10] or both. In general, large, low-grade and deep deposits are suitable for LSM only.

Mineral extraction in LSM is performed by machines and modern open pit trucks with a loading capacity of up to 250 t of ore are not uncommon. Industrial underground mines in South Africa reach a depth of up to 4,000 meters. Economy of scale through mechanization allows to extract deposits at a cutoff-grade as low as 0.35 gram of gold per ton of rock[11] or 0.1 grams of gold per cubic meter gravel. The required investment for such an operation is only justified in case of large ore reserves.[12]

Small deposits, containing only a few kilogram of gold in total, are of interest for ASM only. Rather than the size of the deposits, parameters like grade and depth are important to make predominantly manual artisanal mineral extraction feasible. The amount of gold one miner can extract in a day has to make up for the costs of living of his/her family. As a rule of thumb, a deposit is suitable for ASM if it contains at least 10 g/t hard rock or 1 g/m^3 gravel. In least developed countries and situations of extreme poverty, these thresholds can be lower. The depth artisanal mines can reach, rarely exceeds 30-50 m vertically or 70-100m horizontally.

Consequently, in sulfidic primary deposits, ASM is mostly limited to extract the oxidized, "gossan" zone. Apart from its shallow depth and "softer" rock conditions, geologic weathering processes have enriched the gold in this zone. Usually, in order to proceed into deeper, sulfidic hard rock ore zones, mechanization is required.

In primary deposits, oxidic hard rock ores may be extracted by LSM or ASM. Sulfidic ores are predominantly extracted by LSM.

Gold from refractory ores is highly likely to originate from LSM operations. ASM operations usually lack the technical means to process such ores.

Secondary (placer) deposits are mined by industrial operations (mainly medium-scale LSM) or by ASM.

---

[9] For simplicity, usage of the term "LSM" (large-scale mining) also covers medium-scale mining (MSM). In the context of this study, no relevant differences exist between these two industrialized sub-sectors of mining.

[10] Following common practice, the usage of the term "ASM" (artisanal and small-scale mining) comprises the predominantly manual artisanal mining sector and the semi-mechanized small-scale sector.

[11] E.g. Yanacocha / Peru, one of the lowest grade hard rock mines due to favorable geologic conditions.

[12] The "magic" threshold for major gold companies is a deposit size containing at least one million ounces (1 oz tr = 31.1 g). However, industrial mining also takes place at many smaller deposits containing a few 100,000 oz.

Mineral processing techniques applied in ASM and LSM differ significantly. Although an almost infinite number of methods for gold recovery are known,[13] only a few are technically relevant. Each of them leaves its own signature on their product and/or alters the characteristics of native gold in a specific manner.

Gravimetric Concentration is based on differences in the density of gold (19.3 g/cm^3), heavy minerals (approx. 4–8 g/cm^3) and typical gangue minerals (2-3 g/cm^3). Gravimetric concentration is the principal method for secondary (placer) deposits and can precede other methods for processing of primary (hard rock) ores. Hard rock ore needs to be crushed and milled, to liberate gold particles, before gravimetrical methods can be applied. Typical gravimetrical equipment of ASM are sluices and gold washing pans. Industrialized LSM operations use centrifuges, jigs, shaking tables, spirals or similar. The product of gravimetric concentration is gold dust, flakes or nuggets.

Signature of gravimetrical concentration. The least alteration occurs with pure gravimetric concentration, as the gold is maintained in its natural form of dust, flakes or nuggets.

> Native Gold processed with gravimetric concentration only, maintains all deposit-specific characteristics. Gravimetric processing equipment does not alter the chemical composition of gold and hence leaves no characteristic signature. Origin from ASM or LSM cannot be distinguished.
>
> A “nugget-shape” of gold particles is not a sufficient criterion to identify a gold particle as mined gold. Techniques like those used for producing casting grain can be used to produce fake nuggets.

Amalgamation is the predominant gold processing method in ASM to recover fine (i.e. small) gold particles. In contact with mercury, gold, silver and some of their compounds form an alloy called “amalgam”. This causes small gold particles to gain significantly in weight (by forming the alloy) and in size (as amalgamated particles tend to agglomerate). Increased weight and size alters their behavior in gravimetric concentration (panning, sluicing or simply washing) and facilitates their recovery. Once the amalgam has been recovered, it can be decomposed by burning, producing a gold sponge. Mercury evaporates at 257°C. The resulting gold sponge, which can initially contain up to 10% Hg, is sold by miners. Amalgamation is not needed for coarse gold particles, as nuggets can be easily separated gravimetrically.

Native copper, as well as soluble Pb minerals, As (in arsenopyrite, arsenic sulfides etc.), Sb, and Bi may react with Hg too, forming amalgam or chemical coatings, or dissolve Hg or precious metal amalgam out of the compound, leading to losses of precious metals and Hg. Pyrite and chalcopyrite, to the contrary, do not affect amalgamation. Barite, talc, steatite and viscous hydrogenized magnesium and aluminum silicates also cause disruptions or losses during amalgamation (Priester et al. 1993).

Sodium amalgam, promoted as “activated mercury” for improved amalgamation in order to reduce mercury consumption, is significantly more reactive with other metals than elementary mercury. By forming amalgams with a wider range of elements or pseudo-amalgams with minerals, these components enter the amalgam and subsequently the doré smelted from the gold sponge.

---

[13] E.g. documented in key books on mineral processing such as: Taggart & Behre (1945), Weiss (1985), Marsden & House (2006) and Grayson (2013)

Signature of amalgamation. Amalgamation is used exclusively by ASM. During the amalgamation process, mercury is first added and later eliminated by burning.

Although metallic mercury evaporates at 257°C, gold amalgam only decomposes completely at much higher temperature. Even gold sponges heated up by buyers to cherry red (approx. 750°C) may still contain up to 1 % mercury.[14]

The heat treatment of the amalgam during the burning process may impact the original chemical composition of the native gold. Inclusions, particularly sulfides, oxidize during this processing stage and volatile components may evaporate jointly with the mercury. Still, the chemical composition of the produced sponge reflects widely the composition of the native gold

Gold sponges produced by amalgamation are a clear indicator of ASM origin.

Some gangue minerals containing Pb, As, Sb, and Bi are known to react with mercury too. Traces of these elements may be captured during amalgamation, but are likely to be volatilized during the subsequent burning process. Native elementary Cu, if present in rare occasions, amalgamates similarly as Au and Ag.

Gold sponges from amalgamation, therefore, contain mainly those elements that are already part of the native gold, except for volatile elements lost during burning.

Gold sponges usually contain significant traces of Hg.

Cyanide leaching has completely replaced the amalgamation process in LSM since the 1940s. Gold dissolves easily in low concentrated alkaline solutions of potassium- (KCN) or sodiumcyanide (NaCN). Gold can thus be "leached" out of milled rock by different processes, such as heap-, agitation- or vat leaching.[15] The overall reaction is known as Elsner's equation:

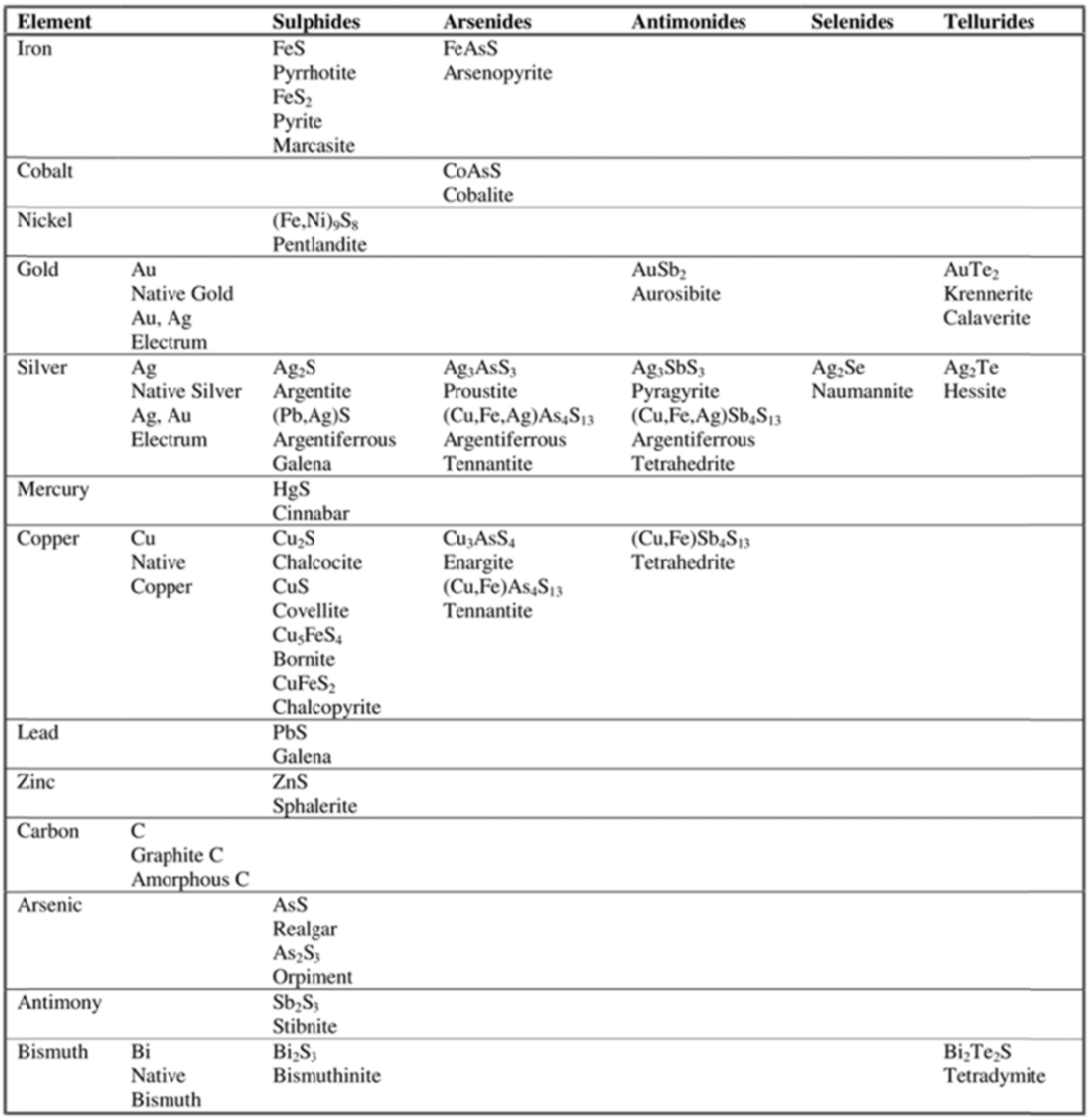
$$4Au + 8NaCN + O_2 + 2H_2O \rightarrow 4NaAu(CN)_2 + 4NaOH$$

The reactions with metallic silver are analogous, although the silver cyanide complex is weaker than the gold cyanide complex and stronger cyanide solutions and/or longer reaction times must be employed for its dissolution. Cyanide also forms complexes with other metals, such as Hg, Zn, Cu, Fe and Ni, which partially accounts for the consumption of cyanide in gold extraction circuits. Some of their minerals react both with cyanide and to a certain extent with hydroxide, which must be present to maintain cyanide in its ionic form. The table in Figure 8 lists several of these minerals (Mudder et al. 2001).

---

[14] Experience of gold shop owners in various countries. Miners sometimes burn the amalgam at even lower temperature, just hot enough to produce a yellow surface. Such gold sponges may have mercury contents in the range of several percent. Gold shop owners therefore often burn sponges again to avoid buying mercury at the price of gold.

[15] For heap leaching, piles of tailings are "irrigated" with cyanide solution; agitation leaching consists of "stirring" cyanide solution with tailings in suspension; vat leaching is similar to heap leaching, but done in small ponds with a filter floor ("vats", such as in Figure 17).



Element		Sulphides	Arsenides	Antimonides	Selenides	Tellurides
Iron		FeS Pyrrhotite FeS_2 Pyrite Marcasite	FeAsS Arsenopyrite			
Cobalt			CoAsS Cobalite			
Nickel		$(Fe,Ni)_9S_8$ Pentlandite				
Gold	Au Native Gold Au, Ag Electrum			$AuSb_2$ Aurosibite		$AuTe_2$ Krennerite Calaverite
Silver	Ag Native Silver Ag, Au Electrum	Ag_2S Argentite (Pb,Ag)S Argentiferrous Galena	Ag_3AsS_3 Proustite $(Cu,Fe,Ag)As_4S_{13}$ Argentiferrous Tennantite	Ag_3SbS_3 Pyragyrite $(Cu,Fe,Ag)Sb_4S_{13}$ Argentiferrous Tetrahedrite	Ag_2Se Naumannite	Ag_2Te Hessite
Mercury		HgS Cinnabar				
Copper	Cu Native Copper	Cu_2S Chalcocite CuS Covellite Cu_5FeS_4 Bornite $CuFeS_2$ Chalcopyrite	Cu_3AsS_4 Enargite $(Cu,Fe)As_4S_{13}$ Tennantite	$(Cu,Fe)Sb_4S_{13}$ Tetrahedrite		
Lead		PbS Galena				
Zinc		ZnS Sphalerite				
Carbon	C Graphite C Amorphous C					
Arsenic		AsS Realgar As_2S_3 Orpiment				
Antimony		Sb_2S_3 Stibnite				
Bismuth	Bi Native Bismuth	Bi_2S_3 Bismuthinite				Bi_2Te_2S Tetradymite

Figure 8: Minerals that commonly react with cyanide or hydroxide during leaching (Mudder et al. 2001).

The dissolved gold can then either be precipitated from the solution by less noble metals (e.g. with zinc using the "Merill-Crowe Process") or be absorbed by active carbon (e.g. CIP: carbon in pulp process, CIL: carbon in leach process). Zinc precipitates are calcinated and smelted into a low grade doré[16]. Gold from loaded active carbon is desorbed (stripped) in hot, higher concentrated cyanide solution and recovered electrolytically. Cathodes are smelted into doré bars.

Cyanide leaching is not effective in case of coarse gold particles, as dissolving would take too long.

Signature of cyanide leaching. Cyanide leaching is the main method in LSM, but increasingly also employed by more advanced ASM operations. Particularly tailings from artisanal mineral processing (gravimetric and/or amalgamation), which still contain significant gold grades, are further processed by small- or medium scale cyanide leaching plants.

For a selective dissolution of gold and silver, precise control of alkalinity (pH) and cyanide concentration are crucial. Below optimum CN^- concentration, recovery drops significantly; above

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[16] Doré is the term used for not refined gold (containing various other metals) smelted into bars.

optimum concentration, cyanide increasingly dissolves non-precious metals, too (particularly Fe, Co, Ni, Hg, Cu, Pb, Zn, As, Bi, as seen in Figure 8). Cyanide solution also dissolves native mercury (Hg) possibly present in the ore. Mercury traces in mine products are therefore not an exclusive characteristic for ASM.

The chemical nature and the selectivity of the cyanide leaching process alter the chemical composition of the raw gold.

At optimal operating parameters (typical for LSM), most non-precious metals remain in the tailings. Still, traces of metals such as Fe, Co, Ni, Hg, Cu, Pb, Zn, As and Bi contained in gangue minerals (and not present in the native gold) are dissolved and enter the doré.

Gold and Silver are dissolved similarly. The Au:Ag ratio of the ore is usually quite representatively reflected in the resulting doré bar, with overall precious metal content above 80-90% achievable.

Doré bars with an extraordinarily low precious metal content (e.g. 30% or even less) and an elevated content of non-precious metals are an indicator for cyanidation processes managed by empirical parameters[17] rather than by laboratory control. This is more common in ASM than in LSM.

The fact that cyanide leaches also gangue minerals can potentially be used to identify the applied processing method. Dixon (2014) presents an example from South Africa, where if Ni or Pd occurs in deposits, these elements will be accumulated into the gold concentrates during LSM processing (cyanide leaching) and stay there even after smelting. Doré gold produced from the same geological environment by ASM (by amalgamation) will contain lower Ni and Pd values. If the Merrill-Crow process is applied, excess Zinc from the precipitation stage finds its way into the doré bar. Resulting Zn levels are higher than those to be expected from the ore.

Other mineral processing methods might be in use and combined with any of the above methods. Refractory ores, in particular, cannot be processed with the above “standard methods” alone. Collectively, however, these other methods (e.g. direct smelting aka “borax method”, chlorination, iGoli, thiourea leaching, flotation, Haber process, etc.) are by far not as widespread as the above standard methods. Their possible influence on gold composition can be evaluated on a case by case basis.

In general terms, mineral processing methods that rely on physical properties of the gold (such as flotation) cause little to no alteration to the composition of the native gold. In such cases, the composition of the mined product reflects the composition of native gold similar to gravimetric concentration. Mineral processing methods that involve chemical reactions (hydro- or pyro-metallurgical, such as leaching or smelting), cause a significant alteration of the gold composition.

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[17] Empirically controlled leaching plants operate usually at higher CN concentration. Elevated cyanide consumption, less selective leaching and lower quality (grade) dorés are the trade-off to ensure satisfactorily high gold recovery.

1.3 Metallurgy – Pre-processing as Part of Gold Trading Activities

Doré from **LSM operations** is usually shipped directly to the refiner. Some LSM mines may pre-process the doré to sell gold and silver separately. In contrast, gold from **ASM operations** is usually traded, processed and pre-refined variably by a range of local, regional, national and international supply chain actors as explained in the following.

Native gold in form of dust, flakes or nuggets is traded as such as long as local supply chain operators are confident about its origin and therefore do not need to verify its quality on a case by case basis for small purchases. Further down the supply chain, and particularly when gold from different ASM mines is mixed, the gold is consolidated and homogenized by **smelting**. This allows determining the fineness of the obtained doré bars by traditional methods such as hydrostatic weighing or touchstone testing.

Similarly, gold buyers smelt the gold sponges to small doré bars, in order to homogenize and consolidate their purchases, but also to eliminate the remaining mercury.

Low grade doré bars (e.g. bars like in Figure 9) from empirical[18] cyanide leaching (e.g. precious metal content below 50%) are often pre-refined by traders or even already by the operators of the leaching plants. Non-precious metals and silver are dissolved in nitric acid. The remaining gold is smelted into doré bars with purity usually above 90%, often above 95%. Silver is precipitated from the acid with NaCl and smelted into raw silver bars.

Smelting into doré bars is also required if gold is legally exported and has to be assayed for that purpose (Figure 10).

Figure 9: Doré bars from different origin need to be consolidated and homogenized for downstream trading.
Image source: www.miningnewszambia.com

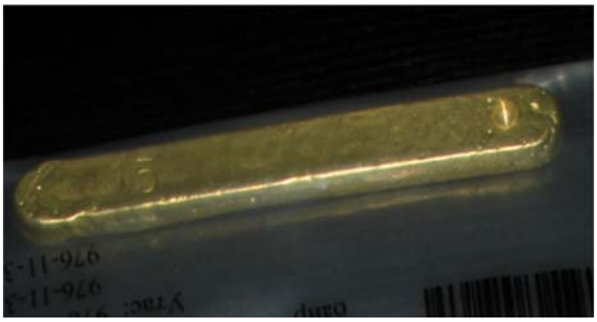

Figure 10: ASM doré bar, assayed and sealed for legal export. Source: F. Hruschka.

Smelting of native gold, gold sponges and dorés not only homogenizes the precious metals. Smelting also increases the purity of the gold, as the less noble metals oxidize and/or react with the fluxes (mainly borax, potash, soda, etc.) and are eliminated in the slag.

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[18] Cyanide leaching done according to empirical experience instead of technically controlled parameters, as usual in small-scale mining.

Findings are non-conclusive on whether significant mercury traces remain even after gold sponges are smelted into doré bars.[19] Even if this is the case, it might not necessarily indicate an ASM origin, as primary gold deposits may contain mercury as a by-product (see Figure 3) and such mercury is soluble in cyanide.

Along the supply chain, when traders consolidate and homogenize volumes of native gold or sponge by smelting, the chemical composition of the gold is altered and the fineness increases. Through smelting, the content of non-precious metals decreases.[20]

The potential presence of mercury in doré is not a conclusive indicator for an ASM origin.

Pre-refining of low grade doré bars in nitric acid not only reduces the content of non-precious metals, but also alters the Au:Ag relation of the doré. Pre-refined doré bars have a purity above 90% to 95% gold.

Contrary to common smelting and pre-refining techniques, which elevate the precious metal content, dilution processes are also reported. Higher purity gold or doré may be alloyed with non-precious metals (e.g. copper scrap) to pretend an origin as low grade doré bars from non-existent mining operations. Such processes are however not part of common ASM practice or technology. Instead, they reflect illegal activities by criminal actors, for example, for tax scams, smuggling and money laundering.

1.4 Metallurgy – Refining

Refining, often abroad, is the last step of the journey. Gold shipments need to be homogenized to produce reliable assay results for a given export lot. Refineries consequently receive the gold in form of doré bars. Additionally, refineries also recycle scrap gold.

Unless in case of small refineries sourcing from local ASM producers[21] and accepting mined gold in form of dust, flakes or nuggets, gold that is not delivered to international refineries in form of doré bars or scrap indicates increased risks for illicit trade (e.g., under-declared values) at some point in the supply chain[22].

Refined gold is gold that meets at least the LBMA specifications of “good delivery”, i.e. a minimum acceptable fineness of “*995.0 parts per thousand fine gold*”[23]. As higher purities are required for different applications, generally accepted refining standards such as ASTM B 562–95 provide specifications for fineness grades 99.5%, 99.95%, 99.99% and 99.995% (Figure 11).

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[19] One refiner claims that gold from ASM causes environmental problems due to mercury contamination. Another refiner indicates that no mercury was detected so far in doré bars from supposed ASM origin.

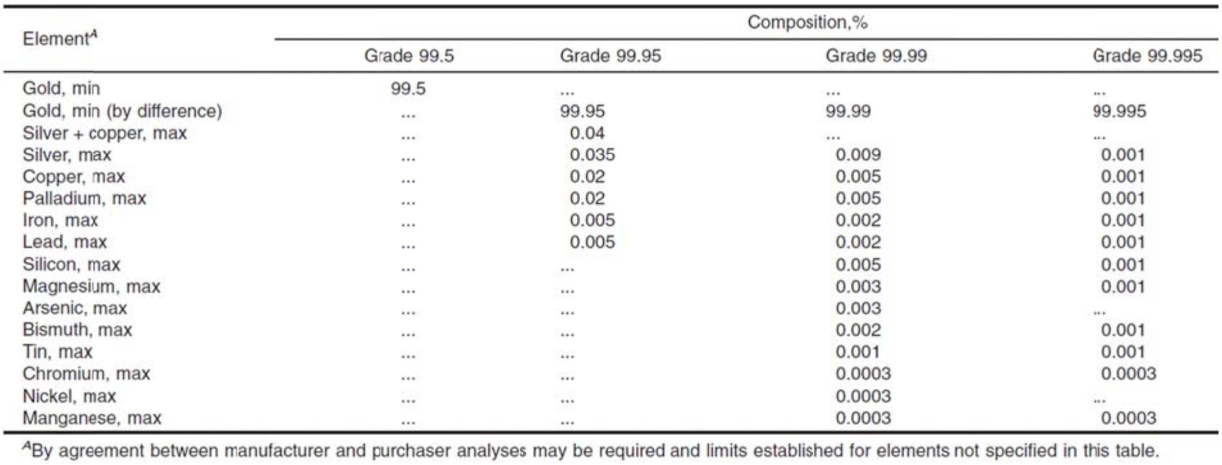
[20] This effect is used in analytical methods such as fire assay.

[21] Common e.g. in Colombia.

[22] Note, however, that special risks also apply to situations where refiners accept gold fraudulently declared as scrap

[23] http://www.lbma.org.uk/good-delivery-rules

The current revision of ASTM B 562–95 (2012) specifies the maximum content of the following trace elements: Ag, Al, As, Bi, Cd, Co, Cr, Cu, Fe, Ga, Hg, In, Ir, Mg, Mn, Ni, P, Pb, Pd, Pt, Rh, Ru, Sb, Se, Si, Sn, Te, Ti, Zn.



Element[A]	Composition,%			
	Grade 99.5	Grade 99.95	Grade 99.99	Grade 99.995
Gold, min	99.5	...	...	...
Gold, min (by difference)	...	99.95	99.99	99.995
Silver + copper, max	...	0.04	...	...
Silver, max	...	0.035	0.009	0.001
Copper, max	...	0.02	0.005	0.001
Palladium, max	...	0.02	0.005	0.001
Iron, max	...	0.005	0.002	0.001
Lead, max	...	0.005	0.002	0.001
Silicon, max	...	...	0.005	0.001
Magnesium, max	...	...	0.003	0.001
Arsenic, max	...	...	0.003	...
Bismuth, max	...	...	0.002	0.001
Tin, max	...	...	0.001	0.001
Chromium, max	...	...	0.0003	0.0003
Nickel, max	...	...	0.0003	...
Manganese, max	...	...	0.0003	0.0003

[A] By agreement between manufacturer and purchaser analyses may be required and limits established for elements not specified in this table.

Figure 11: Specification for refined gold according to ASTM B 562–95, revision 2005[24].

Different refining methods are available:

- For **pyrometallurgical refining**, the historical but still in use *Miller process* employs chlorine gas, which passes into molten gold covered with a layer of borax and silica. The chlorine gas reacts with the other metals present in the molten charge and purifies the gold to a fineness of 995 to 999.[25]
- **Hydrometallurgical refining** processes are required to obtain higher fineness. The *Wohlwill process* is a method, where gold anodes are electrolytically refined in an acidic gold chloride solution. Fineness of 999.9 is achievable. Alternatively, gold can be refined chemically by the *Aqua Regia process*. Doré or scrap is dissolved in aqua regia and subsequently precipitated as refined gold with a fineness of 999.5 to 999.95. Where the feed material contains significant quantities of metallic impurities, a *Solvent extraction* step may be introduced before the gold precipitation stage.

Hydrometallurgical processes need to be fine-tuned to the type of gold to be refined. Refineries therefore often specialize on certain types of material or even origin of doré (e.g. recycling of scrap gold, doré from certain LSM mines). Changes in the composition of processed doré or scrap may impact the efficiency of the process, particularly in case of chemical refining (aqua regia process).[26]

For refining processes, the composition of input material and consequently the origin of gold may be of crucial importance.

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[24] Due to copyright restrictions, the table of the current version (revision 2012) cannot be reproduced here.

[25] The achievable fineness of minimum 995 is compliant with the LBMA good delivery requirements.

[26] One refiner using an aqua regia process reported difficulties to achieve the fineness of 999.9 in a process calibrated for recycling jewelry scrap, after "scrap" with high Se and Te content (supposedly disguised mined doré) was clandestinely introduced into the supply chain by several suppliers. (Source: confidential interview)

Given the typical capacity of refineries, processing ten to hundreds kilogram of gold per day in case of small businesses, and several tons of gold per day in case of major industries, major gold homogenization takes place in refining facilities. Unless a refinery treats doré from a certain origin in a segregated process, gold of a wide variety of origins will be mixed. This substantially reduces the likelihood that compositional characteristics of the origin or signatures of individual processes in the upstream gold supply chain remain identifiable after the refining process.

The product, the refined gold, is expected to conform to refining standards such as ASTM B 562–95. Major allowed components of impurities in refined gold of 999.9 purity are Ag (up to 90 ppm), Cu, Pd and Si (up to 50 ppm), and As, Mg (up to 30 ppm). Other trace element concentrations are expected to be even lower or technically "absent" (i.e. in the ppb[27] range).

Refined gold is a highly homogenized product which usually consolidates gold from a wide variety of origins. This dramatically reduces the possibilities to constrain or even reconstruct the origin of individual sources.

If - at all - attempts should be considered to analytically constrain the origin of gold in refined form, this will only be possible with analytical methods going well beyond an accuracy of ppm.

1.5 Manufacturing

Fineness of gold in jewelry is measured in karats. Karat purity is defined as 24 times the pure mass of Au divided by the total mass. Typical alloys are 24 karat (pure – down to 99.5 wt.% Au)[28], 22 karat (92.5 wt.% Au), 18 karat (75 wt.% Au), 14 karat (58.33 wt.% Au), 10 karat (41.6 wt.% Au)[29], 9 karat (37.5 wt.% Au)[30] and 8 karat (33.3 wt.% Au)[31] .

In order to ensure consistent physical and optical properties of jewelry items, raw (doré) gold cannot be used. Jewelry alloys are always produced from refined gold. Fine gold is alloyed with variable amounts of refined Ag, Cu, Al and Pd, which allow for a wide variation in color. Ni[32] and Zn are added in smaller amounts to increase hardness and durability.

Manufactured gold jewelry and commercial jewelry alloys contain Ag, Cu, Zn, Ni, Co and Pd in different amounts. In older jewelry also As, Cd, Pt and Rh are possible, but the commercial jewelry alloys are much more consistent in their composition (Dixon 2014).

Illicit trafficking of gold sometimes involves the fabrication of alloys from doré, intended to simulate the composition of commercial jewelry alloys that can be declared as scrap gold (Dixon 2014; Roberts et al. 2016).

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[27] ppb = parts per billion = 10^{-9}

[28] Too soft for most jewelry manufacture. Only used for commoditized jewelry in the Middle East and India.

[29] Lowest fineness recognized in USA.

[30] Widely used in UK and Commonwealth countries.

[31] Lowest fineness recognized in most Continental Europe countries.

[32] Quality jewelry in western countries does not contain Ni, to avoid allergic reactions.

Elements commonly associated with native gold, such as As, Se, Sb, Sn, and Te, can be used to identify alloys fabricated from doré, if these elements are present at levels high enough for detection. None of these elements normally occurs in jewelry. Elements present in relatively large amounts in doré, such as Pb and Sn, can also be used to distinguish between jewelry and unrefined gold. Jewelry does not contain Pb or Sn, while Pb is present in most dorés and Sn in brass metal, often used to fake jewelry alloys. (Roberts et al. 2016)

Additionally, alloys with high concentrations of elements that have a low permissive content in the ASTM specifications are unlikely to be genuine jewelry alloys produced from refined gold.

1.6 Summary of Products along the Gold Supply Chain

Along the journey “from vein to vault”, native gold in the Earth’s crust is transformed into refined bullion and further into consumer products. Table 1 summarizes the initial, intermediary and final products available for sampling along the gold supply chain for potential provenance analysis.

Table 1: Primary and intermediate gold supply chain products during gold’s journey “from vein to vault”

Product	Description
Gold deposit	Geologic structure with enriched gold content, discovered by LSM through systematic prospection and exploration, or by ASM through empiric experience.
Gold ore	Rock or gravel that contains an economically valuable concentration of gold.
Native gold	Elemental metallic gold occurring as a mineral in gold deposits, usually as an alloy with silver (electrum) and accompanied by a wide variety of minor and trace elements characteristic for the type of gold deposit where it originates from.
Mined gold	Gold that originates from mines (LSM or ASM) and has never been previously refined. The origin of mined gold is the gold deposit where it was extracted.
Placer gold[33]	Mined gold that has been extracted from sand and gravel deposits, most often in or near streams, typically as very small but visible pieces of gold; placer gold occurs usually in the form of “dust” (< 0.1 mm), “flakes” (0.1 – 0.5 mm) or “nuggets” (> 5 mm).
Gold concentrate	An intermediate material produced from processing of gold ore to achieve a higher concentration, but still requiring further intermediate processing to produce doré.
Gold sponge	Agglomeration of native gold particles from gold ore, gold concentrates or placer gold, resulting from amalgamating these particles with mercury and subsequent decomposition of the amalgam by burning (process nowadays is exclusively applied by ASM).

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[33] Commonly also called “alluvial gold”, although it may origin from alluvial, eluvial, colluvial, etc. deposits.

Product	Description
Doré	Any smelted metallic product from mined gold with a purity less than the minimum specifications of refined gold (99.5 wt.% Au). Typically contains around 90% Au. A bar of metal alloy produced from mined gold. Generally originating from pyrometallurgical or hydrometallurgical processing of gold concentrates (mainly in LSM) or smelting of placer gold or gold sponges from amalgamation (mainly ASM).
Refined gold	Gold purified to standard specifications. Common specifications are "LBMA good delivery" requiring a purity of the metal of at least 99.5 wt.% Au, or the ASTM Standard (ASTM B 562 – 95), specifying requirements for purities 99.5, 99.95, 99.99 and 99.995 wt.% Au.
Bullion	Generic term for refined gold in bar or ingot form.
Jewelry alloy	Fine gold alloyed with different elements in refined form (according to standards for these elements; mainly Ag, Cu, Zn, Ni, Cd, Pt, Rh, etc.) to produce consistent optical, chemical and physical properties, suitable for commercial use in jewelry production.
Fake jewelry alloy	Doré alloyed with other metals with the purpose to simulate jewelry alloys and pretend gold scrap
Manufactured gold jewelry	Jewelry made out of jewelry alloy
Gold artefacts, ancient gold, ancient gold coins	Manufactured gold items from former times[34] that may contain a variety of minor and trace elements or even inclusions not common in contemporary jewelry alloys.
Gold scrap	Waste from jewelry manufacturing, used jewelry, electronics parts, and all other materials previously produced from refined gold, intended to be recycled to refined gold.[35]

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[34] Goldwork from the Varna cemetery in Bulgaria ranks as the oldest manufactured gold and is dated between 4560 -4450 BC (Higham et al. 2007).

[35] Comprises *Unprocessed recyclable gold*, *Melted recyclable gold*, and *Industrial By-products* as per definition of OECD (2016).

2. Parameters Applicable for Gold Provenance Analysis

This chapter presents the fundamental parameters that are considered relevant to constrain the origin of gold analytically. This compilation takes into account the present knowledge on gold composition in primary and secondary gold deposits, as well as compositional modifications that may occur during processing and pre-refining. We will first focus on those parameters that are considered relevant for the distinction of mined gold from different deposit types and ore provinces. Then, the same parameters are discussed for processed gold (Table 2).

Table 2: Parameters of potential use for Gold Provenance Analysis (GPA).

	Parameter		Information	Problems	Usefulness for GPA
Mined gold	Morphology		Transport conditions; secondary vs. authigenic gold	High variability in secondary deposits; difficult to measure in primary deposits	limited
	Mineralogy		Deposit type, formation conditions	Access to inclusions in grains restricted, limited representativeness of single inclusions	limited
	Chemical composition	Major and trace elements	Deposit type	Few lattice-bound elements detectable, low detection limits needed	high
		Stable isotopes (e.g. Cu, Ag, Fe)	Provenance area, processes (primary and secondary)	No published results yet	unknown
		Radiogenic isotopes (e.g. U-Th-He, Re-Os, Pb-Pb)	Formation age, metal source	High analytical effort; not applicable in most cases due to low concentrations of radiogenic elements and/or diffusion problems	moderate
Processed gold (doré)	Chemical composition	Major and trace elements	Type of prevailing gold source (primary, secondary, scrap)	Mixture of different sources possible; some elements mobile during processing	high
		Stable isotopes	Prevailing provenance	Mixture of different sources possible	unknown
		Radiogenic isotopes	Prevailing Pb isotopic composition of the source	High analytical effort; mixture of different sources likely; He diffusion during melting prevents use of U-Th-He method	moderate

Morphology of Gold

Due to its low hardness, grain shapes will not help to trace the provenance of gold, but may give information on transport systems. A large variety of shapes is expected in alluvial systems; morphologies may be used to indicate differences in placer environments (Hallbauer & Utter 1977; Knight et al. 1999; Townley et al. 2003).

Mineralogy of Gold

Primary mineral inclusions in gold grains may be of use to distinguish the origin of gold from its primary source (e.g. Chapman et al. 2002; Chapman & Mortensen 2006). However, such inclusions are rare (for example, about 20% of all gold grains studied in Ireland contained inclusions, e.g. Chapman et al. 2002) and their identification is limited to those cases where they occur at the surface of a polished sample; polishing of gold will often destroy or mask inclusions. Detrital grains in pores and those sticking at the surface will not indicate the primary origin but rather point to a placer source. Processing of gold (smelting) will destroy most of the inclusions (sulfides, tellurides, arsenides) unless they are highly refractory (zircon, monazite, chromite, most silicates).

Chemical composition

Major and trace elements

As gold is a multi-component alloy, its composition is the most useful parameter for provenance analysis. However, only few elements are really alloyed with gold, i.e. substituted for gold in the gold lattice (Figure 12), and low detection limits are needed for most of them. Concentrations of most elements present in gold are in the ppm to sub-ppm range. This poses important constraints and restrictions on the analytical methods of choice, which will be discussed in chapter 3. Therefore, many studies on gold provenance solely reported elements that are detectable by electron microprobe analysis (Au, Ag, Cu and Hg). In combination with inclusion assemblages, this information may be useful to discriminate between different primary deposit types (e.g. epithermal versus mesothermal gold, authigenic gold; e.g. Leake et al. 1998; Chapman et al. 2002; Chapman & Mortensen 2006; Chapman et al. 2006).

The average composition of native gold in three types of gold deposits from Russia is presented in Table 3 (Nikolaeva et al. 2013). By calculating chemical indices from trace element data, these groups are clearly distinguishable. However, a comparison with in-situ measurements of gold grains by LA-ICP-MS (Table 3) illustrates the problems inherent to the analytical techniques used: element concentrations measured in situ in small sample volumes are by factors of magnitude lower than in bulk measurements, most likely due to included minerals detected in bulk samples. Trace elements detected by LA-ICP-MS in a study of placer gold nuggets from globally distributed localities (Tetland 2015) are also quite low and closer to the median calculated from Schmiderer (2009).

Table 3: Average composition of native gold from different deposit types in Russia[36] and an average for gold grains from central Europe[37]. Numbers in brackets indicate number of samples analyzed.

	Deposit type (Nikolaeva et al. 2013)			Schmiderer (2009)
Element [ppm]	Gold-polysulfide-quartz (17)	Low-sulfide gold-quartz (34)	Gold-silver (26)	Central Europe (1,858)
Li	0.12	0.26	0.54	
V	170	610	175	0.5
Mn	590	21	71	4.8
Fe	6,800	2,800	4,400	382
Co	9.9	1.6	4.4	0.3
Ni	8.7	12	9.5	2.1
Cu	980	240	390	139
Zn	180	53	370	6.4
As	106	1,030	950	2.1
Se	13	9.9	130	0.8
Rb	0.22	0.86	1.8	
Sr	3.1	12	8.2	<0.5
Y	2.0	0.41	0.81	0.05
Mo	1.4	1.5	2.5	0.14
Pd	0.8	0.31	1.4	0.24
Ag	63,900	76,200	99,000	62,342
Sn	140	650	120	2.7
Sb	8.6	11	190	7.7
Te	62	4.2	130	1.4
Ba	16	48	23	0.68
La	5.2	1.9	0.53	0.07
Ce	3	1.2	1.9	0.14
W	1.7	5.2	0.92	0.08
Pt	0.58	0.12	0.29	0.06
Hg	650	630	780	6,360
Pb	87	290	600	7.2
Bi	85	22	23	0.45
U	0.58	0.27	0.19	0.03

Chemical heterogeneity of gold grains is widely recognized. For placer material, Schmiderer (2009) demonstrated that a group of elements (Cu, Ag, Sb, Te, Hg, Tl, Bi) is commonly depleted from core to

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[36] Analysis of 490 samples of lode and placer gold by ICP-MS using 5 mg of material devoid of visible impurities

[37] Median from 1858 point measurements of gold grains from Europe by LA-ICP-MS, Schmiderer (2009) unpublished data

rim by one order of magnitude, whereas Se and Pd do not change. All other elements measured (mostly siderophile[38] and lithophile elements, Figure 7) increase in concentration from core to rim.

In his seminal work on pre-historic gold artefacts, Hartmann (1970, 1982) determined the concentrations of Au, Ag, Cu, Bi, Ni, Pt, Pb, Sn, Zn, As, Sb and Hg using spectral analysis; detection limits ranged from 30 ppm (As) to 500 ppm (Zn). Elements determined qualitatively but not detected in most cases included Rh, Ru, Pd, In, Tl, Cd, Mo, Te. By quantification of Ag, Cu, Sn and Pt, 11 "material groups" were defined for artefacts originating from Ireland, central Europe, the Danube region, Iberia, Denmark, Greece and Bulgaria.

Gold recovered from the Nebra Sky Disc has been analyzed along with other artefacts, and compared with a large dataset from more than 2000 gold grains recovered from primary and secondary deposits in Europe (Schmiderer 2009). Trace elements were divided into three groups according to their geochemical behavior (Table 4).

Table 4: Classification of trace elements in gold according to geochemical criteria from Schmiderer (2009).

Lithophile elements	Elements sensitive to smelting	"Robust" elements
Al, B, Ba, Be, Ca, Cs, Ga, Hf, K, Li, Mg, Na, Nb, P, Rb, Sc, REE, Si, Sr, Ta, Th, U	Cr, Mn, Fe, Co, As, Se, Cd, In, Sn, Sb, Te, Pb, Bi, Hg	Ag, Cu, Rh, Pd, Pt, Ir, Ge, Ni, Os, Ru

The Sky Disc consists of bronze containing 2.5 wt.% Sn as well as Fe, Ni, Zn and As. The gold application ($Au_{75}Ag_{25}$) of the disc carries all elements present in bronze except for As, plus considerable Sn, Pt and Hg. The composition recalculated for the addition of 0.4% bronze did not fit to any of the investigated primary and secondary gold occurrences (Schmiderer 2009). Ehser et al. (2011) propose an origin of the gold from Cornwall, along with Sn in the bronze, whereas the Cu originates from the Mitterberg deposit in Salzburg, Austria (Lutz & Pernicka 2013). An origin of Sn from Cornwall is also corroborated by the determination of Sn isotopes in the Sky Disc, in comparison to Sn ores from Cornwall and the Erzgebirge (Haustein et al. 2010).

Stable isotopes

Natural gold (^{197}Au) is mono-isotopic; therefore, there is no isotopic variation of the major element that may be used for GPA. The major alloying elements Ag and Cu both have two stable isotopes with comparable abundances (natural abundances of ^{107}Ag 51.829%; ^{108}Ag 48.161%; ^{63}Cu 69.15%; ^{65}Cu 30.85%); they can be measured with high precision only using solution-MC-ICP-MS and TIMS, requiring time-consuming sample preparation (dissolution, element separation, spiking[39]). Mercury has seven stable isotopes with ^{202}Hg being the most abundant (29.86%). However, detection of Hg is notoriously difficult using ICP-MS (trace Hg in gases). As the abundances of all other trace elements are very low (e.g. including Fe), isotopic ratios are not detectable unless larger amounts of these elements have been chemically separated. All these points limit or exclude the use of in-situ mass spectrometric methods. Detection of stable isotope ratios in gold is in its infancy and therefore not yet applicable to GPA.

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[38] Siderophile – elements that dissolve readily in iron, basically the high-density transition metals

[39] M. Brauns (CEZ Mannheim) assumes the Ag isotope composition as reliable (i.e. not altered during transport processes), whereas Cu isotope ratios may change by diffusion.

Radiogenic isotopes

Natural gold has very low U and Th concentrations[40] (median values <0.03 ppm; dataset from Schmiderer 2009). Nevertheless, the U-Th-He method used by some research groups provides formation ages of gold (Eugster 1996; Eugster et al. 2009a; Eugster et al. 2009b; Cabral et al. 2013). It is based on the production of ^{4}He from α-decay of U and Th, and He retention in gold up to the melting temperature (ca. 1064°C). However, analytical problems including the necessity to use high-sensitivity mass spectrometers and unforeseeable problems with sample material (He diffusion) limit the applicability of the method.

Natural gold contains low Pb (e.g. median 7.2 ppm in dataset of Schmiderer (2009), Table 3) that has the following average isotopic composition: ^{208}Pb (52.4%; produced by radiogenic decay from ^{232}Th); ^{207}Pb (22.1%; radiogenic decay product of ^{235}U); ^{206}Pb (24.1%; radiogenic decay product of ^{238}U); ^{204}Pb (1.4%; “common lead”). Lead isotope ratios depend on the time of formation (by U-Th decay) and on the local and regional gold-forming processes (type of reservoirs, regional crust-mantle evolution etc.). The Pb isotopic signature of gold does not change from primary to secondary (placer) deposits (e.g. Standish et al. 2014). Lead model ages may be calculated from the data providing information on the age of the mantle or crustal reservoirs from which Pb has been extracted.

Lead isotope compositions are frequently used by archeometallurgists (e.g. Guerra 2004, Pernicka 2014). However, it remains open to debate if the Pb measured in artefacts and objects was really present in the original gold, as inclusions, or has been later introduced during processing.

Rhenium (^{187}Re) decays to ^{187}Os; both are very minor constituents of gold. Rhenium and Os will mostly be present in inclusions of platinum-group minerals (PGM) and not be gold lattice-bound. Nevertheless, the ^{187}Re-^{187}Os isotope system has been successfully used for dating gold and gold artefacts in some cases (Kirk et al. 2002). There is only little chance for in-situ measurement of Re-Os isotopes in gold unless concentrations of Os are high enough, e.g. in inclusions of Re-Os-rich minerals. Typical PGM present in gold are Os-rich and Re-poor; from them, an Os model age may be calculated similar to the Pb model ages discussed above (Junk 2001; Junk & Pernicka 2003; Jansen et al. 2016).

Conclusion from chapter 2, Parameters Applicable for Gold Provenance Analysis

The trace element composition of gold using methods allowing for low detection limits and reasonable spatial resolution (µm scale) will provide the most promising results for primary and secondary gold. The combination with stable isotopes (e.g. Ag, Cu, Hg) and Pb isotopes may be useful. Inclusions in natural gold may help for provenance of natural (untreated) gold, but their low abundance likely will limit the use. Radiometric dating is only possible using sophisticated technologies on samples in solution, and is therefore not practically applicable to the needs of gold provenance studies in general, and to supply chain questions addressed in the DRC in particular. An example of provenance analysis of other conflict minerals is provided in the case study below. In processed gold, the chemical composition will reflect the mixture of materials processed. In addition, some mobile elements may be lost (e.g. As, Sb, Hg) whereas others may be introduced by the processing method used.

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[40] Radioactive elements that produce characteristic decay products

Case Study: Example of a provenance study for minerals: the 3Ts

Starting in 2006, the Analytical Fingerprint Method (AFP) for the "3Ts" (tantalum, tin and tungsten ores) has been developed. The goal was to identify certain mineral shipments originating from conflict regions in the DRC and elsewhere. In an extensive pilot study initiated by the BGR and co-financed by the BMZ, analytical methods to determine the origin of ore concentrates were developed and a database on relevant deposits of the 3T was initiated. The database comprises ore concentrate samples from both, ASM and LSM operations, as well as concentrates and single mineral grains from museum collections (i.e. the RMCA in Tervuren, Belgium). Although the focus was on central Africa, samples from deposits outside this region have been included to validate the method.

Two main parameters were in the focus of the investigations: (1) the mineralogical composition of the ore concentrates, and (2) the chemical composition of the major ore minerals of interest, namely columbite-tantalite (for tantalum), cassiterite (for tin) and wolframite (for tungsten). Methods tested for the mineralogical composition included X-ray diffraction analysis with Rietveld refinement and scanning electron microscopy coupled with Mineral Liberation Analysis (SEM-MLA). The chemical composition of bulk ore samples was measured using wavelength-dispersive XRF and portable energy-dispersive XRF, whereas single mineral grains were analyzed by electron microprobe, LA-ICP-MS, solution ICP-OES and ICP-MS, and TIMS methods.

Method development is still on-going, results so far are as follows:

1. All investigations are carried out using polished blocks produced from a few grams of ore concentrates by embedding the grains in resin and subsequent polishing the surface.
2. The mineralogical composition of ore concentrates cannot be used to unequivocally constrain the origin of a sample. This is due to different processing methods in use and due to the processing skills of the individual miners. For "coltan" (tantalum ores), the mineralogical composition may be useful as an additional information indicator.
3. The method of choice to quantify mineralogy is SEM-MLA because it also greatly facilitates identification of target grains for subsequent chemical analysis using in-situ methods.
4. The elements most useful for provenance analysis of 3T ores were identified. In general, they are minor to trace elements, including the rare earth elements.
5. Therefore, they need to be measured using sensitive techniques (low detection limits) and appropriate spatial resolution (depending on grain size, but commonly in the range of 0.05-0.1 mm).
6. The composition of about 50 single grains must be analyzed per sample to cover the internal compositional variability of the sample.
7. The method of choice for compositional analysis is LA-ICP-MS, combining rapid measurement with good analytical and spatial resolution. Electron beam methods have superior spatial resolution, but higher detection limits and therefore the number of parameters for statistical analysis is limited.

8. Some of the minerals allow determination of mineral ages using the U-Pb isotope system. Highly accurate ages are derived using TIMS, at low sample throughput and using complex chemical procedures, whereas LA-ICP-MS allows for direct in-situ measurement of “model ages” that help to constrain the ore province and homogeneity of a sample.
9. The variability of the minor and trace element composition of the major ore minerals is high (in the range of several orders of magnitude), and so is the variability within a given ore deposit.
10. Statistical methods are used to decide upon the similarity of a sample to a reference sample in the database, similar to a forensic DNA test.
11. The AFP is based on a comparison of the major and trace element composition of a sample in question to reference samples of known origin stored in a database.
12. High data variability and nonparametric data distributions are characteristic for grains originating from one ore concentrate.
13. The Kolmogorov-Smirnov (KS) statistic is used as a measure for the similarity of two samples.
14. Based on the KS statistic, a ranking procedure (Gäbler et al. 2013) or a procedure based on empirically deduced threshold values are used to check the documented origin.

After finalization of the pilot study on coltan (tantalum) concentrates in 2009, similar methods were developed for tin and tungsten ores. Starting in 2011, the AFP method was integrated into the “RINR” (Regional Initiative against the illegal exploitation of Natural Resources) proposed by the ICGLR (International Conference on the Great Lakes Region). At present, the German BMZ finances installation of analytical laboratories and a management unit in the ICGLR region while work on statistical data evaluation continues at BGR. AFP has not been applied in actual supply chain practice yet.

3. Gold Analysis

This chapter provides an overview on the analytical methods that are currently in use to measure the major, minor and trace element composition of gold. Some of these methods are mainly employed in a business environment, for example in the context of processing and refining activities, while others have theoretical or practical scientific applications. From among these methods, only some might serve as useful tools for the purposes of Gold Provenance Analysis. In order to guide the reader through the various methods, the underlying systematics for gold analysis are illustrated allowing for a categorization of different analytical approaches. A range of key applications are then sketched below. Subsequently, basic parameters and practical application cases are introduced for each analytical method. Details on all methods are shown in Annex B.

3.1 Categories of Gold Analysis Methods

Gold can be analyzed as bulk sample or as a spatially focused single spot measurement. However, native gold is not a homogenous phase. Impurities are abundant; as illustrated in Figure 12, they may occur:

- in the lattice
- as "dirt" in the pores (material accidentally trapped during transport or weathering)
- as mineral inclusions formed during gold genesis (the assemblage is then characteristic for the deposit type)

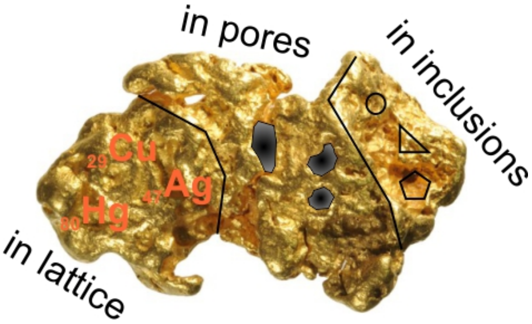

Figure 12: Sketch of the different possibilities of impurities in gold.

Depending on the specific field of application different techniques are applied for gold analysis. There are only few techniques for measuring samples with very high (e.g. >50%) and low (trace) concentrations of elements at the same time. Major elements are considered to occur in concentrations above 1%, minor elements are between 0.001% and 1%, and trace element concentrations are below 0.001% (corresponding to < 10 ppm).

In this report, the techniques used for gold analysis are grouped on the basis of the type of excitation energy (Table 5).

Table 5: Grouping of commonly used methods for gold analysis.

Group 1: Emission and mass spectrometric techniques	Group 2: Electron beam methods	Group 3: Ion beam methods	Group 4: X-ray methods	Group 5: Others
Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)	Electron Microprobe Analysis (EPMA)	Proton-induced X-ray Emission (PIXE)	X-ray fluorescence analysis (XRF)[41]	Fire Assay / gravimetry
Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES)	Scanning Electron Microscopy (SEM)	Particle Induced Gamma-ray Emission (PIGE)	Synchrotron Radiation X-ray Fluorescence (SR-XRF)	Instrumental Neutron Activation Analysis (INAA)
Laser-Ablation Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS)				
Multi-Collector Inductively Coupled Plasma-Mass Spectrometry (MC-ICP-MS)				
Spark Optical Emission Spectrometry (Spark OES)				
Glow Discharge Mass Spectrometry (GD-MS)				
Laser Induced Breakdown Spectroscopy (LIBS)[42]				

The largest group (group 1) comprises **methods using any type of spectrometry** applied to samples that have been atomized or, more commonly, ionized. ICP-OES is mainly used for major and minor elements, whereas ICP-MS measures trace elements (more precisely: isotopes) down to very low detection limits. Both methods have the advantage of being able to determine a range of elements simultaneously. MC-ICP-MS determines the isotope ratios of minor and trace elements in gold with very high precision (e.g. Pb, Os, Ag, U). While the methods have been originally developed to determine element and isotope concentrations in liquid samples (i.e. by dissolution of solid samples), LA-ICP-MS is used to analyze solid materials by ablating small sample volumes using a focused laser beam (spot analysis). Thus, single mineral grains or specific zones within grains (e.g. inclusions or core-rim areas in zoned grains) can be quantified. LA-ICP-MS, however, requires the use of well-equilibrated and characterized matrix-matched standard materials that are not easily available for complex materials. Spark OES and GD-MS are used for the determination of the gold content and impurities in high-purity gold bars or gold alloys. LIBS has been tested in recent years for the determination of the composition of precious alloys (e.g. jewelry alloy or gold alloys). This method possesses 1-100 ppm limits of detection and an information depth of 10 µm. Practically all elements in the periodic table can be measured, but quantification and calibration remain poorly solved problems. LIBS is available as a portable device (pLIBS).

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[41] Including portable XRF = pXRF

[42] Including portable LIBS = pLIBS

The **non-destructive electron beam-based methods** such as EPMA and SEM (group 2) offer the choice of simultaneously imaging and analyzing the chemical composition of points and areas in native gold samples, including mineral inclusions, at high spatial resolution. For EPMA the sample is mounted into resin and polished to obtain a flat surface, which is then carbon-coated to obtain appropriate conductivity. The generated characteristic X-rays are analyzed by energy-dispersive (EDS) or wavelength-dispersive (WDS) methods. Major advantage of EDS is the simultaneous measurement of the complete energy spectrum in a short time, whereas WDS offers better detection limits (down to <100 ppm in cases), less line interferences, but longer measurement times.

Ion beam techniques (group 3) are non-destructive methods and are often used in archaeology and archaeometallurgy for analyzing the elemental composition of ancient gold (e.g. coins, jewelry). These are techniques restricted to analyzing only the surface of the sample. The maximum penetration depth of these techniques is around 30 µm.

Group 4 techniques are based on **emitted X-rays**. XRF is a method for the qualitative and quantitative determination of major, minor and some trace elements. For quantitative analysis a calibration standard with known composition is needed. This technique is also available as portable ”handheld” instruments (pXRF). The method has a penetration depth of only about 1-2µm. For gold, XRF is mainly used for incoming lot inspection at the refinery or gold purchaser. A refiner may opt to perform additional quantitative analyses after an initial screening check using XRF[43].

Fire assaying followed by gravimetry has been used throughout the world for centuries and remains to this day the industry standard method for analysis of precious metals. It is used for the determination of Au, Ag and PGE contents in all types of materials (e.g. bullion, jewelry, ores and concentrates). However, it is not suitable for provenance analysis due to the low number of elements remaining in the cupel.

The INAA method provides accurate results for some major and trace elements. Unfortunately a nuclear reactor is needed and the analysis of gold samples can only be finished after seven days.

Spark OES and GD-MS are not widely used and little or no published data for native gold samples is available. GD-MS was used in a study of the Royal Canadian Mint for fingerprinting doré (LBMA Assaying & Refining Conference 2015). A good potential was claimed for this method, although it is destructive, expensive and with a low sample throughput. The advantages are low detection limits, good reproducibility and accuracy.

Short descriptions of all methods for gold analysis tabulated in Table 5 and details on the techniques are presented in Annex B.

3.2 Applications for the Analysis of Gold

Gold Artefact Analysis for Archeometry

In archeology, ancient gold artefacts need to be investigated in a non-destructive manner. Guerra (2008) emphasized that PIXE and SR-XRF are adequate for analyzing gold artefacts, but a large

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[43] E.g., some refiners may analyze trace elements through ICP-MS or ICP-OES; personal communication from a refiner laboratory manager

database is needed for identifying the origin of the gold (Guerra 2014). Bugoi et al. (2008) and Cristea-Stan et al. (2012) applied PIXE and SR-XRF for 14 native gold samples.

PGE, Sn, Sb, Hg, Pb, Te, Cu were analyzed in artefacts by micro-PIXE at Dresden-Rossendorf and ANKA Synchrotron Radiation Facility, Karlsruhe (Constantinescu et al. 2008; Constantinescu et al. 2009). The analyses show that traces of Sn are characteristic for gold artefact derivation from placer gold, and traces of Sb and Te (mostly present as mineral inclusions) for derivation from primary gold. High-temperature melting point trace elements (Ta, Nb, Cr) and PGE were found in gold objects (Pietroasa, Romania) at the micrometer scale and attributed to four possible sources: southern Urals, Nubia (Sudan), Persian Empire (Pactolus river, Anatolia), and Roman Empire coins.

Major improvements in the characterization of gold materials have been made with LA-ICP-QMS[44], LA-ICP-SF-MS[45] and LA-MC-ICP-MS. These methods enable both the determination of major, minor and trace elements, as well as isotope ratios.

Gold Forensics and Fingerprinting

LA-ICP-MS has been used for forensic gold fingerprinting since the 1990s (Watling et al. 1994). This technique has been developed to claim stolen or relocated gold. Australia and South Africa have established databases for reference materials of mined and processed gold. Australia decided not to embody regular gold analysis from gold producers by law (Crundwell 2009). In contrast, the government of South Africa passed the “Precious Metals Act, 2005”. Every six month, each licensed gold producer has to submit a representative sample from different stages of production (native gold and doré) to the FSL (Forensic Science Laboratory of the South African Police Services). This will be analyzed by ICP-OES (major elements) and LA-ICP-MS (trace elements). Published data from South African gold is available from Dixon (2014) and Roberts et al. (2016).

According to Dixon (2014), the majority of samples stored in the South African gold database consist of drillings from doré gold bars which are the product of mining activity at a single shaft or a few close shafts mining the same reefs and supplying a mine smelter; this unrefined gold is representative of the mineralization, type of extraction, and original compositional variation. In order to determine whether the trace element content of doré is representative of the trace element content of the in-situ gold, prills from fire assaying of reef samples were analyzed by LA-ICP-MS and added to the database. They are believed to represent the best record of in-situ gold composition at a sampling point. A large number of prills (400 per reef, for 3 reefs per mine from 2 mines) were supplied by Gold Fields, forming an important dataset in the gold database. Each mine needs to supply raw gold and processed gold (bar, bullion, amalgamated button). The original gold database (Grigorova et al. 1998) was insufficient because a “beyond reasonable doubt” probability (>95%) is needed in criminal prosecution. A statistical solution was developed by Merkle et al. (2004) and Merkle & Dixon (2006).

Roberts et al. (2016) investigated 858 different gold samples in order to determine differences between jewelry alloys, jewelry, bullions and “suspects” from illegal origin. The commercial alloys are much more consistent in their composition than jewelry. Older jewelry contains elements that are no longer commonly used (Roberts et al. 2016). Bullions and gold alloys (as well as jewelry) can be distinguished by their gold content. In bullions the gold content in general reaches 70 wt.% and more.

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[44] QMS – quadrupole mass spectrometer

[45] SF-MS – sector field mass spectrometer

Gold alloys and jewelry have distinctive gold contents related to their fineness. Zinc and Cu contents are in general higher in gold alloys and jewelry than in bullions (with few exceptions). Cadmium, Pd, Pt, Ni and Co sometimes occur in jewelry, but not consistently. Lead is present in low concentrations in all natural gold deposits and is found in different concentrations in the mine bullions as well. Lead, As, Sb, Sn, Se and Te are undesirable in refined gold and are removed. High levels of Sn, as well as the presence of Hg and Pb indicate crude processing (amalgamation and low temperature smelting) (Roberts et al. 2016). These elements are sufficient to identify a material as illegal according to South African law.

Schmiderer (2009)[46] analyzed 60 elements in more than 2000 gold grains using LA-ICP-MS (New Wave 213 nm laser, Thermo Element XSeries II ICP-QMS at the CEZ Mannheim) and "wet plasma" technique (addition of water to He/Ar gas mixture) with detection limits commonly below 1 ppm (for 40 elements <0.1 ppm). 75% of the analyses are above the detection limits for the following elements: Mn, Fe, Cu, Zn, Ge, As, Zr, Nb, Mo, Pd, Ag, Sn, Sb, I, Ba, Ce, Pr, Nd, Sm, Gd, Dy, Er, Ir, Pt, Au, Hg, Pb and Bi (n = 28). If 90% of all analyses are considered, the number of elements above the detection limit is reduced to 16: Mn, Fe, Cu, Ge, Zr, Mo, Pd, Ag, Sn, Sb, I, Ba, Sm, Au, Hg and Pb are left in sufficient concentration for statistical evaluation. Annex B.12 provides the percentage of positive detections of an element in the dataset, and the median of all analyses as a proxy for the composition of natural gold measured by LA-ICP-MS at high spatial resolution (see also Table 3 for comparison).

In contrast, in a set of 385 measurements on 242 gold grains from different primary and secondary gold deposits in Africa and Asia from the polished section collection of the BGR using LA-ICP-MS (different laser, same mass spectrometer, different spot size, dry plasma), more than 75% of the analyses were above detection limits only for Au, Ag, Cu and Hg (Dr. Brauns, CEZ Mannheim, pers. comm.). The elements Ti, Cr, Mn, Fe, Ni, Zn, Pd, Cd, Sb and Pb were positively detected in 10-40% of all measurements. The concentrations of As, Se, Ru, Rh, Sn, Te, Re, Os, Ir, Pt and Bi were below detection limit in more than 90% of the measurements (Annex B.12). Gold flakes from the Rhine River were also analyzed using the same instrument. Here, trace elements were more abundant, with Fe, Cr, Cu, Zn, Ag, Sn, Sb, Au, Hg, Pb and Bi detectable in >75% (Annex B.12).

Chapman et al. (2006) discussed problems that occur with LA-ICP-MS and the interpretation of the data. Firstly, the assumption that the chemical signature of natural gold is unaffected by fabrication processes is often not met, especially when dealing with ASM (contamination from crucible, fuel ash, Cu, Sn addition). Secondly, they note potential difficulties in gaining a useful signature of natural gold due to the heterogeneity both in terms of alloy composition and, as a consequence, of micro-inclusions. Populations of placer gold exhibit wide variations in Au, Ag, Cu, Hg, and Pd contents between individual gold grains due to variation within a single source or as a result of different sources being mixed together. However, LA-ICP-MS produces meaningful results when studying homogenized smelted gold. Linking ore composition to artefact composition is problematic because literature data on natural gold are often inappropriate or non-existing. Therefore, GPA is often speculative concerning artefacts.

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[46] Unpublished dataset from Schmiderer forming the basis of his PhD thesis (2009), after elimination of about 400 extreme values that are classified as clear outliers

Isotope Analysis

Osmium isotopes were measured in PGM inclusions in gold coins for provenance analysis (Junk 2001; Junk & Pernicka 2003; Jansen et al. 2016). The PGM inclusions are usually not affected by metallurgical processes during smelting and coin minting, but enough inclusions need to be present for a meaningful statement for gold provenance. Furthermore, the database for Os isotope compositions in natural PGM is still small. Due to its high volatility, osmium, if present in solid solution in gold, will leave the gold lattice during smelting. Osmium isotopes therefore mainly reflect the composition of inclusions in gold artefacts, not of the gold itself. Direct dating of gold using the Re-Os method is very rarely applicable because of the very low Re concentrations in natural gold.

Lead concentrations in native gold are also very low; thus, it is difficult to impossible to measure Pb isotopes in small samples using MC-ICP-MS. Standish et al. (2013) and Bendall et al. (2009) demonstrated that the Pb isotope characterization with solution and LA-MC-ICP-MS is useful for archaeological and native gold samples. They investigated two gold reference materials, 14 samples from different Irish gold deposits and two gold artefacts. The solution analysis is preferred for natural gold grains due to their possible inhomogeneity, but both techniques can be applied for gold artefacts.

Eugster (1996) and Eugster et al. (2009b) described a method of dating ancient gold (i.e., the last melting process) using the U-Th-^{4}He dating technique applied to a gas mass spectrometer. The technique is still in development, but it was used for direct dating the Diamantina gold mineralization in Brazil. The result was comparable to ages calculated from isotopic ratios in rutile grains (Cabral et al. 2013).

Determination of stable isotope ratios by MC-ICP-MS has a large potential for Ag and Cu isotopes in gold, but the database is still small and the experimental and theoretical background needs to further developed.[47]

Gold Compositional Data Comparison and Evaluation

In order to test methods for in-situ analysis of gold, Gauert et al. (2015) compared (non-destructive) FE[48]-EPMA, (mildly destructive) LA-ICP-MS and (non-destructive) SR-XRF techniques for the application in gold fingerprinting. Standard reference materials used were solid gold materials produced by Norddeutsche Affinerie AG (nowadays Aurubis AG), and standard NA-Au-31 was repeatedly tested for homogeneity. FE-EPMA provides high reproducibility at high spatial resolution; besides Au, Ag and Cu, the trace elements Hg, S, Fe, Ti, Co, Ni, Pb, Cd and Sn were measured above their detection limits. Detection limits achieved were around 15 ppm for Ti, Fe, Ni and Cu, 30 ppm for S and 81 ppm for Ag. LA-ICP-MS analyses provide detection limits (1 sigma absolute) of <1 ppm for Ti, Cr, Mn, Co, Rh, Cd; 1-5 ppm for Zn, Sb, Bi; 5-15 ppm for Fe, Ni, Cu, As, Se, Pd, Te, Pt, Pb; and 30 ppm for Sn. For SR-XRF, intermediate detection limits were achieved, commonly between 1-4 ppm (Cr, Mn, Fe, Co, Ni, Cu, Zn, Pd, Cd, Sn, Sb, Te). Application to real gold samples from the Archean Barberton greenstone belt, the Witwatersrand gold reefs and the Black Reef showed that FE-EPMA is able to compete with the other techniques because of its small beam diameter and reasonable detection limits achieved using "extreme" conditions (high acceleration voltage, long counting times). However, problems occur for

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[47] Interview with Dr. Brauns, CEZ Mannheim

[48] Field emission gun (FEG), an improved type of EMPA where field emission is used in contrast to common tungsten filament machines. The method gives high beam stability and smaller spot sizes at low acceleration voltage, and thus improved spatial resolution.

Fe, S, Ni and Co in gold close to pyrite grains within a distance of 15 µm from the sulfide. LA-ICP-MS requires minimum grain sizes of 60 µm to avoid contamination. Reproducibility was worse and variability was higher compared to the other techniques, probably due to the presence of micro-inclusions. Discriminator elements were Ag, Cu, Pb, Fe, As, and Pd, Mn, Cr, Ni, Te, Sb and Bi and different gold sources could be distinguished based on Ag, Hg, Cu, Ni, Co, Pb, Pd, Pt, As, Bi and Te concentrations. SR-XRF allows the measurement of small particles (few µm) with detection limits superior to FE-EPMA. The analyses revealed the presence of Ag, Fe, Cu, Pb, Ti, U, Cr, Sr, Zr and V; Hg and the PGE could not be measured. As a result for gold from locations in South Africa, the following characteristic fingerprints emerged:

- Black Reef (Modder East Mine of Gold One International): low and variable finesses (838-881), elevated Fe, S and Hg (0.56-0.78%), variable but low Cu, Co, Ni, Th, U, Cr, As, Pb, Pt, Pd, Sn, Sb, Ta.
- B-Reef gold (Witwatersrand, Harmony Tshepong, Welkom Goldfield): constant fineness (926-947), elevated Hg (2.1-2.3%), Fe and Cu (0.02-0.23%); Co, Ni, Pb, Ti, Pd, Ru, Se, Te, U above detection limits.
- ZK-MRC reefs in Sheba Mine of Barberton Mines, Barberton greenstone belt: high and constant fineness (939-978), average Ag 2.2-5.2%, elevated Hg (0.07-0.61%), Fe, Cu (0.026-0.1%); occasional Co, Ni, Pb, Ti, U, Th, Co.

The conclusion is that Ag, Hg and probably Cu may be used to discriminate between the 3 sites in South Africa, whereas the other trace elements may be related to minute invisible inclusions – a result that seems quite disappointing regarding the analytical efforts made in this study. The combination of composition, texture and inclusion assemblages available from EPMA is state-of-the-art. However, instruments are expensive and detection limits are not good enough for trace elements. In addition, minor element detection by EPMA is very time-consuming (e.g., 30 minutes per element for detection limits below 50 ppm in many cases; commonly, EPMA are equipped with 4 to 5 WD spectrometers, allowing for simultaneous detection of 4-5 elements in 30 minutes, or 8-10 elements per hour). Therefore, LA-ICP-MS analysis, although operating at much larger spot sizes and with less control on sample surface, morphology and inclusions, is preferred if trace elements are in the focus of the investigation. The performance of SR-XRF, both in spatial and analytical resolution, is in between EPMA and SR-XRF, but instruments are not readily available.

In a feasibility study on the provenance of gold from Guyana carried out by the French BRGM on behalf of a WWF project, the following laboratory methods have been used (Augé et al. 2015): optical and electron microscopy, EPMA, LA-ICP-MS analysis for trace elements and MC-ICP-MS analysis for Pb, Cu and Ag isotopes. These methods aimed at deciphering differences in inclusion assemblages and grain morphology, as well as chemistry between gold recovered from concentrates of various artisanal mine sites in Guyana and locally processed doré. Comparison of micro-inclusions assemblages in non-processed gold ("primary") and processed gold ("doré") from the same locality produced quite equivocal results: although the primary inclusions consisted of Bi-Te phases (exsolution droplets), the corresponding doré was rich in Pb inclusions, often combined with Te and Bi. This was explained by the presence of lead bullets during smelting; such bullets are often found in the rivers and are recovered along with the gold. Addition of Pb (as contamination during smelting) to the gold particles will then produce various Pb-metal alloys depending on gold composition, melting temperature and procedural "recipe" of the doré producer.

The authors of the study made the following observations and claims: (1) distinction of primary (vein gold and eluvial gold) from secondary (alluvial) gold[49] using morphology, inclusions and chemistry; (2) identifying the imprint of amalgamation producing a characteristic texture ("chou-fleur") accompanied by elevated concentrations of Hg, especially at grain boundaries; (3) distinction of the different producers of doré using inclusions (including anthropogenic material, e.g. lead bullets from hunting); (4) poor match between inclusions detected in primary and doré gold from the same locality; (5) doré provenance interpretation using Au, Ag and Cu concentrations; (6) in-situ trace element analysis by LA-ICP-MS did not discriminate between locations; (7) trace elements analyzed in solution prepared from gold concentrates in order to measure lead isotopic compositions enabled discrimination of several geographical gold sources (districts) using Cu, Te and Zn; (8) copper and silver isotope analysis (from gold-hosted Cu and Ag as minor elements) permits a useful provenance indicator. As a result, Augé et al. (2015) state that a "satisfactory" discrimination of the origin of gold concentrates from Guyana was possible.

Sample materials and mining/processing conditions in Guyana are similar to those expected to be found in many artisanal mining areas under tropical conditions, including central Africa. Therefore, the results are of utmost importance to judge on the type of samples and methods used in the present context. It is obvious that a direct correlation of mine gold composition and doré cannot always be made, as doré production parameters will interfere with the composition of the primary gold. However, signatures of doré producers operating in a restricted area and using different sources and types of gold (primary versus alluvial) could be established, and correlation with the untreated gold could be made based on the investigation of micro-inclusion assemblages and chemistry.

The principal feasibility of gold provenance analysis has been verified by the BRGM study in Guyana and in similar projects in South Africa. Geological and mineralogical arguments might seem in favor of successfully applying a similar approach in the DRC (see below). However, a setup of complex methods such as the one described above does not appear practical or feasible under the special circumstances encountered in the DRC and in other conflict-affected and high-risk areas. This is due to the lack of infrastructure and technical support in the region, the lack of reliable and trained personnel for sampling and analysis, and the considerable time involved in carrying out the analyses and obtaining results. A complex analytical system is useful for exploring the scientific context and might indeed be helpful in special circumstances such as forensic applications involving court cases in particular supply chain settings. However, it does not seem suitable for typical everyday application in ASM gold supply chains. The latter may require fast decision-making processes (e.g., by airport customs authorities or by gold buyers such as refiners). Therefore, analytical methods that are robust, fast and easy to use while, at the same time, providing sufficient discriminative power need to be considered. Portable devices may provide a feasible option to address these questions as explained below.

3.3 Gold Analysis through Portable Devices

Considering the logistical framework of gold supply chains, in particular artisanal gold in many conflict-affected and high-risk areas, portable devices seem attractive for application scenarios of potential Gold Provenance Analysis. They allow fast in-situ analysis of gold directly at the production or

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[49] Note on differences between eluvial and alluvial gold: Alluvial is transported gold, not just weathered. It is characterized by Ag depletion whereas eluvial gold (weathering of a primary deposit, but no transport) is most commonly not Ag depleted.

processing site. However, there are also particular caveats associated with portable devices that need to be considered when employing these methods. In addition, there is a lack of publicly available data in order to perform a comprehensive evaluation on data generated through these methods.

Five techniques capable of in situ portable analytical measurements of inorganic material are discussed by Potts & West (2008): (1) spark source optical emission spectrometry, (2) gamma spectrometry, (3) chemical test kits, (4) portable LIBS (pLIBS) and (5) portable XRF (pXRF). Restrictions on sample preparation and measurable parameters imply that, at present, only two types of portable instrumentation meet the likely requirement to employ GPA in a meaningful way: pXRF and pLIBS. Table 6 provides a summary on technical details and capabilities of portable instrumentation.

Table 6: pXRF versus pLIBS, modified from Potts & West (2008), supplemented by information from Galbács et al. (2008), and Harmon et al. (2006).

Technique	pXRF	pLIBS
Excitation source	Miniature X-ray tube or sealed radioactive source	Pulsed laser light (e.g., 1064 nm Nd:YAG laser), pulsed in the nanosecond time regime
Element range	Most of the elements in periodic table above Si, lower sensitivity for elements with Z > Mo	Almost all elements in periodic table including light elements, reduced sensitivity for high atomic numbers
Non-destructive?	Yes	Practically yes (negligible mass of material ablated)
Typical sample mass	Milligram to gram, depending on energy of characteristic X-ray	ng to µg range
Sample preparation	Powder or melt pellet for quantification of fine-grained materials; flat surface for rocks or chips	none
Penetration (information) depth	1-2 µm (light elements), 1-10 mm for K-lines of high atomic number	>10 µm (crater diameter ca. 100 µm)
Detection limits	10-100 ppm	1-100 ppm
Disadvantages	Country-specific regulatory requirements are needed for radioactive sources as well as for using X-ray sources, and production of ionizing radiation	Quantification of element concentrations is much more difficult than for pXRF

To assess the applicability of pXRF for in-situ gold analysis, preliminary tests were performed using two different instruments at the MU Leoben[50]. These tests indicate that the number of elements detected in gold grains, dust, flakes, and gold sponge (Figure 13) seems to be sufficiently high for certain forms of GPA application.

Figure 13: Photograph of samples tested with pXRF, source: B. Kain-Bückner.

Quantification is hampered by sample geometry. In order to receive quantitative data, samples must be powdered and pressed into a pellet, or homogenized by melting. Also, a minimum amount of sample material (to be specified; we were able to analyze 40 mg of fine gold dust) is required. Line overlaps may hamper data evaluation, e.g. for Hg concentrations in gold. Nevertheless, the method offers a large potential for GPA, in particular, where the features of products traded along the gold supply chain already correlate with analytical requirements. An example for the latter is doré which, due to its homogenized nature caused by smelting, allows direct, non-destructive pXRF analysis without the need for further physical sample preparation.

Our analytical tests indicate a reasonable reproducibility of the measurements; e.g., analyzing the same sample (gold flakes from an alluvial concentrate) five times under identical conditions, we obtained relative standard deviations of 0.2% for Au, 1.1% for Ag, 1.2% for Pb, 1.8% for Fe and 0.6% for Zr. If measurements are repeated after shaking the sample several times, relative standard deviations are higher (Au 3.9%, Ag 2.3%, Pb 29%, Fe 24.6%, Zr 24%); this is interpreted as a measure of within-sample chemical variability due to heterogeneity, as individual gold flakes and the associated heavy minerals all have different compositions. From these pilot tests we conclude that the concentrations of Au and associated minor elements can be determined with sufficient reproducibility using a portable instrument. However, repeated measurements must be made for mineral concentrates to ensure that the natural variability (heterogeneity) is taken into account.

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[50] Chair of General and Analytical Chemistry, analyst: Dr. A. Rachetti

Exact determination of sampling conditions is crucial in order to differentiate source effects from processing/analytical artefacts. For example, pilot tests included doré spheres (droplets of 0.1 to 1 mm diameter) lost in slag during smelting. The material had been collected from the floor of an artisanal processing plant where amalgamation with open burning was extensively used. pXRF analysis of the doré droplets showed extremely elevated Hg contents. However, these elevated Hg contents were not characteristic for the doré material itself but rather represented contamination from the floor, adhering to the surface of the droplets.

Some XRF companies provide "precious metal" analytical programs that must be purchased along with a portable instrument. Calibration is of major importance in order to obtain accurate results. It must be performed before the instrument is delivered to the customer using well-characterized reference materials. The selection of elements and absorption lines included in the program must be discussed with the customer a priori. For commercial instruments, there is no (simple) way to recalibrate or to change the analytical program retrospectively. Analyzing precious metals or other elements outside of the instrument's calibration range renders results inaccurate such that they may not be used reliably.

The use of LIBS for in-situ gold analysis has been sufficiently demonstrated (Galbács et al. 2008; Dzyubenko et al. 2010). In contrast to pXRF, however, very few pLIBS devices are available on the market and the method is therefore less used and tested. Nevertheless, the efficiency of LIBS, its speed and high analytical resolution should make it a viable alternative to pXRF. Broadband LIBS in which a wavelength spectrum from 200-980 nm is collected allows for fast single-shot analysis in order to characterize materials (Harmon et al. 2006).

3.4 Summary of Analytical Methods for Gold Analysis

As a summary of chapter 3, a matrix was compiled, comparing various analytical methods to analyze gold. This matrix (Table 7) provides an overview and an evaluation of methods that may be applied to analyze gold as gold grains, gold concentrates, gold sponge, doré, artefact and refined gold.

Table 7: Comparison of analytical methods for gold analysis.

Analysis item→ Method ↓	Solution	Solid sample	Bulk sample	In-situ	Major element	Minor element	Trace element	Isotope ratios	Destruc-tive
ICP-OES	x		x		+++	+++	+		---
ICP-MS	x		x		++	+++	+++	+	---
ICP-MC-MS	x		x					+++	---
LA-ICP-MS		x		+	++	+++	+++	+	-
LA-MC-ICP-MS		x		+				+++	-
LIBS		x		+	++	++	++		-
Spark OES		x		++	+++	+++	++		--
GD-MS		x	x		+++	+++	++		--
EPMA		x		+++	+++	+++			
SEM		x		+++	+++	++			
PIXE		x		++	+++	+++	+		

Analysis item→ Method ↓	Solution	Solid sample	Bulk sample	In-situ	Major element	Minor element	Trace element	Isotope ratios	Destruc-tive
XRF	x	x	x		+++	+++	+		-
SR-XRF		x		+	++	+++	++		
INAA		x	x		++	++	++		--
pXRF		x	x		+++	++	+		
pLIBS		x		+	++	++	+		-

Explanations:

x: – applies; empty field – does not apply; Relative strength in application: +++, very strong; ++, strong; +, fair.

Solution – sample needs to be dissolved prior to analysis

Solid sample – sample can be measured in its solid state

Bulk sample – method analyzes larger sample volumes, usually of homogenized or dissolved samples

In-situ – method analyzes small sample volumes by bombardment with electrons, ions, X-rays or laser energy

Major element – major elements (>1 wt.%)

Minor element – minor elements (0.001-1 wt.%)

Trace element – trace elements (<0.001 wt.%)

Isotope ratios – precise isotope ratios can be determined

Destructive – destruction and loss of the sample during analysis (except for sample preparation such as polishing). Relative rating: ---, highly destructive (complete sample loss); --, moderately destructive; -, little destructive (little amount of sample loss)

A number of analytical methods have been screened to comment on their usefulness for GPA. Every final conclusion and decision must take into account various parameters that will influence the selection of the most appropriate method for GPA. Such parameters include:

- Question to be addressed
- Type of sample to be analyzed
- Type of information desired (parameter selection)
- Instrument performance with respect to selected parameters
- Availability of instrumentation
- Costs
- Availability of trained personnel
- Data calculation, manipulation and statistical evaluation tools

4. Geological Gold Provinces in the DRC

Meaningful application of Gold Provenance Analysis in a context of supply chain due diligence is based on the knowledge of impact factors on gold composition, that is, gold deposit geology and processes taking place along the associated supply chains. This chapter summarizes the knowledge on the geology of gold deposits in the eastern DRC and neighboring areas, with special emphasis on compositional data and parameters that may help to distinguish these deposits in the context of gold provenance analysis. The DRC is used here as a case study in order to develop potential application scenarios for GPA. Detailed information on the geology of DRC gold provinces is attached in Annex C.

Gold production in the provinces of (former) Orientale, North Kivu, South Kivu, Maniema and (former) Katanga is significant. According to a report published by the International Peace Information Service, (IPIS 2015a) a dramatic change has taken place over the past five years, with decreasing artisanal mining of the “3T” (tin, tungsten and tantalum) and increasing artisanal gold mining; 76% of the mines visited by IPIS produced gold.

The industrial Kibali (Orientale Province), Namoya (Maniema Province) and Twangiza (South Kivu Province) mines began production between 2012/2013 and 2016 (Namoya) and produced 2 t of gold in 2012 and 5 t in 2013. As these mines reach their full capacity, industrial production is growing and, in 2015, totaled 31.8 t according to Congolese export statistics (Ministère des Mines 2016). In addition, an estimated 5-7 t of gold were produced from 15 large and 70-100 smaller artisanal and small scale mining operations in the North Kivu and South Kivu Provinces, and 6-7 t of gold from 813 sites in the Ituri region in 2012 (Yager 2013).

According to the “conflict mineral mapping” conducted by IPIS, more than 176,000 people were active in artisanal gold mining in Orientale (Ituri only), North Kivu, South Kivu, Katanga and Maniema. IPIS has mapped 860 gold sites including more than 16,000 individual pits in the area[51] (Table 8). Overall, the percentage of gold sites classified as “presence of armed groups” (including illegal actions by the Congolese army) was 62% (average calculated for all provinces except Katanga) indicating significant conflict risks. This percentage is approximately twice as high as for artisanal “3T” mines.

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[51] IPIS webmapping project, data from 2013/2014. The BGR database includes 1,515 gold mining sites for the DRC. The most recent update from IPIS (IPIS 2016, Weyns et al. 2016) was released at editorial deadline and could therefore not be incorporated in this report.

Table 8: Overview of the estimated ASM gold production in different provinces in the DRC (IPIS 2015a).

Province	Territoire	Number of sites	Number of miners	Number of pits	Percentage of "occupied" sites
Orientale	Ituri	176	>47,000[52]	>4,000	36
North Kivu	Lubero and Beni	113	>25,000[53]	>2,150	96
North Kivu	Walikale and Masisi	159	18,500	3,655	82
South Kivu	All	288	>66,000	>5,100	64
Maniema	All	72	6,900	1,171	19

A comparison of the gold production/exports in eastern-central African countries bordering the DRC illustrates a dramatic increase in production in the DRC from 2011 to 2014 (Table 9). The official gold production of the DRC (excluding the non-registered ASM production) is now third in the region, behind Sudan and Tanzania, and 7th in Africa, with South Africa in the lead (151.6 t), followed by Ghana (98.5 t), Sudan, Mali (45.8 t), Tanzania and Burkina Faso (36.5 t). The DRC's eastern neighbors –in the spotlight as potential transit states for smuggled ASM gold from the DRC – all have small but significant (in the case of Tanzania, major) ASM gold sectors of their own. For these countries (Burundi, Uganda, Tanzania as well as Kenya) the question of gold provenance becomes particularly relevant.

Table 9 : Gold production in countries bordering to the DRC (in kg, World-Mining-Data 2016).

Country	2011	2012	2013	2014
Congo, D.R. (Kinshasa)	309	2,813	6,149	23,937
Congo, Rep. (Brazzaville)	35	35	35	35
Burundi	1,052	2,046	2,823	650
Central African Republic	53	55	55	55
Gabon	300	666	1,137	1,012
Sudan	23,739	46,133	70,000	73,300
Tanzania	40,390	39,012	43,390	40,481
Uganda	1	4	5	24
Zambia	3,493	4,232	5,207	4,802

Current gold production in the eastern DRC is grouped into four major areas that are termed "gold provinces" (Figure 14):

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[52] Matthysen et al. (2011) estimated the number of artisanal gold miners in Ituri district to 123,000; in the larger Orientale province (including the Haut Uele, Bas-Uele and Tshopo districts), a total of 16.5 tons of gold per year is produced by more than 150,000 miners. No detailed data on the number of sites, miners and pits are available for the districts Haut Uele, Bas-Uele and Tshopo from the IPIS webmapping project.

[53] For one site (Mushigha), IPIS (2015a) states the presence of 16,458 "creuseurs" operating 147 "puits"; subtracting this number, less than 10,000 miners remain for 2,000 pits in the northern part of Kivu Nord.

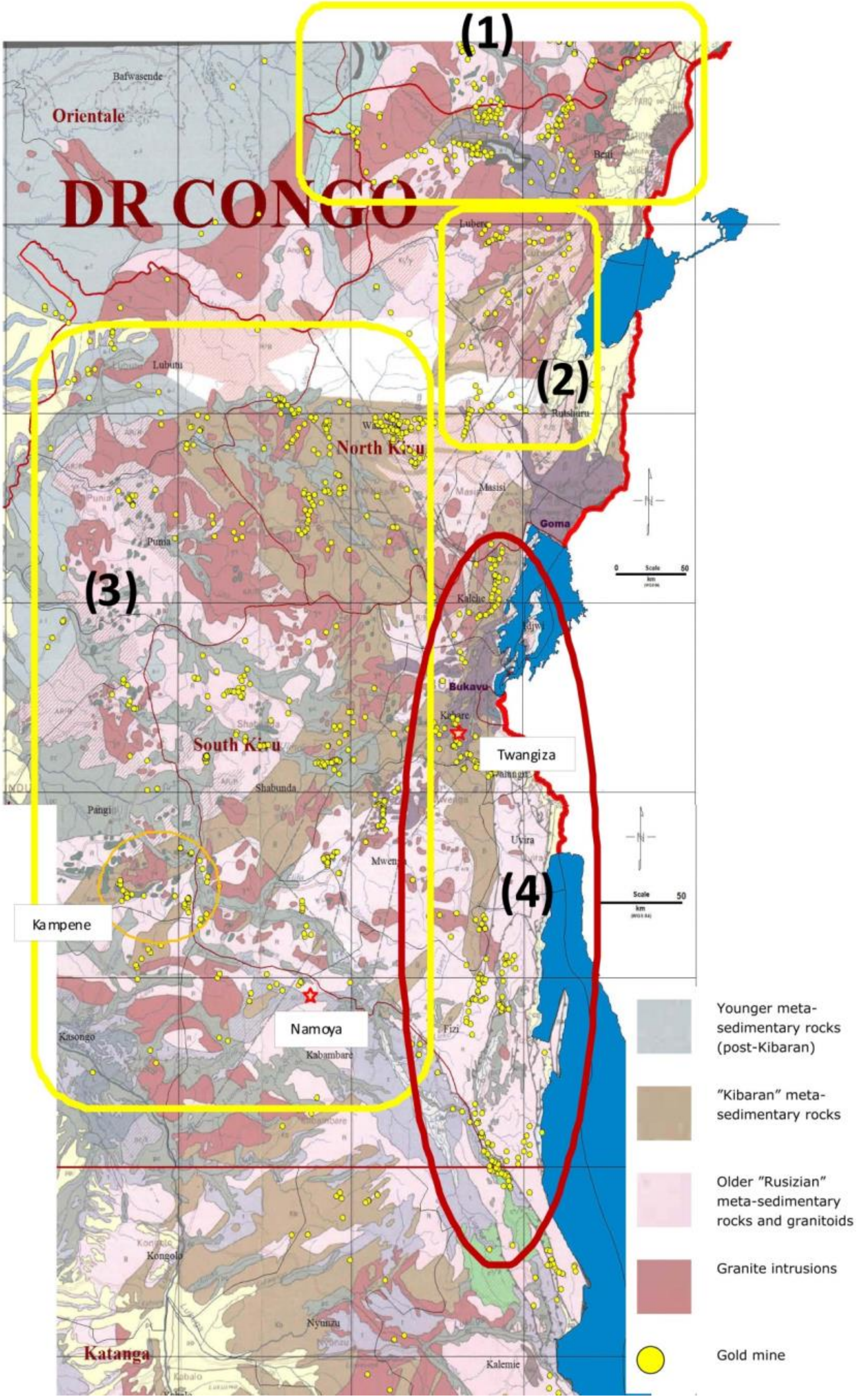

Figure 14: Geological map of the eastern DRC with location of gold deposits as yellow dots. Geological Map of the Congo with gold deposits from BGR internal database (pers. comm. U. Näher, 2016)

(1) "Northern gold province", in Province Orientale, with a focus around Kilo-Moto in Ituri (Table 10 and Table 11). It mainly comprises Archean (ca. 2.6-2.7 Ga[54]) greenstone belts embedded in a gneiss basement. This belt continues towards the east into Uganda (Busia-Kakamega greenstone belt[55]) and towards the southeast into the well-endowed Tanzanian Craton where a number of gold mines are active[56] (www.kilogoldmines.com).

(2) "Lubero gold province", in North Kivu, west of Lake Edwards: Archean and Paleoproterozoic rocks (Ubendian system, Ruwenzori fold belt, ca. 2.1-1.8 Ga), with rivers carrying gold and platinum-group minerals (Table 12). The province extends to the east into western Uganda[57].

(3) "Kibaran gold province", with gold related to late Mesoproterozoic (ca. 1 Ga) Kibaran-age granites. Centres in North Kivu are around Walikale and to the west (Lubutu), in Maniema in the area around Punia and Pangi, and in South Kivu around Shabunda (Table 13 and Table 14). The province extends east of the rift valley into Rwanda[58], Burundi and southwestern Uganda[59].

(4) "Panafrican gold province" in North and South Kivu, concentrated in areas north and south of Bukavu close to Lake Kivu and Lake Tanganyika. It comprises shear-zone hosted gold of probably Panafrican (ca. 0.5 Ga) age (Table 14); its extension east of the rift valley is documented from northwestern Burundi (Brinckmann 2001).

These "gold provinces" have different geological histories, and gold formed due to different processes at different times. Therefore, trace elements substituted in gold (e.g. Ag, Cu, Hg, Te, Bi, Pt, Pd, Ni) and associated minerals (sulfide inclusions, refractory mineral inclusions such as zircon, monazite) will differ according to deposit type, and may thus form the basis of a regional gold fingerprint as provenance indicator. Unfortunately, data on gold composition and associated minerals do not exist for most of the area with the exception of Twangiza mine (Walemba 2014), NW Burundi (Brinckmann 2001) and a few analyses from Kilo-Moto carried out almost 100 years ago.

A further subdivision of gold deposits within a defined "gold province" may be possible due to the heterogeneity commonly observed within a gold province. This, however, necessitates the evaluation of a large number of gold deposits. As these data are completely missing in the DRC, this remains speculative.

For secondary deposits (eluvial, alluvial) additional processes modifying the composition of gold and trace components come into play. Nevertheless, an "informed guess" is made in the following concerning the signature derived from the host geology of primary deposits.

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[54] Ga = billion years

[55] The currently active Tira mine (production of 3 kg gold a month) operates auriferous quartz veins in the Archean Busia gold district in SW Uganda (Nyakecho & Hagemann 2014).

[56] Some references to gold in Tanzania: van Straaten (1984); Borg (1994); Rammlmair et al. (1994); Henckel et al. (2016). At the high-tonnage Geita mine, the gold contains 10-18 wt.% Ag (Borg 1994) and is associated with pyrite, chalcopyrite, magnetite; at Nyarkagwe gold ranges from 0.2-24 at.% Ag with low Hg, Bi and Fe (Rammlmair et al. 1994). Gold production in Tanzania in 2013 was 43.39 tons (George 2015).

[57] The Mubende gold district in central Uganda west of Kampala includes the Kamalenge and Kisita gold mines hosted by metasediments of the Ruwenzori fold belt. The Buhweju-Mashonga gold district in SW Uganda includes the Kitaka mine hosted by metagranodiorite and metadolerite and the Mashonga mine hosted by metasediments and altered granite (Nyakecho & Hagemann 2014).

[58] ASM gold production in Rwanda is currently at a low level. Historically, the areas around Miyove in northern Rwanda and at Nyungwe in the southwest have been small producers (MIRENA 1982).

[59] In the Kabale-Kisoro area of southwestern Uganda, gold is associated with cassiterite, wolframite and bismuthinite (Nyakecho & Hagemann 2014).

4.1 Northern Gold Province: Greenstone-hosted Gold in Orientale

According to Lavreau (1979, 1984), about 350 t of gold have been mined in the province north of 1° northern latitude until the early 1980s. About half originated from alluvial deposits, and half was mined from primary and secondary deposits ("impregnation deposits") in Archean greenstone belts and "more recent" structures. About 90% of the production derives from the zones of Kilo and Moto. Recently, production has increased due to the opening of industrial mines. Artisanal mining is still very active, although the large-scale dredging operations active in Ituri (especially Mambasa) have been reduced in recent years (Matthysen et al. 2011). These authors estimated the current ASM gold production of Orientale Province to 16.5 tons per year.

Table 10: Summary of information on gold mining and gold deposits in Ituri district, Orientale province.

Province	Orientale				
Territoire	Ara	Djugu	Irumu	Mahagi	Mambasa
Sites[60]	5	45	34	14	66
ASM Miners	2,090	>27,000	6,282	3,230	8,057
Pits	76	>2,250	1,071	143	498
Conflict %	0	0	100	0	38
Type of gold mineralization	Mesothermal shear-zone-hosted gold associated with greenstone belts; alluvial deposits				
Host rocks	Mafic to ultramafic rocks, metapelites, banded iron formation, granite, gneiss; "albitite", mylonite				
Age of mineralization	Late Archean? (some references also indicate Paleoproterozoic ages)				
Ore assemblage	gold, pyrite, pyrrhotite, magnetite; quartz, epidote, albite, chlorite, sericite; rare arsenopyrite, chalcopyrite, sphalerite, galena				
Gold composition	Ag 7.7-24.3%; Cu 0.05-3.3%; other metals below 0.5% (Anthoine 1921-1922); (Angermeier et al. 1974) report up to 30% Ag				
Industrial mines	Kibali mine (total resource 16 Moz[61]; operated by Randgold); production in 2015 was reported to 642,720 oz[62]				
Exploration	Adumbi (1.9 Moz; Kilogold), Makapela (1 Moz), Mongbwalu (1.2 Moz; see also Fahey, 2007 on artisanal mining in this area and the takeover by AGK), Pangoy (no numbers), Zani & Kodo prospects (1.8 Moz)				
Production	Production started in 1905, delivering >300 t until the early 1970s and >350 t until the early 1980s. Alluvial production was superseded by primary deposits in the 1950s, but appears to have reached a second maximum around 2000. Average gold grade decreased from 17.8 g/t (1969) to 9.4 g/t (1974). Production reached a maximum in 1941 (8.1 t) and attained a constant level of 4-5 tons per year in the 1970s. Current estimates (Matthysen et al. 2011) for ASM production in the Ituri district are 9-10 tons per year and 16.5 t for Orientale Province.				

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[60] Numbers for sites, ASM miners, pits and conflict % (percentage of sites with conflict risks) in this and the following tables are taken from the IPIS webmapping project. http://www.ipisresearch.be/mapping/webmapping/drcongo/v3/

[61] Moz = million ounces

[62] oz = (troy) ounce = 31.1 g

Province	**Orientale**
Selected references	Anthoine (1921-1922), Cahen (1954), Service Géologique Zaïre (1974), Angermeier et al. (1974), Lavreau (1973), Milesi et al. (2006); www.kilogoldmines.com; www.randgold.com; www.loncor.com;

The few compositional data of gold published demonstrate large variations in Ag and Cu concentrations, as well as a few minor and trace elements (Table 11). However, as these data result from wet chemical analysis of gold ingots produced from mined ores, they likely include impurities not separated before smelting. Nevertheless, the presence of As, Sb and Bi might be indicative of this gold province.

Table 11: Analytical data for gold ingots from Orientale (Anthoine 1921-1922).

Element (wt.%)	F.9 (Kilo, Nizi), filon D	F.34 (Kilo, Nizi), filon D	U.433 (Uélé)	K.16 (Nouveau-Kilo)
Au	71.80	71.65	89.45	91.75
Ag	24.30	24.31	9.82	7.70
Cu	3.29	3.32	0.048	0.068
Zn	0.26	0.35	0.003	0.102
Pb	0.17	0.583	0.32	0.17
Fe	0.07	0.045	0.33	0.15
Ni	0.007	trace	trace	trace
Bi	0.001	0.002	0.012	0.009
Sb	trace	0.068	trace	trace
As	0.036	null	0.015	0.050
Se	trace	trace	null	trace
S	0.066	trace	0.002	0.001

4.2 Lubero Gold Province: Gold in Paleoproterozoic Terranes

The area between Kilo and Kivu has never been mapped in detail, and information on rocks and minerals is scarce. However, gold has been (and still is - see IPIS maps and Table 12) mined in the region. Loncor holds a large concession (the “North Kivu Project”, 17,760 km^2). Part of the area is underlain by the Ruwenzori Fold Belt of Paleoproterozoic age (2050 Ma); granitic magmatism in the area gave rise to rare-element pegmatites (Melcher et al. 2015). Scale and mineral endowment, however, are minor compared to the Kibara Belt, and artisanal mining for the “3T” is of very minor importance in this area (IPIS 2015a).

In the alluvials of the Lubero river network (29°E, 0°06´S), gold and platinum-group minerals (PGM) have been identified in the beginning of the 20th century, and were subsequently mined from 1934 until 1938. Thus, the presence of PGE and related elements (e.g. Cr, Ni) might represent provenance indicator elements for gold derived from this area.

Table 12: Summary of information on gold mining and gold deposits in Lubero and Beni/North Kivu.

Province	North Kivu	
Territoire	Beni	Lubero
Sites	12	101
Miners	1,560	13,584
Pits	259	1,902
Conflict %	100	96
Type of gold mineralization	Type of primary deposits unknown, most probably mesothermal quartz veins; association of gold and platinum-group elements probably in mafic-ultramafic intrusions (magmatic gold-PGE?); alluvial	
Host rocks	Poorly known; Ruwenzori Fold belt with metasedimentary rocks, diorite and granite intrusions, mafic-ultramafic intrusions; few rare-element pegmatites	
Age of mineralization	Paleoproterozoic (?), some areas probably Archean	
Ore assemblage	Gold associated with platinum-group minerals in alluvial placers. Doré produced from alluvial material might carry PGE and associated elements (Cr, Ni).	
Gold composition	No information available	
Industrial mines	none	
Exploration	North Kivu project (Loncor), with focus on the Manguredjipa prospect. Other gold prospects warranting follow up include Lutunguru, Lubero, Makwasu, Lutela, Bilolo, Manzia, Mohanga and Lundjulu (www.loncor.com)	
Production	In the alluvials of the Lubero river network (29°E, 0°06´S), gold and PGM have been identified in the beginning of the 20th century, and were subsequently mined from 1934 until 1938. The Belgian company "Minière des Grands Lacs" (MGL) mined alluvial gold between the 1920s and 1960s. In the Manguredipa area, over 300,000 ounces of alluvial gold and platinum were extracted. MGL's alluvial operations eventually led to the discovery of numerous primary high-grade quartz veins, stockworks and disseminated gold deposits. These deposits were tested by MGL during the 1940s and 1950s by trenching, adits and diamond drilling. However, low gold prices and civil unrest caused the cessation of activities in 1960.	
Selected references	Cahen (1954), Jedwab et al. (1992), Rumvegeri et al. (2004), Cabral et al. (2012), Melcher et al. (2015); www.loncor.com	

4.3 Kibaran Gold Province: Gold related to Late-Kibaran Granites

In the provinces of North and South Kivu, Maniema and northern Katanga, gold is mostly related to late-stage (900-1,000 Ma[63]) "G4" granites intruding pre-Kibaran and Kibaran-age rocks. G4 granites are known to host abundant mineralization of granitophile minerals and trace elements in pegmatites[64], greisen[65] and quartz vein deposits. They are associated with cassiterite, Nb-Ta oxides (in the literature

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[63] Ma = million years

[64] Pegmatites are coarse-grained rocks of granitic composition that are host to the 3T in the Kibara belt

[65] Greisen are altered granitic rocks hosting Sn mineralization

often referred to as "colombo-tantalite" or simply "coltan"), wolframite, spodumene, beryl, tourmaline, zircon, and monazite. Primary gold is mainly restricted to hydrothermal quartz veins external to the G4 granites. Gold-bearing veins likely are more closely associated with wolframite and cassiterite than with Nb-Ta oxides that are usually found in pegmatites only. Thus, it is assumed that some of the above-mentioned elements may be found in gold from this area, either substituted or as inclusions; this hold especially for placer material where Sn (from cassiterite), Nb-Ta (from columbite-tantalite) and W (from wolframite) co-occur with gold.

The NI43-101 report for Namoya (Clay et al. 2014), the only industrial gold mine in the province, summarizes that gold mineralization is associated with quartz veins and quartz stockworks striking NW-SE. Quartz veins are deformed and have abundant tourmaline. There are no granitic intrusions in the vicinity, although quartz porphyry intrusions have been intersected by drill holes. The deposit characteristics are typical of the intrusion-related, W-/Sn-associated type, often associated with Bi, W, As, Sn, Mo, Te, Sb. Information on gold composition in the report is sparse: Ag, Sb and base metal content is low in head grade assays of oxide ore running 3.49 g/t Au (p. 59); 62% of the gold is relatively large-grained and well liberated; 35% are liberated and locked grains; 87% of the gold is amenable to cyanidation.

Table 13: Summary of information on gold mining and gold deposits in Walikale and Masisi territories/North Kivu and in Maniema.

Province	North Kivu		Maniema					
Territoire	Walikale	Masisi	Kabambare	Kailo	Kasongo	Lubutu	Pangi	Punia
Sites	158	1	9	1	19	13	16	9
Miners	18,509		3,282	76	1,226	986	722	630
Pits	3,655		297	23	402	124	189	148
Conflict %	82	100	0	0	0	69	0	44
Type of gold mineralization	mesothermal granite-related quartz veins; rare-metal pegmatites; sulfide-mineralized schists; eluvial and alluvial placers							
Host rocks	Low-grade metasediments, granites, metabasic rocks							
Age of mineralization	• Mesoproterozoic (Kibaran, associated with G4 granite-pegmatite systems, ca. 950-1,000 Ma); • Paleoproterozoic (Rusizian)? • Neogene (placer)							
Ore assemblage	Gold, cassiterite, Nb-Ta oxides, wolframite, spodumene, beryl, tourmaline, zircon, monazite, garnet;							
Gold composition	No information available							
Industrial mines	Namoya (Banro): proven and probable mineral reserve of 20.94 million tons grading 2.02 g/t Au containing 1.36 million ounces of gold. Measured and indicated resources are 25.68 million tons grading 1.96 g/t Au containing 1.62 million ounces of gold plus an inferred resource of 5.03 million tons grading 1.63 g/t Au containing 260,000 oz Au. The updated resource calculation used a cut-off grade of 0.4 g/t Au (www.banro.com)							
Exploration	Twangiza-Kamituga-Namoya belt (Banro)							

Province	**North Kivu**	**Maniema**
Production	"Symétain" held large concessions (2,433 km^2) in Maniema between 1° and 3°30´S, in addition to 8,660 km^2 in Kivu; no production data of gold are published in (Angermeier et al. 1974)	
Selected references	Safiannikoff (1952), Cahen (1954), Service Géologique Zaïre (1974), Angermeier et al. (1974), Pohl et al. (2013), Milesi et al. (2006), Büttner et al. (2016); www.banro.com	

Table 14: Summary of information on gold mining and gold deposits in South Kivu

Province	**South Kivu**						
Territoire	Fizi	Kabare	Kalehe	Mwenga	Shabunda	Uvira	Walungu
Sites	74	1	40	74	96	1	16
Miners	18,887	5	1,481	20,146	14,411	10	9,189
Pits	1,695		279	1,562	248	3	318
Conflict %	99	100	40	47	60	0	50
Type of gold mineralization	(1) mesothermal granite-related quartz veins; rare-metal pegmatites; (2) mesothermal orogenic vein deposits (shear-zone) in low-grade metasediments (3) epithermal vein and ferruginous breccia-hosted deposits; (4) sulfide-mineralized schists; (5) eluvial and alluvial placers						
Host rocks	Low-grade metasediments, granites, metabasic rocks						
Age of mineralization	(1) Mesoproterozoic (Kibaran, associated with G4 granite-pegmatite systems, ca. 950-1,000 Ma); (2) Neoproterozoic (Panafrican)? ca. 677-522 Ma (3) Neoproterozoic (Panafrican)? ca. 535 Ma (4) Paleoproterozoic (Rusizian)? (5) Neogene						
Ore assemblage	(1) Gold, cassiterite, Nb-Ta oxides, wolframite, spodumene, beryl, tourmaline, zircon, monazite, garnet; (2) Gold, graphite, beryl, tourmaline, cassiterite, scheelite, native bismuth, bismuthinite, pyrite, pyrrhotine, arsenopyrite, galena, sphalerite, chalcopyrite, actinolite and calcite (3) Gold, Fe oxides/hydroxides, pyrite, arsenopyrite, chalcopyrite, native copper, covellite, rare cassiterite, tourmaline, and rutile (Brinckmann 2001)						

Province	**South Kivu**
Gold composition	(1) Type (1) gold in NW Burundi: 71-100 wt.% Au, 0-30 wt.% Ag and up to 0.5 wt.% Bi (average 12.2 wt.% Ag, median 8.9 wt.% Ag); (2) Type (3) gold in NW Burundi: 94-99 wt.% Au, 1-5 wt.% Ag, up to 2.6 wt.% Fe and up to 0.2 wt.% Hg (average 2.5 wt.% Ag, median 2.0 wt.% Ag); (3) Alluvial gold in NW Burundi: average 3.4% Ag (maximum 7.3%). Gold nuggets from Burundi by LA-ICP-MS: 2-3 wt.% Ag, detectable Fe, Cu, Pd, Sb and Hg (Table 15). • Type 1-mineralization at Namoya (Maniema) is associated with Bi, W, As, Sn, Mo, Te, Sb • Type 2-mineralization at Twangiza shows relative enrichment of Au, Ag, As, variable enrichment of Mo, Nb, W and Ta; base metals (Cu, Pb, Zn, Ni, V, Cr, Co) are not enriched (in bulk ore; Walemba 2014). The Au/Ag ratio is high (10 – 35), and the gold is associated with a metal association Ag, As, Bi, S • Ion microprobe data Twangiza (type 2 gold): high gold fineness (992-998), traces of S, Fe, Pd, Cu, Hg, As, Cd (data questionable; Table 16) • NI43-101 report on Twangiza (Clay et al. 2014) states that oxide ore is coarse (mostly >75 µm) liberated gold (>99%), whereas the main oxide ore is finer-grained (<75 µm) with ca. 20% locked in gangue minerals. A table providing "full elemental analysis" of the ore indicates low Ag, Hg, Cd, Cu, Pb, Zn, Sn, some Co, Ni, and considerable As (see Table 17 in NI43-101).
Industrial mines	Twangiza (5.6 Moz; Banro); oxide ore resource of 17.9 Mt @ 2.3 g/t Au, and sulfide ore of 89.6 Mt @ 1.5 g/t Au
Exploration	Twangiza-Kamituga-Namoya belt (Banro)
Production	• In the Kamituga area around Banro´s producing Twangiza mine, 2.5 Moz alluvial gold have been produced since 1924, with gold nuggets weighing up to 65 kg. • CNKI – "Kivumines" worked concessions between Kasese and Lake Kivu: mainly alluvial production, 0.3 t gold in 1965. • Gold production of MGL – "Compagnie Minière Zairoise des Grands Lacs" ranged from 936 kg to 1798 kg between 1965 and 1972.
Selected references	Safiannikoff (1952), Cahen (1954), Service Géologique Zaïre (1974), Angermeier et al. (1974), Villeneuve (1983); Villeneuve (1987), Pohl (1994), Brinckmann (2001), Milesi et al. (2006), Pohl et al. (2013), Walemba (2014), Büttner et al. (2016); www.banro.com

4.4 Gold Related to Shear Zones of Panafrican Age

In a narrow corridor on both sides of the East African rift system (western branch, Lake Kivu and Lake Tanganyika) gold is mined from hydrothermal veins as well as from mainly north-south trending shear zones dissecting rocks of pre-Kibaran (Rusizian) and Kibaran age.

Brinckmann (2001) differentiates the Kibaran and Panafrican gold parageneses in northern Burundi based on differing mineralogy and structural setting; this information may help to fingerprint them in neighboring areas such as the eastern DRC. In the first (Kibaran) phase, gold is associated with the pegmatitic minerals columbite-tantalite, cassiterite, rutile, tourmaline, as well as with a late sulfide stage carrying pyrite, arsenopyrite, chalcopyrite, and bismuthinite. Concentrates or doré produced from this type of gold will be characterized by elevated Sn, Nb, Ta, Ti, Bi, and As. Coarse gold forms during late-stage limonitic alteration and is associated with bismuthite, scorodite, and covelline.

According to microprobe analysis (n = 23[66]), gold compositions range from 71-100 wt.% Au, 0-30 wt.% Ag and up to 0.5 wt.% Bi (average 12.2 wt.% Ag, median 8.9 wt.% Ag). Bulk analysis of mineralized quartz-vein samples associated with G4 pegmatites indicates variable concentrations of As, Bi, Cu, Sn, and low Pb, Ni and Ba; gold concentrations range from a few ppb to 16 ppm[67].

Breccia-hosted type 2 (Panafrican) gold mineralization is associated with pyrite, arsenopyrite, chalcopyrite, native copper, covellite, rare cassiterite, tourmaline, and rutile. Microprobe data of gold (n = 13[68]) indicate a narrow compositional range with 94-99 wt.% Au, 1-5 wt.% Ag, up to 2.6 wt.% Fe and up to 0.2 wt.% Hg (average 2.5 wt.% Ag, median 2.0 wt.% Ag). The ferruginous breccia is geochemically characterized by anomalous concentrations of Ba (up to 1.1 wt.%), As, Bi, moderate Cu, Pb, Zn and Ni, and low Sn. Gold concentrations exceeding 125 ppm have been determined in breccia samples, and 136 ppm in separated pyrite[69].

Gold recovered from alluvial deposits in NW Burundi (8 locations) reaches a maximum of 7.3 wt.% Ag; the average and median of 32 analyses is 3.4 wt.%, and 1.9 wt.% respectively (see Brinckmann 2001). The composition of gold analyzed by LA-ICP-MS from two placer deposits in NW Burundi (sample 3910, Rugogo source; sample 3918b, Cendaraju) is given in Table 15 below, and compared to (two) gold nuggets from Kamiranzowu, Rwanda (sample 0001)[70].

Table 15: Composition of placer gold from Burundi and Rwanda (LA-ICP-MS analyses).

Sample		Au %	Ag %	Fe ppm	Cu ppm	Pd ppm	Sb ppm	Hg ppm
3901	*median*	97.38	2.58		406			236
	range	86.2-99.6	0.30-13.83	<5 – 155	151-1,274	<1 – 4,135	<0.4 – 9.2	10 - 2,733
3918b	*median*	97.20	2.74		817			18
	range	92.5-99.0	0.94-7.50	<5 – 256	182-1,360	<1- 9.2	<0.4 – 5.4	3-151
0001	*median*	98.0	1.83		1,246			0.8
	range	96.8-99.9	0.12-2.99	<5	95-2,157	<1-1.5	<0.4	0.5-3.5

Below detection limits: Ti, Cr, Mn, Co, Ni, Zn, As, Se, Ru, Rh, Cd, Sn, Te, Ir, Pt, Pb, Bi
Samples: BGR collection; analysis: Dr. M. Brauns (CEZ Mannheim)

Walemba (2014) distinguished two mineralization phases in the Twangiza deposit, South Kivu. The earlier phase comprises sulfide mineralization within saddle reef structures, whereas the second fault-controlled phase is synchronous with dextral strike-slip faulting. A radiometric age from hydrothermal muscovite of 522 ± 15 Ma probably dates the saddle reef gold mineralization. The chemical composition of bulk ore samples indicates relative enrichment of Au, Ag, As, variable enrichment of Mo, Nb, W and Ta; base metals (Cu, Pb, Zn, Ni, V, Cr, Co) are not enriched. The Au/Ag ratio is high (10 –

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[66] Brinckmann (2001), Table 4

[67] Brinckmann (2001), Table 3

[68] Brinckmann (2001), Table 7

[69] Brinckmann (2001), Table 5 and 6

[70] Sample numbers: BGR polished section database. Analysis Dr. M. Brauns, CEZ Mannheim; contract with the BGR 212-4500072679

35), and the gold is associated with a metal association Ag, As, Bi, Se. Free gold is rare in the sulfide zone (grain size a few µm up to 200 µm), and most probably Au is present submicroscopic or in solid solution in pyrite (up to 0.5 mm in size) and arsenopyrite (up to 3 mm in size). Ion microprobe analyses of pyrite indicate Au concentrations up to 0.4 wt.%, As up to 2.3 wt.%, Ag up to 0.06 wt.% and Pd up to 1.2 wt.% (!!). Arsenopyrite only occasionally carries up to 0.54 wt.% Au, up to 0.16 wt.% Pd and up to 0.12 wt.% Ag. Gold composition as determined by ion microprobe at Rand Afrikaners University, South Africa, is as follows (Table 16).

Table 16: Composition of gold from Twangiza (ion microprobe data, Walemba, 2014).

	Au	Ag	S	Fe	Pd	Cu	As	Hg	Cd
Unit	*wt.%*	*wt.%*	*ppm*	*ppm*	*ppm*	*ppm*	*ppm*	*ppm*	*ppm*
Average	83.1	0.39	766	273	866	360	363	0	535
Median	84.7	0.41	655	105	0	400	385	0	60
Min	60.4	0.1	150	0	0	50	50	0	0
Max	100.8	0.56	1,470	380	1,546	690	750	0	1,730

The low Au and Ag concentrations and low totals in this dataset are intriguing – the analyses should therefore be treated with caution. According to the data presented by Walemba (2014), gold fineness ranges from 992 to 998.

Mineralogical test work conducted on the main and north oxide composite samples proved that oxide ore is coarse (mostly >75 µm) liberated gold (>99%), whereas the main oxide ore is finer-grained (<75 µm) with ca. 20% locked in gangue minerals. There are no data on gold composition in the report. A table providing “full elemental analysis” indicates low Ag, Hg, Cd, Cu, Pb, Zn, Sn, some Co, Ni, and considerable As. (Table 17)

Table 17: Full elemental data on different carbonaceous mudstone (CMS) ore types from Twangiza (Pittuck et al. 2011).

Element	*Unit*	Fresh CMS	Transition CMS	Element	*Unit*	Fresh CMS	Transition CMS
Au	*g/t*	2.65	2.23	**Li**	*ppm*	<10	<10
Ag	*g/t*	<1	<1	**Mg**	*%*	0.42	0.14
Hg	*ppm*	<3	<3	**Ni**	*ppm*	52	54
As	*%*	0.93	0.46	**P**	*ppm*	310	330
Al	*%*	6.20	5.80	**Pb**	*ppm*	33	<30
Ba	*ppm*	140	210	**Sn**	*ppm*	<20	<20
Ca	*%*	0.76	0.16	**Sr**	*ppm*	15	13
Co	*ppm*	32	32	**V**	*ppm*	51	60
Cu	*ppm*	<10	<10	**Zn**	*ppm*	16	41
Fe	*%*	10.9	7.9	**Zr**	*ppm*	100	150
K	*%*	0.24	0.32	**S**	*%*	10.2	5.61

4.5 Summary of Gold Composition in the Four Geological "Gold Provinces"

The combination of geological arguments and the sparsely available chemical data on gold composition in the eastern DRC indicates that significant differences in mineral inclusions and gold composition are to be expected among the four geological gold provinces. Depending on the point of sampling and the processing methods used, trace minerals associated with gold and trace elements within gold might vary and eventually disappear – first the inclusions (during amalgamation), then some trace elements (during smelting). Table 18 provides a summary of the data available for the four "gold provinces" addressed in this chapter. It is clear, however, that there will be local variations and overlapping compositions that could make distinction of gold derived from deposits of similar geological history difficult or impossible.

Table 18: Summary of information on gold composition in the four "gold provinces" defined within the eastern DRC.

Gold Province	Northern	Lubero	Kibaran	Panafrican
Administrative province	Orientale/Ituri	North Kivu	North and South Kivu, Maniema, Katanga	South Kivu
Geological extension to neighboring countries	Uganda, Tanzania	Uganda	Burundi, Rwanda, SW Uganda	NW Burundi, SW Rwanda(?)
Age of mineralization	2.5-2.7 Ga	1.8-2.1 Ga	0.9-1.0 Ga	0.5-0.6 Ga
Types of gold mineralization	Mesothermal shear-zone-hosted gold associated with greenstone belts; alluvial deposits	Mesothermal quartz veins; association of gold and platinum-group elements in mafic-ultramafic intrusions; alluvial deposits	Mesothermal granite-related quartz veins; rare-metal pegmatites; eluvial and alluvial placers	Epithermal vein and ferruginous breccia-hosted deposits; eluvial and alluvial placers
Relative Silver concentration	7-30%	No data	0-30%	<1-5%
Associated inclusions in gold	Pyrite, pyrrhotite, rare arsenopyrite, chalcopyrite, sphalerite, galena	PGM	Cassiterite, bismuthinite, arsenopyrite	Pyrite, arsenopyrite, native bismuth, bismuthinite, pyrrhotite, galena, sphalerite, chalcopyrite, covellite, native copper
Common detrital minerals in placer	magnetite; epidote	PGM, chromite	cassiterite, Nb-Ta oxides, wolframite, spodumene, beryl, tourmaline, zircon, monazite, garnet	graphite, beryl, tourmaline, cassiterite, scheelite, actinolite, calcite, Fe hydroxide/oxide
Typical trace elements to be expected	Cu, Zn, Pb, Bi, As	PGE, Ni	Bi, W, As, Sn, Mo, Te, Sb	Fe, Hg, Pd, Cu, As, Cd, Se

5. The DRC Gold Supply Chain

This chapter describes the structure and procedures along gold supply chain of LSM and ASM gold originating from the DRC. In combination with the previous chapter on gold deposit geology, this provides an overview on all impact factors on gold composition as relevant for GPA purposes. While the LSM supply chain is quite straightforward, the ASM supply chain is characterized by a high degree of complexity. Along the upstream supply chain associated with the DRC gold deposits (described in the previous chapter 4), the product is transformed as part of gold mining, processing and trading activities, until it reaches its final upstream destination (usually Dubai for ASM gold; South Africa for LSM gold). This chapter describes these transformations, to determine typical product compositions at each stage.

Depending on different possible purposes of Gold Provenance Analysis, these product characteristics determine at what stage of the supply chain potential gold provenance analysis could be optimally performed. Gold Provenance Analysis may be performed at different segments of the gold supply chain. It may be applied selectively in a closed pipe setting, or it may aspire to be applied in a broader context, subject to a number of feasibility restrictions. It may attempt to use and interpret compositional analysis of a given gold sample to identify a certain mining or processing step, or to compare gold composition against a reference database.

5.1 LSM Gold Supply Chain from DRC to South Africa

Industrially mined gold has seen an impressive increase in production over recent years, with promising projects such as Banro's Twangiza and Namoya sites, as well as Randgold's Kibali project.

The **Kibali Gold mine** owned by Randgold, AngloGold Ashanti and the DRC entered in production in 2013. It initially mines oxide ores (oxide circuit commissioned 09/2013) and, as the pit deepens and the underground mine is developed, will mine sulfide ore. Both types of ore are pre-concentrated by flotation and gold is extracted from concentrates by cyanide leaching (CIL) (Wark 2014). The doré is exported to Johannesburg via Nairobi (Mthembu-Salter 2015b).

The **Twangiza mine of Banro Corporation** (Banro) is located in the South Kivu Province, 45 kilometers to the south-southwest of Bukavu, the provincial capital. Banro reports measured and indicated resources of 17.9 Mt oxide ore at an average grade of 2.3 g/t and 89.6 Mt non-oxide ore at an average grade of 1.5 g/t. Capacity for oxide ore was recently increased from 1.3 to 1.7 Mtpa at a cut-off grade of 0.5 g/t gold. The processing circuit consists of centrifugal concentrators to recover the free gold ahead of CIL (Pittuck et al. 2011).

Banro's Namoya mine lies at the southern end of the Twangiza-Namoya gold belt in Maniema province, approximately 210 kilometers southwest of Twangiza, and entered commercial production in January 2016. The mining operation will consist of four opencast pits that will mine oxide, transitional and sulfide/fresh materials, which will be processed using a heap leach pad and CIL. At full capacity of the Namoya mine, the hybrid heap leach – CIL plant is expected to produce 9,000 to 10,000 ounces of gold per month (Clay et al. 2014).

Mthembu-Salter (2014b) describes **Banro's gold supply chain** as follows: "*Banro's gold output from Twangiza is not traded in South Kivu. Banro refines its Twangiza gold onsite to 92% purity, and the* *resulting bullion is flown out to Rand Refinery in Johannesburg (South Africa). According to Banro, the gold export process is triggered by a provincial mines ministry representative at Twangiza, who signs a document making up part of the pack of export documents. After this, officials from the Office Congolais de Controle (OCC) and from the Centre d'Expertise d'Evaluation et de Certification des substances minérals précieuses et semi-précieuses (CEEC) participate in an assay procedure at the Twangiza mine, in which each bullion bar is drilled three times, and then one sample analyzed by the company and the other two by the OCC and CEEC. Once these agencies' assay reports are completed, the Direction Générale des Douanes et Accises (DGDA) signs an export clearance, which is also signed by the mine's clearing agent. After this, each individual gold bullion bar is jointly sealed by DGDA and Banro representatives. At this point, a private security company retained by Rand Refinery takes physical custody of the bullion, and issues a receipt for this to Banro. The gold is then flown to Kinshasa, and custody is transferred to the CEEC. Once Banro has paid its export taxes, and provided proof of payment to the CEEC, the CEEC advises the national minister of mines to sign an export certificate of origin [now: ICGLR certificate]. Once the CEEC receives the signed certificate from the minister, it transfers custody of the gold back to the security company, which accompanies the gold to Johannesburg. After this, the gold is cleared by the South African Revenue Services (SARS), and then transferred to the Rand Refinery."*

Common Characteristics

Common characteristics of the main hard-rock large-scale mines are that, initially, near-surface oxide ores are mined. Eventually, all mines progress through a transition zone towards extracting sulfide ores in the deeper opencast levels and in particular when continuing underground. State of the art cyanide leaching, i.e. CIL or heap leaching, is the main processing technology, with either pre-concentration and/or early recovery of coarse gold through gravimetric methods and flotation[71].

Gold from the mines owned by Banro, AngloGold Ashanti and Randgold is exported to Rand Refinery in South Africa (Bafilemba & Lezhnev 2015). Rand Refinery (53% owned by AngloGold Ashanti) refines 100% of the LSM gold mined in South Africa, and 80% of all LSM gold mined throughout the rest of the African continent. Rand Refinery only buys product from registered companies. Due to regulatory changes in South Africa reflecting increased risks of purchasing illicitly mined gold, Rand Refinery no longer buys gold from uncertain sources, including South African ASM (whom often operate illegally)[72].

LSM gold supply chains in the DRC are characterized by a functioning and widely applied traceability and certification system. Potential insecurity along transportation routes is bypassed with helicopters and fixed wing aircrafts (Levin et al. 2014). However, artisanal miners may operate (with or without consent) in high-grade zones on large LSM mining permits and extract gold that is subsequently being processed through ASM supply chains as described below.

The process characteristics of LSM gold are:

- it originates **partly or entirely from sulfidic ores** ,
- it has been processed by **cyanide leaching** and/or **gravimetric concentration and flotation**
- it has (as in case on Banro) undergone a step of **pre-refining**

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[71] in case of Kibali

[72] Pers. comm., P. Schütte, BGR 2016.

Consequently, doré bars of high fineness can be expected from cyanide leaching, which contain the components of the native gold together with leachable elements originating from the host rock and gangue minerals[73].

Potentially, part of the gold may also be exported as concentrates. Such concentrates recovered by gravimetry or flotation maintain the chemical and mineralogical properties of native gold.

A **closed pipe supply chain** assures physical traceability from mine to refiner. The composition of doré bars leaving the mines and exported from DRC should be identical to the doré bars imported to South Africa and arriving at the refiner.

All doré is assayed prior to export. If not already in place for internal traceability[74] and quality control, analysis of minor and trace elements for GPA could be easily added as part of standard procedures.

5.2 ASM Mineral Extraction and Processing in the DRC

ASM gold mining is widespread in the eastern DRC. The IPIS database[75] currently registers 1,266 ASM mine sites of which 896 extract exclusively gold. Although the mine inventory is – according to IPIS – by far not yet complete (see inaccessible areas in Figure 15), 176,000 miners working in more than 16,000 individual pits have been recorded to date (see chapter 4).

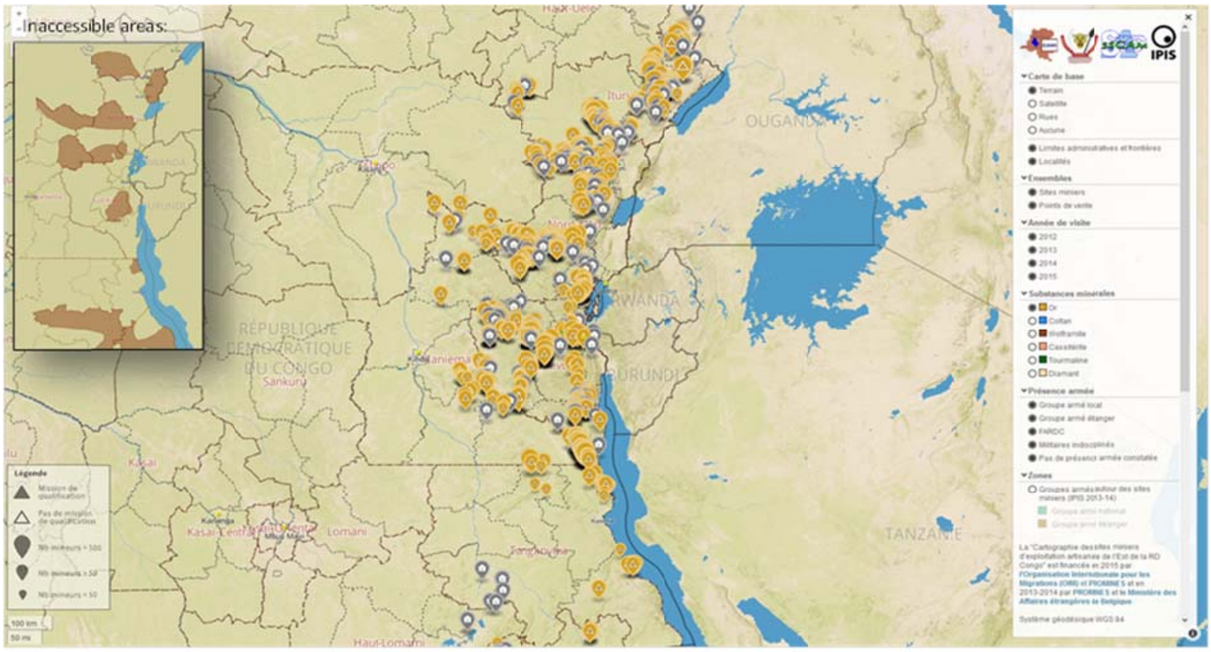

Figure 15: Interactive IPIS map with ASM gold mines (http://www.ipisresearch.be/mapping/webmapping/drcongo/v3).

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[73] See chapter 1.2, notes on gravimetric concentration and cyanide leaching

[74] And eventually as part of legal anti-fraud requirements implemented at Rand Refineries in South Africa.

[75] Interactive IPIS Map: http://www.ipisresearch.be/mapping/webmapping/drcongo/v3/; Database: www.ipisresearch.be/mapping/webmapping/drcongo/v3/script/mines_2015b.js The most recent update (IPIS 2016, Weyns et al. 2016) was released at editorial deadline and could therefore not be incorporated in this report.

BGR maintains a more extensive (but still not complete) mine site database on the eastern DRC. As of July 2016, it lists a total of 1515 gold mines.[76] Gold production from ASM is estimated in the range of 8-10 t/a (IPIS 2014, 2015a). Other estimates indicate a production of at least 12 t/a ASM gold (Martin & Taylor 2014). According to the IPIS database, only 17 ASM sites extract gold accompanied by other minerals (cassiterite, wolframite, tourmaline, etc.) and 5 sites gold as by-product of coltan or wolframite. ASM gold production originates from primary (hard rock) and secondary (dry and wet placer[77]) deposits.

i) Hard Rock and Dry Placer ASM

ASM gold production in the DRC is a predominantly manual activity (see Figure 16). Hard rock-hosted ore or gold placers concentrated in less consolidated gravel are dug from the earth with shovels, picks, hammers, and iron bars. Hard-rock ore is then manually ground to a powder with a mortar and pestle, often made up of a pair of rocks, or an old iron tire-rim on a concrete floor. Placer mining does not require grinding and milling; gold is directly concentrated in sluices and pans.

Figure 16: Crushing, grinding and washing at different ASM sites, source: ARM (2014b).

Hayes et al. (2010) describes mercury as "*handled widely in gold mining areas …*" in the context of hard-rock mining where *"… explosives are used in some mines*". In a general appreciation, mercury use does not appear to be widespread in the DRC. UNEP (2012, p. 30) estimates annual anthropogenic mercury emissions from ASM in the range of 10-50 t. Considering an estimated total ASM gold production of 8-12 t/a this value is much lower than for countries with a comparable ASM population where Hg-use is common. Two out of three sites described by ARM (2014b) use no mercury (in North and South Kivu), while mercury usage in Maniema is described in the same report as widespread.

With the relative stability of the DRC over the past five years, new players have begun arriving on the scene, artisanal miners evolve, and semi-mechanized to mechanized small-scale mining techniques are introduced. An increasing number of ASM hard rock sites now count on mechanical crushers, though the overall number of thus equipped sites still appears to be marginal (<5%). Tanzanian-style ball mills are crossing the border - these are now particularly common in Orientale, and even small excavators and gold detectors are reported from some sites in Haut Katanga and other provinces.

Small-scale cyanide leaching plants, operated with Tanzanian ASM know-how and applying vat leaching with gold recovery by active carbon (CIL) have recently been established in South Kivu.[78]

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[76] Pers. comm., U. Näher, BGR, 2016.

[77] Dry placer: on land; Wet placer: in water bodies such as rivers (i.e. dredging).

[78] Leaching of amalgamated tailings in Misisi, Fizi / South Kivu. Pers. comm., D. Ruppen, BGR, 2016

Figure 17: Small-scale cyanide leaching plant in Misisi / South Kivu, source: D. Ruppen.

Examples of ASM operational setups are documented in detail by D'Souza (2007), ARM (2014b)[79], in the OECD baseline studies by Mthembu-Salter (2014a, 2014b, 2015b)[80] and by Blore (2015a).

The main characteristics of gold from hard rock and dry placer ASM are:

- it originates mainly from **oxidized zones of hard-rock deposits** or from **placer deposits**
- it might be processed purely **gravimetrical** in some placer and hard-rock deposits if grain sizes are coarse enough
- or it might be processed by **amalgamation,** e.g., in case of gold from hard-rock deposits that was milled with the gangue .

Consequently, gold flakes or nuggets (in case of coarse gold) or gold sponges from amalgamation can be expected as products, which contain (i) in case of pure gravimetric concentration the gold in its native form, or (ii) in case of amalgamation, the non-volatile components of native gold, accompanied by an elevated mercury content.[81]

Still less frequent products to expect (in case of incipient empiric cyanide leaching) are small doré bars (probably similar to those in Figure 9) containing gold, silver and an elevated content of leachable elements from gangue minerals. As CIL is used, no elevated Zn levels from a Merril-Crowe process are expected.

ii) Wet Placer ASM (River dredging)

River dredging has become widespread and is increasing in relevance (Matthysen et al. 2011). Blore (2015a) reports Chinese river dredges on the rivers of Ituri, South and North Kivu, and a Brazilian-style hydraulic land dredge near Nia Nia in Orientale. According to IPIS (2015a), increased gold dredging since January 2014 has been observed on the Ulindi river. Similar trends are reported by the UN Group of Experts: until June or July 2013, more than 60 gold dredges operated on the Osso River (GoE 2014). In October 2014, the Group visited the Shabunda territory, where gold dredging had increased on the Ulindi River; 40 dredges were reported, many of which worked previously in the Osso River (GoE 2015a). In April 2015, the General Directorate for Administrative, Judicial, Property and Share Revenues in Shabunda counted at least 150 dredges along the length of the Ulindi River (GoE 2015b).

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[79] Luizi (North Kivu), Nyamurhale (South Kivu), Matete (Maniema).

[80] Musebe (Katanga), Mukungwe (South Kivu), Concession 40 (Orientale)

[81] See chapter1.2, notes on gravimetric concentration and amalgamation

For the same period COSOC reported 175 suction dredges (COSOC 2015) for the territory of Shabunda (171 operating on Ulindi river, 4 on Elila), and an additional four bucket line dredges.

Figure 18:Gold dredges in the DRC, suction dredges *[Top left - Gangu River (IPIS 2012), Top right - Osso River (GoE 2014), Bottom left – Ulindi river (COSOC 2015)]* **and bucket line dredge** *[bottom right – Ulindi river (COSOC 2015)].*

Figure 18 shows some typical dredge designs. Artisanal suction dredges consist of improvised floating platforms, equipped with a generator and an 8-inch gravel pump. Gold concentration is done gravimetrically in a sluice on board of the dredge. Such dredges can be dismantled and re-installed at a new site within a few days and are consequently highly mobile. The UN GoE (2015a) reports that, on a good day, a dredge can produce about 60 g of gold, COSOC (2015) estimates an average of 150 g of gold per day. The mechanical bucket dredge (bottom right) employs similar gravimetric concentration.

Sluice concentrates are amalgamated. COSOC (2015) estimates a weekly mercury consumption of artisanal dredges in the range of 1 - 2 kg.[82, 83]

The main characteristics of gold from dredging operations are:

- it originates from **alluvial placer deposits**, where gold particles are entirely liberated
- it is processed **gravimetrically** and in most cases subsequently **amalgamated** with mercury.

Gold sponges from amalgamation can be expected as main products that contain the non-volatile components of native gold, accompanied by elevated mercury content.

Additionally, unaltered nuggets of native gold can be expected.

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[82] At a dredge capacity of 150 g/d Au this corresponds to approx. 2 g Hg / g Au. Other estimations are in the range of 6 g Hg / g Au. Source: comment from BGR project staff.

[83] Mercury use on dredges needs to be further investigated. The turbulent flow visible in the bottom left image (marked with [A]) suggests that only coarse gold is trapped on the sluice, which could be easily recovered without mercury.

Implications for Gold Provenance Analysis (GPA)

The large number of ASM gold mine sites (with an even larger number of small workgroups of individual miners sharing a pit, shaft or tunnel), their remote location in partly inaccessible areas, and the high mobility of placer mining, particularly dredges, would pose formidable challenges for a mine-site scope of a potential GPA reference database.

- IPIS (2014, 2015a) identified approx. 1,300 ASM sites, out of which 860 are gold sites, employing 80% of the total ASM workforce. The BGR database (2016) indicates approx. 1500 gold sites in the eastern DRC. This is a minimum estimate for the unknown total number of ASM gold sites. The authors estimate that the total number of ASM gold sites may well be in the range of 2,000-3,000.
- Many of these sites are operated by various ASM workgroups, dwelling in individual pits, shafts or tunnels (possibly located in different parts of the same deposit), with a spatial variation of ore characteristics (e.g. shallow or deeper gossan). Some sites, as documented by IPIS, refer to different sections of the same deposit and may share characteristics. Consequently, in a first, rough approximation, the number of sampling sites to construct a reference gold database covering the whole eastern DRC could easily exceed 5,000.
- Given the high mobility of dredges as well as the temporary nature of some smaller sites, where mines are abandoned and new mines are (re-)opened, combined with the likelihood that some mines are operated seasonally (during either dry or rainy season), a frequent update of the mine site inventory – and corresponding re-sampling – would need to be considered for meaningful results of a mine site reference database.
- The practical feasibility of sampling is intimately related with accessibility of mine sites which, in turn, is an issue of security concerns in conflict affected areas and, hence, difficult to predict.

5.3 Local and National Supply Chain for ASM Gold

Miners are usually organized by financers (*"Président Directeur Général"* - PDG), but in some cases also as cooperatives. In a typical gold supply chain sourcing from ASM, the PDG or the miners sell their gold to small traders (Category B négociant; "petit négociant") at the mine site or in the nearby village. Typical transactions between miners and B-traders are in the range of 0.1 to 5 grams. The *petits négociants* aggregate their purchases and sell them on to mid-level traders (Category A négociant; "grand négociant"). In some cases, PDG's or cooperative members are B-traders themselves and sell directly to A-Traders[84] (Blore 2015a, 2015b; ARM 2014b). In some cases miners even sell directly to *comptoirs*, i.e. the highest level in the supply chain.[85]

i) Petits Négociants (Category B Trader)

A case study of trade relations between miners and local traders in an ASM community (Kamituga, near Bukavu, South Kivu) is analyzed in depth by Geenen (2011). For the 150 to 200 mining shafts in Kamituga, each employing some 5-10 miners, at least 17 larger and 60 smaller *petits négociants* buying

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[84] Described from Matete by ARM (2014b).

[85] Pers. comm., D. Ruppen, BGR, 2016.

offices operated in 2009. Geenen's findings demonstrate that interactions between miners and traders are based on personal relations, rather than on pure market exchange. The analysis of these relationships results in the finding that economic exchange between miners and traders is highly "regulated" and follows clearly defined patterns of customary rules and norms. Relations between miners and traders can consequently be seen as "stable".

As *petits négociants* operate locally on one single mine site, they know the site-specific fineness of the gold they buy from each miner by experience, similarly as the Category A traders, who buy from them, know the fineness of their B trader's mine sites. Small quality fluctuations are mostly irrelevant and on average absorbed by trading margins at that stage. Transactions between B- and A-Traders therefore do usually not require any homogenization and gold is sold forward "as is" (as dust, flakes, nuggets or gold sponges).

The main characteristics of gold accumulated at the level of Category B traders are:

- The gold, which the *petits négociants* trade, consists of dust, flakes or nuggets from gravimetrical concentration or gold sponge from amalgamation.
- The gold originates exclusively from the ASM mine site where the *petit négociant* operates, and even the groups of miners (and therefore the individual pits, shafts of tunnels) from whom the *petit négociant* buys may be relatively constant over time. The gold is therefore representative for the mine site and can be expected to reflect characteristics of the deposit.
- Typical volumes accumulated by B-traders before being sold on to A-Traders are in the range of 50 g.[86]

As several *petits négociants* may be buying from different groups of one mine site, the total number of B-traders is higher than the total number of mine sites.

ii) Grands négociants (Category A Trader)

Grands négociants (Category A traders) either have permanent offices in larger villages or towns (e.g. in Bukavu) where they buy from B-traders delivering their gold, or travel to mine sites on a regular basis to buy locally from B-traders or directly from miners[87]. It is not uncommon that A-Traders act as financers and provide B-traders or even miners (i.e. PDGs) with the required operating capital. This ensures them a constant supply. Travelling A-Trader needs to aggregate enough gold to finance the journey to mine sites or to local markets where they establish regional mineral trading centers or *"centres de négoce"*. (Blore 2015a, 2015b; ARM 2014b)

Unsurprisingly, all *centres de négoce* recorded by IPIS (2014) are not only located along main transport routes (roads or rivers) but appear to form clusters with adjacent mine sites. Interestingly, gold mined

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[86] This number is subject to significant variations. It depends on the individual financial capacity of the B-trader, but seems to be also location-specific. Contradicting data are therefore found in different reports.

[87] ARM (2014b) points out that *"because of poor means of transportation in rural areas, miners prefer to sell their gold right at the production sites to petits négociants than to wait and travel between 10 and 20 km to the nearest local gold market and sell their production at a higher price. The reason is that the time consumed in travel and trade represents a greater loss in production than the discounted mine gate price and it is also less risky to sell it immediately instead of travelling with the gold."*

in the vicinity of a major town like Bukavu seems to be absorbed directly by traders located in that town[88], despite comparatively greater distances. (Figure 19)

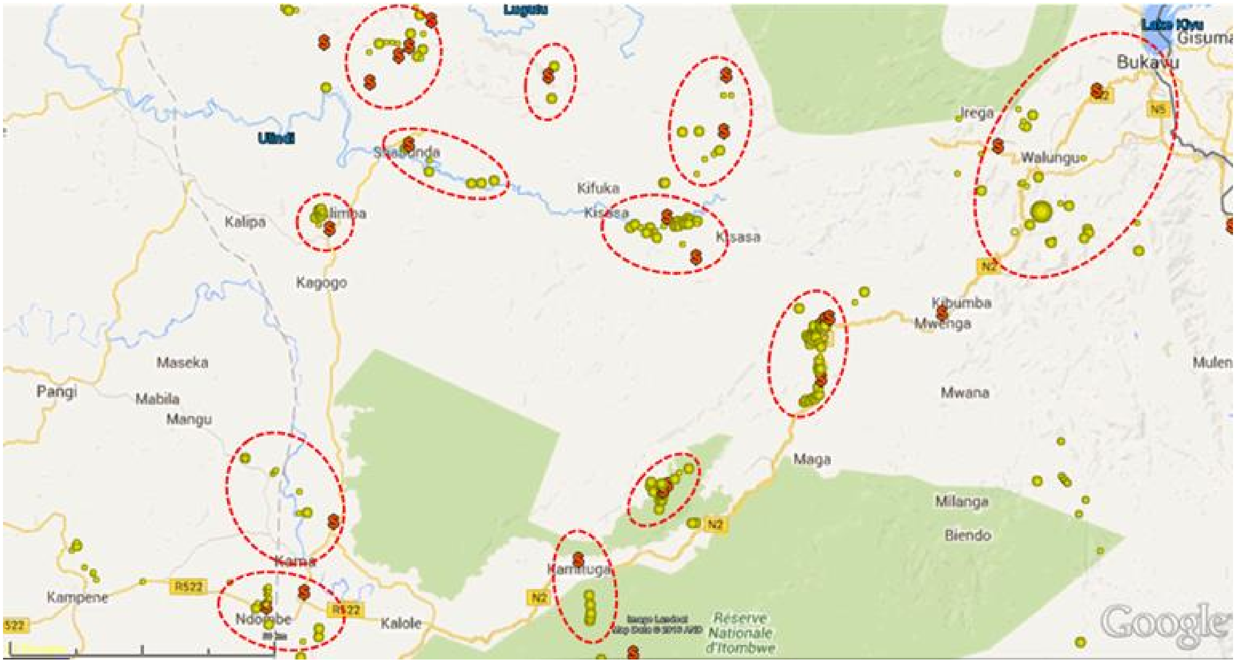

Figure 19: Apparent clusters of *Centres de négoce* (orange) and ASM mine sites (yellow). Data Source: online database of IPIS.[89]

When Category A traders buy from various B-traders or miners, the origin and consequently the quality of the gold is known to them by experience. The average fineness of their accumulated purchases however will vary according to how much was bought from each B-trader (i.e. mine site). Consequently, for onward selling, they have to consolidate and homogenize their purchases. This is done by smelting all purchases of a determined period into a single doré bar as described in chapter 1.3. As described by ARM (2014b), such smelting is typically done in simple, “artisanal” furnaces (Figure 20).

Alternatively, and based on analogy with common practice in other countries, it might be possible that in some cases *comptoirs* provide such service to A-Traders at the moment of purchase.

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[88] No *centre de négoce* is recorded in Mukungwe, the largest ASM community (large yellow dot close to Bukavu).

[89] Database: www.ipisresearch.be/mapping/webmapping/drcongo/v3/script/mines_2015b.js (downloaded May 2016)

Figure 20: Artisanal smelting furnace of a *grand négociant*, source: ARM (2014b).

Grands négociants (Category A Traders) usually sell their doré bars to legal *comptoirs* or non-registered *Maisons d'Achats* (see below).

The main characteristics of gold at the level of Category A traders are:

The product to be expected at A-Trader level are ASM **doré** bars

- The ASM doré bars produced by A-Traders[90] consist of the consolidated mined gold (dust, flakes, nuggets, gold sponge) from various B-traders and/or miners, acquired during a certain period of time, homogenized by smelting.
- The smelting process **alters the chemical composition** of the gold and **i**ncreases its fineness. A portion of the originally contained lithophile elements and elements sensitive to smelting (see Table 4) ends up in the slag or is volatilized.
- Typical volumes accumulated by A-traders before dorés are sold on to *comptoirs* (see below) are in the **range of 250-2,500 g**

Due to existing clusters of mine sites and *centres de négoce,* the doré bars produced by Category A traders may still maintain some chemical characteristics of the gold mined in certain mining clusters. As some of the clusters encompass alluvial as well as hard-rock deposits, deposit- or process-specific chemical characteristics may be disguised. However, it is likely, that the ASM doré bars produced by one A-Trader reflect the chemical composition of gold (although altered by smelting) of the limited geographical area of his sources. This "average" composition is subject to variation, according to varying proportions acquired from these sources.

- While **mine-site-specific geochemical information is lost** at the level of A-Traders, sub-regional geochemical characteristics (see Table 18) of the gold are likely to be retained
- The chemical composition of ASM doré bars produced by a certain A-Trader is likely to **correlate with the sub-regional origin** of this mix of sources

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[90] Typically in own artisanal furnaces, but possible also at the premises of the *comptoirs*.

iii) Comptoirs and other wholesale gold traders

Legally established *comptoirs*[91] usually buy from Category A- or B- traders, with the purpose of exporting the gold. *Comptoirs* are also legally entitled to buy directly from formal miners.[92] According to Blore (2015a), typical purchase volumes are in the range of 250–2,500 grams. In some cases, *comptoirs* even set minimum purchase volumes higher, in the range of 500 g (PAC 2014). This limits the possibilities for miners or small traders to sell directly to *comptoirs*.

Similar to A-Traders, *comptoirs* consolidate and homogenize their purchases prior to onwards selling. Little is documented regarding technical processes applied by *comptoirs* prior to selling the gold into the downstream supply chain. George (2015) reports that gold "*is sold to comptoirs who may further increase the purity before it is exported to a refinery*". In any case, this involves (re-)smelting of the acquired doré bars. Smelting increases the purity of the precious metals and reduces the content of impurities in the doré (i.e. possible trace elements for GPA). Smelting facilities of *comptoirs* are usually equipped with furnaces or blowtorches with which the gold is smelted at elevated temperatures (up to 1200 °C). After pouring the gold into bars and weighting, XRF equipment is used for determining precious metal contents and setting the price with the seller.[93] It is possible that some *comptoirs* also pre-refine the gold with nitric acid treatment, however this is rather unusual.[94, 95]

Doré bars produced by *comptoirs* will have a varying composition and quality according to proportions of gold received from different suppliers in a given period. However, Mthembu-Salter (2014a, 2014b, 2015b) identified quite clearly established in-country trading routes, as also corroborated by BGR[96]. C*omptoirs* in different parts of the country operate using specific (individual) catchment areas. Within these areas, *comptoirs* use a (mostly) fixed network of traders, some of which may benefit from pre-financing offered through the *comptoirs*. The number of legal *comptoirs* that record exports is limited. In 2013 they were located in <u>Kinshasa</u> (4), <u>Orientale</u>: Kisangani (4) and Bunia (1)[97], <u>North Kivu</u>: Butembo (1) and <u>South Kivu</u>: Bukavu (4). No *comptoir* was reported from Maniema. Main (transit) routes for unregistered exports pass through Uganda, Burundi and Tanzania. Kenya plays a role as further transit country (Martin & Taylor 2014; Blore 2015b). As shown in Figure 21, most likely a northern and a southern catchment area can be distinguished. These catchment areas correlate geographically to some degree with the four gold provinces identified in chapter 4.

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[91] Code Minier, page 31: "Comptoir agréé : toute personne autorisée à acheter des substances minérales d'exploitation artisanale provenant des négociants ou des exploitants artisanaux, en vue de les revendre localement ou de les exporter conformément aux dispositions du présent Code

[92] Whether they do or not, depends on the individual business model of each comptoir.

[93] Pers. comm., D. Ruppen, BGR, 2016.

[94] See technology description in chapter 1.3

[95] This is less likely in case of "barter traders" (see below), who buy gold with the only purpose to use it as a viable financial instrument for their trading activities in other goods.

[96] Pers. comm., D. Ruppen, BGR, 2016.

[97] Reportedly closed in September 2014. (Mthembu-Salter 2015b)

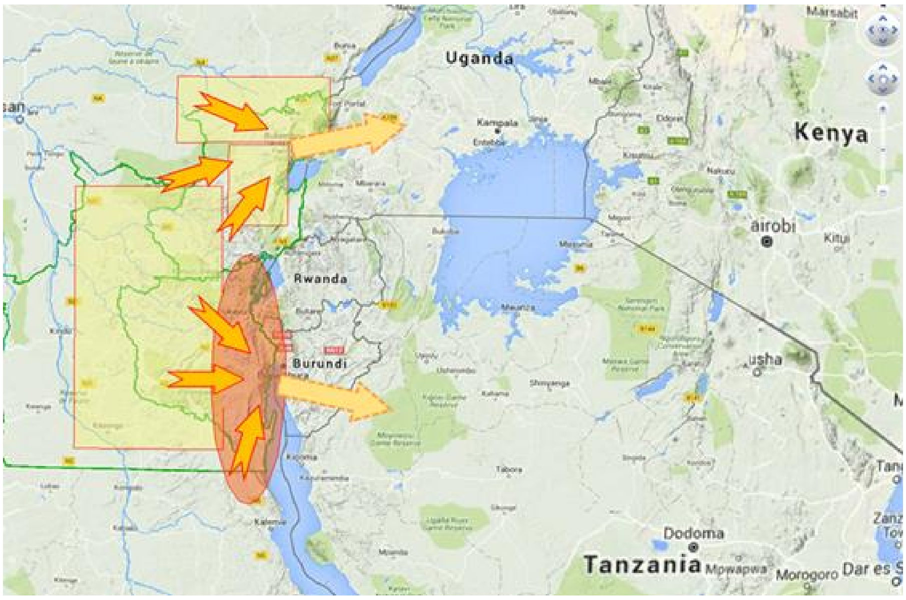

Figure 21: Possible gold catchment areas of northern and southern *comptoirs* involved in informal ASM gold trade

The main characteristics of gold consolidated at the level of *comptoirs* are:
The product at *comptoir* level are **doré** bars

- The doré bars may be composed of all kind of ASM products (gravimetric, amalgamated and leached gold). They consequently may contain traces of **all chemical elements** originally contained in the native gold as well as in leachable gangue minerals.
- The doré bars cast by *comptoirs* have most likely undergone two smelting processes. A further portion of the originally contained lithophile elements and elements sensitive to smelting (see Table 4) ends up in the slag or is volatilized. **Precious metals** are therefore **enriched** and **trace elements (impurities) reduced**, compared to mined gold and to ASM doré of A-Traders.
- Changes in chemical composition can be even more pronounced in case pre-refining with nitric acid has been applied. Pre-refined doré can be identified by a significantly altered **Au:Ag ratio**.

It is assumed, that most *comptoirs* have their specific catchment area. This is determined by their geographic location in relation to in-country trading routes, but also by possible long-term trade relations with suppliers.

- Most likely all **location-specific geochemical** information (type of deposit, method of processing, etc.) **is lost** by homogenization
- As the northern and southern catchment area (with different export routes) correlates to some degree with the four ore provinces, it is considered possible that doré bars of *comptoirs* **retain some of the characteristic geochemical properties** of these **geologic provinces**.

In major gold mining towns in the interior of the country (such as Kamituga, Kampene, Misisi, and Shabunda) an unknown number of *Maisons d'Achats* operate. These are either extension offices of legally established *comptoirs, or* buying offices of A-Traders, B-Traders or informally established wholesale gold traders. Legal *comptoirs* claim that they face serious competition by informal gold traders who do not pay export taxes and/or may be generating all the profit they need from a counter-trade in other merchandize (Mthembu-Salter 2015b; Blore 2015b). However, in 2013, all 14 legal *comptoirs* together reported 202 kg ASM gold exported to the United Arab Emirates (UAE) (GoE 2014; Martin & Taylor 2014). Current numbers are not significantly higher, with 254 kg ASM gold reported in 2015 (Ministère des Mines 2016). This number contrasts sharply with the estimated ASM production of the DRC in the range of 8-12 tons per year.

This suggests, that both, legal *comptoirs* as well as informal *gold traders* are similarly involved in unregistered exports (i.e. “smuggling”). As *comptoirs* and informal *gold traders* are competing, and even *comptoirs* are declaring only part of their exports, it becomes obvious that “legally” or ”illegally” exported gold shares the same upstream supply chain.

Legally exported gold (by *comptoirs*) **and illegally exported** gold (by *comptoirs* or *gold traders*) shares the **same characteristics**. Therefore, physical or chemical characteristics of gold cannot be used to differentiate legal from illegal ASM gold.

Implications for Gold Provenance Analysis (GPA)

Characteristic differences among the key stakeholder groups of the local and national ASM gold supply chain in the DRC with regards to GPA-relevant gold product features are summarized in Table 19 below.

Table 19: GPA-relevant characteristics of products at different stages of the local and national ASM gold supply chain

Characteristics	ASM gold mines	Petits Négociants	Grands Négociants	Comptoirs or Maisons d’Achats
Number	> 1,515 sites > 16,000 pits > 176,000 miners	X * 1,000 (thousands)	X * 100 (hundreds)	X * 10 (tens)
Typical volume of transaction (sales)	0.1 – 5 g	~ 50 g	~ 500 g	~ 5,000 g (and higher)
Type of product sold	Mined gold (gravimetric or amalgamated)	Mined gold (gravimetric or amalgamated)	ASM Doré (from gravimetric or amalgamated gold)	Doré (from all kind of ASM products)
Purity of product sold	Mined gold (extracted and processed with ASM technology)	As produced by miners	Increased purity due to smelting	Further increased purity due to re-smelting and possible pre-refining
Geo-characteristics of deposit potentially retained in product	Characteristics of individual mine sites or pits	Characteristics of individual mine sites	Characteristics of sub-regional mineralized zones (clusters of similar deposits)	Possibly characteristics of single or mixed geological provinces (e.g. north / south)
Signatures of mining and processing methods potentially retained in product	Clear identification of processing method applied at the mine site	Clear distinction between gravimetric processing and amalgamation	Limited; mercury traces from amalgamation possibly detectable	None. Highly homogenized mix of sources

5.4 Cross-border Gold Traffic within the Great Lakes Region

Total official gold exports of DRC in 2015 are reported as 31.8 t. This volume originates almost exclusively from LSM. Kibali exported 25.0 t, Twangiza 4.9 t and Namoya 1.7 t. Together, the three LSM mines contribute to more than 99% of official gold exports. In contrast, out of the estimated 8 to 12 t of gold produced by ASM, only 254 kg are reported as officially exported (Ministère des Mines 2016). Almost 98% of the gold produced by ASM crosses the border without being registered when leaving the country or paying export taxes.[98]

Blore (2015b) distinguishes between "in-region cross-border gold traffic", as the illegal trade of gold across borders within the ICGLR region, and "out-region smuggling" as the unregistered export of gold from the ICGLR region to overseas destinations such as Dubai. While both are of concern, the study highlights that priority should be given to efforts curbing international gold smuggling out of the Great Lakes Region, given the significant collective revenue loss for the region as a whole.

Main transit destinations for of DRC ASM gold are Uganda, Burundi, Tanzania and Kenya. While traditionally it has not acted as a major transit country for ASM gold, Rwanda has recently (2015-2016) started to show substantially increased risks to contribute as a transit actor to the regional gold smuggling network. Gold flows are highly volatile, and react rapidly to changes in tax regimes or export procedures. The discussion of drivers for cross-border gold traffic exceeds the scope of this report. The flows are studied in detail by Martin & Taylor (2014), Mthembu-Salter (2015a), and Blore (2015b) based on UN Comtrade data. Snapshots of typical trading routes are presented in Figure 22.

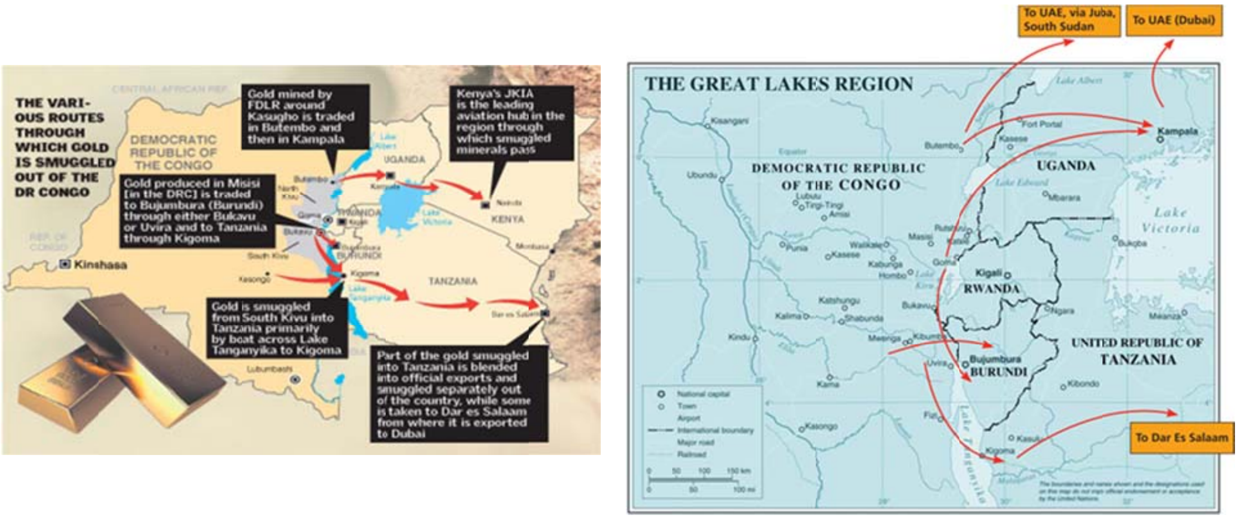

Figure 22: Two recent snapshots of in-region gold trading routes. Left: Kelley (2014). Right: Martin & Taylor (2014).

All three traditional main transit countries, Uganda, Burundi and Tanzania, count on in-country know-how to refine gold.[99] It is highly likely that at least part of the illegal regional cross-border gold traffic

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[98] Export taxes are independent from other local and national levies, fees and taxes collected by the State from miners and traders. "Illegal export" therefore does not imply that the gold has been illegally mined and/or ASM does not contribute to government revenues.

[99] In 2010, Victoria Gold Star established a 10 kg/d refinery in Kampala/**Uganda**, later upgraded to 60 kg/d, with the explicit purpose to "refine gold from the DRC and other countries in the region" BBC 5/5/2010; Kelley (2014). Another refinery operating in Uganda and openly announcing to refine gold from DRC is Carvataro (http://www.carvatarorefinery.com). African Gold Refinery Limited (http://www.agr-afr.com) is a Uganda based company claiming to regulate its business activities and practices in accordance with the OECD and ICGLR guidelines.

transiting through these countries involves gold refined or at least pre-refining (to increase the trading margin) prior to the gold continuing its journey to Dubai. Little is documented on the technical details, but these intermediary buyers most probably follow the same common ASM supply chain procedures of consolidating and homogenizing their purchases. Gold from the DRC can be physically mixed with gold from a different origin (country) at that stage or simply re-branded in terms of origin without actual physical mixing taking place.

During illegal regional cross-border gold trafficking, doré from the DRC undergoes at least another smelting process to consolidate and homogenize volumes. During this smelting process

- Doré is further **purified** (by smelting it the second or third time);
- Doré may be consolidated and blended with domestic gold or gold from third-country provenance.

At least Uganda and Tanzania count on commercial refiners attending the ASM supply chain. Both countries also count on local know-how on pre-refining (cleaning gold with nitric acid)

- If doré is **refined or pre-refined**, possibly together with gold from other origin, the likelihood that such gold can be identified as gold from DRC origin reduces significantly.

5.5 International Gold Import and Smuggling Risks

Main destination for ASM gold smuggled from the DRC (and other ICGLR countries) is **Dubai** in UAE. Government export documents, the UN Group of Experts and various NGOs, and the customs statistics of UAE identify Dubai as the main destination for ASM gold produced in the ICGLR region. Of the seven Emirates, Dubai has by far the largest gold market. According to its own customs figures, the UAE imported 28,516 kg of gold from the ICGLR region in 2011. Only 5,978 kg of this total had been legally taxed and exported from the region (Blore 2015b).

ASM gold from the ICGLR region arrives by plane, most of it as “hand carry”. For such gold, the “gold souk” in Dubai is the primary destination. The souk is remarkably well equipped for such transactions. Buyers can provide an initial assay of the gold, based upon which a price can be agreed. The gold can then be smelted forthwith and re-assayed for a final purity determination, after which payment is made (Blore 2015b).

Gold bought by jewelers in the souk may be turned into jewelry, or it may be sold on to one of Dubai’s gold refineries. Buyers in the souk wishing to sell their gold on to a Dubai refiner are required to keep a record of the nature and origin of their gold purchases, in order to satisfy the due diligence requirements of the refiners. Blore (2015b) indicates that, questioned on this point, souk buyers responded that they would classify the gold as scrap. Martin & Taylor (2014) report that a souk jeweler *“told PAC that he could mix mined gold, from DRC or anywhere else, with scrap gold and sell it to*

In 2007, the Federal Bank of Middle East Ltd. had invested over US$ 1million in a new gold refinery plant in **Tanzania**'s Mwanza region to add value to gold exports from small-scale miners. In 2013 the gold refinery firm Mwananchi Gold Company Ltd was liquidated and closed. The Dar-es-Salaam based refinery TMR (http://www.tmrtz.com) offers gold refinery services. Operators of the many ASM cyanide leaching plants count on know-how to – at least – pre-refine doré bars.

In **Burundi**, export *comptoirs* in Bujumbura are known to perform limited pre-refining of gold, sometimes pouring it into (doré) ingots and exporting it to Dubai. Plans of a Lebanese investor to establish a gold refinery were backed up by a Presidential Decree 2013 assuring a 10 year monopoly to process and refine gold. IPIS (2015b). However, a successful refining process could not yet be established due to a number of reasons.

refiners without this being detected" but it is "*more likely [for such gold] to be absorbed in the jewelry market, or exported to countries like India*".

With 383 t of gold sold in 2011 locally in Dubai according to Martin & Taylor (2014), supposedly mainly in form of jewelry (Figure 23), it does not seem difficult to absorb volumes in the range of 8-12 t/a, corresponding to DRC's ASM production.

Figure 23: Gold jewelry in the Souk of Dubai, source: F. Hruschka.

Most jewelry in the gold souk of Dubai (Figure 23) is commoditized jewelry. The price is not determined by its design but by the gold content, i.e. the heavier, the more precious. Such jewelry has been produced for centuries in the Middle and Far East, long before modern refineries started refining gold to a fineness of 999.9. While it is convenient for jewelers to source pure gold from one of the refineries based in Dubai, it is not a mandatory technical requirement for them. "*Every advanced goldsmith knows how to refine gold and produce alloys at a quality appropriate for producing commoditized jewelry*".[100]

Characteristics of doré and gold **arriving** in Dubai

- Gold from DRC, jointly with gold from many other ASM countries, may arrive in Dubai either as **doré**, as **pre-refined gold**, as **refined gold** or as **fabricated scrap** intentionally alloyed with copper or brass to disguise its origin
- Gold from DRC delivered in form of **doré** without further transformation has undergone smelting for consolidation and homogenization at least twice. However, it might (to be confirmed) still carry a **chemical signature representative** for one or more geological provinces (see chapter 4 and 5.3)
- Gold delivered in **pre-refined or already refined** form, and eventually mixed with sources from other countries, is highly unlikely to retain an origin-specific characteristic signature (see chapter 1.4)

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[100] Comment from a Syrian goldsmith

- Mined gold processed by ASM, **disguised as scrap**, is likely to retain geochemical and/or even process characteristics of its actual origin as mined gold.

Refined gold produced at Dubai refineries has typically a purity of 999.9 or higher. Additionally, due to elevated processing capacities in the range of several hundred kg/d up to some t/d and continuous refining processes in the factory, the refined represents a mix of a wide variety of sources[101]. It is therefore **unreasonable** to expect any conclusive results from **GPA applied to refined ASM gold** using currently available analytical technology.[102]

The above considerations allow extending Table 19:

Table 20: GPA-relevant characteristics of gold at the refiner stage

Characteristics	Refiner
Number	in UAE < 10
Typical volume of transaction (sales)	N/A
Type of product sold	Refined gold, Jewelry alloys
Purity of product sold	Fineness: > 99.5%, mostly 99.99%
Geo-characteristics of deposit potentially retained in product	None. Highly homogenized mix of sources
Signatures of mining and processing methods potentially retained in product	None. Highly homogenized mix of sources

5.6 Summary of Supply Chain Considerations for Gold Provenance Analysis

The **LSM gold supply chain** from the DRC is seen as a straightforward closed pipe from three LSM mines (Kibali, Twangiza, Namoya; accounting for 99% of the official gold exports) delivering to a single destination (Rand Refinery) in South Africa. The composition of all doré bars leaving the mines and exported from the DRC should be identical to the doré bar imported into South Africa and arriving at the refiner. All doré is assayed prior to export. If not already in place for internal traceability and quality control, analysis of minor and trace elements for GPA could easily be added as part of standard procedures for LSM gold, as further explored in the follow up report.

The **ASM gold supply chain** from the DRC consists of highly complex trade relations involving a large number of supply chain actors. Almost all of the ASM gold leaving the DRC ends up in Dubai, mostly without any official export documents[103] or, in some cases, with export documents issued by a transit country[104]. The number of involved stakeholders (i.e. possible sampling points for GPA) increases exponentially with every step towards the upstream end of the supply chain. The volumes of

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[101] However, certain refineries may also be equipped for batch processing with full physical segregation.

[102] Unless probably in case of closed pipe trading schemes with physically segregated refining.

[103] Fraudulent / fake documents may accompany some shipments, though. As recently documented for Rwanda, transit countries may also issue official transit papers based on fake DRC gold export documents. GoE (2016)

[104] E.g. DRC ASM gold smuggled into Burundi and then being issued a Burundian Certificate of Origin for official export. GoE (2016)

transactions (grams of gold traded per transaction) decreases in inverse proportion. Smaller trading volumes, in turn, retain more mine-site specific information.

Depending on the intended purpose of GPA, control points at different stages of the supply chain may be considered as further explored in the next chapter.

- The accuracy of GPA in terms of parameters characterizing the deposit and the applied mining and processing methods increases with each step upwards the supply chain.
- However, the number of required sampling points and samples for GPA increases proportional to the number of involved stakeholders at each trading stage and, therefore, exponentially with each step upwards the supply chain.

6. Scenarios for Applying Gold Provenance Analysis

Gold Provenance Analysis (GPA), as defined in this report, uses the chemical and mineralogical composition of gold to make reasonable assumptions on the origin of gold traded along a supply chain. This is done by analyzing gold composition and comparing quantitative (concentrations) or semi-quantitative (spectra) analytical results with stored database records. Applying GPA in this fashion serves a contribution to due diligence and risk assessments.

In its most straightforward form, GPA refers to analytically confirming the identity and, possibly, verifying the integrity of a gold shipment in a tightly controlled supply chain, e.g. a closed pipe sourcing scheme. If gold is produced at a limited number of large mines and shipped directly to a processor or refiner, a reference database reflecting gold composition at the mine (and, if necessary, after processing) can readily be constructed, as it is the case in, for example, South Africa (Dixon 2014; Roberts et al. 2016). Gold shipments may then be analyzed and their composition compared to the reference database.[105] In this sense, GPA may be regarded as a tool for tracking and tracing gold to well identified points of origin. In the particular case of South Africa, an additional consequence of the system is that any gold whose compositional features does not reflect gold data as stored in the national reference database implies it may have been produced outside of the legal production system. Even though operational procedures need to be designed carefully, applying GPA as a tool to validate supply chain integrity in a closed pipe setting, overall, appears to be a feasible process in terms of management complexity and costs.

The situation becomes significantly more complex when considering an open system of widely dispersed gold mining and trading networks characterizing the ASM sector, notably in conflict-affected and high-risk areas such as the DRC. Given such a context, an approach where reference samples are taken at each mine (or processing step) is unfeasible, given (1) the huge number of supply chain actors and the resulting logistical, economic and political challenges of a potential sampling program as well as (2) the technical constraint that physical transformation along the supply chain (see chapter 1), from ore to doré, modifies the compositional characteristics of gold. This chapter introduces three scenarios for potential GPA application and describes general considerations on their practical feasibility in a complex setting such as the ASM supply chain originating from the DRC. The scenarios differ in their provenance scope (local, national, regional) and in the extent to which they meet expectations and requirements of the private and public sector.[106]

6.1 Potential Scenarios for GPA Application

The findings of this report suggest three theoretical scenarios for gold provenance analysis: (i) product confirmation along local (closed pipe) supply chains, (ii) sub-regional (inside the DRC) verification of origin from gold “catchment areas” such as geological provinces, and (iii) evaluation of regional-

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[105] In its simplest form, for a single gold shipment, integrity of the product can even be assured without a database, by matching analysis results at the point of origin and the point of destination.

[106] Two examples can illustrate this: Verification that the compositional characteristics of a doré at a certain transit point reasonably meets its claimed origin may satisfy the purpose of proof of legality of the shipment, but is insufficient for due diligence of downstream companies. Verification of identity of a trans-border shipment in a closed pipe supply chain involves business partners in different countries (DRC and import country) acting under different national jurisdictions. The first application of GPA represents a possible application of GPA under control of the State, the second might be a safeguard measure for supply chain integrity applied by the private sector.

international gold smuggling risks through assessment and validation of claims of origin at international export, transit and import points, in particular airports.

Figure 24 below illustrates the ASM gold supply chain and the potential scope of the different scenarios. For LSM gold supply chains, the network of intermediaries (traders and *comptoirs*) does not exist; gold (doré) shipments go straight from the mine to the international refiner using special transport security arrangements and applying state-controlled export procedure.

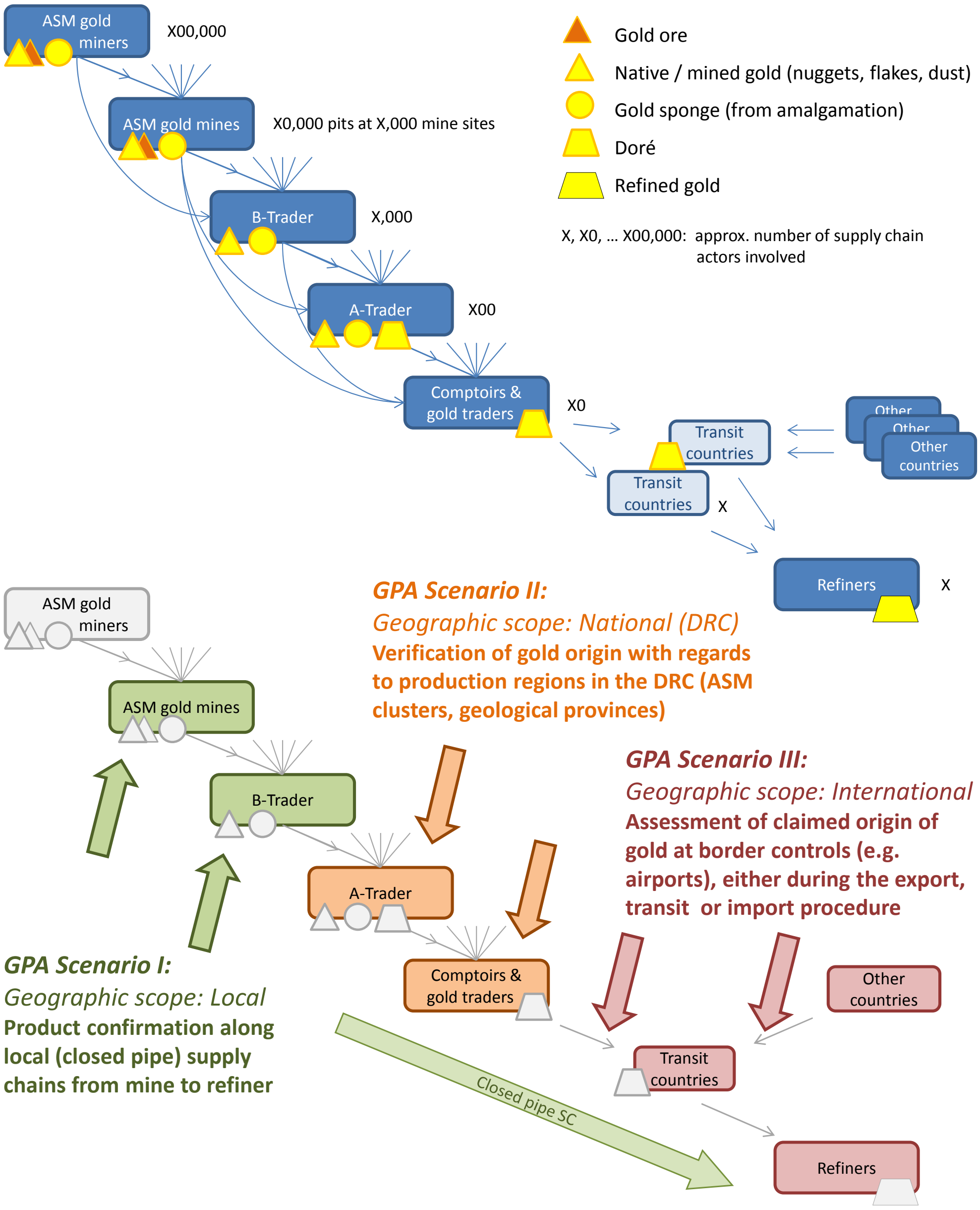

Figure 24: Artisanal gold supply chain from the DRC and possible scenarios for gold provenance analysis.

GPA Scenario I: Local Product Confirmation

The mine site where the gold is extracted is considered the *Provenance* of this scenario. At each ASM mine site in the DRC, several Category B Traders *(petits négociants)* purchase the gold from the miners, consolidating volumes and usually selling the gold to Category A Traders *(grands négociants)*.[107] The main assumption for the feasibility of GPA at local level is that the compositional characteristics of the gold are typical, although not necessarily unique, for each mine site. This comprises the geochemical/mineralogical characteristics of the gold as well as the characteristics imprinted on the material by the applied mining and processing methods.

More than 1,500 ASM gold mine sites in the Eastern DRC have already been mapped and are registered in databases by BGR and other organizations. Although theoretically possible in the long term, this scenario is not rooted in the idea of a countrywide coverage of analytical data from all these mine sites. It rather focuses on the verification of a claimed origin in specific cases: if gold is said to originate from a certain mine, then it must match the site-specific compositional characteristics. This is directly relevant for providing an extra layer of certainty to closed pipe supply chains and for due diligence purposes (e.g. audits, risk assessments). Such a local GPA scenario in combination with a closed supply chain approach is already in place for the existing supply chains of LSM operations, where doré produced at the mines is directly exported to the Rand Refinery in South Africa.

Additional details on the scenario are provided in Annex D.

GPA Scenario II: Verification of Gold Production Regions

Doré bars have varying composition and quality according to proportions of gold received from different suppliers in a given period. A high likelihood exists that *comptoirs* and other wholesale trading houses receive their gold from relatively well defined “catchment areas” (overlapping with one or more of the four geological provinces in the DRC) according to established and stable trade relations.[108] These geographic catchment areas within the DRC are considered the *Provenance* of this scenario.

The main assumption is that the compositional characteristics of the gold are typical, although not necessarily unique, for each catchment area or, by implication, for *comptoirs* sourcing from different areas. The GPA scenario is therefore expected to allow for plausibility checks of provenance claims; i.e. the verification of gold origin with regards to production regions in the DRC, to the extent that such regions reflect different geological provinces and “catchment areas” for *comptoirs* and exporters to source gold from.

Additional details on the scenario are provided in Annex E.

GPA Scenario III: International Claims of Origin Assessment

Almost 98% of the gold produced by ASM in the DRC crosses the border without being registered and taxed when leaving the country.[109] The challenge of revenue loss from tax evasion and smuggling of ASM gold pertains not only to the DRC but to many producing gold countries in the Great Lakes Region and elsewhere. At the same time, this practice represents a challenge for gold importing industries and countries[110] with regards to their international reputation and regulatory requirements in the context

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[107] Individual trade relations may differ from this generic supply chain sequence.

[108] i.e. the geographic areas where their suppliers operate. (See chapter 5.3).

[109] Export taxes are independent from other local and national levies, fees and taxes collected by the State from miners and traders. “Illegal export” therefore does not necessarily imply that the gold has been illegally mined and/or ASM does not contribute to government revenues. However, in many cases taxation challenges at the mine and export level are correlated.

[110] e.g. the United Arab Emirates as current main destination for ASM gold from the DRC and many other African countries.

of due diligence or risks of illicit financial flows. The DRC (or, potentially, any other country for that matter) is considered the *Provenance* of this scenario.

The main assumption is that a series of compositional characteristics of the gold are typical, although not necessarily unique, for gold originating from the DRC (or, potentially, any other country for that matter).

The GPA scenario serves the purpose of assessing the claimed origin of gold at international airports, either during the export or import procedure (the former in the Great Lakes Region and the latter taking place in Dubai or other international gold import destinations). If the compositional characteristics of a gold shipment are as expected for the claimed origin (country), a green flag mechanism could apply; otherwise further investigations of the provenance may be triggered.

Additional details on the scenario are provided in Annex F.

6.2 Scientific and Practical Considerations for GPA Setup

This chapter describes general considerations to be taken into account when assessing the practical feasibility of each of the GPA scenarios in Annex D to Annex F.

Stakeholders

The internal dynamics of the current supply chain network for ASM gold (partly formal but largely informal) in the DRC have evolved over many years. They reflect economic and power relations among stakeholder groups and an optimization of individual revenues for each supply chain actor. Depending on the GPA scenario, different stakeholder groups may be involved or affected. Some stakeholders may benefit from implementation of a GPA scenario (e.g., through consolidating their position or influence in the supply chain) while others may be negatively affected. As a result, stakeholders may support or oppose implementing GPA system components.

Each scenario, therefore, requires a stakeholder analysis.

- Governmental institutions, international donors, most downstream industries, civil society and responsible consumers can be seen as drivers, demanding increased transparency of gold supply chains. Expectations related to GPA may be diverse, related to improved control of extractive activities, implementation of the rule of law, increased revenue collection, reduced human rights violations, mitigation of reputational risks and responsible sourcing.
- Involvement of gold traders and exporters at the national (DRC) or regional level is crucial, but expectations will vary widely. On one hand, possibly improved traceability through GPA (e.g. possibility to verify provenance claims) can open new markets currently reluctant to source from the DRC. On the other hand, stakeholders operating outside formal or legal trading channels may associate the possibilities of GPA with threats to their business model and oppose it.
- The degree of involvement of ASM mine operators (mine owners, associations, cooperatives) depends on the geographic scope of the GPA scenario. It increases with higher geographic resolution and is highest in case of a scenario focusing on local provenance. Depending on the purpose of GPA (e.g. for law enforcement along legal supply chains or for assurance of

legitimate origin and responsible supply chains) expectations and levels of engagement will vary.

Table 21 summarizes the main considerations the stakeholder analysis of the scenarios. Further details are presented in the corresponding report annexes.

Table 21: Key considerations from stakeholder analysis for DRC ASM gold supply chains

Scenario	Considerations
Scenario I: Local Product Confirmation	Miners (cooperatives) and B-traders are the GPA target group, but the key stakeholder to work with for a closed pipe setup is the party aggregating the gold, i.e. the A-trader or agent of the *comptoir* that purchases the gold locally from mines or local B-traders and dispatches it for export (into the closed pipe supply chain). The role of miners/cooperatives will become more important in case the closed pipe approach includes consolidation of the upstream supply chain by cutting out middlemen, as is sometimes the case.
Scenario II: Verification of Gold Production Regions	*Comptoirs* (and at a later stage A-trader) are the GPA target group. Key stakeholder(s) to be initially involved are the governmental agencies in charge of assaying gold for export (OCC: *Office Congolais de Controle*, and the CEEC: *Centre d'Expertise d'Evaluation et de Certification des substances minérals précieuses et semi-précieuses*) and, in a second roll-out phase, the *comptoirs* purchasing from A-traders.
Scenario III: International Claims of Origin Assessment	Exporting *comptoirs* and traders in transit countries are the GPA target group. Key stakeholder(s) to involve are customs authorities of export countries (e.g. ICGLR member states) and import countries (e.g. Dubai, United Arab Emirates)

Types of Samples and Sampling Procedures

Sample material will differ according to the segment of the supply chain where the sample is being taken (or analyzed): this refers to gold ore, gold dust, flakes or nuggets, gold sponge, and gold doré. As illustrated in the previous chapters of this study, these different products in the gold supply chain have variable levels of internal compositional heterogeneity and are, hence, not always directly comparable. Also, in case of non-destructive analysis using portable equipment, there is no physical process of "taking a sample" involved.

The actual physical accessibility of samples depends on several factors:

1. There are economic and logistical constraints that prevent comprehensive high-resolution sampling of gold ore or mine products across several thousand production sites. This aspect becomes even more pronounced when considering the typical mobility characterizing many ASM gold mining operations in the DRC. Additionally, at the level of mines or miners, even small quantities of gold (in the range of 1 gram) represent the result and hence the income of several workdays. Collecting physical samples is therefore conditioned on payment of the gold value (purchase of sample material).
2. In a conflict-affected or high-risk area the local security situation imposes significant constraints on the ability to collect samples properly and regularly, independently from the

actual actors in the gold supply chain. Furthermore, a potential extensive physical sample collection (even with individual samples in the range of only 1 gram) will rapidly accumulate several kilogram of gold. Custody of such a collection becomes an additional security issue.

3. Cooperation of private stakeholders in the gold supply chain (particularly at the level of miners and traders) is needed to establish a sustainable GPA system. Highly effective law enforcement, such as observed in the South African LSM sector, is unlikely to become a realistic option for the ASM sector of the DRC in the near future. Also, the resourcefulness of private actors to avoid unwanted procedures in a largely informal sector should not be underestimated. Therefore, a cooperative approach is advisable. Focusing GPA scenarios on gold trading hubs in the supply chain is seen as a viable option for more effective control and, hence, better opportunities for sampling.

The above considerations strongly suggest the use of non-destructive analytical methods in combination with on-site sampling/measuring that allows for returning the sample material to its owner as soon as the measurement has been concluded. Sampling, therefore, should not be understood as the collection of material, but as the collection of data.

The required frequency of sampling depends on the type of sample material and, mainly, on the GPA objective. The compositional characterization of the ore from a mineral deposit, for example, requires much lower sampling frequency than monitoring individual gold shipments (where it is common commercial practice to analyze the fineness of every single doré bar). According to the specific GPA scenario objective, sampling frequency may be continuous (sampling of all items), systematic (in specific time intervals or triggered through other pre-determined events), on demand, in case of doubt, or random. This creates further sub-scenarios.

Scenarios also differ with regards to the number of required sampling points. Table 22 summarizes the main considerations for sampling in the scenarios. Further details are presented in the corresponding annexes.

Table 22: Key considerations for GPA sampling procedures

Scenario	Considerations
Scenario I: Local Product Confirmation	Main sample materials are gold dust, flakes or nuggets (in case of coarse gold) or gold sponges from amalgamation purchased from mines and locally operating B-traders, and doré dispatched by a *comptoir* (or LSM mine) into a closed pipe supply chain. For acceptance of the scenario, sampling of mined material must be performed without physical loss, i.e. no significant quantity of sample material must be withheld or consumed by the analysis. Sampling material could also be purchased at local market prices.

Scenario	Considerations
Scenario II: Verification of Gold Production Regions	A first roll-out stage of this scenario would cover the exporter level (*comptoirs*). There, sampling procedures could be integrated into already compulsory assaying of export doré bars by OCC and CEEC. In a second roll-out stage, expanding to A-traders, sampling of doré purchased by *comptoirs* and attributed to A-traders can be performed at *comptoir* offices or at independent facilities serving A-traders. This sampling would have to be done in front of officials or other witnesses, and the employed analysis should be non-destructive such that sampling material can be returned after analysis.
Scenario III: International Claims of Origin Assessment	Sampling material would almost exclusively be doré. With few exceptions, all other types of material (dust, flakes, nuggets, sponges) would likely raise red flags if encountered at this stage of the supply chain, given a high risk that the associated upstream supply chain was illegal. Sampling and analysis procedures in the DRC and all participating organizations in other countries need to follow the same standardized protocol in order to produce comparable results. Sampling (e.g. by customs or airport authorities; particularly of hand-carried gold) needs to be expedite and if possible instant, to avoid security risks of keeping large volumes of gold in custody.

Laboratory Equipment, Personnel Resources and Skills Required

On-site gold analysis using portable instruments must be distinguished from analysis performed in a well-equipped laboratory requiring different levels of scientific sophistication. Scenarios including affordable and portable equipment are more realistic in the DRC context. This would allow rapid analysis without requiring a high degree of infrastructure and personnel. The parameters that may be measured using portable equipment are limited (major and minor element chemistry) and the results may hence not reach the accuracy and elevated degree of certainty required for robust forensic evidence. However, for day-to-day operation, providing basic supply chain integrity safeguards as recommended for due diligence in an ASM environment, instruments that are portable and easy to use, such as pXRF or pLIBS, are considered suitable for the purpose. The analytical method and instrumental calibration will likely be set up by the company selling the instrument at their factory. Once this has been done, training of personnel in charge of the GPA process needs to be organized. The personnel must have a certain level of understanding of chemical analysis, but does not necessarily require a university degree in analytical chemistry or mineralogy.

Full characterization of various types of gold deposits or products using the parameters outlined in the previous chapters requires the use of a high-technology laboratory, such as the one used at the BRGM (Augé et al. 2015) or at the BGR for the AFP process for 3T concentrates (Gäbler et al. 2013). Such laboratories variably consist of several operational units, including sample preparation laboratory (production of polished samples for microscopy, electron microscopy and electron microprobe analysis), optical microscopy, scanning electron microscope and/or electron microprobe, LA-ICP-MS, and a special clean laboratory setup for the production of ultrapure solutions from which accurate isotope determinations can be made. Such high-technology laboratories may in some cases also require support by IT specialists and/or by mathematicians for data processing. All in all, such a laboratory may require an investment of up to several million € and well-trained personnel. The infrastructure to maintain such a laboratory is mostly available in developed countries only.[111]

Table 23 summarizes the main considerations for analytical methods and equipment required for the scenarios. Further details are presented in the corresponding annexes.

Table 23: Key considerations for GPA analytical methods and facilities

Scenario	Considerations
Scenario I: Local Product Confirmation	Analytical equipment must be able to carry out measurements at traders' offices as well as "in the field". Analytical devices must therefore be portable, independent of local power supply and easy to use, but sensitive enough to provide the required parameters (major and minor elements) used for GPA. For the time being, such requirements are only met by pXRF spectrometers (so-called "handhelds").[112]
Scenario II: Verification of Gold Production Regions	Analysis must be performed by an independent party. This may comprise government institutions (e.g., OCC, CEEC, SAESSCAM) or NGOs. Composition of doré produced at *comptoir* offices is most practically analyzed using pXRF or pLIBS spectrometers. Stationary equipment (e.g. binocular microscope or a small scanning electron microscope) may additionally be used to identify inclusions in doré.
Scenario III: International Claims of Origin Assessment	Time is an important issue when export hubs (airports, customs) are involved, thus necessitating instant results. Portable XRF instruments offer highest speed (a few minutes per analysis). For instantaneous results, the system needs to be automated, thus probably requiring lower skills from operating personnel than scenarios I and II.

Database Management

A database system is required in order to host compositional reference data and receive queries for comparing sample compositions. A database consists of the database (data) itself and a database management system, e.g. MS Access, MySQL or others. The architecture can be divided into two systems: (i) standalone (one computer, one user), or (ii) multiuser (client/ server based) systems. One of the advantages of a server based system is the security of the data and possibility to restore the database. The following points should be considered for building a database:

- Planning the database (design, proposed applications, volume)
- Definition of the user groups
- Selection of the database management system
- Designing the application software (user interface)
- Pilot run (testing, corrections)
- Implementation and data acquisition
- Database maintenance, improvements

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[111] Even though BGR has recently established a similar laboratory at the African Minerals and Geosciences Centre in Dar-es-salaam, Tanzania

[112] Portable LIBS devices offer significant potential but are less frequently used and certainly need more research input.

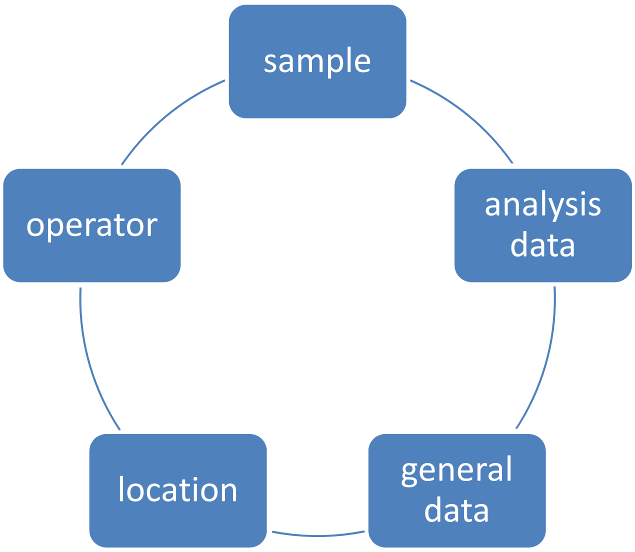

Figure 25: Simplified structure of data to be collected for a GPA system.

One of the most important requirements is the user-friendliness and practicability of such a system. This is necessary for both, data input and statistical analysis. The main bullet points for establishing a database for field and lab data will be discussed in the GPA scenario profiles given in the annex. In addition some examples and options will be elaborated.

Results using portable spectrometers (pLIBS or pXRF) will consist of spectra. These may have been calibrated against standard material, such that quantitative numbers on concentrations may be obtained. Spectra are stored on the instrument´s storage device from where data must be exported in time intervals to a central database. Data transmission may pose a serious challenge to the system because they require the presence of a stable internet system allowing for an online system (concerning Scenario III).

Table 24 summarizes the main considerations for database management. Further details are presented in the corresponding annexes.

Table 24: Key considerations for GPA database management systems

Scenario	Considerations
Scenario I: Local Product Confirmation	Data/spectra collected by the “agent” or in the *comptoir* will be stored in the *comptoir* and ,on demand, be submitted to a local independent laboratory or to the refiner at the downstream end of the closed pipe supply chain. Two different database systems are possible: a standalone system can be used in the context of a single closed pipe supply chain; alternatively, a multiuser system is possible where the database is located on a server and the clients use a terminal or a web interface for data entry. The database has to include different types of data (spectrum, location, information about geology, information about the ASM miners, information about the sample type, etc.). To simplify data collection, QR codes can be used.

Scenario	Considerations
Scenario II: Verification of Gold Production Regions	In the first roll-out stage, a database needs to be set up enabling comparisons of doré compositions from different *comptoirs*. This can be done either in a standalone or in a multiuser system, depending on who maintains the database and how the data entry should take place. In the second roll-out stage, expanding to A-traders, analysis data (pXRF or pLIBS spectra) acquired by *comptoirs* (including data of purchased gold dust, nuggets and sponge) need to be systematically collected in a country-wide database. This makes a server based DBMS with online data transmission mandatory. To simplify data collection, QR codes can be used.
Scenario III: International Claims of Origin Assessment	XRF spectra must be collected and stored in a server-based DBMS. For rapid and practical application, a multiuser system for the database is recommended for this scenario. Clients with different permissions can access the database via a web interface. Additional modules for online statistical evaluation of an unknown spectrum from a doré can be integrated.

Data Interpretation

Data interpretation is variable depending on specific scenarios. The situation in South Africa may be used as a reference for general illustration of a data interpretation approach. The Forensic Science Laboratory in Pretoria has established an extensive collection of samples from gold producers and deposits across southern Africa and elsewhere in the world. In addition, gold seized from illegal sources for which the provenance is known has been included in the collection. This collection is continually updated. The samples are analyzed with ICP-OES and LA-ICP-MS methods for major and trace elements. Dixon et al. (2007) states that "*the results are entered into a database that is linked to purpose-built statistical software. The software applies and compares two different statistical techniques in source-identification, to ensure consistency. Firstly the similarity, or dissimilarity, between a questioned sample and all other samples in the database is assessed and calculated as distances between each pair, and a probability for correct allocation is determined. The second procedure is based on Principle Component Analysis and the comparison of unknown and reference data in n-dimensional space. This allows allocation of individual analyses to material groups and probabilities are allocated for similarity to other data in the database.*" This database and the statistical software are powerful tools and can be used to identify the original source of the gold.

Table 25 summarizes the main considerations related to data interpretation for each of the scenarios.

Table 25: Key considerations for GPA data interpretation

Scenario	Considerations
Scenario I: Local Product Confirmation	In a closed pipe supply chain a gold shipment may be analyzed at an aggregation point along the supply chain (e.g., a *comptoir*) as well as by the customer upon reception of the product. A spectra-match software should be available for comparing the two spectra (on-site and at destination) for the purpose of compensating for possibly different calibration of the instruments employed at both locations.

Scenario	Considerations
Scenario II: Verification of Gold Production Regions	For the interpretation of a country-wide reference database of all measured spectra statistical evaluation software is needed.
Scenario III: International Claims of Origin Assessment	For the interpretation of a country-wide or international reference database of all measured spectra statistical evaluation software is needed. An automated, standardized online system needs to be developed to speed up the procedure (at airports or other “choke points”) of allocating probabilities for similarity to reference material in the database.

6.3 Assumptions to be addressed through Piloting of GPA Scenarios

Gold Provenance Analysis is a new and innovative approach, using existing methods for the analysis of chemical gold composition to serve as scientifically robust and practically feasible tools to increase the transparency of gold supply chains.

Although the GPA approach is somewhat similar to earlier initiatives such as the development of an Analytical Fingerprint (AFP) for 3T minerals (tin, tungsten, tantalum), GPA poses new challenges. In contrast to 3T minerals, where traded concentrates maintain compositional provenance characteristics from the mine site, gold undergoes significant transformation processes during mining, processing and trading. It is extracted as primary gold ore or alluvial gold, but reaches the export point mostly as doré. Consequently, high geographical resolution (e.g. a mine site database) is of limited use when attempting to determine the provenance of traded gold products. On the other hand, the homogenized nature of doré gold offers the opportunity for employing portable analytical instruments generating rapid results, rather than requiring lengthy analytical procedures in high-tech laboratories as necessary for 3T minerals (AFP).

All three GPA scenarios presented in this study are based on informed assumptions – these needed to be validated by testing and piloting.

6.4 Summary of GPA Scenarios

The scenarios, summarized in Table 26 and illustrated in detail in the Annexes, provide different starting points to enhance supply chain transparency at different segments of the upstream gold supply chain.

Table 26: Summary of GPA Scenarios based on the DRC ASM Gold Supply Chain

	(I) Local product confirmation	(II) Verification of production regions	(III) International claims of origin assessment
Main stakeholders	A-trader/*comptoir* (“agent”)	Phase 1: OCC, CEEC; Phase 2: *comptoirs*	International organizations or customs authorities
Beneficiaries	Miners, obtaining access to formal markets Industry, through enhanced due diligence tools State, collecting government revenues	State, obtaining a tool to validate claims of origin of gold at export point, and increased government revenues through enhanced transparency of the national gold supply chain	Reputational benefit for international gold trading hubs. ICGLR member states and international community, through curbing conflict financing and illicit financial flows
Samples	Concentrates, nuggets, sponge, (doré) Samples to be analyzed and returned to owner	Doré Samples to be analyzed and returned to owner	Doré Samples to be analyzed and returned to owner
Sampling points	Gold sold by mines and B-traders Gold exported by *comptoir* Gold imported by refiner	Stage 1: Gold exported by *comptoirs* Stage 2: Gold bought by *comptoirs* (or sold by A-traders)	Gold at export from producer country Gold passing through transit countries Gold at import into destination country
Analytical method	Major and trace element analysis (spectra) Non-destructive	Major and trace element analysis (spectra, quantified data), inclusions Non-destructive	Major and trace element analysis (spectra, quantified data) Non-destructive
Analytical equipment	pXRF or pLIBS	a) pXRF or pLIBS, b) stationary XRF or LIBS, microscopy	pXRF or pLIBS
Personnel skills	Sample preparation, measurement, data transfer, safety, data management	Sample preparation, measurement, data transfer, safety, data management	Sample preparation, measurement, safety, data management
Data processing	Standalone database, QR codes	Multiuser system, QR codes	Multiuser system, data comparison to international database
Outcome	Enhanced supply chain transparency, responsible supply chains	Good Governance through enhanced supply chain transparency	Peace building and combatting organized crime through reduced illicit financial flows

Implementing any single scenario would reinforce potential implementation of other scenarios. To this end, adequate sequencing as well as collaboration or support opportunities among different scenario beneficiaries should be explored. In particular the third, international scenario would require sampling efforts to build a reference database of regional gold compositions that could not easily be implemented by the direct users or beneficiaries of the scheme (e.g., State, represented by customs authorities). However, such users could explore opportunities for supporting database building by other stakeholders while, in turn, gaining access to data generated through other scenarios.

In this sense, Scenarios I and II are seen as possible entry points and Scenario III as part of an upscaling strategy. All three scenarios require piloting to validate the underlying scientific and practical assumptions. It is recommended to conduct further research into development of the analytical methods, which represent a new application of known and available “high-tech” appliances, and to pilot the methods in (i) a closed pipe scenario and (ii) at national level export points from the DRC or other gold-producing countries.

7. Summary

The GPA method screening and practical scenario development documented in this report has resulted in various findings that must be taken into account when developing analytical tools to constrain the origin of gold from conflict-affected and high-risk areas such as the DRC. These findings have been summarized in various tables throughout the report and are repeated in this summary.

The analysis of the generic gold production process and evaluation of literature on the composition of mined and traded gold (chapter 1) showed that a number of intermediate and final gold products need to be distinguished along the value chain from ore to the final product (Table 27).

Table 27: Primary and intermediate gold supply chain products during gold's journey "from vein to vault".

Product	Description
Gold deposit	Geologic structure with enriched gold content, discovered by LSM through systematic prospection and exploration, or by ASM through empiric experience.
Gold ore	Rock or gravel that contains an economically valuable concentration of gold.
Native gold	Elemental metallic gold occurring as a mineral in gold deposits, usually as an alloy with silver (electrum) and accompanied by a wide variety of minor and trace elements characteristic for the type of gold deposit where it originates from.
Mined gold	Gold that originates from mines (LSM or ASM) and has never been previously refined. The origin of mined gold is the gold deposit where it was extracted.
Placer gold[113]	Mined gold that has been extracted from sand and gravel deposits, most often in or near streams, typically as very small but visible pieces of gold; placer gold occurs usually in the form of "dust" (< 0.1 mm), "flakes" (0.1 – 0.5 mm) or "nuggets" (> 5 mm).
Gold concentrate	An intermediate material produced from processing of gold ore to achieve a higher concentration, but still requiring further intermediate processing to produce doré.
Gold sponge	Agglomeration of native gold particles from gold ore, gold concentrates or placer gold, resulting from amalgamating these particles with mercury and subsequent decomposition of the amalgam by burning (process nowadays is exclusively applied by ASM).

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[113] Commonly also called "alluvial gold", although it may origin from alluvial, eluvial, colluvial, etc. deposits.

Product	Description
Doré	Any smelted metallic product from mined gold with a purity less than the minimum specifications of refined gold (99.5 wt.% Au). Typically contains around 90% Au. A bar of metal alloy produced from mined gold. Generally originating from pyrometallurgical or hydrometallurgical processing of gold concentrates (mainly in LSM) or smelting of placer gold or gold sponges from amalgamation (mainly ASM).
Refined gold	Gold purified to standard specifications. Common specifications are "LBMA good delivery" requiring a purity of the metal of at least 99.5 wt.% Au, or the ASTM Standard (ASTM B 562 – 95), specifying requirements for purities 99.5, 99.95, 99.99 and 99.995 wt.% Au.
Bullion	Generic term for refined gold in bar or ingot form.
Jewelry alloy	Fine gold alloyed with different elements in refined form (according to standards for these elements; mainly Ag, Cu, Zn, Ni, Cd, Pt, Rh, etc.) to produce consistent optical, chemical and physical properties, suitable for commercial use in jewelry production.
Fake jewelry alloy	Doré alloyed with other metals with the purpose to simulate jewelry alloys and pretend gold scrap
Manufactured gold jewelry	Jewelry made out of jewelry alloy
Gold artefacts, ancient gold, ancient gold coins	Manufactured gold items from former times[114] that may contain a variety of minor and trace elements or even inclusions not common in contemporary jewelry alloys.
Gold scrap	Waste from jewelry manufacturing, used jewelry, electronics parts, and all other materials previously produced from refined gold, intended to be recycled to refined gold.[115]

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[114] Goldwork from the Varna cemetery in Bulgaria ranks as the oldest manufactured gold and is dated between 4560 -4450 BC (Higham et al. 2007).

[115] Comprises *Unprocessed recyclable gold*, *Melted recyclable gold*, and *Industrial By-products* as per definition of the OECD (2016).

Should the provenance of these types (products) of gold be evaluated, parameters will have to be defined that have the potential for distinguishing them. Therefore, a number of chemical and morphological attributes were defined and their usefulness for provenance analysis of (1) mined gold and (b) processed gold (doré) was discussed in chapter 2. Table 28 summarizes these findings.

Table 28: Parameters of potential use for gold provenance analysis (GPA)

	Parameter		Information	Problems	Usefulness for GPA
Mined gold	Morphology		Transport conditions; secondary vs. authigenic gold	High variability in secondary deposits; difficult to measure in primary deposits	limited
	Mineralogy		Deposit type, formation conditions	Access to inclusions in grains restricted, representativeness	limited
	Chemical composition	Major and trace elements	Deposit type	Few lattice-bound elements detectable, low detection limits needed	high
		Stable isotopes (e.g. Cu, Ag, Fe)	Provenance area, processes (primary and secondary)	No published results yet	unknown
		Radiogenic isotopes (e.g. U-Th-He, Re-Os, Pb-Pb)	Formation age, metal source	High analytical effort; not applicable in most cases due to low concentrations of radiogenic elements and/or diffusion problems	moderate
Processed gold (doré)	Chemical composition	Major and trace elements	Type of prevailing gold source (primary, secondary, scrap)	Mixture of different sources possible; some elements mobile during processing	high
		Stable isotopes	Prevailing provenance	Mixture of different sources possible	unknown
		Radiogenic isotopes	Prevailing Pb isotopic composition of the source	High analytical effort; mixture of different sources likely; He diffusion during melting prevents use of U-Th-He method	moderate

In chapter 3, methods are introduced that are presently used to analyze different types of gold, with a focus on gold grains, nuggets, concentrates, but also on processed (gold sponge) and smelted gold (doré). The methods have been classified according to the type of excitation energy and detection in Table 5. Additional method details are presented in Annex B.

Table 29 evaluates method performance to analyze certain parameters (outlined in Table 28), the type of analysis and the degree of sample destruction. It thus allows ranking of different methods with regards to their general suitability for Gold Provenance Analysis.

Table 29: Comparison of analytical methods for gold analysis.

Analysis item→ Method ↓	Solution	Solid sample	Bulk sample	In-situ	Major element	Minor element	Trace element	Isotope ratios	Destructive
ICP-OES	x		x		+++	+++	+		---
ICP-MS	x		x		++	+++	+++	+	---
ICP-MC-MS	x		x					+++	---
LA-ICP-MS		x		+	++	+++	+++	+	-
LA-MC-ICP-MS		x		+				+++	-
LIBS		x		+	++	++	++		-
Spark OES		x		++	+++	+++	++		--
GD-MS		x	x		+++	+++	++		--
EPMA		x		+++	+++	+++			
SEM		x		+++	+++	++			
PIXE		x		++	+++	+++	+		
XRF	x	x	x		+++	+++	+		-
SR-XRF		x		+	++	+++	++		
INAA		x	x		++	++	++		--
pXRF		x	x		+++	++	+		
pLIBS		x		+	++	++	+		-

See abbreviation list for full description of methods, and Table 7 in chapter 3 for explanation of symbols.

Chapter 4 explores the state of knowledge on the types and chemistry of gold mined in the eastern DRC. Four gold provinces are distinguished differing in deposit type (formation conditions), geological age, host rocks and mineralogy. Publicly available data on gold chemistry in central Africa is very limited. Therefore, it is not possible to evaluate in detail whether gold compositions really do differ significantly between these provinces. Similarly, the compositional variability within a given gold province cannot be assessed reliably. Compilation of the data available in the literature suggests that gold compositions might differ considerably. However, this needs to be further explored. Table 30 summarizes the findings on gold provinces in the eastern DRC and their geological extension into neighboring countries. It can accordingly be assumed that mined gold, gold processed by amalgamation and also smelted gold (doré), will preserve some – though not all – of the chemical characteristics inherent to their geological background. Potentially, these characteristics may be exploited for applying Gold Provenance Analysis.

Table 30: Summary of information on gold composition in the four "gold provinces" defined within the eastern DRC.

Gold Province	Northern	Lubero	Kibaran	Panafrican
Administrative province	Orientale/Ituri	North Kivu	North and South Kivu, Maniema, Katanga	South Kivu
Geological extension to neighboring countries	Uganda, Tanzania	Uganda	Burundi, Rwanda, SW Uganda	NW Burundi, SW Rwanda (?)
Age of mineralization	2.5-2.7 Ga	1.8-2.1 Ga	0.9-1.0 Ga	0.5-0.6 Ga
Types of gold mineralization	Mesothermal shear-zone-hosted gold associated with greenstone belts; alluvial deposits	Mesothermal quartz veins; association of gold and platinum-group elements in mafic-ultramafic intrusions; alluvial deposits	Mesothermal granite-related quartz veins; rare-metal pegmatites; eluvial and alluvial placers	Epithermal vein and ferruginous breccia-hosted deposits; eluvial and alluvial placers
Silver concentration	7-30%	No data	0-30%	<1-5%
Associated inclusions in gold	Pyrite, pyrrhotite, rare arsenopyrite, chalcopyrite, sphalerite, galena	PGM	Cassiterite, bismuthinite, arsenopyrite	Pyrite, arsenopyrite, native bismuth, bismuthinite, pyrrhotite, galena, sphalerite, chalcopyrite, covellite, native copper
Common detrital minerals in placer	magnetite; epidote	PGM, chromite	cassiterite, Nb-Ta oxides, wolframite, spodumene, beryl, tourmaline, zircon, monazite, garnet	graphite, beryl, tourmaline, cassiterite, scheelite, actinolite, calcite, Fe hydroxide/oxide
Typical trace elements to be expected	Cu, Zn, Pb, Bi, As	PGE, Ni	Bi, W, As, Sn, Mo, Te, Sb	Fe, Hg, Pd, Cu, As, Cd, Se

Chapter 5 reviews the gold supply chain originating from the DRC for both LSM and ASM settings. The LSM supply chain is seen as a straightforward closed pipe from three LSM mines (Kibali, Twangiza, Namoya; accounting for 99% of the official gold exports) delivering to one single destination (Rand Refinery) in South Africa. In contrast, the ASM supply chain consists of highly complex trade relations involving a large number of supply chain actors. Almost all of the ASM gold leaves the DRC without official export documents and ends up in Dubai. Table 31[116] shows that:

- The accuracy of potential Gold Provenance Analysis in terms of parameters characterizing the deposit and the applied mining and processing methods increases with each step upwards the gold supply chain.
- However, the number of required sampling points and samples for GPA increases proportional to the number of involved stakeholders at each trading stage and, therefore, exponentially with each step upwards the supply chain. This renders sampling progressively more unfeasible.

Table 31: Characteristics of products at different stages of the supply chain

Characteristics	ASM gold mines	Petits Négociants	Grands Négociants	Comptoirs or Gold Trader	Refiner
Number	> 1,515 sites > 16,000 pits > 176,000 miners	X * 1,000 (thousands)	X * 100 (hundreds)	X * 10 (tens)	in UAE < 10
Typical volume of transaction (sales)	0.1 – 5 g	~ 50 g	~ 500 g	~ 5,000 g (and higher)	N/A
Type of product sold	Mined gold (gravimetric or amalgamated)	Mined gold (gravimetric or amalgamated)	ASM Doré (from gravimetric or amalgamated gold)	Doré (from all kind of ASM products)	Refined gold, Jewelry alloys
Purity of product sold	Mined gold (extracted and processed with ASM technology)	As produced by miners	Increased purity due to smelting	Further increased purity due to re-smelting and possible pre-refining	Fineness: > 99.5%, mostly 99.99%
Geo-characteristics of deposit potentially retained in product	Characteristics of individual mine sites or pits	Characteristics of individual mine sites	Characteristics of sub-regional mineralized zones (clusters of similar deposits)	Possibly characteristics of single or mixed geological provinces (e.g. north / south)	None. Highly homogenized mix of sources
Signatures of mining and processing methods potentially retained in product	Clear identification of processing method applied at the mine site	Clear distinction between gravimetric processing and amalgamation	Limited; mercury traces from amalgamation possibly detectable	None. Highly homogenized mix of sources	None. Highly homogenized mix of sources

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[116] Combined from Table 19 and Table 20 in chapter 5.

Chapter 6 develops and describes three possible scenarios for GPA implementation.

(i) Product confirmation along local (closed pipe) supply chains from mine to refiner, notably for LSM or well-controlled ASM supply chains;

(ii) Verification of gold origin with regards to production regions in the DRC, to the extent that such regions reflect different geological provinces and fixed "catchment areas" for *comptoirs* and exporters to source gold from;

(iii) Assessment of the claimed origin of gold at international airports, either during the export or import procedure (the former in the Great Lakes Region and the latter taking place in Dubai or other international gold import destinations).

The scenarios, summarized in Table 32 and portrayed in detail in the Annexes, provide different starting points to enhance supply chain transparency at different segments of the upstream gold supply chain.

Table 32: Summary of GPA Scenarios based on the DRC ASM Gold Supply Chain

	(I) Local product confirmation	(II) Verification of production regions	(III) International claims of origin assessment
Main stakeholders	A-trader/*comptoir* ("agent")	Phase 1: OCC, CEEC; Phase 2: *comptoirs*	International organizations or customs authorities
Beneficiaries	Miners, obtaining access to formal markets Industry, through enhanced due diligence tools State, obtaining fiscal export revenues	State, obtaining a tool to validate claims of origin of gold at export point, and increased government revenues through enhanced transparency of the national gold supply chain	Reputational benefit for international gold trading hubs. ICGLR member states and international community, through curbing conflict financing and illicit financial flows
Samples	Concentrates, nuggets, sponge, (doré) Samples to be analyzed and returned to owner	Doré Samples to be analyzed and returned to owner	Doré Samples to be analyzed and returned to owner
Sampling points	Gold sold by mines and B-traders Gold exported by *comptoir* Gold imported by refiner	Stage 1: Gold exported by *comptoirs* Stage 2: Gold bought by *comptoirs* (or sold by A-traders)	Gold at export from producer country Gold passing through transit countries Gold at import into destination country

	(I) Local product confirmation	**(II) Verification of production regions**	**(III) International claims of origin assessment**
Analytical method	Major and trace element analysis (spectra) Non-destructive	Major and trace element analysis (spectra, quantified data), inclusions Non-destructive	Major and trace element analysis (spectra, quantified data) Non-destructive
Analytical equipment	pXRF or pLIBS	c) pXRF or pLIBS, d) stationary XRF or LIBS, microscopy	pXRF or pLIBS
Personnel skills	Sample preparation, measurement, data transfer, safety, data management	Sample preparation, measurement, data transfer, safety, data management	Sample preparation, measurement, safety, data management
Data processing	Standalone database, QR codes	Multiuser system, QR codes	Multiuser system, data comparison to international database
Outcome	Enhanced supply chain transparency, responsible supply chains	Good Governance through enhanced supply chain transparency	Peace building and combatting organized crime through reduced illicit financial flows

Implementing any single scenario would reinforce potential implementation of other scenarios. To this end, adequate sequencing as well as collaboration or support opportunities among different scenario beneficiaries should be explored. In particular the third, international scenario would require sampling efforts to build a reference database of regional gold compositions that could not easily be implemented by the direct users or beneficiaries of the scheme (e.g., customs authorities). However, such users could explore opportunities for supporting database building by other stakeholders while, in turn, gaining access to data generated through other scenarios.

In this sense, Scenarios I and II are seen as possible entry points and Scenario III as part of an upscaling strategy. All three scenarios require piloting to validate the underlying scientific and practical assumptions. It is recommended to conduct further research into development of the analytical methods, which represent a new application of known and available “high-tech” appliances, and to pilot the methods in (i) a closed pipe scenario and (ii) at national level export points from the DRC or other gold-producing countries.

ANNEXES

Annex A References

Altigani, M.A.H.; Merkle, R. K.W.; Dixon, R. D. (2016): Geochemical identification of episodes of gold mineralisation in the Barberton Greenstone Belt, South Africa. In *Ore Geology Reviews* 75, pp. 186–205. DOI: 10.1016/j.oregeorev.2015.12.016.

Angermeier, H.-O.; Krauß, U.; Kruszona, M.; Schmidt, H. (1974): Zaire. In *Rohstoffwirtschaftlicher Länderbericht* (3), p. 120.

Anthoine, R. (1921-1922): Sur la composition de l'or non affine des mines de Kilo-Moto. (PRCB XLV, C39-41).

Antweiler, J. C.; Campbell, W. L. (1977): Application of gold compositional analyses to mineral exploration in the United States. In *Journal of Geochemical Exploration* 8 (1-2), pp. 17–29. DOI: 10.1016/0375-6742(77)90041-3.

Antweiler, J. C.; Sutton, A. L., Jr. (1970): Spectrochemical analyses of native gold samples. In : US Geological Survey Report USGS-GD-70-003. Commerce National Technical Information Service: Springfield. Va.; US Geological Survey.; US Dept.

ARM (2014a): Fairmined Standard for Gold from Artisanal and Small-scale Mining, including Associated Precious Metals. Version 2. Available online at http://www.responsiblemines.org/images/sampledata/EstandarFairmined/Fairmined%20Stnd%202%200_2014_.pdf, checked on 9/18/2016.

ARM (2014b): Conflict Minerals Assessment in the DRC. USAID/IOM Regional Office (DRC) (COD/IMPL/NA0202/2014). Available online at n/a (copy from BGR).

ASTM B 562 – 95 (2005). Standard Specification for Refined Gold. Reapproved 2005. ASTM, checked on 6/20/2016.

Augé, T.; Bailly, L.; Bourbon, P.; Guerrot, C.; Viprey, L.; Telouk, P. (2015): Faisabilité technique d'une traçabilité physico-chimique de l'or de Guyane. Rapport WWF-BRGM/RP-64880-FR. BRGM. Orléans (FR) (145p). Available online at http://infoterre.brgm.fr/rapports/RP-64880-FR.pdf, checked on 8/25/2016.

Bafilemba, F.; Lezhnev, S. (2015): Congo's Conflict Gold Rush. Bringing gold into the legal trade in the Democratic Republic of Congo. The Enough Project. Available online at http://www.enoughproject.org/files/April%2029%202015%20Congo%20Conflict%20Gold%20Rush%20reduced.pdf, checked on 3/23/2016.

Baker, T.; Pollard, P.; Mustard, R.; Mark, G.; Graham, J. (2005): A comparison of granite-related tin, tungsten and gold-bismuth deposits: implications for exploration. In *Society of Economic Geologists Newsletter* 61, pp. 5–17.

BBC (5/5/2010): BBC News - Uganda opens refinery for Congo gold. Available online at http://news.bbc.co.uk/2/hi/africa/8662680.stm, checked on 7/24/2016.

Bendall, C.; Wigg-Wolf, D.; Lahaye, Y.; Kaenel, H.-M. von; BREY, G. P. (2009): Detecting changes of celtic gold sources through the application of trace element and Pb isotope laser ablation analysis of celtic gold coins. In *Archaeometry* 51 (4), pp. 598–625. DOI: 10.1111/j.1475-4754.2008.00423.x.

Blore, S. (2015a): Capacity Building for a Responsible Minerals Trade (CBRMT). Working with Producers to Responsibly Source Artisanal Gold from the Democratic Republic of the Congo. Tetra Tech. Burlington (US). Available online at http://www.resolv.org/site-ppa/files/2015/06/CBRMT-Gold-Assessment_REVISED-FINAL-WITH-COPY-EDIT.pdf, checked on 3/21/2016.

Blore, S. (2015b): Contraband Gold in the Great Lakes Region. In-region Cross-border Gold Flows Versus Out-region Smuggling. Hannover (DE): BGR. Available online at http://www.bgr.bund.de/EN/Themen/Min_rohstoffe/CTC/Downloads/contraband_gold_in_the_GLR.pdf?__blob=publicationFile&v=2, checked on 3/21/2016.

Bobin, O.; Guegan, H. (2009): A new approach to the authentication of goldwork. In *archeosciences* (33), pp. 341–347. DOI: 10.4000/archeosciences.2431.

Borg, G. (1994): The Geita gold deposit in NW Tanzania—geology, ore petrology, geochemistry and timing of events. In *Geologisches Jahrbuch D* 100, pp. 545–595.

Boyle, R. W. (1979): The geochemistry of gold and its deposits (together with a chapter on geochemical prospecting for the element). Ottawa: Geological Survey of Canada (Geological Survey bulletin, 280).

Brinckmann, J. (Ed.) (2001): La géologie et la minéralisation primaire de l'Or de la Chaîne Kibarienne, Nord-ouest du Burundi, Afrique Orientale. Avec 10 tableaux. Bundesanstalt für Geowissenschaften und Rohstoffe. Stuttgart: Schweizerbart (Geologisches Jahrbuch Reihe D, Mineralogie, Petrographie, Geochemie, Lagerstättenkunde, 101).

Bugoi, R.; Cojocaru, V.; Constantinescu, B.; Calligaro, T.; Pichón, L.; Röhrs, S.; Salomon, J. (2008): Compositional studies on Transylvanian gold nuggets: Advantages and limitations of PIXE–PIGE analysis. In *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 266 (10), pp. 2316–2319. DOI: 10.1016/j.nimb.2008.03.044.

Büttner, S. H.; Reid, W.; Glodny, J.; Wiedenbeck, M.; Chuwa, G.; Moloto, T.; Gucsik, A. (2016): Fluid sources in the Twangiza-Namoya Gold Belt (Democratic Republic of Congo). Evidence from tourmaline and fluid compositions, and from boron and Rb-Sr isotope systematics. In *Precambrian Research. DOI:* 10.1016/j.precamres.2016.05.006.

Cabral, A. R.; Eugster, O.; Brauns, M.; Lehmann, B.; Rosel, D.; Zack, T. et al. (2013): Direct dating of gold by radiogenic helium. Testing the method on gold from Diamantina, Minas Gerais, Brazil. In *Geology* 41 (2), pp. 163–166. DOI: 10.1130/G33751.1.

Cabral, A. R.; Lehmann, B.; Jedwab, J. (2012): Empirical Pt_7Cu from an alluvial platinum concentrate and its significance for platiniferous quartz lodes in the Lubero region, DR Congo. In *N. Jb. Miner. Abh.* 189 (2), pp. 217–221. DOI: 10.1127/0077-7757/2012/0222.

Cahen, L. (1954): Géologie du Congo Belge. Vaillant-Carmanne: Liège.

Chapman, R. J.; Leake, B.; Styles, M. T. (2002): Microchemical Characterization of Alluvial Gold Grains as an Exploration Tool. In *Gold Bull* 35 (2), pp. 53–65. DOI: 10.1007/BF03214838.

Chapman, R. J.; Leake, R. C.; Moles, N. R.; Earls, G.; Cooper, C.; Harrington, K.; Berzins, R. (2000): The Application of Microchemical Analysis of Alluvial Gold Grains to the Understanding of Complex Local and Regional Gold Mineralization: A Case Study in the Irish and Scottish Caledonides. In *Economic Geology* 95 (8), pp. 1753–1773. DOI: 10.2113/gsecongeo.95.8.1753.

Chapman, R. J.; Leake, R. C.; Warner, R. A.; Cahill, M. C.; Moles, N. R.; Shell, C. A.; Taylor, J. J. (2006): Microchemical characterisation of natural gold and artefact gold as a tool for provenancing prehistoric gold artefacts: A case study in Ireland. In *Applied Geochemistry* 21 (6), pp. 904–918. DOI: 10.1016/j.apgeochem.2006.01.007.

Chapman, R. J.; Mortensen, J. K. (2006): Application of microchemical characterization of placer gold grains to exploration for epithermal gold mineralization in regions of poor exposure. In *Journal of Geochemical Exploration* 91 (1-3), pp. 1–26. DOI: 10.1016/j.gexplo.2005.12.004.

Chapman, R. J.; Mortensen, J. K. (2016): Characterization of Gold Mineralization in the Northern Cariboo Gold District, British Columbia, Canada, Through Integration of Compositional Studies of Lode and Detrital Gold with Historical Placer Production. A Template for Evaluation of Orogenic Gold Districts. In *Economic Geology* 111 (6), pp. 1321–1345. DOI: 10.2113/econgeo.111.6.1321.

Clay, A.; Orford, T.; Ojo, G.; Myburgh, J.; Chirisa, M.; Dyke, S. (2014): Technical Report on the Namoya Gold Project, Maniema Province, Democratic Republic of the Congo. Prepared for Namoya Mining SARL (a subsidiary of Banro Corporation). Venmyn Deloite (Independent National Instrument 43-101, D1417R). Available online at http://www.banro.com/assets/docs/reports/2013-12-31_Namoya_NI-43-101.pdf, checked on 3/26/2016.

Constantinescu, B.; Bugoi, R.; Cojocaru, V.; Radtke, M.; Calligaro, T.; Salomon, J. et al. (2008): Micro-SR-XRF and micro-PIXE studies for archaeological gold identification – The case of Carpathian (Transylvanian) gold and of Dacian bracelets. In *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 266 (10), pp. 2325–2328. DOI: 10.1016/j.nimb.2008.03.054.

Constantinescu, B.; Bugoi, R.; Cojocaru, V.; Simon, R.; Grambole, D.; Munnik, F.; Oberländer-Târnoveanu, E. (2009): Elemental analysis through X-ray techniques applied in archeological gold authentication — the case of Transylvanian gold and of the Dacian bracelets. In *Spectrochimica Acta Part B: Atomic Spectroscopy* 64 (11-12), pp. 1198–1203. DOI: 10.1016/j.sab.2009.08.007.

Constantinescu, B.; Bugoi, R.; Cojocaru, V.; Voiculescu, D.; Grambole, D.; Herrmann, F.; Ceccato, D. (2005): Romanian ancient gold objects provenance studies using micro-beam methods: the case of "Pietroasa" hoard. In *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 231 (1-4), pp. 541–545. DOI: 10.1016/j.nimb.2005.01.114.

Constantinescu, B.; Vasilescu, A.; Radtke, M.; Reinholz, U.; Pacheco, C.; Pichón, L.; Oberländer-Târnoveanu, E. (2012): SR XRF and micro-PIXE studies on ancient metallurgy of thirteen Dacian gold bracelets. In *Appl. Phys. A* 109 (2), pp. 395–402. DOI: 10.1007/s00339-012-7306-7.

COSOC (2015): La ruée vers l'or à Shabunda. (gold rush in shabunda). COSOC-GL. Available online at http://cosoc-gl.org/wp-content/uploads/2016/05/15-ao%C3%BBt-2015-COSOC-GL-Etude-finale-sur-lexploitation-de-lor-par-dragues-%C3%A0-Shabunda-1.pdf, checked on 7/12/2016.

Cristea-Stan, D.; Constantinescu, B.; Chiojdeanu, C.; Ceccato, D.; Pacheco, C.; Pichón, L. (2012): Micro-PIXE and XRF studies on native gold from Cavnic ore deposit (Baia Mare District). In *Romanian Journal in Physics* 57 (3-4).

Crundwell, G. R. (2009): Enhancing the validity of the SAPS gold fingerprinting database through improved sample-collection techniques.

D'Souza, K. (2007): Artisanal Mining in the Democratic Republic of Congo. Key Issues, Challenges and Opportunities. Washington DC, Stoke-on-Trent (UK). Available online at http://www.eisourcebook.org/cms/Feb%202013/DRC%20Artisianal%20Mining,%20Key%20Issues,%20Challenges%20&%20Opportunities.pdf, checked on 12/23/2015.

Desborough, G. A. (1970): Silver depletion indicated by microanalysis of gold from placer occurrences, western United States. In *Economic Geology* 65 (3), pp. 304–311. DOI: 10.2113/gsecongeo.65.3.304.

Dixon, R. D. (2014): Provenance of illicit gold with emphasis on the Witwatersrand basin. Dissertation. University of Pretoria, Pretoria (SA). Faculty of Natural and Agricultural Sciences.

Dixon, R. D.; Ueckermann, H.; Espach, H. J.; Jager, L. L. de; Roberts, R. J. (2007): Combating the Illegal Gold Trade Using Chemical Profiling. In The American Academy of Forensic Sciences (Ed.): Proceedings of the American Academy of Forensic Sciences. AAFS annual meeting. San Antonio, February (XIII).

Dube, R. K. (2006): Interrelation between gold and tin. A historical perspective. In *Gold Bull* 39 (3), pp. 103–113. DOI: 10.1007/BF03215537.

Dussubieux, L.; van Zelst, L. (2004): LA-ICP-MS analysis of platinum-group elements and other elements of interest in ancient gold. In *Applied Physics A: Materials Science & Processing* 79 (2), pp. 353–356. DOI: 10.1007/s00339-004-2532-2.

Dzyubenko, M. I.; Kolpakov, S. N.; Kulishenko, D. F.; Priyomko, A. A. (2010): Rapid analysis of emission spectra for gold alloys. In *J Appl Spectrosc* 77 (2), pp. 279–284. DOI: 10.1007/s10812-010-9327-3.

Ehser, A.; Borg, G.; Pernicka, E. (2011): Provenance of the gold of the Early Bronze Age Nebra Sky Disk, central Germany: geochemical characterization of natural gold from Cornwall. In *Eur.J.Mineral.* 23 (6), pp. 895–910. DOI: 10.1127/0935-1221/2011/0023-2140.

El-Taher, A.; Kratz, K.-L; Nossair, A.; Azzam, A.H (2003): Determination of gold in two Egyptian gold ores using instrumental neutron activation analysis. In *Radiation Physics and Chemistry* 68 (5), pp. 751–755. DOI: 10.1016/S0969-806X(03)00401-8.

Eugster, O. (1996): Dating gold artifacts applications for noble gas analyses of gold. In *Gold Bull* 29 (3), pp. 101–104. DOI: 10.1007/BF03214743.

Eugster, O.; Kramers, J.; Krähenbühl, U. (2009a): Detecting forgeries among ancient gold objects using the U,Th-4 He dating method. In *Archaeometry* 51 (4), pp. 672–681. DOI: 10.1111/j.1475-4754.2008.00426.x.

Eugster, O.; Pernicka, E.; Brauns, M.; Shukolyukov, A.; Olive, V.; Roellin, S. (2009b): Helium, uranium and thorium analyses of ancient and modern gold objects. Estimates of their time of manufacturing. In *archeosciences* (33), pp. 59–69. DOI: 10.4000/archeosciences.2017.

Freyssinet, Ph; Butt, C. R. M.; Morris, R. C.; Piantone, P. (2005): Ore-forming processes related to lateritic weathering. In *Economic Geology 100th Anniversary Volume* 1, pp. 681–722.

Gäbler, H.-E.; Rehder, S.; Bahr, A.; Melcher, F.; Goldmann, S. (2013): Cassiterite fingerprinting by LA-ICP-MS. In *J. Anal. At. Spectrom.* 28 (8), p. 1247. DOI: 10.1039/c3ja50106j.

Galbács, G.; Jedlinszki, N.; Cseh, G.; Galbács, Z.; Túri, L. (2008): Accurate quantitative analysis of gold alloys using multi-pulse laser induced breakdown spectroscopy and a correlation-based calibration method. In *Spectrochimica Acta Part B: Atomic Spectroscopy* 63 (5), pp. 591–597. DOI: 10.1016/j.sab.2008.03.001.

Gauert, C.; Schannor, M.; Hecht, L.; Radtke, M.; Reinholz, U. (2015): A Comparison of In Situ Analytical Methods for Trace Element Measurement in Gold Samples from Various South African Gold Deposits. In *Geostand Geoanal Res*, pp. n/a. DOI: 10.1111/j.1751-908X.2015.00362.x.

Geenen, S. (2011): Relations and regulations in local gold trade networks in South Kivu, Democratic Republic of Congo. In *Journal of Eastern African Studies* 5 (3), pp. 427–446. DOI: 10.1080/17531055.2011.611676.

George, M. W. (2015): Conflict minerals from the Democratic Republic of the Congo--Gold supply chain (ver. 1.1, December 10, 2015). Edited by U.S. Geological Survey (Fact Sheet, 2015-3075). Available online at http://dx.doi.org/10.3133/fs20153075.

GoE (2014): Letter dated 22 January 2014. UN Security Council. New York (UN) (S/2014/42*). Available online at https://documents-dds-ny.un.org/doc/UNDOC/GEN/N14/215/15/PDF/N1421515.pdf, checked on 3/21/2016.

GoE (2015a): Letter dated 12 January 2015. UN Security Council. New York (UN) (S/2015/19*). Available online at https://documents-dds-ny.un.org/doc/UNDOC/GEN/N14/663/72/PDF/N1466372.pdf, checked on 3/21/2016.

GoE (2015b): Letter dated 16 October 2015. UN Security Council. New York (UN) (S/2015/797*). Available online at https://documents-dds-ny.un.org/doc/UNDOC/GEN/N15/292/17/PDF/N1529217.pdf, checked on 3/21/2016.

GoE (2016): Letter dated 23 May 2016. UN Security Council. New York (UN) (S/2016/466). Available online at http://www.un.org/ga/search/view_doc.asp?symbol=S/2016/466, checked on 8/8/2016.

Goldmann, S. (2016): Mineralogical-Geochemical Characterisation of Cassiterite and Wolframite Ores for an Analytical Fingerprint: Focus on Trace Element Analysis by LA-ICP-MS. Dissertation. Leibniz Universität Hannover, Hannover (DE). Naturwissenschaftliche Fakultät.

Gondonneau, A.; Guerra, M. F.; Cowell (2000): Searching for the provenance of gold. The methodology of gold analysis by ICP-MS: first developments. In *Archaeometry*.

Grayson, R. (2013): The Gold Miners Book. Ulaanbaatar (MN) & Manchester (UK): Eco-Minex International.

Grigorova, B.; Anderson, S.; Bruyn, J. de; Smith, W.; Stülpner, K.; Barzev, A. (1998): The AARL gold fingerprinting technology. In *Gold Bulletin* 31 (1), pp. 26–29.

Groves, D. I.; Goldfarb, R. J.; Gebre-Mariam, M.; Hagemann, S. G.; Robert, F. (1998): Orogenic gold deposits: A proposed classification in the context of their crustal distribution and relationship to other gold deposit types. In *Ore Geology Reviews* 13 (1-5), pp. 7–27. DOI: 10.1016/S0169-1368(97)00012-7.

Guerra, M. F. (2004): Fingerprinting ancient gold with proton beams of different energies. In *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 226 (1-2), pp. 185–198. DOI: 10.1016/j.nimb.2004.02.019.

Guerra, M. F. (2008): An overview on the ancient goldsmith's skill and the circulation of gold in the past: the role of x-ray based techniques. In *X-Ray Spectrom.* 37 (4), pp. 317–327. DOI: 10.1002/xrs.1013.

Guerra, M. F. (2014): Role of radiation physics in the study and authentication of ancient gold work. In *Radiation Physics and Chemistry* 95, pp. 356–361. DOI: 10.1016/j.radphyschem.2013.01.041.

Guerra, M. F.; Calligaro, T. (2003): Gold cultural heritage objects: a review of studies of provenance and manufacturing technologies. In *Measurement Science and Technology* 14 (9), p. 1527. Available online at http://stacks.iop.org/0957-0233/14/i=9/a=305.

Guerra, M. F.; Calligaro, T. (2004): Gold traces to trace gold. In *Journal of Archaeological Science* 31 (9), pp. 1199–1208. DOI: 10.1016/j.jas.2002.05.001.

Guerra, M. F.; Radtke, M.; Reiche, I.; Riesemeier, H.; Strub, E. (2008): Analysis of trace elements in gold alloys by SR-XRF at high energy at the BAMline. In *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 266 (10), pp. 2334–2338. DOI: 10.1016/j.nimb.2008.03.008.

Hallbauer, D. K.; Utter, T. (1977): Geochemical and morphological characteristics of gold particles from recent river deposits and the fossil placers of the Witwatersrand. In *Mineral. Deposita* 12 (3). DOI: 10.1007/BF00206168.

Hancock, E. A. (2009): Mineralogy and trace element chemistry of lode and alluvial gold from the Western Capricorn Orogen. East Perth, W.A.: Geological Survey of Western Australia (Record, 2009/6).

Hark, R. R.; Remus, J.; East, L. J.; Harmon, R. S.; Wise, M. A.; Tansi, B. M. et al. (2012): Geographical analysis of “conflict minerals” utilizing laser-induced breakdown spectroscopy. In *Spectrochimica Acta Part B: Atomic Spectroscopy* 74-75, pp. 131–136. DOI: 10.1016/j.sab.2012.06.052.

Harmon, R. S.; DeLucia, F. C.; McManus, C. E.; McMillan, N. J.; Jenkins, T. F.; Walsh, M. E.; Miziolek, A. W. (2006): Laser-induced breakdown spectroscopy – An emerging chemical sensor technology for real-time field-portable, geochemical, mineralogical, and environmental applications. In *Applied Geochemistry* 21 (5), pp. 730–747. DOI: 10.1016/j.apgeochem.2006.02.003.

Harmon, R. S.; Remus, J.; McMillan, N. J.; McManus, C. E.; Collins, L.; Gottfried, J. L. et al. (2009): LIBS analysis of geomaterials. Geochemical fingerprinting for the rapid analysis and discrimination of minerals. In *Applied Geochemistry* 24 (6), pp. 1125–1141. DOI: 10.1016/j.apgeochem.2009.02.009.

Harmon, R. S.; Shughrue, K. M.; Remus, J.; Wise, M. A.; East, L. J.; Hark, R. R. (2011): Can the provenance of the conflict minerals columbite and tantalite be ascertained by laser-induced breakdown spectroscopy? In *Analytical and bioanalytical chemistry* 400 (10), pp. 3377–3382. DOI: 10.1007/s00216-011-5015-2.

Hartmann, A. (1970): Prähistorische Goldfunde aus Europa II. Studien zu den Anfängen der Metallurgie (SAM), Band 5, Gebr: Mann Verlag, Berlin.

Hartmann, A. (1982): Prähistorische Goldfunde aus Europa II. Spektralanalytische Untersuchungen und deren Auswertung. SAM 5. Berlin: Gebr: Mann Verlag.

Haustein, M.; Gillis, C.; Pernicka, E. (2010): Tin Isotopy- A New Method for Solving Old Questions. In *Archaeometry* 52 (5), pp. 816–832. DOI: 10.1111/j.1475-4754.2010.00515.x.

Hayes, K.; Bawa, Y.; et.al. (2010): PROMINES Study. Artisanal Mining in the Democratic Republic of Congo. Pact. Washington DC. Available online at http://congomines.org/system/attachments/assets/000/000/349/original/PACT-2010-ProminesStudyArtisanalMiningDRC.pdf, checked on 3/21/2016.

Henckel, J.; Poulsen, K. H.; Sharp, T.; Spora, P. (2016): Lake Victoria Goldfields. In *Episodes* 39 (2), p. 135. DOI: 10.18814/epiiugs/2016/v39i2/95772.

Hinds, M. W. (2015): Study of Element Fingerprinting in gold doré by glow discharge mass spectrometry. Presentation at LBMA Assaying & Refining Conference 8.-10. 03. 2015. London (UK), 2015, checked on 5/17/2016.

Hoffman, E. L. (1992): Instrumental neutron activation in geoanalysis. In *Journal of Geochemical Exploration* 44 (1-3), pp. 297–319. DOI: 10.1016/0375-6742(92)90053-B.

Hoffman, E. L.; Clark, J. R.; Yeager, J. R. (1998): Gold analysis; fire assaying and alternative methods. In *Exploration and Mining Geology* 7 (1-2), pp. 155–160.

Hough, R. M.; Butt, C. R. M.; Fischer-Buhner, J. (2009): The Crystallography, Metallography and Composition of Gold. In *Elements* 5 (5), pp. 297–302. DOI: 10.2113/gselements.5.5.297.

Hruschka, F.; Melcher, F.; Kain-Bückner, B. (2016): Analytical Tools to Constrain the Origin of Gold from Conflict-affected and High-Risk Areas Scoping Study, Part I: Method Screening. Hannover (DE): BGR.

IPIS (2012): The Formalisation of Artisanal Mining in the Democratic Republic of the Congoand Rwanda. Bogor (ID) (CIFOR, EuropeAid/ENV/2010-242904/TPS). Available online at http://www.cifor.org/fileadmin/subsites/proformal/PDF/RIPIS1212.pdf, checked on 3/21/2016.

IPIS (2014): Analysis of the interactive map of artisanal mining areas in Eastern DR Congo: May 2014 update. IPIS. Antwerp (BE). Available online at http://ipisresearch.be/wp-content/uploads/2014/04/20141031-Promines_analysis.pdf, checked on 3/25/2016.

IPIS (2015a): Mineral supply chains and conflict links in eastern Democratic Republic of Congo. Five years of implementing supply chain due diligence. OECD. Paris (FR) (Responsible business conduct). Available online at http://mneguidelines.oecd.org/Mineral-Supply-Chains-DRC-Due-Diligence-Report.pdf, checked on 12/28/2015.

IPIS (2015b): Review of the Burundian Artisanal Gold Mining Sector. BGR. Available online at http://www.bgr.bund.de/EN/Themen/Min_rohstoffe/CTC/Downloads/burundi_ASM_gold.pdf?__blob=publicationFile&v=2, checked on 7/24/2016.

IPIS (2016): Interactive map of artisanal mining areas in eastern DR Congo. IPIS. Website. Available online at http://www.ipisresearch.be/mapping/webmapping/drcongo/v4, updated on 10/25/2016, checked on 10/27/2016.

Jansen, M.; Aulbach, S.; Hauptmann, A.; Höfer, H. E.; Klein, S.; Krüger, M.; Zettler, R. L. (2016): Platinum group placer minerals in ancient gold artifacts – Geochemistry and osmium isotopes of inclusions in Early Bronze Age gold from Ur/Mesopotamia. In *Journal of Archaeological Science* 68, pp. 12–23. DOI: 10.1016/j.jas.2016.02.004.

Jedwab, J.; Cervelle, B.; Gouet, G.; Hubaut, X.; Piret, P. (1992): The new platinum selenide luberoite Pt_5Se_4 from the Lubero region (Kivu province, Zaire). In *European journal of mineralogy* 4 (4), pp. 683–692.

Junk, S. A. (2001): Ancient artefacts and modern analytical techniques – Usefulness of laser ablation ICP-MS demonstrated with ancient gold coins. In *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 181 (1-4), pp. 723–727. DOI: 10.1016/S0168-583X(01)00366-4.

Junk, S. A.; Pernicka, E. (2003): An Assessment of Osmium Isotope Ratios as a New Tool to Determine the Provenance of Gold with Platinum-Group Metal Inclusions*. In *Archaeometry* 45 (2), pp. 313–331. DOI: 10.1111/1475-4754.00110.

Kelley, K. J. (2014): EA fingered in $400m worth of DR Congo gold smuggled to Uganda. The EastAfrican. Kenya. Available online at http://www.theeastafrican.co.ke/news/Smuggled--400m-DR-Congo-gold-fuels-war-/-/2558/2198074/-/view/printVersion/-/ujr30v/-/index.html., checked on 5/29/2016.

Kirk, J.; Ruiz, J.; Chesley, J; Walshe, J.; England, G. (2002): A major Archean, gold- and crust-forming event in the Kaapvaal craton, South Africa. In *Science (New York, N.Y.)* 297 (5588), pp. 1856–1858. DOI: 10.1126/science.1075270.

Knight, J. B.; Mortensen, J. K.; Morison, S. R. (1999): Lode and placer gold composition in the Klondike District, Yukon Territory, Canada; implications for the nature and genesis of Klondike placer and lode gold deposits. In *Economic Geology* 94 (5), pp. 649–664. DOI: 10.2113/gsecongeo.94.5.649.

Kovacs, R.; Schlosser, S.; Staub, S. P.; Schmiderer, A.; Pernicka, E.; Günther, D. (2009): Characterization of calibration materials for trace element analysis and fingerprint studies of gold using LA-ICP-MS. In *J. Anal. At. Spectrom.* 24 (4), p. 476. DOI: 10.1039/b819685k.

Krüger, M. (2014): Beiträge zur präzisen Bestimmung von Os-Isotopenverhältnisse. Dissertation. Gottfried Wilhelm Leibniz Universität Hannover, Hannover (DE). Naturwissenschaftliche Fakultät. Available online at http://edok01.tib.uni-hannover.de/edoks/e01dh14/789531704.pdf.

Kucha, H.; Raith, J. G. (2009): Gold-oxysulphides in copper deposits of the Greywacke Zone, Austria. A mineral chemical and infrared fluid inclusion study. In *Ore Geology Reviews* 35 (1), pp. 87–100. DOI: 10.1016/j.oregeorev.2008.10.004.

Lavreau, J. J. (1973): New data about the kilo-moto gold deposits (Zaire). In *Mineral. Deposita* 8 (1). DOI: 10.1007/BF00203345.

Leake, R. C.; Chapman, R. J.; Bland, D. J.; Stone, P.; Cameron, D. G.; Styles, M. T. (1998): The origin of alluvial gold in the Leadhills area of Scotland. Evidence from interpretation of internal chemical characteristics. In *Journal of Geochemical Exploration* 63 (1), pp. 7–36. DOI: 10.1016/S0375-6742(98)00012-0.

Levin, E.; Cook, R.; Chishugi, A.; Jorns, A.; Mulumeoderhwa, P. (2014): Etude comparative des systèmes de Certification et de Traçabilité en cours en République Démocratique du Congo (RDC) et dans le monde, en vue de proposer un système approprié aux besoins du pays et répondant aux exigences internationales. Projet du Rapport Final. Estelle Levin Ltd. Cambridge (UK) (AMI N°21/UEP-PROMINES/05-2013). Available online at n/a (copy from BGR).

Lutz, J.; Pernicka, E. (2013): Prehistoric copper from the Eastern Alps. In *Open Journal of Archaeometry* 1 (1), p. 25. DOI: 10.4081/arc.2013.e25.

Marsden, J.; House, I. (2006): The chemistry of gold extraction. 2nd ed. Littleton, Colo: Society for Mining Metallurgy and Exploration. Available online at http://purl.oclc.org/DLF/benchrepro0212.

Martin, A.; Taylor, B. (2014): All that Glitters is Not Gold: Dubai, Congo and the Illicit Trade of Conflict Minerals. Otawa (CA): Partnership Africa Canada (PAC). Available online at http://www.pacweb.org/images/PUBLICATIONS/All%20That%20Glitters.pdf, checked on 12/10/2015.

Matthysen, K.; Hilgert, F.; Schouten, P.; Mabolia, A. (2011): A detailed analysis of Orientale Province's gold sector. IPIS. Antwerp (BE). Available online at https://www.academia.edu/19573097/A_detailed_analysis_of_Orientale_Province_s_gold_sector, checked on 7/12/2016.

McInnes, M.; Greenough, J. D.; Fryer, B. J.; Wells, R. (2008): Trace elements in native gold by solution ICP-MS and their use in mineral exploration: A British Columbia example. In *Applied Geochemistry* 23 (5), pp. 1076–1085. DOI: 10.1016/j.apgeochem.2007.12.027.

Melcher, F.; Graupner, T.; Gäbler, H.-E.; Sitnikova, M.; Henjes-Kunst, F.; Oberthür, T. et al. (2015): Tantalum–(niobium–tin) mineralisation in African pegmatites and rare metal granites. Constraints from Ta–Nb oxide mineralogy, geochemistry and U–Pb geochronology. In *Ore Geology Reviews* 64, pp. 667–719. DOI: 10.1016/j.oregeorev.2013.09.003.

Merkle, R. K.W.; Dixon, R. D. (2006): Possibilities and limitations of trace element characterization (fingerprinting) of precious materials. Kobe, Japan, 7/23/2006 (Abstract 016-01).

Merkle, R. K.W.; Dixon, R. D.; Kijko, A. (2004): Trace element characterization of gold and platinum-group element deposits and products in South Africa. In *Applied Mineralogy: Developments in Science and Technology, ICAM 2004*.

Milesi, J. P.; Toteu, S. F.; Deschamps, Y.; Feybesse, J. L.; Lerouge, C.; Cocherie, A. et al. (2006): An overview of the geology and major ore deposits of Central Africa: Explanatory note for the 1:4,000,000 map "Geology and major ore deposits of Central Africa". In *Journal of African Earth Sciences* 44 (4-5), pp. 571–595. DOI: 10.1016/j.jafrearsci.2005.10.016.

Ministère des Mines (2016): Statistiques Minières de l'année 2015. Kinshasa, DRC. Available online at http://mines-rdc.cd/fr/documents/Statistiques/2015/Statistiques_minieres_annee_2015.pdf, checked on 7/24/2016.

MIRENA (1982): Carte des gîtes minéraux du Rwanda. 1:250,000. Paris (FR).

Morrison, G. W.; Rose, W. J.; Jaireth, S. (1991): Geological and geochemical controls on the silver content (fineness) of gold in gold-silver deposits. In *Ore Geology Reviews* 6 (4), pp. 333–364. DOI: 10.1016/0169-1368(91)90009-V.

Mortensen, J. K.; Chapman, R. J.; Lebarge, W. P.; Crawford, E. C. (2005): Compositional studies of placer and lode gold from western Yukon: Implications for lode sources. In *Yukon Exploration and Geology*, pp. 247–255.

Mortensen, J. K.; Chapman, R. J.; Lebarge, W. P.; Jackson, L. (2004): Application of placer and lode gold geochemistry to gold exploration in western Yukon. In *Yukon Exploration and Geology* 2004, pp. 205–212.

Mthembu-Salter, G. (2014a): Baseline study one: Musebe artisanal mine, Katanga Democratic Republic of Congo. OECD. Paris (FR) (9th Multi-stakeholder forum on responsible mineral supply chains, 4-6 May 2015). Available online at http://www.oecd.org/daf/inv/mne/Gold-Baseline-Study-1.pdf, checked on 12/28/2015.

Mthembu-Salter, G. (2014b): Baseline study two: Mukungwe artisanal mine, South Kivu, Democratic Republic of Congo. OECD. Paris (FR) (9th Multi-stakeholder forum on responsible mineral supply chains, 4-6 May 2015). Available online at http://www.oecd.org/daf/inv/mne/Gold-Baseline-Study-2.pdf, checked on 12/28/2015.

Mthembu-Salter, G. (2015a): Baseline study four: Gold trading and export in Kampala, Uganda. OECD. Paris (FR). Available online at https://www.oecd.org/daf/inv/mne/Gold-Baseline-Study-4.pdf, checked on 7/24/2016.

Mthembu-Salter, G. (2015b): Baseline study three: Production, trade and export of gold in Orientale Province, Democratic Republic of Congo. OECD. Paris (FR) (9th Multi-stakeholder forum on responsible mineral supply chains, 4-6 May 2015). Available online at http://www.oecd.org/daf/inv/mne/Gold-Baseline-Study-3.pdf, checked on 12/28/2015.

Mudder, T.; Botz, M.; Smith, A. (2001): Chemistry & Treatment of Cyanidation Wastes. Second. London (GB): Mining Journal Books. Available online at http://dana6.free.fr/3%20060713%20English%20Compendium.pdf, checked on 5/31/2016.

Nikolaeva, L. A.; Nekrasova, A. N.; Milyaev, S. A.; Yablokova, S. V.; Gavrilov, A. M. (2013): Geochemistry of native gold from deposits of various types. In *Geol. Ore Deposits* 55 (3), pp. 176–184. DOI: 10.1134/S1075701513030045.

Nyakecho, C.; Hagemann, S. G. (2014): An overview of gold systems in Uganda. In *Australian Journal of Earth Sciences* 61 (1), pp. 59–88. DOI: 10.1080/08120099.2013.831773.

Oberthür, T.; Saager, R. (1986): Silver and mercury in gold particles from the Proterozoic Witwatersrand placer deposits of South Africa; metallogenic and geochemical implications. In *Economic Geology* 81 (1), pp. 20–31. DOI: 10.2113/gsecongeo.81.1.20.

OECD (2016): OECD Due diligence guidance for responsible supply chains of minerals from conflict-affected and high-risk areas. 3. edition. Paris (FR): OECD. Available online at http://www.oecd.org/daf/inv/mne/OECD-Due-Diligence-Guidance-Minerals-Edition3.pdf, checked on 5/30/2016.

Outridge, P. M.; Doherty, W.; Gregoire, D. C. (1998): Determination of trace elemental signatures in placer gold by laser ablation–inductively coupled plasma–mass spectrometry as a potential aid for gold exploration. In *Journal of Geochemical Exploration* 60 (3), pp. 229–240. DOI: 10.1016/S0375-6742(97)00049-6.

PAC (2014): Tracking, Certifying and Exporting Artisanal Gold from Eastern DRC. Summary Evaluation of Pilot Project at Mangi. Partnership Africa Canada (PAC). Available online at http://www.resolv.org/site-ppa/files/2013/02/Final-phase-III-and-summary-evaluation-FINAL-GC-WG-PAC-Comments-FINAL.pdf, checked on 3/21/2016.

Pernicka, E. (2014): Possibilities and limitations of provenance studies of ancient silver and gold. Metalle der Macht - frühes Gold und Silber. Halle (Saale): Landesamt für Denkmalpflege und Archäologie Sachsen-Anhalt Landesmuseum für Vorgeschichte (Tagungen des Landesmuseums für Vorgeschichte Halle).

Pittuck, M.; Waldeck, H.; Rautenbach, R. (2011): Technical Report, Twangiza Phase 1 Gold Project, South Kivu Province, Democratic Republic of the Congo. Senet. Modderfontein (SA) (Independent National Instrument 43-101.). Available online at http://www.banro.com/assets/docs/reports/Twangiza_Phase_I_43-101_Technical_Report_24_March_2011.pdf, checked on 3/26/2016.

Pohl, W. L. (1994): Metallogeny of the northeastern Kibara belt, Central Africa—Recent perspectives. In *Ore Geology Reviews* 9 (2), pp. 105–130. DOI: 10.1016/0169-1368(94)90024-8.

Pohl, W. L. (2011): Economic Geology Principles and Practice. Oxford, UK: Wiley-Blackwell.

Pohl, W. L.; Biryabarema, M.; Lehmann, B. (2013): Early Neoproterozoic rare metal (Sn, Ta, W) and gold metallogeny of the Central Africa Region. A review. In *Applied Earth Science* 122 (2), pp. 66–82. DOI: 10.1179/1743275813Y.0000000033.

Pop, D.; Ionescu, C.; Forray, F.; Tămaş, C. G,; Benea, Marcel (2011): "Transylvanian gold" of hydrothermal origin. An EMPA study in an archaeological provenancing perspective. In *Eur.J.Mineral.* 23 (6), pp. 911–923. DOI: 10.1127/0935-1221/2011/0023-2156.

Potts, Philip J.; West, Margaret (2008): Portable X-ray Fluorescence Spectrometry. Cambridge: Royal Society of Chemistry.

Priester, M.; Hentschel, T.; Benthin, B. (1993): Tools for mining. techniques and processes for small scale mining. Braunschweig (DE): Vieweg.

Radtke, M.; Reinholz, U.; Riesemeier, H. (2009): Synchrotron Radiation Induced X-Ray Fluorescence for the characterization of ancient gold objects. In *archeosciences* (33), pp. 39–44. DOI: 10.4000/archeosciences.1969.

Rammlmair, D.; Lyatuu, D.; Makyao, F. (1994): Gold Quartz Veins in the Nyarkagwe Area of NW Tanzania: Structural, Geochemical and Mineralogical Investigations. In *Geologisches Jahrbuch* D100, pp. 597–637.

Roberts, R. J.; Dixon, R. D.; Merkle, R. K.W. (2016): Distinguishing Between Legally and Illegally Produced Gold in South Africa. In *J Forensic Sci* 61, pp. S230-S236. DOI: 10.1111/1556-4029.12886.

Rumvegeri, B. T.; Bingen, B.; Derro, M. H. (2004): Tectonomagmatic evolution of the Kibaran belt in Central Africa and its relationships with mineralizations: a review. In *Africa Geoscience Review* 11, pp. 65–74.

Safiannikoff, A. (1952): Minéralisation aurifère et stannifère dans la concession sud de la Compagnie Minière des Grand Lacs Africains (vol. II) (t. II), p.465-483.

Schink, W. (2014): Geochemical characteristics of the Twangiza orogenic gold deposit, DR Congo. Masterthesis. TU Clausthal, Clausthal-Zellerfeld. Institute of Disposal Research.

Schlosser, S.; Kovacs, R.; Pernicka, E.; Günther, D.; Tellenbach, M. (2009): Fingerprints in Gold. In M. Reindel, G. A. Wagner (Eds.): New Technologies for Archaeology. Berlin, Heidelberg: Springer Berlin Heidelberg (Natural Science in Archaeology), pp. 409–436.

Schlosser, S.; Reinecke, A.; Schwab, R.; Pernicka, E.; Sonetra, S.; Laychour, Vin (2012): Early Cambodian gold and silver from Prohear: composition, trace elements and gilding. In *Journal of Archaeological Science* 39 (9), pp. 2877–2887.

Schmiderer, A. (2009): Geochemische Charakterisierung von Goldvorkommen in Europa. Dissertation. Martin Luther Universität Halle-Wittenberg. Institut für Geowissenschaften.

Service Géologique Zaïre (1974): Notice explicative de la carte des gîtes minéraux du Zaire.

Standish, C. D.; Dhuime, B.; Chapman, R. J.; Coath, C; Hawkesworth, C. J.; Pike, A.W.G. (2013): Solution and laser ablation MC-ICP-MS lead isotope analysis of gold. In *J. Anal. At. Spectrom.* 28 (2), pp. 217–225. DOI: 10.1039/C2JA30277B.

Standish, C. D.; Dhuime, B.; Chapman, R. J.; Hawkesworth, C. J.; Pike, A.W.G. (2014): The genesis of gold mineralisation hosted by orogenic belts: A lead isotope investigation of Irish gold deposits. In *Chemical Geology* 378-379, pp. 40–51. DOI: 10.1016/j.chemgeo.2014.04.012.

Standish, C. D.; Dhuime, B.; Hawkesworth, C. J.; Pike, A.W.G. (2015): A Non-local Source of Irish Chalcolithic and Early Bronze Age Gold. In *Proc. Prehist. Soc.* 81, pp. 149–177. DOI: 10.1017/ppr.2015.4.

Stumpfl, E. F.; Clark, M. (1965): Electron-probe microanalysis of gold-platinoid concentrates from southeast Borneo. In *Transactions of the Institution of Mining and Metallurgy* 74, pp. 933–946.

Tack, L.; Wingate, M.T.D.; Waele, B. de; Meert, J.; Belousova, E.; Griffin, B. et al. (2010): The 1375 Ma “Kibaran event” in Central Africa. Prominent emplacement of bimodal magmatism under extensional regime. In *Precambrian Research* 180 (1-2), pp. 63–84. DOI: 10.1016/j.precamres.2010.02.022.

Taggart, A. F.; Behre, H. A. (1945): Handbook of mineral dressing. New York: John Wiley & Sons (Wiley handbook series).

Tetland, M. (2015): Trace element analysis of placer gold. Dissertation. University of British Columbia.

Townley, B. K.; Herail, G.; Maksaev, V.; Palacios, C.; Parseval, P. d.; Sepulveda, F. et al. (2003): Gold grain morphology and composition as an exploration tool: application to gold exploration in covered areas. In *Geochemistry: Exploration, Environment, Analysis* 3 (1), pp. 29–38. DOI: 10.1144/1467-787302-042.

UNEP (2012): Mercury. Time to act. Geneve (CH): Unep. Available online at http://www.unep.org/PDF/PressReleases/Mercury_TimeToAct.pdf, checked on 5/27/2016.

van Straaten, H. P. (1984): Gold mineralization in Tanzania—a review. In : Gold, vol. 82, pp. 673–685.

Vasilescu, A.; Constantinescu, B. (2011): XRF-based Compositional Microanalysis for Provenance Studies of Metallic Artifacts. In *Romanian Reports in Physics* 63 (4), pp. 901–911.

Vasilescu, A.; Constantinescu, B.; Bugoi, R. (2011): Micro-SR-XRF studies of gold provenance in archaeology. In *Rom. J. Phys* 56, pp. 366–372.

Villeneuve, M. (1983): Les sillons tectoniques du Precambrien superieur dans l’est du Zai’re; comparaisons avec les directions du rift est-africain. In *Bull Centres Rech Explor-Prod Elf-Aquitaine* 7 (1), pp. 163–174.

Villeneuve, M. (1987): Géologie du synclinal de l'Itombwe (Zaïre oriental) et le problème de l'existence d'un sillon plissé pan-africain. In *Journal of African Earth Sciences (1983)* 6 (6), pp. 869–880. DOI: 10.1016/0899-5362(87)90046-7.

Walemba, K.M.A. (2014): Geology, geochemistry, and tectono-metallogenic evolution of neuproterozoic gold deposits in the Kadubu area, Kivu, Democratic Republic of Congo. Dissertation. University of the Witwatersrand, Johannesburg. Faculty of Science.

Walemba, K.M.A.; Master, S. (2005): Neoproterozoic diamictites from the Itombwe Synclinorium, Kivu Province, Democratic Republic of Congo. Palaeoclimatic significance and regional correlations. In *Journal of African Earth Sciences* 42 (1-5), pp. 200–210. DOI: 10.1016/j.jafrearsci.2005.08.009.

Wark, L. (2014): Kibali Gold Mine (Randgold). Site visit January 2014. Randgold, 2014. Available online at http://www.randgoldresources.com/sites/randgoldresources/files/Site%20visit%20…%20Kibali%20Gold%20Mine%20-%20January%202014.pdf, checked on 3/26/2016.

Watling, R. J.; Herbert, H. K.; Delev, D.; Abell, I. D. (1994): Gold fingerprinting by laser ablation inductively coupled plasma mass spectrometry. In *Spectrochimica Acta Part B: Atomic Spectroscopy* 49 (2), pp. 205–219. DOI: 10.1016/0584-8547(94)80019-7.

Weiss, N. L. (1985): SME mineral processing handbook. New York, N.Y.: Society of Mining Engineers of the American Instituteof Mining (S.W. Mudd series).

Weyns, Y.; Hoex, L.; Matthysen, K. (2016): Analysis of the interactive map of artisanal mining areas in eastern DR Congo: 2015 update. IPIS. Antwerp (BE). Available online at http://ipisresearch.be/wp-content/uploads/2016/10/Mapping-minerals-in-eastern-DR-Congo_v005.pdf, checked on 10/27/2016.

World-Mining-Data (2016) Vol. 31, checked on 7/27/2016.

Yager, T. R. (2013): THE MINERAL INDUSTRY or CONGO (KINSHASA). In *Minerals Yearbook-Area Reports: International Review: 2011, Africa and the Middle East*.

Youngson, J.; Wopereis, P.; Kerr, L.; Craw, D. (2002): Au-Ag-Hg and Au-Ag alloys in Nokomai and Nevis valley placers, northern Southland and Central Otago, New Zealand, and their implications for placer-source relationships. In *New Zealand J. of Geology & Geophysics* 45 (1), pp. 53–69. DOI: 10.1080/00288306.2002.9514959.

Žitňan, P.; Bakos, F.; Schmiderer, A. (2010): Importance of alluvial gold geochemistry for exploration: Examples from placers in the Western Carpathians. In *Mineralia Slovaca* 42, pp. 57–68.

Annex B Overview of Gold Analysis Methods

B.1 ICP-MS / ICP-OES

Method	Inductively Coupled Plasma-Mass Spectrometry / Inductively Coupled Plasma-Optical Emission Spectrometry
Approach	Measurement of major, minor and trace element concentrations
Participant	Universities, commercial laboratories, industrial laboratories
Procedure	The dissolved sample is injected into the argon plasma (ion source). Separation of the analyte solution and signal detection is done by mass spectrometry (MS) or based on the emitted UV/Vis light spectrum (OES). Widely available multi-element methods for the determination of gold composition in liquid samples. Wide range of overlap in usage of both instruments.
Standard	Suitable standard solutions are needed
Sample	Gold grains, ancient gold (jewelry, coins), gold ores, 2-5 mg
Elements	All of interest (Li to U)
Limits	Detection limit is in ng/kg in solid samples that need to be dissolved prior to analysis
References	Gondonneau et al. (2000); Hancock (2009) (2009); Nikolaeva et al. (2013)
Advantages	• Well established methods • Multi-element methods • Low detection limits
Disadvantages	• Dissolution of the sample (contamination) • Loss of the sample • Some matrix and interference problems
Application	Relatively inexpensive method for the chemical analysis of geological materials and metals, commonly used for noble metal analysis

B.2 LA-ICP-MS

Method	Laser Ablation-Inductively Coupled Plasma Mass Spectrometry
Approach	Quantitative analysis of major, minor and trace elements in solid samples without necessity of dissolving the sample. Performance and type of application depend on the choice of laser and type of mass spectrometer: quadrupole (Q), sector-field (SF) or multi collector (MC[117]) mass spectrometers are available; currently, also time-of-flight instruments (TOF) gain importance[118]
Participant	Universities, commercial laboratories
References	Outridge et al. (1998); Dussubieux & van Zelst (2004); McInnes et al. (2008); Schmiderer (2009); Bendall et al. (2009); Kovacs et al. (2009); Schlosser et al. (2009); Ehser et al. (2011); Žitňan et al. (2010); Schlosser et al. (2012); Nikolaeva et al. (2013); Dixon (2014); Gauert et al. (2015); Roberts et al. (2016)
Procedure	Fast and widely available multi-element method for in situ gold analysis. Ablation of a solid sample by a small laser spot (commonly 20-100 µm in size) using laser systems of different wavelengths; most applied are 213 nm (Nd:YAG) and 193 nm excimer laser systems. Aerosol is transported via carrier gas stream into the plasma of the mass spectrometer where it is ionized.
Standard	Suitable solid matrix-matched standards are needed to avoid matrix effect; different gold standards are available
Sample	Gold grains, ancient gold (jewelry, coins)
Elements	All of interest (Li to U)
Detection limit	ppb – ppm to wt.% in solid samples, depending on spot size (see Annex B.12)
Advantages	• Well established method • Good spatial resolution • No sample dissolution required
Disadvantages	• Matrix-matched standards with known trace element concentrations are not easily available • Destructive, loss of tiny amounts of sample (holes in the surface)
Treatment of results	• Various software programs in use, e.g. GLITTER, IOLITE • For further comparative analysis: multivariate statistical tools, e.g. PCA • Spider diagrams • Spectrum classification (chemometric analysis)
Application	The method is the most commonly used for the analysis of trace elements in gold. The analytical setup (type of laser and mass spectrometer used) and conditions applied to LA-ICP-MS (e.g. spot size, fluence, gas mixtures) will influence the performance of the measurements. In order to illustrate this point, a comparison is made between datasets measured on natural gold samples under different conditions (Annex B.12).

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[117] See chapter 3.3

[118] Interview with Roger Dixon, South Africa

B.3 (LA)-MC-ICP-MS

Method	Laser Ablation-Multi Collector-Inductively Coupled Plasma Mass Spectrometry
Approach	Determination of isotope ratios in liquid and in solid (LA) samples; Pb isotopic pattern (e.g., $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$, $^{206}Pb/^{204}Pb$, $^{208}Pb/^{206}Pb$, $^{207}Pb/^{206}Pb$ ratios), Os isotopes and stable isotopes in gold for dating and provenance analysis
Participant	Universities
Procedure	• In solution: drilling (2-10 mg), aqua regia dissolution, drying and re-dissolving in HCl, two-stage chromatographic separation • With laser: Tl elemental spike; He carrying the sample from the laser cell and Ar carrying the Tl from the nebulizer are mixed before entering the ICP; Pb standard measured before and after the sample measurement
Standard	Special standard for the Pb decay and reference material for gold
Sample	Native gold, gold coins, doré
Elements	Isotopes of Pb, isotopes of Os, stable isotopes (e.g. Ag, Cu)
Limits	Elements present in low concentrations cannot be analyzed
References	Junk & Pernicka (2003); Bendall et al. (2009); Standish et al. (2013); Standish et al. (2014); Standish et al. (2015); Krüger (2014); Jansen et al. (2016)
Advantages	Accurate determination of isotope ratios
Disadvantages	• time-consuming process if dissolution is required • chromatographic element separation and spiking often necessary • loss of sample
Treatment of results	ISOPLOT for radiogenic isotopes
Application	Bendall et al. (2009) show that the laser ablation MC–ICP-MS method is suitable for the Pb isotope analysis of gold artefacts and for alloys with over 70% gold. Standish et al. (2013) further developed LA-MC-ICP-MS for the in situ measurement of lead isotope ratios in natural gold samples.

B.4 LIBS

Method	Laser-Induced Breakdown Spectroscopy
Approach	LIBS is an atomic spectroscopy technique capable of real-time, essentially non-destructive analysis. Portable instruments have been developed for on-site measurements.
Participant	Refiners, jewelry manufacturers
Procedure	A highly energetic laser pulse is focused on a small analysis point to form a plasma, which atomizes and excites samples. Detection is by light emission followed by spectral analysis.
Standards	Compositionally similar standards
Sample	Any kind of sample (solid, liquid, gas), also good for metals
Elements	In principle all elements depending on the equipment
Limits	1-30 ppm
References	Harmon et al. (2006); Harmon et al. (2009); Harmon et al. (2011); Hark et al. (2012)
Advantages	• Minimally destructive • Fast • Multielemental
Disadvantages	• Low reproducibility • Accuracy not better than 10% • Quantification of element abundances difficult
Treatment of results	Chemometric analysis; linear correlation analysis of broadband spectra
Application	LIBS is used as an alternative to XRF and Spark OES for the determination of high purity gold and gold alloys. The LIBS method, although in principle long-known, has gained importance over the past 10 years. It has the potential of application in the field of conflict minerals and supply chain issues (Harmon et al. 2011). Companies have already advertised instruments for geochemical fingerprinting of conflict minerals. [119]

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[119] www.AppliedSpectra.com

B.5 EPMA

Method	Electron Probe Micro Analysis
Approach	Accurate analysis of major and minor elements in gold at superior spatial resolution in solid samples including point analysis, element maps, petrography, inclusion analysis
Participant	Universities
Procedure	A beam of accelerated electrons is focused on the polished surface of a sample placed into a vacuum chamber, producing characteristic X-rays that are detected at particular wavelengths and energy levels; X-ray intensities are translated into concentrations. EPMA can be equipped with energy-dispersive (EDS) or wavelength-dispersive (WDS) systems or both. EDS systems are used for rapid phase identification, whereas WDS systems are used for quantitative point analysis due to the better spectral resolution. In addition different types of imaging are possible for grain morphology studies (secondary electrons, back-scattered electrons). Field emission (FE) system allow better spatial resolution (e.g. Gauert et al. 2015)
Standards	Suitable pure metal or mineral standards, e.g. NA-Au-31 gold standard
Sample	• Geological samples (gold grains, gold-bearing ores, concentrates) are mounted in resin and polished. • Gold coins (polishing first, best on the edge, then mounted vertically)
Elements	Au, Ag, Hg, Cu, As, Fe, Bi (Pd, Sn) in most routine cases Ag, Au, Hg, Cu, S, Ti, Pb, Fe, Cd, Co, Sn, Ni for FE-EPMA (Gauert et al. 2015) Elements of atomic numbers <8 cannot be detected by most instruments.
Limits	The detection limits differ for each element and are affected by the matrix composition of the sample and the analytical conditions. For most elements, the detection limits for WDS range between 30 and 300 ppm. Heavy elements, e.g. Hg, have high detection limits (0.X wt.%). An accuracy of ± 1% is attainable for major elements but is lower for trace and light elements or when significant differences exist between the composition of the standard and the sample.
References	Stumpfl & Clark (1965); Desborough (1970); Antweiler & Campbell (1977); Knight et al. (1999); Chapman et al. (2000); Townley et al. (2003); Chapman & Mortensen (2006); Pop et al. (2011); Bendall et al. (2009)
Advantages	• Superior spatial resolution (1 µm) • Best control on sample surface, morphology, inclusions • Good sensitivity • Quick point analysis and phase identification • Individual mineral grains and small areas within grains can be analyzed in situ • Non-destructive (beside sample preparation)

Disadvantages	• Need of a flat well-polished surface • Detection limits too high for trace elements • No information on isotope ratios • Long counting times needed for minor elements
Application	Electron microprobes have been used since the 1960s for quantitative analysis of gold (alluvial and primary). Most of the studies used EPMA for petrological description of gold grains and for the identification of the inclusions in native gold. FE-EPMA can be used for trace elements (Gauert et al. 2015). It was concluded that FE-EPMA has a good reproducibility and detection limits well below elemental concentrations of most trace elements in native gold.

B.6 SEM

Method	Scanning Electron Microscopy
Approach	Similar to EPMA, with a focus on imaging. Microstructural characteristics of gold, element mapping of gold-bearing concentrates
Participant	Universities, commercial laboratories
Procedure	A focused electron beam irradiates the selected area. Different types of electron signals are produced including secondary electrons, backscattered electrons and characteristic X-rays.
Standard	Standardless or as with EPMA
Sample	• Geological samples (gold grains, gold-bearing ores, concentrates) • Gold coins, doré Sample size may vary from <0.1 mm up to several centimeters
Elements	Major and minor elements
Limits	Usually operated using EDS, therefore detection limits in the 100s to 1,000 ppm range
Advantages	• Spatial resolution (1 µm) for X-ray images • Spatial resolution of 10 nm for secondary-electron (SE) images • Quick point analysis and phase identification • Individual mineral grains can be analyzed in situ • Non-destructive (beside sample preparation) • Sample can be tilted and even unpolished samples can be analyzed
Disadvantages	Detection limits
Application	Fast and accurate characterization of morphology and inclusion assemblages

B.7 (µ)-PIXE

Method	Proton-Induced X-ray Emission (on a micron-scale)
Approach	PIXE is a non-destructive technique to determine the surface composition of a sample and to construct depth and surface elemental maps
Participant	Universities, research centers
Procedure	The samples are glued to a holder and positioned in vacuum.
Standards	Gold standards 6971 and 6905 from Comptoir Lyon Allemand Louyot & Co. can be used (Constantinescu et al. 2012) FAU8 natural gold standard from the Royal Canadian Mint (Bugoi et al. 2008)
Sample	Small pieces from ancient gold, native gold grains. The sample should be flat to avoid roughness effects.
Elements	Au, Ag, Cu, Fe, Cr, Ca, Ni, Zn, Ru, Rh, Cd ,Sn, Sb, Pb, Te
Limits	The detection limit for lighter elements (Z= 20-60) is 13-90 ppm and for elements with atomic number > 75 it is 100-600 ppm.
References	Guerra & Calligaro (2003); Guerra & Calligaro (2004); Constantinescu et al. (2005); Bugoi et al. (2008); Guerra (2008); Cristea-Stan et al. (2012); Vasilescu & Constantinescu (2011); Guerra (2014)
Advantages	• Non destructive • Lower X-ray background than EPMA
Disadvantages	• Difficult to obtain high spatial resolution • The spatial resolution to depth is poor (30 µm) • Detection of Hg or Pt is not possible due to overlapping with Au L-rays; Bobin & Guegan (2009)
Treatment of results	The data is processed with the software GUPIX. GUPIX or GUPIXWIN (new version) are PIXE spectrum fitting software from the University of Guelph (Canada)
Application	Is commonly used in archaeology for ancient gold (jewelry and coins) since the mid 2000s. Low set of published analysis of native gold.

B.8 XRF

Method	X-ray Fluorescence Spectrometry
Approach	Bulk method for elemental analysis by measuring characteristic emitted X-rays. Accurate chemical analysis of major, minor and many trace elements down to ppm levels
Participant	Refiners for incoming quality control, mining companies, universities
Procedure	In the case of ore concentrates, the powdered (or molten with fluxes for better homogeneity) sample is excited using X-rays. Metal samples can be analyzed with little sample preparation. Similar to EPMA and SEM, EDS and WDS systems are available with advantages in speed (EDS) or detection limit and spectral resolution (WDS).
Standards	Compositionally similar standards
Sample	Solid or liquid
Elements	• Bulk chemical analyses of major, minor and trace elements (Ba, Ce, Co, Cr, Cu, Ga, La, Nb, Ni, Rb, Sc, Sr, Rb, Th, U, V, Y, Zr, Zn)
Limits	Around 1-10 ppm for major and trace elements, depending on matrix (for gold, worse)
Advantages	• Low costs • Good accuracy for major elements • Analysis of light elements possible (atomic number >8) • Powdered material may be re-used after analysis (no losses)
Disadvantages	• Sample preparation necessary • Large amount of sample needed (expensive in the case of gold) • Elements with Z<11 are not precisely measureable • Several mm spot size
Application	Frequently used method for bulk ores and concentrates; single specks, doré or other solid gold (metallic) materials may be analyzed without extensive sample preparation

B.9 SR-XRF

Method	Synchrotron Radiation-X-Ray Fluorescence
Approach	Synchrotron radiation as source of high X-ray intensities produces non-destructive point analyses of gold alloys
Participant	Large scientific institutions, few universities (e.g. ANKA in Karlsruhe, DESY in Hamburg and Zeuthen, BESSY in Berlin, CERN in Geneva, SRS in Cheshire, England)
Procedure	In situ measurement, no sample dissolution necessary
Sample	Ancient gold, native gold without preparation
Elements	Nearly all elements
Limits	Elemental detection limits, ranging from 1 ppm for Zn to 2 ppm for Ni (Gauert et al 2015). The minimum detection limits (MDL) of Pt can be improved to 20 ppm (Guerra et al. 2008). The detection limits of trace elements in gold are around 1 ppm (Radtke et al. 2009).
References	Guerra et al. (2008); Radtke et al. (2009); Vasilescu et al. (2011); Constantinescu et al. (2012); Gauert et al. (2015)
Advantages	• High spatial resolution • Low detection limits
Disadvantages	The accessibility of this technique is limited
Application	Detection limits for critical elements are partly too high; certain elements such as Hg and some PGE could not be measured. Quantification of trace elements such as Cu, Zn, Ta, Zr and Nb could be problematic using synchrotron radiation induced X-ray fluorescence spectrometry at energies of 33.2 keV and above, due to strong line overlap of trace element lines with the Au and Ag lines (Gauert et al. 2015)

B.10 Fire Assay / Gravimetry

Method	Fire Assay followed by Gravimetry or any spectrometric method
Approach	Fire assaying is the industry standard process for obtaining analytical gold and PGE data from ores.
Participant	Mining companies, commercial laboratories
Procedure	A sample powder is heated at temperatures ranging from 1100 °C to 1200 °C. Lead and Ag in the melt settle to the bottom scavenging precious metals from the melt. The hot mixture is poured into a mold forming a slag by cooling. A clean Pb button forms and is cupelled at 950 °C in a magnesia cupel. In the bullion fire assay method, the product of cupellation (doré) is flattened and treated with nitric acid to remove Ag, followed by precision weighing (gravimetry). Alternatively, a tiny Ag bead (+ Au, Pt, and Pd) can be dissolved and analyzed by different techniques: • Atomic absorption spectroscopy (AAS), ICP-OES, ICP-MS, INAA, XRF • Non-mandatory procedure provided in Annex of Standard ASTM B 562 – 95
Sample	Mixing an aliquot of a powdered sample (10-50 g) with soda ash, borax, litharge, flour, silica and possible niter. Ag can be added as collector in solution or as a foil. Samples can be from drill core, soil, chips or gold-bearing concentrates.
Elements	Precious metals (Ag, Au, Pd, Pt), using Ni sulfide fire assay: also Rh, Ru, Pd, Ir, Os
Limits	• Bullion fire assay process: accuracies of 1 part in 10,000 • Trace levels of gold (range from 1 ppb – 10 ppm with ICP-OES finish, 5 ppb – 10 ppm with AAS finish) • Gold in ore (0.01 ppm-100 ppm with AAS finish, 3 g/t gravimetric) • Gold in rocks (2 ppb with INAA finish)
References	Hoffman et al. (1998); www.actlabs.com; LBMA assaying & refining seminar 2011
Advantages	• Long history of success • Reproducible results (depends on the skills of the assayer or analyst) • Low cost (e.g. Au Fire Assay – AAS costs 12 €, preparation about 10 €)
Disadvantages	• Most steps carried out in unmarked crucibles and cupels -> danger of sample mix-ups • Sulfide bearing rocks or rocks with higher levels of base metals must be pre-treated • Deleterious effect of Cu on Au collection
Application	Method for gold grade evaluation; quality control, ISO 11426-2014 determination of gold in gold jewelry alloys (333 ‰ up to 999 ‰)

B.11 INAA

Method	Instrumental Neutron Activation Analysis
Approach	The technique determines element concentrations in a sample by measuring the activity induced by irradiation with neutrons
Participant	Few universities, commercial laboratories and industry
Procedure	The sample is irradiated in a nuclear reactor or an isotope source. The neutrons from the reactor bombard the sample and interact with the nucleus of the elements present. The captured gamma-rays emitted due to decay are measured and quantified. The elemental contents are determined relative to certified reference materials which are irradiated and counted under the same conditions as those of the samples.
Sample	Powdered sample (few mg to one kg), commonly 30 g
Elements	Au and up to 73 elements (e.g. Co, As, Sb, W, Ta, U, Th, Cs, In, Re, Cl and lower levels of REE see Hoffman et al. 1998)
Limits	• < 0.1 ppm (Mn, Au, Sm, V, Cs, Eu, Hf, Lu, Sc, Ta, Th, Yb) • 1 ppm (Ti, Ce, Co, Cr, Ga, U, Sn) • 10 ppm (Al, Ca, Mg, Na, Nb, Nd, Rb, Zn) • 10-150 ppm (Fe, K, Ba, Sr, Zr) published by El-Taher et al. (2003), provided by TRIGA research reactor at Universität Mainz
Advantages	• no matrix effect • no sample pretreatment (except of powdering) • little sample material necessary • non-destructive • very sensitive • accuracy 5%, relative precision often better than 0.1%
Disadvantages	• time-consuming: 7 day waiting period until measurement • Cu, Pb, Zn, Ni and Cd are not easily determined (Hoffman 1992) • High levels of As, Sb, REE, U may cause background irradiation • Regionally limited due to declining number of reactors • the sample becomes strongly radioactive, requiring handling, storage and disposal protocols
Application	INAA is not a routine method in gold analysis, but may be used as an alternative method if access to a source is given.

B.12 Evaluation of LA-ICP-MS Datasets on Gold

		Schmiderer (2009)				Brauns Africa[120]	Brauns Rhine[121]
Element	*Mass*	**detection limit (ppm)**	**percent values above dl**	**median (ppm)**	**detection limit (ppm)**	**percent values above dl**	**percent values above dl**
S	*33*	7.6	75	3579			
Ti	*47*	3.0	73	6.7	2.3	18	69
V	*51*	1.1	32	0.5			
Cr	*52*	0.4	64	1.1	2.2	17	31
Mn	*55*	0.4	92	4.8	2.0	13	42
Fe	*56*	0.9	93	382	5.0	37	87
Co	*59*	0.1	65	0.3	0.6	2	83
Ni	*60*	2.3	48	2.1	3.0	11	55
Cu	*63*	1.1	99	139	3.3	100	100
Zn	*66*	0.5	82	6.4	3.3	13	75
Ga	*71*	2.7	8	0.4			
Ge	*72*	0.1	97	0.8			
As	*75*	0.3	85	2.1	7.0	2	20
Se	*80*	0.7	51	0.8	9.7	4	32
Rb	*85*	20.1	1	0.5			
Sr	*88*	0.5	41	0.3			
Y	*89*	0.03	58	0.05			100
Zr	*90*	0.004	92	0.09			100
Nb	*93*	0.002	87	0.03			
Mo	*95*	0.004	91	0.14			
Ru	*101*	0.07	60	0.09	4.8	0	5
Rh	*103*	0.01	45	0.01	0.3	0	5
Pd	*105*	0.001	95	0.24	1.0	22	29
Ag	*107*	0.04	100	62,342	10.7	100	100
Cd	*112*	7.1	21	0.76	0.7	17	17
In	*115*	0.03	53	0.04			
Sn	*118*	0.01	99	2.7	0.8	8	99
Sb	*121*	0.8	77	7.7	0.4	27	100
Te	*127*	0.2	68	1.4	2.2	2	22
I	*127*	0.1	100	9.2			
Cs	*133*	5.1	0	0.07			
Ba	*137*	0.015	98	0.68			
La	*139*	0.029	59	0.07			100
Ce	*140*	<0.001	87	0.14			100
Pr	*141*	0.001	85	0.03			100

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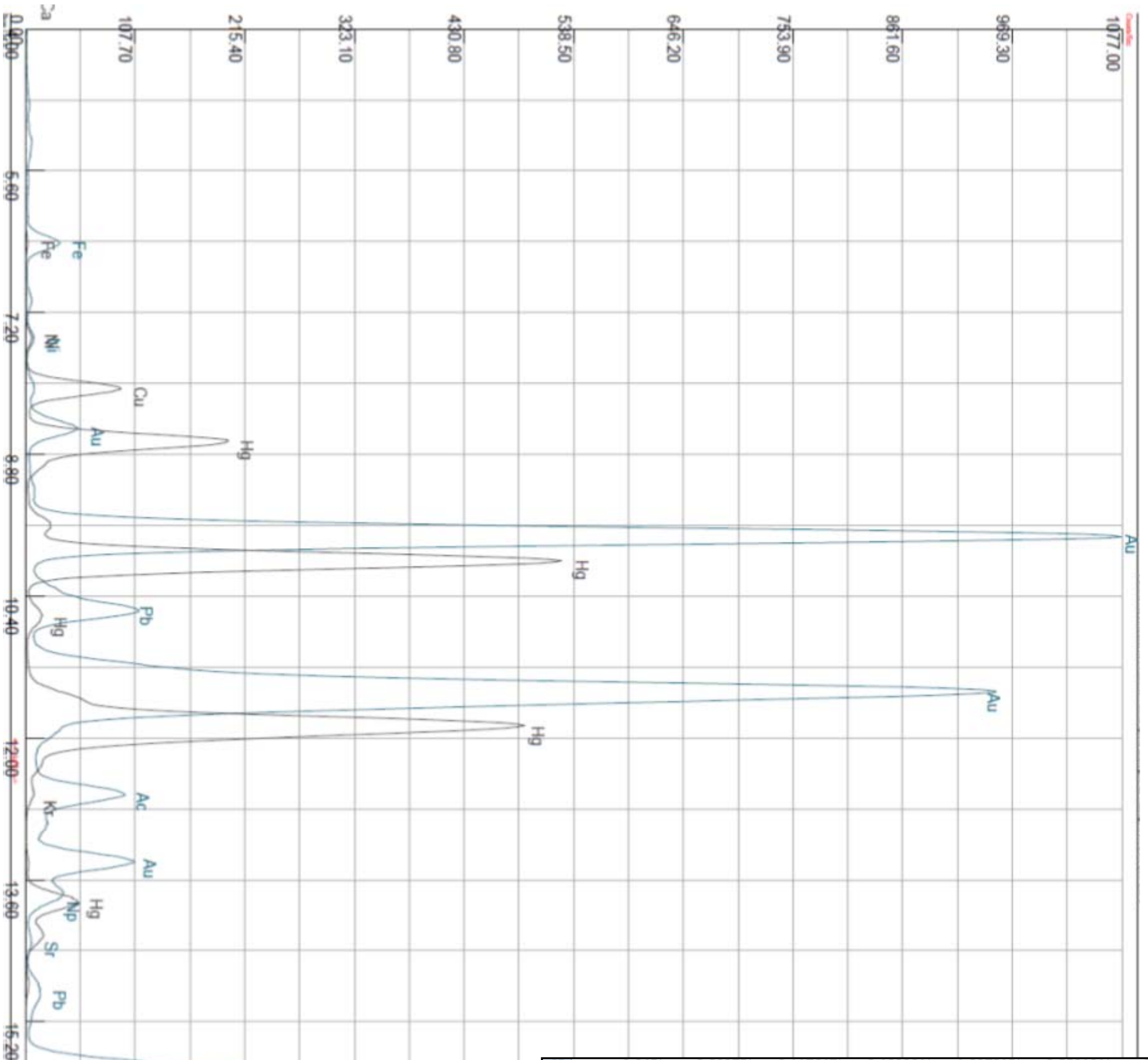
[120] Unpublished data provided by Michael Brauns, CEZ Mannheim

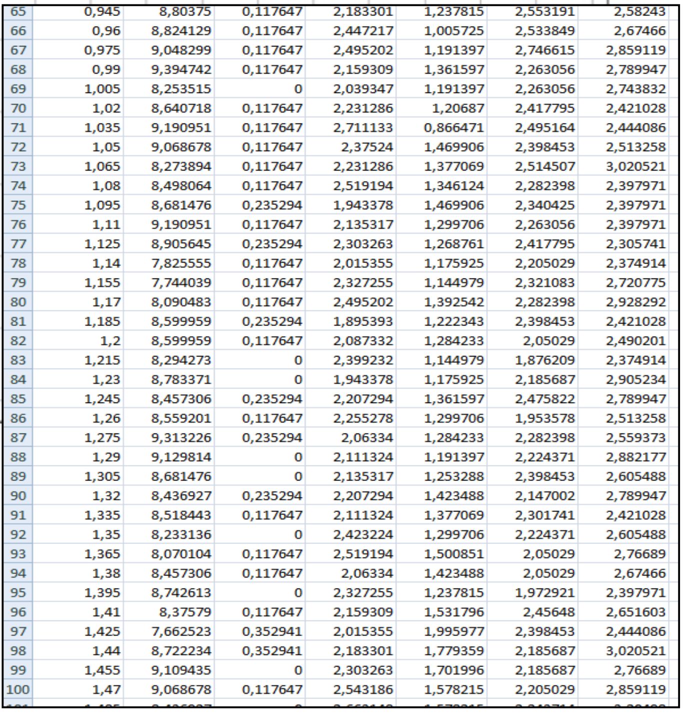
[121] Michael Brauns, CEZ Mannheim, contract 212-4500072679 for the BGR Hannover (2012)

		Schmiderer (2009)				Brauns Africa[120]	Brauns Rhine[121]
Element	*Mass*	detection limit (ppm)	percent values above dl	median (ppm)	detection limit (ppm)	percent values above dl	percent values above dl
Nd	*146*	<0.001	89	0.12			100
Sm	*147*	0.002	96	0.10			100
Eu	*153*	0.001	66	0.01			100
Gd	*157*	<0.001	87	0.04			100
Tb	*159*	0.001	46	0.00			100
Dy	*163*	<0.001	87	0.03			100
Ho	*165*	0.001	63	0.01			100
Er	*166*	<0.001	79	0.02			100
Tm	*169*	<0.001	62	0.01			100
Yb	*172*	<0.001	60	0.01			100
Lu	*175*	0.001	31	0.00			100
Hf	*178*	<0.001	65	0.01			
Ta	*181*	<0.001	53	0.00			
W	*182*	<0.001	65	0.08	0.7		96
Re	*185*	0.610	0	0.01	0.2	0	0
Os	*189*	0.005	38	0.00	0.7	0	0
Ir	*193*	0.003	79	0.06	0.2	0	14
Pt	*195*	<0.001	89	0.06	0.7	0	15
Au	*197*	0.01	73	897,670	10.7	100	100
Hg	*201*	9.9	97	6,360	semi-quant	99	100
Tl	*205*	162.9	0	0.13			
Pb	*208*	0.2	83	7.2	0.4	23	100
Bi	*209*	0.04	84	0.45	0.3	7	93
Th	*232*	0.01	52	0.02	0.3		66
U	*238*	<0.001	86	0.03	0.3		37
Number of analyses				1,868		385	126

B.13 Example of a pXRF Spectrum



Example (screenshot) of
digital data records of spectra: →



65	0,945	8,80375	0,117647	2,183301	1,237815	2,553191	2,58243
66	0,96	8,824129	0,117647	2,447217	1,005725	2,533849	2,67466
67	0,975	9,048299	0,117647	2,495202	1,191397	2,746615	2,859119
68	0,99	9,394742	0,117647	2,159309	1,361597	2,263056	2,789947
69	1,005	8,253515	0	2,039347	1,191397	2,263056	2,743832
70	1,02	8,640718	0,117647	2,231286	1,20687	2,417795	2,421028
71	1,035	9,190951	0,117647	2,711133	0,866471	2,495164	2,444086
72	1,05	9,068678	0,117647	2,37524	1,469906	2,398453	2,513258
73	1,065	8,273894	0,117647	2,231286	1,377069	2,514507	3,020521
74	1,08	8,498064	0,117647	2,519194	1,346124	2,282398	2,397971
75	1,095	8,681476	0,235294	1,943378	1,469906	2,340425	2,397971
76	1,11	9,190951	0,117647	2,135317	1,299706	2,263056	2,397971
77	1,125	8,905645	0,235294	2,303263	1,268761	2,417795	2,305741
78	1,14	7,825555	0,117647	2,015355	1,175925	2,205029	2,374914
79	1,155	7,744039	0,117647	2,327255	1,144979	2,321083	2,720775
80	1,17	8,090483	0,117647	2,495202	1,392542	2,282398	2,928292
81	1,185	8,599959	0,235294	1,895393	1,222343	2,398453	2,421028
82	1,2	8,599959	0,117647	2,087332	1,284233	2,05029	2,490201
83	1,215	8,294273	0	2,399232	1,144979	1,876209	2,374914
84	1,23	8,783371	0	1,943378	1,175925	2,185687	2,905234
85	1,245	8,457306	0,235294	2,207294	1,361597	2,475822	2,789947
86	1,26	8,559201	0,117647	2,255278	1,299706	1,953578	2,513258
87	1,275	9,313226	0,235294	2,06334	1,284233	2,282398	2,559373
88	1,29	9,129814	0	2,111324	1,191397	2,224371	2,882177
89	1,305	8,681476	0	2,135317	1,253288	2,398453	2,605488
90	1,32	8,436927	0,235294	2,207294	1,423488	2,147002	2,789947
91	1,335	8,518443	0,117647	2,111324	1,377069	2,301741	2,421028
92	1,35	8,233136	0	2,423224	1,299706	2,224371	2,605488
93	1,365	8,070104	0,117647	2,519194	1,500851	2,05029	2,76689
94	1,38	8,457306	0,117647	2,06334	1,423488	2,05029	2,67466
95	1,395	8,742613	0	2,327255	1,237815	1,972921	2,397971
96	1,41	8,37579	0,117647	2,159309	1,531796	2,45648	2,651603
97	1,425	7,662523	0,352941	2,015355	1,995977	2,398453	2,444086
98	1,44	8,722234	0,352941	2,183301	1,779359	2,185687	3,020521
99	1,455	9,109435	0	2,303263	1,701996	2,185687	2,76689
100	1,47	9,068678	0,117647	2,543186	1,578215	2,205029	2,859119

Annex C Gold Provinces in the DRC

(1) The Northern Gold Province: Greenstone-hosted Gold in Orientale

In the Kilo zone west of Lake Albert, primary vein deposits are located along four belts hosted by amphibolite, chlorite-actinolite-talc schist, quartz diorite and tonalite as part of a greenstone belt attributed to the Kibalian Series. Greenstone-belt hosted gold (>2,500 Ma) is commonly associated with mafic to ultramafic rocks, occasionally with granites and gneisses, and with metapelites and banded iron formation. The company KiloGold (www.kilogoldmines.com) distinguishes two associations: Type A association (about 95% of the gold output) comprising greenstones, mafic-ultramafic volcanics (including komatiites) and scarce sediments. Associated granitoids correspond to a typical tonalite-trondhjemite-granodiorite ("TTG") suite, intruded at ca. 2.8 to 2.9 Ga. The type B association (5% of the gold output) comprises mafic-intermediate volcanics and sediments (mainly banded iron formations). Associated granodiorites and granites are 2.4 to 2.5 Ga old. Angermeier et al. (1974) distinguished three major districts:

(a) **Kilo district** (30°14´E – 1°48´N) or Bunia, >2,000 km^2, discovered in 1903. Eastern group of deposits around Mont Tsi and Mont Nizi is almost completely mined out. Production in the 1970s was mainly from the western group of deposits between Yedi and Mongbwalu: Andissa, Creek, Senzere, Kanga, Nzebi, Issuru, Yedi, Galaya, Yemoliani, Agoye, Pokwo.

(b) **Moto district** (Watsa district) at 29°32´E, 3°03´N, discovered in 1906, >2,000 km^2. Deposits close to and north of Watsa include Moto, Dila, Durba, Gormubwa, Agbarobo; Rambi 65 km E of Watsa; Egbeu 40 km W of Watsa. Alluvial gold has been recovered from stream sediments along the Kibali river for more than 100 km downstream of Watsa.

(c) **Zami (Zani)-Kodo** (30°28´E, 2°40´N) is a smaller gold district.

The mesothermal Kilo-Moto gold deposits are hosted by brittle-ductile shear zones; mineralization is controlled by granitoids (Milesi et al. 2006). Discordant lodes and veins, with thicknesses exceeding 50 cm, occur in clusters or isolated, and are accompanied by lenses of massive to submassive sulfide ore. Mining includes underground and alluvial mining, including dredging. Kilo comprises a potential of 250 t gold including 100 t alluvial, whereas Moto is estimated to 200 t gold (Milesi et al. 2006).

(2) The Lubero Gold Province: Gold in Paleoproterozoic Terranes

The area is underlain by schists, quartzites and phyllites crosscut by granites and diorites. Recent aeromagnetic data, however, indicate the presence of a layered intrusion (www.loncor.com). It is assumed that the PGE derive from hydrothermal sulfide deposits (Database "The mineral occurrences map of the République Démocratique du Congo, compiled by the Royal Museum for Central Africa and GF Consult; DB Congo). Jedwab published some papers on PGM from the area, including the first description of luberoite Pt_5Se_4 (Jedwab et al. 1992; Rumvegeri et al. 2004; Cabral et al. 2012). Thus, PGE could represent a possible fingerprint for alluvial gold from this area. The age of the host rocks most probably ranges from 2,100 to 1,800 Ma ("Rusizian", Paleoproterozoic[122]).

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[122] The Proterozoic is a geological eon and is subdivided into the Paleoproterozoic (2.5-1.6 Ga), the Mesoproterozoic (1.6-1.o Ga) and the Neoproterozoic (1.0-0.542 Ga).

Rumvegeri et al. (2004) infer that the “great shear zone” outlined by the “late-Kibaran” (1,110 ± 38 Ma; but 1,375 Ma according to Tack et al. 2010) mafic-ultramafic bodies in eastern Burundi and Tanzania (“nickel belt”) represents a suture zone which was remobilized during a late collisional stage; the northern extension of that shear zone is situated in the northern Lubero region, with mafic-ultramafic masses in the Luhule-Mobisio complex (between Butembo in the SE and Manguredjipa in the W) and the Rwate-Bilati complex to the SW (see Fig. 3 in Rumvegeri et al. 2004). Rumvegeri et al. (2004) advocate for a subduction-collision model for the Kibara Belt, in contrast to the “ensialic model” proposed by Pohl (1994), Pohl et al. (2013), Tack et al. (2010) and others.

(3) The Kibaran Gold Province: Gold related to late-Kibaran Granites

In North and South Kivu, Maniema and northern Katanga, gold is mostly related to late-stage (900-1,000 Ma) “G4” fertile granites intruding pre-Kibaran and Kibaran-age rocks (Cahen 1954; Pohl 1994; Pohl et al. 2013). Cahen (1954) distinguished three zones of mineralization around the Kama-Kampene granite batholith in Maniema, with monazite and other REE minerals plus colombotantalite close to or within the granite, followed by cassiterite, colombotantalite and/or gold, and finally by gold only in the outermost zone. Gold deposits are “probably around 27°14' E and 3°39'S” (source: DB Congo). Quartz veins are rare, but schists are spotted with pyrite, and although the exact derivation of the detrital gold has not been identified, its association with Sn-bearing vein systems is assumed. The gold seems to be of Burundian (Mesoproterozoic) or Rusizian (Paleoproterozoic) age, but the deposits occur in Burundian formations (Mesoproterozoic). According to Milesi et al. (2006), secondary alluvial and eluvial deposits of Sn, Nb-Ta and gold at Kampene are derived from primary quartz aplites and pegmatite veins.

In contrast, at Sarambila (Kabambare area, Maniema), fine-grained gold occurs in metasediment-hosted (Groupe de Rusizi), NW-SE trending quartz veins that are cropping out along the mountains Mwendakombo, Kakula and Namoya. The veins form diffuse systems associated with little sulfide and exceptionally with tourmaline. The origin of the mineralization has been discussed by Belgian geologists as a two-stage process with primary enrichment in metasediments (“Rusizien”) but metasomatically transferred into quartz veins by granite-derived fluids (“Urundien”).

At Kamituga, South Kivu, quartz veins related to G4 granites carry the following minerals: graphite, beryl, tourmaline, cassiterite, scheelite, native bismuth, bismuthinite, gold, pyrite, pyrrhotine, arsenopyrite, galena, sphalerite, chalcopyrite, actinolite and calcite (Safiannikoff 1952).

Gold mineralization at Lubongola, in the Mihamba and Pulungwe basins, 110 km west of Bukavu is hosted by uralitized gabbro and altered tonalite.

The “Compagnie Minière Zairoise des Grands Lacs” (MGL) was the second largest gold producer in the DRC, with most important deposits west of Kamituga along the Mobale, and 50 km SW of Kamituga along the Lugushwa rivers (Angermeier et al. 1974). These (secondary) placers host large gold resources, deriving from non-economic (primary) quartz vein deposits (Table 14).

At Ruhembe in NW Burundi, the gold-bearing assemblage develops from a pegmatitic stage into a hydrothermal system with refractory gold and sulfides; gold is associated with Bi minerals. In a late stage, magnetite and pyrite are replaced by hematite (Brinckmann 2001; Pohl et al. 2013). Pohl et al.

(2013) state that most of the Kibaran gold is extracted from Fe-rich lateritic regolith and alluvial placers.

In the Kamituga area around Banro´s producing Twangiza mine, 2.5 Moz alluvial gold have been produced since 1924, with gold nuggets weighing up to 65 kg. These placers are worked by numerous artisanal miners (IPIS webmapping project). Pohl et al. (2013) infer that the geological setting of the source for the placer material is Kibaran metasediments interlaced with Rusizian basement in a fold and thrust belt and intruded by G4 granites.

At Namoya in Maniema, gold is associated with Kibaran leucogranite. Circa 80 t gold are associated with pyrite, pyrrhotine, arsenopyrite, chalcocite, sphalerite, bismuthinite (see Brinckmann (2001) for type 1 gold veins in NW-Burundi), gangue minerals are quartz, chlorite, and sericite (Milesi et al. 2006). The mineralization at Namoya is structurally controlled by a 2.5 km, NW-SE trending shear zone within sericite schists, which hosts a series of quartz 'stockwork' deposits. The auriferous vein systems outcrop at the summits of Mt. Mwendamboko, Mt. Namoya, Mt. Kakula, and Mt. Muviringu. Mineralized 'stockwork' outcrops have also been located on eight other hills in the general area. (www.banro.com)

“Alluvial deposits of gold were first discovered at Namoya in 1930 and mined between 1931 and 1947. Primary gold was also discovered during this period and underground mining commenced on the Filon 'B' deposit in 1947. Further discoveries of primary gold mineralization were made at Mwendamboko, Kakula and Muviringu, where selective mining was carried out. The majority of this mining was based on small-scale underground development along specific mineralized quartz veins or stockwork zones. During the 1950s a small open pit was established on Mt. Mwendamboko. Mining ceased in 1961, although there remained substantial un-mined resources in the various deposits plus several other untested mineralized targets. Limited regional and exploration along strike appears to have been conducted since 1961. Total historical production at Namoya has been estimated at 278,000 ounces of gold” (www.banro.com).

(4) The Panafrican Gold Province

In a narrow corridor on both sides of the East African rift system (western branch, Lake Kivu and Lake Tanganyika) gold is mined from hydrothermal veins as well as from mainly north-south trending shear zones dissecting rocks of pre-Kibaran (Rusizian) and Kibaran age. In NW Burundi, Brinckmann (2001) were able to distinguish mesothermal (400°C, 2 kbar) quartz-tourmaline-muscovite-(rutile) vein systems, in which gold occurs as refractory micron-sized gold enclosed in pyrite and arsenopyrite, and as free gold after supergene enrichment in weathered caps. Such veins overlap with granite-related rare metal pegmatite and hydrothermal systems of late Kibaran age (ca. 900-1,000 Ma). A second stage of epithermal hematite/limonite-rich breccia zones with visible gold formed at low temperatures (140-190°C) and pressure (ca. 200 bar) during a Panafrican (ca. 535 Ma, monazite age) phase of rapid uplift, rifting and high heat flow. The presence of Panafrican deformation within the Kibara belt is questioned by many researchers (see also Pohl et al. 2013); however, abundant rejuvenation of mica Ar-Ar and Rb-Sr ages as well as the U-Pb isotopic dating of cassiterite and columbite-tantalite (Melcher et al. 2015; Goldmann 2016) are regarded as evidence for hydrothermal activity during the Panafrican in a narrow corridor along the rift. Therefore, hydrothermal gold mineralization related to Panafrican brittle structures is probable.

In the DRC, gold in shear zones oriented parallel to the rift axis is of likely Panafrican age (500-550 Ma) and is hosted by a variety of low-grade Meso- and Neoproterozoic metasediments (i.e., the Itombwe syncline), and minor volcanic and subvolcanic rocks. Of major importance is the Twangiza-Kamituga-Namoya gold belt of 210 km length and NE-SW strike, currently explored by Banro Corporation.

Orogenic gold mineralization at the active 5.6 Moz Twangiza mine (operated by Banro) forms in quartz-carbonate (albite-pyrite-arsenopyrite) vein networks hosted by Neoproterozoic black shale (Tsibangu Formation) and feldspar porphyry “sills” (Schink 2014). A geochemical association of gold has been established with As, Sb, Bi and S, but not with base metals (Schink 2014). Milesi et al. (2006) classify Twangiza as a Meso-Neoproterozoic deposit with possible Neoproterozoic structural control, hosted by diorite, black schist, mica schist, quartzite and sandstone. Gold occurs in fold-related gold-quartz-carbonate veins with envelopes of disseminated ore. Pohl et al. (2013) attribute the Twangiza deposit to G4 granite activity in late-Kibaran times because small G4 outcrops and pegmatites as well as some cassiterite and wolframite was found in the area. They provide a number of arguments stressing a granite-related origin of vein-hosted gold in the Kibara Belt in general, and of Twangiza in particular.

Walemba´s thesis (2014) focusses on the Kadubu area in South Kivu, a complex area containing two gold deposits (Twangiza, Tshondo), several gold occurrences (Nambo, Mufwa and Kakere) as well as one Sn-W deposit (Kashwa). At Twangiza, 4 vein sets are distinguished: QV1 is characterized by anhedral milky quartz, dolomite, rare pyrite and arsenopyrite, hematite, albite; QV2, the most important type, of laminated veins consisting of multiple laminae of sulfides separated by black shale wall rocks; QV3, vuggy fault-breccia in black shale and albitite carrying fragments of sulfide or iron oxide; QV4, stockwork veining, brecciated and disseminated veins. Walemba (2014) distinguished two mineralization phases in the Twangiza deposit. The earlier phase comprises sulfide mineralization within saddle reef structures, whereas the second fault-controlled phase is synchronous with dextral strike-slip faulting. Radiometric Ar-Ar ages from hydrothermal muscovite of 522 ± 15 Ma probably date the saddle reef gold mineralization (Figure 26).

The Technical Report on Twangiza published by Banro (Pittuck et al. 2011) highlights the geological position of the deposit within Neoproterozoic sediments of the Itombwe syncline (Villeneuve 1983, 1987; Walemba & Master 2005), providing a strong argument for a Panafrican age of mineralization. A recent publication on tourmaline-bearing gold-mineralized quartz veins from the Lugushwa and Kamituga deposits in the Namoya-Twangiza gold belt adds to the understanding of the mineralizing systems (Büttner et al. 2016). Whereas pegmatite formation was constrained at 981 ±16 Ma by Rb-Sr dating of tourmaline, sericite and apatite, tourmaline-rich alteration was dated at 677 ± 17 Ma; this is interpreted to reflect fluid mobilization from metasedimentary sources during the early Panafrican.

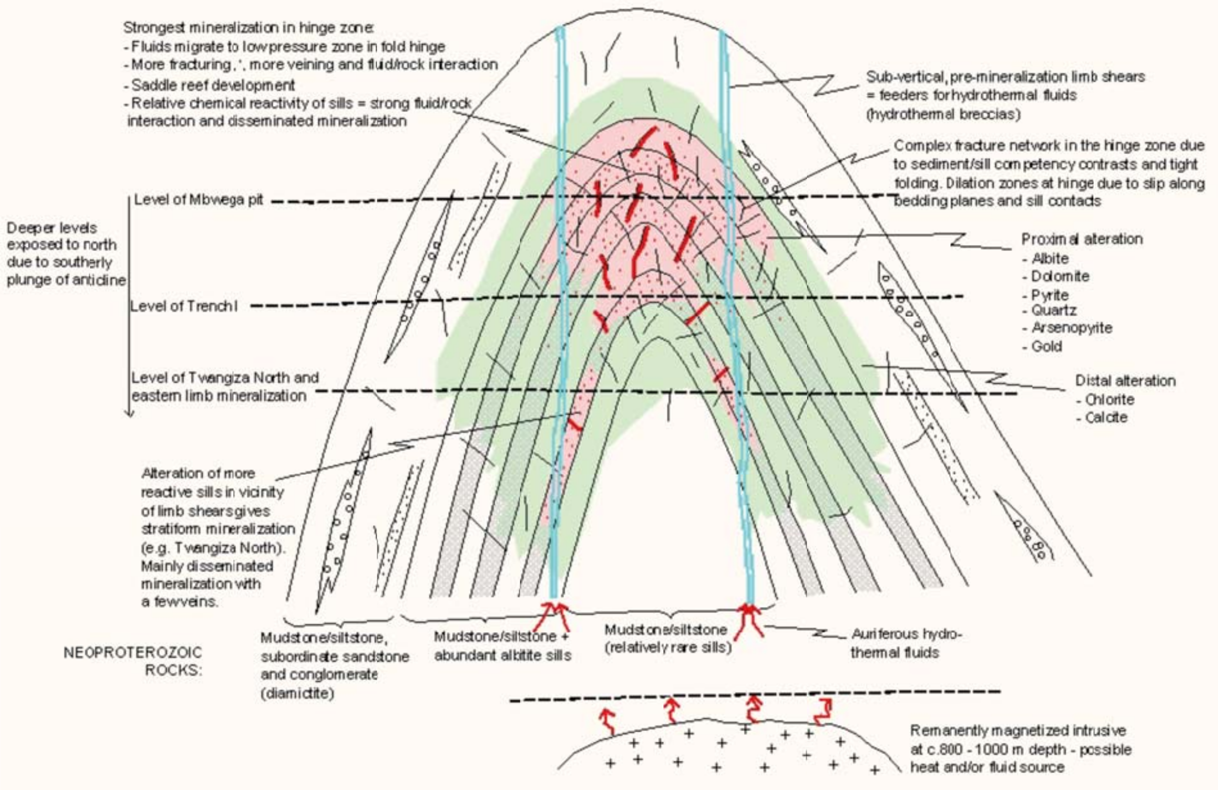

Figure 26: Geology of the Twangiza gold deposit, South Kivu (Pittuck et al. 2011).

The Mobale deposit, located in proximity to Twangiza and representing the hot spot of artisanal mining activity in Mwenga territory[123], is also classified as of Meso-Neoproterozoic, possible Neoproterozoic structural control (Milesi et al. 2006). The fault-related syn- to late-orogenic mesothermal, sulfide-rich (gold, pyrite, pyrrhotine, arsenopyrite, sphalerite, chalcopyrite, bismuthinite, molybdenite, also cassiterite; gangue quartz and carbonates) deposits carry ca. 100 t gold. An association with Kibaran leucogranite is, however, also indicated. Angermeier et al. (1974) report on two shallow dipping gold-quartz veins, 0.6-1.2 m wide and 1.5 km long, intersecting Rusizian mica schist and quartzites. In the vicinity, fossil placer deposits are covered by Cenozoic basalt.

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[123] 2500 miners reported by IPIS webmapping project for November 2013

Annex D Local Product Confirmation (GPA Scenario I)

The mine site where the gold is extracted is considered the "**Provenance**" of this scenario. Currently more than 1,500 ASM gold mine sites in the Eastern DRC have been mapped and are registered in the BGR database. At each mine site several Category B Trader *(petits négociants)* purchase the gold from the miners, consolidate volumes and usually sell the gold to Category A Trader *(grands négociants)*.[124]

The main assumption for the feasibility of GPA at local level is that the compositional characteristics of the gold are typical, although not necessarily unique, for each mine site. This comprises the geochemical/mineralogical characteristics of the gold as well as the characteristics imprinted on the material by the applied mining and processing methods. Although theoretically possible in the long term, the scenario is not rooted in the idea of a countrywide coverage of analytical data from all mine sites. It focuses rather on the verification of a claimed origin: if gold is said to originate from a certain mine, then it must match the site-specific compositional characteristics. This is directly relevant for providing an extra layer of certainty to closed pipe supply chains or for due diligence purposes (e.g. audits, risk assessments).

The scenario is expected to provide meaningful results as long as physical segregation can be maintained. It is anticipated that the compositional characteristics remain verifiable as long as the gold is not mixed with gold from other sources, as part of trading and volume-consolidating practices (melting into doré bars of mixed origin) further down the supply chain.

A potential local GPA scenario in combination with a closed supply chain approach is already in place for the existing supply chains of LSM operations, where doré produced at the mines is directly exported to the Rand Refinery in South Africa. The viability of closed pipe supply chains for ASM gold is demonstrated by the Fairmined Initiative of the Alliance for Responsible Mining (ARM) which currently assures physical traceability and integrity of gold from 11 ASM producer organizations in 4 countries to 11 refiners and other supply chain operators in 8 countries.[125]

Notwithstanding, size matters. Closed pipe supply chains for small volumes like those produced from a single ASM mine sites become extremely costly to operate and are therefore of limited attractiveness to buyers.[126] This practical limitation can be overcome by delimiting **local catchment areas**, as shown in the example provided in Figure 27. The figure additionally shows that:

- Local catchment areas consist of adjacent deposits or mines with either river or road access. This most likely correlates with the type of deposit and consequently compositional characteristics.
- Areas with river access agglomerate most likely wet placer operations (e.g. Shabunda area), while areas with road access (Figure 28) represent more likely combined primary and placer deposits extracted in form of open pit or hard rock mining. Area-specific compositional characteristics can be expected.
- Most local catchment areas count on *centres de négoce*, where miners and B-trader sell their gold to A-traders or their agents.

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[124] Individual trade relations may differ from this generic supply chain sequence.

[125] www.fairmined.org

[126] Experience from closed pipe Fairmined Gold supply chains. (Personal communication ARM)

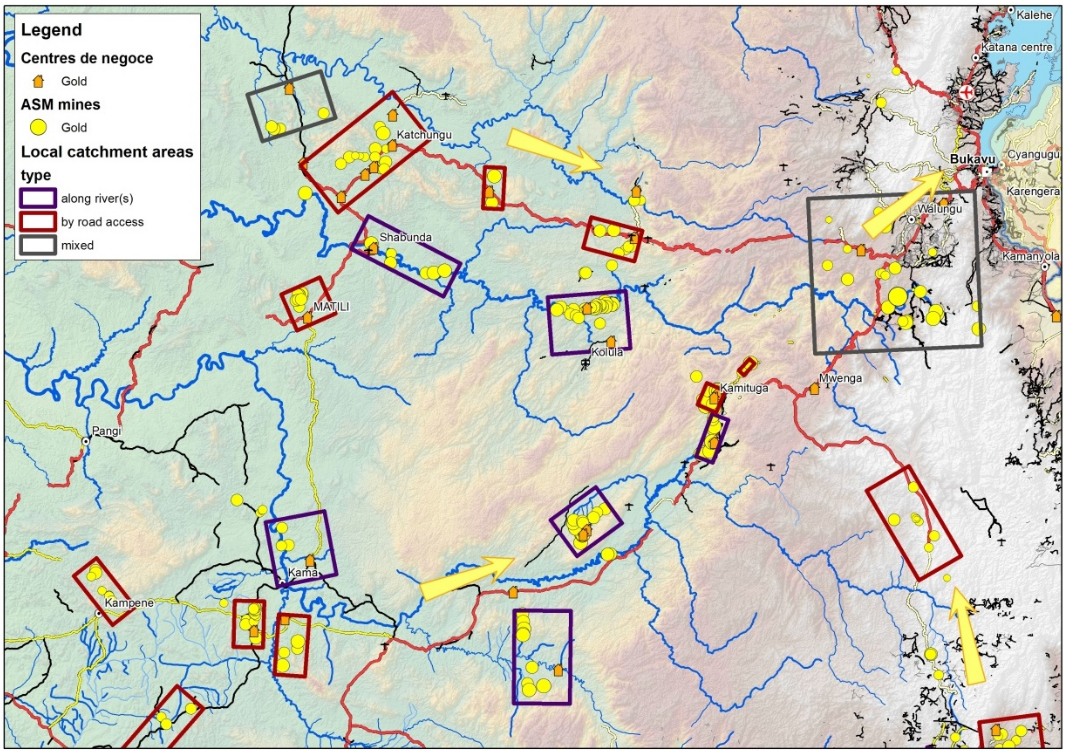

Figure 27: Local catchment areas.[127]

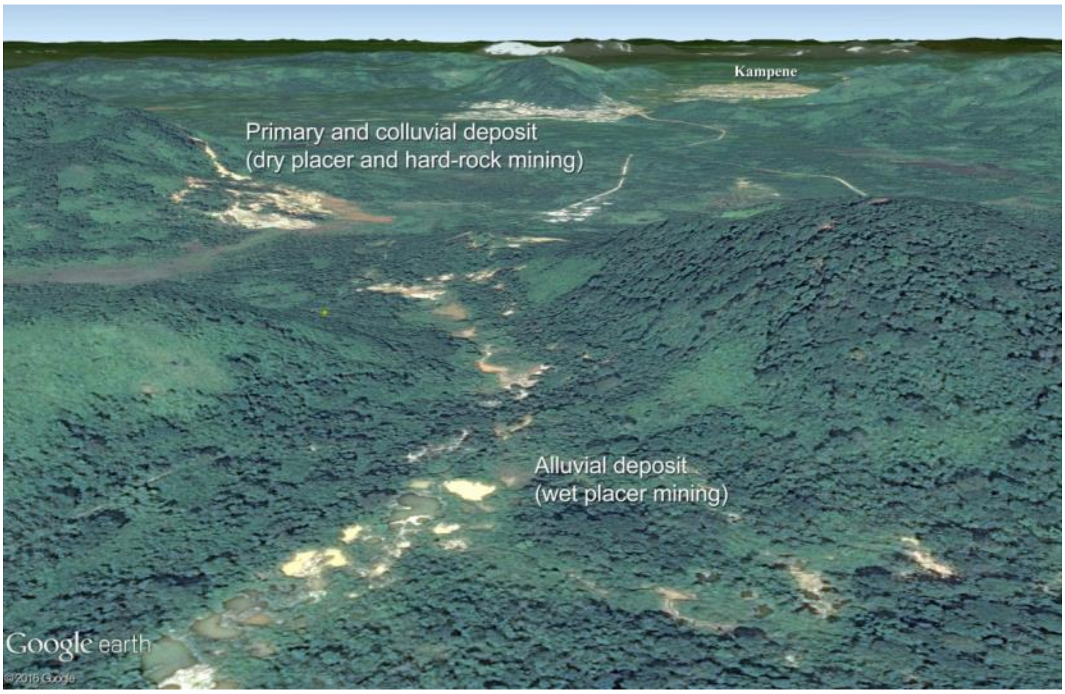

Figure 28: Example for an ASM mining area combining a wet placer, dry placer and hard-rock deposit, sharing the characteristics that gold has not undergone alluvial transport over a large distance.

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[127] Data source: Mine sites and Centres de négoce: IPIS (2015a); Roads and Rivers: Open Street Map.

D.1 Stakeholders

Target stakeholders of the scenario are the ASM mines (operated by mine owners, associations, cooperatives, etc.) and the B-Traders buying at the mines from groups or individual miners. While the number of ASM mine sites in the eastern DRC exceeds 1,500, the total number of B-traders in this area is estimated in the range of several thousands. However, for a single closed pipe supply chain, the number of involved stakeholders from the ASM sector reduces significantly.[128] The scenario involves other stakeholders as outlined in Table 33 below.

Table 33: Stakeholder Analysis for GPA Scenario I

	Level of involvement	Effective or prospective role	Possible expectation	Impact
ASM mines and miners	• High = **GPA target**	• **Granting access for GPA sample collection**	• Benefits from CPSC • Fear of increased control and taxes	• Formalization • Improved market access
B-Trader	• High = **GPA target**	• **Granting access for GPA sample collection**	• Benefits from CPSC • Fear of increased control and taxes	• Formalization
A-Trader	• Low	• None	• Fear of losing role in CPSCs	• Shorter supply chain
Comptoirs and trading houses	• Low • **High (for CPSC)**	• Export of gold into CPSC • **GPA sample collection**	• Participation in CPSCs	• Increased formal export
International Refiners	• None or • **High (for CPSC)**	• Import of gold from CPSC	• Increased certainty of due diligence • Conflict free sourcing	• Reduced reputational risk
Downstream industry	• Potentially interested in CPSC	• Responsible sourcing	• Responsible sourcing	• Reduced reputational risk • Market opportunities
State (mining sector)	• High	• **GPA sample collection** • **GPA analytics**	• Improved control of the ASM sector • Improved geologic data	• Enhanced control and transparency of EI sector
State (finance sector)	• Low	• None	• Increased Government revenues	• Reduction of IFFs
State (local government)	• Low	• **GPA sample collection**	• Improved control of the ASM sector • Tax collection	• Enhanced control of ASM sector
ODA projects and initiatives	• High	• Technical assistance • Human and financial resources	• Economic development • Peace building and improved human rights situation	• Enhanced impact of programs
Civil society (nat. NGOs) & consulting firms	• Medium to high	• **GPA sample collection** • **GPA analytics**	• Involvement in programs	• Enhanced impact of programs
Civil society (int. NGOs) & consulting firms	• Medium to low	• Support to CPSCs	• Synergy with existing programs • Involvement in new programs	• Enhanced impact of programs

Abbreviations: CPSC: Closed Pipe Supply Chain; EI: Extractive Industries; IFF: Illicit Financial Flows

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[128] Geenen (2011) reports 150 to 200 mining shafts in Kamituga (near Bukavu, South Kivu), each employing some 5-10 miners. In 2009, their production was purchased by approx. 17 larger and 60 smaller *petit négociant's* buying offices.

D.2 Type of Samples and Sample Collecting Procedures

Type of samples[129]

The main **characteristics of gold from hard rock and dry placer ASM** are:

- it originates mainly from oxidized zones of hard-rock deposits or from placer deposits
- it might be processed purely gravimetrically in some placer and hard-rock deposits if grain sizes are coarse enough
- or it might be processed by amalgamation, e.g., in case of gold from hard-rock deposits that was milled with the gangue.

The main **characteristics of gold from dredging operations** are:

- it originates from alluvial placer deposits, where gold particles are entirely liberated
- it is processed gravimetrically and in most cases subsequently amalgamated with mercury.

The main **characteristics of gold accumulated at the level of Category B traders** are:

- The gold, which the *petits négociants* trade, consists of dust, flakes or nuggets from gravimetrical concentration or gold sponge from amalgamation.
- The gold originates exclusively from the ASM mine site where the *petit négociant* operates, and even the groups of miners (and therefore the individual pits, shafts of tunnels) from whom the *petit négociant* buys may be relatively constant over time. The gold is therefore representative for the mine site and can be expected to reflect characteristics of the deposit.

Consequently, **gold dust, flakes or nuggets** (in case of coarse gold) or **gold sponges** from amalgamation can be expected as products, which contain (i) in case of pure gravimetric concentration the gold in its native form, along with heavy minerals that could not be separated by techniques available on site, or (ii) in case of amalgamation, the non-volatile components of native gold, accompanied by an elevated mercury content.

Transaction volumes between miners and B-traders are typically in the range of below 10 g. Accumulated volumes of gold for onward sale by B-traders (main sampling target) are in the range of **50 g to 1 kg**.

In case of closed supply chains, gold would need to be consolidated and homogenized for assaying prior to dispatch. In this case, the product to be sampled would be doré bars.

Sampling procedures

At local level, due to mainly stable trade relations as described by Geenen (2011), gold produced by ASM mines can be considered identical to the gold purchased by locally operating B-traders. Sampling of gold accumulated by B-traders is therefore widely representative for the mine sites on which they operate.

For additional certainty and to assess local variations of compositional characteristics over time, sampling of gold at B-trader level should be complemented by on-site sampling of the ASM mines. Such requirements are in place in South African gold mines, where every six month, each licensed gold producer has to submit a representative sample from different stages of production (native gold and doré). This requirement proved successful for establishing a national gold database (Dixon 2014).

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[129] See chapter 5.2and 5.3 for further details.

Submission of mine samples (like in the above example from South Africa) by traders or miners is not considered reliable for remote ASM mine sites. The recommended sampling procedure is to obtain witnessed samples by the entity in charge of GPA. Sampling may be carried out by a governmental entity or outsourced to a contracted (private sector or civil society) organization.

For a **closed pipe supply chain**, three systematic sampling points are required (Figure 29):

- **Gold sold by B-traders**. Initial sampling should cover all B-traders operating in the catchment area, to assess the range of local variation of compositional characteristics. Once a site-specific profile has been established, frequency of sampling depends on the purpose of GPA. This involves one or more A-trader, or in case of a shortened closed-pipe supply chain the agent of the *comptoir* that buy(s) the gold from B-traders (or miners).

  Criteria: Gold sold by B-traders and claimed to originate from the catchment area, must not contain any compositional characteristic absent in the deposits of the catchment area.

- **Gold accumulated by the exporting *comptoir***, prior to export. Sampling should ideally be done for every shipment.

  Criteria: Gold exported by the *comptoir* and claimed to originate from the catchment area, must not contain any compositional characteristic absent in the analysis results of gold supplied by B-traders.

- **Gold received by refiner**.

  Criteria: Analysis must be identical (i.e. close match) to the analysis results provided by the *comptoir* that dispatched the shipment.

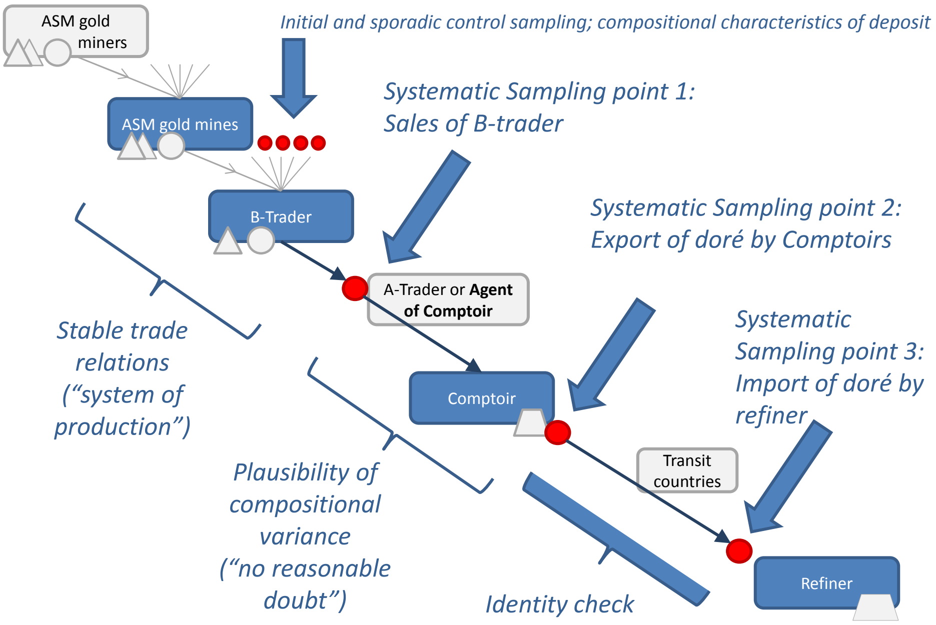

Figure 29: Sampling points for GPA Scenario I, applied to a closed pipe supply chain

D.3 Analytical Methods

Analysis must be carried out “in the field”, including mine sites and offices buying from B-traders. Thus, A-traders or in case of a shortened closed pipe supply chain the local agent of the *comptoir* will be in charge. In cases it might be necessary to analyze gold collected or “confiscated” under suspicion of infiltrating or by-passing the closed pipe supply chain. Due to largely or completely missing infrastructure in terms of power supply, gas supply, internet access, access to service etc., a most “rugged” type of analysis is required. Analytical devices must be portable, independent of local power supply and easy to use, but sensitive enough to provide a number of parameters that may be used for GPA; these are the major and minor element levels. For the moment being, such requirements are only met by pXRF spectrometers (so-called ”handhelds”). Portable LIBS devices offer significant potential (Table 6) but are less frequently used and certainly need more research input.

D.4 Laboratory Equipment, Personnel Resources and Skills Required

In a closed pipe supply chain approach, local personnel must be equipped with pXRF spectrometers. In a likely scenario, a specially trained A-trader (termed “agent” in the following) working with/for a *comptoir* may serve as a local focal point for GPA. This person will have good relationships with local miners and B-traders that offer him their production; he will know his clients and their production sites and will be able to judge if this production meets the due diligence criteria laid out by his company. Thus, the “agent” will collect spectra of the production and store the data for later export, along with written information on the source. Handling of the instrument and software requires a certain degree of technical skills and should not be underestimated. Thus, proper training by a knowledgeable person (e.g. instrument provider) on sample preparation, measurement, data storage, data export along with information on the risks and dangers working with X-rays (safety) is absolutely necessary.

On the *comptoir* level, X-ray spectra from doré produced from the gold analyzed before must also be collected, in order to be available for a provenance plausibility check that must be carried out by an independent actor, such as a local government institution or a local NGO. Personnel in this unit must be trained as data analyst in addition to the skills mentioned above.

At the downstream end of the closed pipe supply chain, systematic-, random- or on-demand sampling and analysis can be performed by the refiner, in accordance to corporate policies and due diligence procedures in place.

D.5 Data Processing

Data/spectra collected by the “agent” or in the *comptoir* will be exported to a laptop in certain time intervals, stored in the *comptoir*, and on demand submitted to a local independent laboratory or to the refiner at the other end of the closed pipe supply chain. There, plausibility checks will be performed for doré produced from “certified” gold in the *comptoir*. The independent laboratory is equipped with software allowing import of spectra, data managing and spectra comparison. These data may also be used for export permitting and as quality/grade checks for buyers. This is considered a positive asset for the *comptoir* partner in the closed pipe supply chain.

In this scenario two different database systems are possible. First, a standalone system can be used in the context of a closed pipe supply chain. The responsible trader for the participating mines can plausibly demonstrate from whom he buys. Due to different types of gold (nuggets, flakes, sponge) a standard routine for the data recording should be developed (pilot project). Over time a characteristic spectrum could turn out for certain regions. Either the trader or an independent organization has to collect the spectra from the gold of the attending participants. The spectra will be exported from the instrument to the database. A simple spreadsheet calculation will not be sufficient. The database has to include different types of data (spectrum, location, information about geology, information about the ASM miners, information about the sample type). Therefore, the design of the database has to be determined before starting such a project.

The second possibility is a multiuser system, where the database is located on a server and the clients use a terminal or a web interface for data entry. A mobile phone application may be used if the spectral data can be transferred by Bluetooth; the new generation of pXRF systems already uses this function. An independent organization with the resources for maintenance should be responsible for the multiuser system. An active internet connection is required for sending the data to the server. One of the advantages is that the downstream buyer in a closed pipe supply chain (i.e. the refiner) can be granted read access to the database for due diligence; e.g. the refiner can see in the browser the spectrum of the doré before transport or even the spectra from the gold of the participating mines.

To simplify the data collection, every B-trader registered as actor of the closed pipe supply chain (or miner, if gold is traded at that supply chain level) could receive a QR code[130] on his license card with his ID-Number and other information. The trader only needs a smartphone with a camera and an application to manage his purchases.

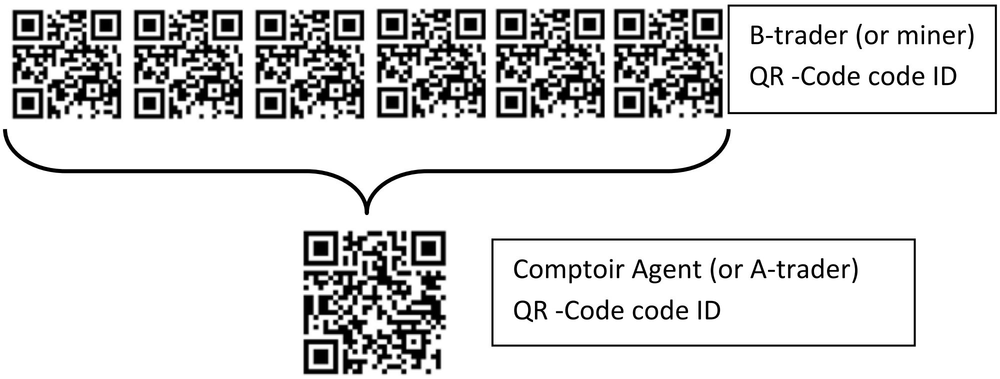

Figure 30: ID's identifying the supply chain actors of a closed pipe supply chain.

D.6 Issues to be addressed

Proof of concept. Proof that spectra collected from mined gold and gold sponge are useful to define local sites must be worked out in a pilot study with a minimum of two participating companies (*comptoirs*, mining companies). The relationship of these spectra with doré produced from them is likely but needs to be further evaluated. The pilot study also has to address the eventuality of a possible large compositional overlap of spectra from adjacent (or even worse from several non-

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[130] A QR code pattern can save up to 7089 numbers or 4296 alphanumeric symbols

adjacent) catchment areas, which would reduce the meaningfulness of analytical results for validating the integrity of the supply chain significantly.

Local supply chain mapping. In order to maintain a reasonable and manageable number of systematic sampling points (A-trader or agent of a *comptoir* buying from B-traders), the scenario bases on the assumption that the integrity of the supply chain at its upstream end is provided by stable trade relations between miners and B-traders. The alternative (providing analytical equipment and training to all local B-traders) is unrealistic[131]. The assumption of stable trade relations needs verification through a local supply chain mapping, to reduce chances that sampling is not representative or gold from outside the closed pipe supply chain is introduced before measurement.

Interference with trade relations and the need for incentives. Implementation of a closed pipe supply chain interferes necessarily with existing trade relations and eventually even with established terms of trade. In order to ensure broad based uptake of a closed pipe supply chain, positive impacts need to prevail and incentives need to be created. Otherwise gold will find its way to bypass the controls, as it is currently the case for most ASM gold produced in the DRC.

Product segregation from a "system of production". In a given catchment area or even at a single mine site, not all ASM operations or operators might be willing to participate in a closed pipe supply chain initiative from the outset, or be able to comply with standards expected by buyers. In practice, it is even unlikely that a local closed supply chain can kick-start with all supply chain actors participating. Similar challenges were also encountered in other certification schemes for ASM gold and led in case of the Fairmined Standard (in version 2) to the introduction of the concept of a "system of production" (ARM 2014a). All miners, mines and B-traders committing to participate in the closed pipe supply chain constitute the system of production, and gold produced by the system of production needs to be segregated from non-certified gold.

Single- or multi-track closed supply chains. A closed pipe supply chain is not necessarily equivalent to single-track trade relations. Experience shows that downstream buyers prefer to have more than one supplier[132] and miners (and B-traders) more than one possible buyer (*comptoir*). A dual- or multi-track closed supply chain also ensures uninterrupted operation of the closed pipe supply chain in case of non-conformities of one operator.

Use of marker elements. Integrity of the gold shipment on the way from the exporting *comptoir* to the importing refinery is crucial for international buyers, willing to invest in due diligence to source from ASM. Reliability of GPA can be optionally complemented and enhanced by "doping" of dorés with marker elements, as already practiced by some refiners.[133] Hinds (2015) reports that marker elements such as Ce, La, Sc and Y in concentrations below 3 ppm are appropriate for that purpose. Addition of tracer elements does not require analytical facilities at the export point.

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[131] Cost-benefit relation of analysing purchases of B-traders from miners in the range of a few grams is highly unfavourable. Additionally, the price of a pXRF equipment exceeds by far the annual income of B-traders: Risks are high that a considerable number of B-traders sell the provided equipment and disappear forever.

[132] Experience from closed pipe Fairmined Gold supply chains. (Personal communication ARM)

[133] Personal communication of a Swiss-based refiner.

Annex E Verification of Gold Production Regions (GPA Scenario II)

Doré bars produced by *comptoirs* in the DRC have a varying composition and quality according to proportions of gold received from different suppliers in a given period. Based on in-country trading routes identified by Mthembu-Salter (2014a, 2014b, 2015b) and corroborated by BGR[134], a high likelihood exists that *comptoirs* and other wholesale trading houses receive their gold from relatively well defined "catchment areas" according to established and stable trade relations.[135] In combination with the four identified geological provinces[136], this leads to the assumption that at least dorés from northern and southern *comptoirs* have different compositional characteristics; with the possibility of an even finer geographic resolution, ascending the supply chain towards Category A Traders.

"**Provenance**" of this scenario represents geographic catchment areas within the DRC, determined by trade relations between *comptoirs* and their suppliers (mainly A-trader, but occasionally also B-trader or miner). These trade relations may be based on a variety of criteria, but will, in absence of a price differential, be mainly determined by existing transport infrastructure. Figure 31 shows a possible delimitation of such catchment areas based on road transport.

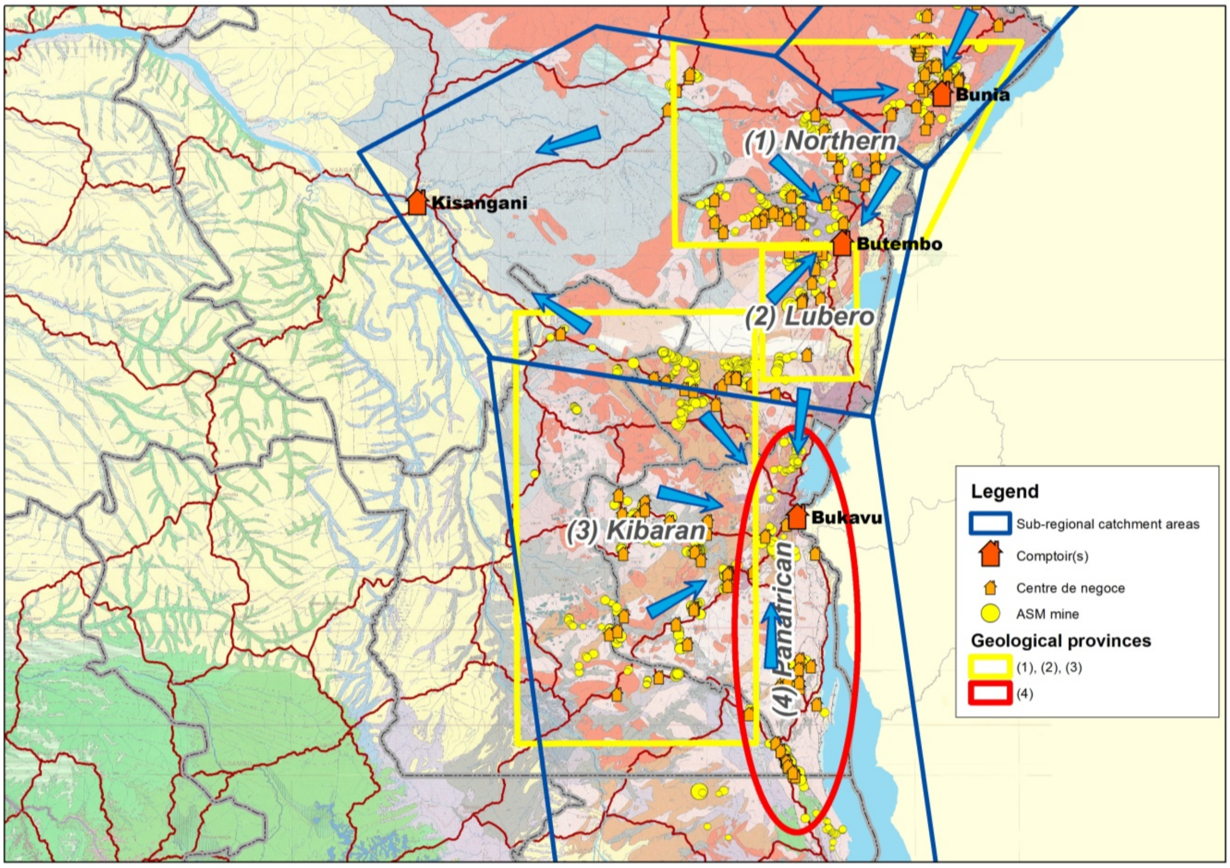

Figure 31: Catchment areas based on road infrastructure for the *comptoirs* in Eastern DRC.

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[134] Pers. comm., D. Ruppen, BGR, 2016.

[135] i.e. the geographic areas where their suppliers operate. (See chapter 5.3 iii).

[136] See chapter 4.

Catchment areas overlap with the Geological Provinces identified in chapter 4. The resulting "mix of sources" of gold purchased by *comptoirs* (under the assumption that transport logistics are a key parameter of trade relations) is shown in Table 34.

Table 34: Sub-regional catchment areas of *comptoirs*.

Location of comptoir(s)	Number of comptoirs[137]	Geological provinces			
		Northern	Lubero	Kibaran	Panafrican
Bunia	1	●			
Kisangani	4	•		●	
Butembo	1	●	●		
Bukavu	4		•	●	●
Kinshasa	4	•	•	•	•

Symbols:

●: expected to be a main source of gold for the *comptoir*, due to geographical proximity of mines;

•: expected to be a minor source of gold for the *comptoir*, due to distance to mines

The scenario is expected to provide meaningful results for validating provenance claims at sub-regional level (e.g. gold from a certain area within the DRC). It will not necessarily allow positive confirmation of a claimed origin, but it is expected to allow raising a red flag and trigger further due diligence if the compositional characteristics of a sample does not match the claimed origin.

The particular advantage of the scenario is that it has the potential for a rapid countrywide deployment, initially covering >10 *comptoirs* and progressively up-scaling into the segment of A-traders and possibly beyond.

E.1 Stakeholders

Target stakeholders of the scenario are the *comptoirs* and other wholesale trading houses, as well as Category A Traders as their main suppliers. According to chapter 5.3, the number of legal *comptoirs* that record exports is limited in the range of 10 to 20. In 2014 they were located in Kinshasa (4), Orientale (4), Bunia (1), North Kivu (1) and South Kivu (4). The number of informally exporting trading houses is unknown, which does not affect the scenario, as their active cooperation in GPA is anyway unlikely. The number of registered A-traders is in the lower range of the hundreds. The scenario involves other stakeholders as outlined in Table 35 below.

Table 35: Stakeholder Analysis for GPA Scenario II.

	Level of involvement	Effective or prospective role	Possible expectation	Impact
A-Trader	• High **= GPA target**	• **Granting access for GPA sample collection**	• Fear of increased control and taxes • Reliable information of gold fineness	• Formalization of trade

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[137] See chapter 5.3 (iii) based on Martin & Taylor (2014).

	Level of involvement	Effective or prospective role	Possible expectation	Impact
Comptoirs and trading houses	• High **= GPA target**	• **Granting access for GPA sample collection**	• Fear of increased control and taxes • Advantage of *comptoirs* in competition with illegal exporters[138]	• Increased formal export
International Refiners	• Medium	• Validation of purchases against sub-regional provenance profile	• Increased certainty of due diligence • Conflict free sourcing	• Reduced reputational risk
Downstream industry	• Low	• Due diligence	• Due diligence	• Reduced reputational risk
State (mining sector)	• High	• **GPA sample collection** • **GPA analytics**	• Improved control of gold trading	• Enhanced control and transparency of EI sector
State (finance sector)	• High	Potentially at export point • **GPA sample collection** • **GPA analytics**	• Increased Government revenues	• Reduction of IFFs
State (local government)	• Low	• Facilitation of GPA sample collection	• Improved control of gold trading • Tax collection	• Enhanced control of financial flows
ODA projects and initiatives	• High	• Technical assistance • Human and financial resources	• Economic development • Peace building and improved human rights situation	• Enhanced impact of programs
Civil society (nat. NGOs) & consulting firms	• Medium	• GPA sample collection[139] • **GPA analytics**	• Involvement in programs	• Enhanced impact of programs
Civil society (int. NGOs) & consulting firms	• Medium	• Independent assurance schemes	• Synergy with existing programs • Involvement in new programs	• Enhanced impact of programs

Abbreviations: EI: Extractive Industries; IFF: Illicit Financial Flows

E.2 Type of Samples and Sample Collecting Procedures

Type of samples[140]

The **main characteristics of gold at the level of Category A traders** are:

- The ASM doré bars produced by A-Traders[141] consist of the consolidated mined gold (dust, flakes, nuggets, gold sponge) from various B-traders and/or miners, acquired during a certain period of time, homogenized by smelting.
- The smelting process alters the chemical composition of the gold and increases its fineness. A portion of the originally contained lithophile elements and elements sensitive to smelting ends up in the slag or is volatilized.
- While mine-site-specific geochemical information is lost at the level of A-Traders, sub-regional geochemical characteristics (particularly characteristics related with geological provinces) of

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[138] Although 98% of the gold produced by ASM crosses the border without being registered, *comptoirs* “complain” against competition from illegal exporters.

[139] Less likely in this scenario.

[140] See chapter 5.3 for further details.

[141] Typically in own artisanal furnaces, but possible also at the premises of the *comptoirs*.

the gold are likely to be retained. The chemical composition of ASM doré bars produced by a certain A-Trader is likely to correlate with the sub-regional origin of this mix of sources

The **main characteristics of gold consolidated at the level of *comptoirs*** are:

- The doré bars may be composed of all kind of ASM products (gravimetric, amalgamated and leached gold). They consequently may contain traces of all chemical elements originally contained in the native gold as well as in leachable gangue minerals.
- The doré bars cast by *comptoirs* have most likely undergone two smelting processes. A further portion of the originally contained lithophile elements and elements sensitive to smelting ends up in the slag or is volatilized. Precious metals are therefore enriched and trace elements (impurities) reduced, compared to mined gold and to ASM doré of A-Traders.
- Changes in chemical composition can be even more pronounced in case pre-refining with nitric acid has been applied. Pre-refined doré can be identified by a significantly altered Au:Ag relation.

Consequently, the predominant sample type at this stage of the supply chain is **doré**.

Transaction volumes (to be sampled) between A-traders and *comptoirs* are typically in the range of **250-2,500 g**. Export shipments of *comptoirs* are typically in the range of **several kg**.

Sampling procedures

In a first stage of roll-out of the scenario, covering the exporter level (*comptoirs*), sampling procedures can be integrated into the already compulsory assaying of export doré bars. Assaying procedures for export consist of triple sampling to determine precious metal contents and corresponding taxes: by the exporter, the *Office Congolais de Controle* (OCC) and the *Centre d'Expertise d'Evaluation et de Certification des substances minérals précieuses et semi-précieuses* (CEEC) (Mthembu-Salter 2014b). Analysis of minor and trace elements as needed for GPA can be integrated in OCC's or CEEC's assay protocol, without need for additional sample collection.

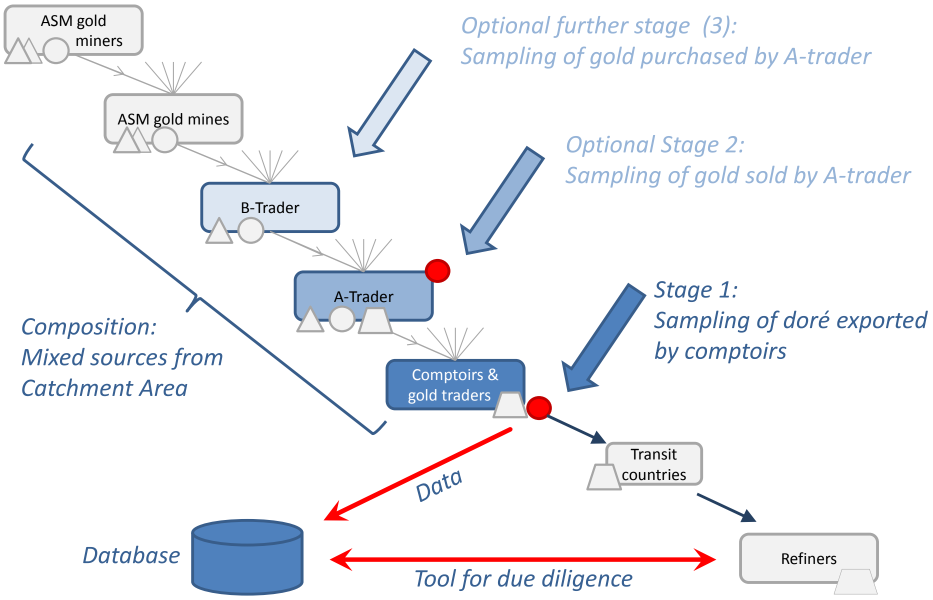

Figure 32: Sampling points for GPA Scenario II.

In a second stage of roll-out, outreaching to A-traders, witnessed sampling of dorés purchased by *comptoirs* and attributed to A-traders can be performed at *comptoir* offices. Sampling at a major number of A-trader offices could however become logistically challenging. Alternatively, analytical facilities could be established (e.g. by SAESSCAM) in mayor gold trading cities, where A-traders can obtain an independent analysis of their doré prior to onward sales.[142]

E.3 Analytical Methods

The focus of GPA Scenario II is the chemical composition of doré. "Certifiable" doré production at the *comptoir* level must comprise only gold collected from "clean" mine sites and traders (e.g., conflict-free, obeying to due diligence, etc.). Thus, doré composition is a function of geology and mineralogy in the source area, techniques of concentrate production by gravity separation or amalgamation, as well as the number, composition and variability of the sources mixed to produce doré. As outlined by (Augé et al. 2015), inclusions may aid in deciphering its origin.

E.4 Laboratory Equipment, Personnel Resources and Skills Required

Similar to the situation outlined in chapter D.4, the composition of doré produced at *comptoir* offices is most practically analysed using pXRF or pLIBS spectrometers. This way, the instruments may travel to the doré production sites and the production does not have to be moved around, reducing the danger of security issues. However, for XRF the use of stationary instruments equipped with a vacuum pump may help receiving better count rates and also offering the possibility to analyse the lighter elements. Stationary LIBS systems are much more widespread than pLIBS systems and probably more suitable for analysis of small samples. In both cases, doré production needs to be transported to a laboratory.

In either case, the analysis must be performed by an independent party. This may comprise government institutions (OCC, CEEC, SAESSCAM) or NGOs. In the second case (stationary equipment), a binocular microscope or a small scanning electron microscope may additionally be used to identify inclusions in doré that typically record processing steps and contamination.

In order to cover production from several *comptoirs*, a unit equipped with a few instruments (ca. 3-5 portable instruments) and personnel (ca. 5-10) must be trained and financed. Training includes basic security, technical and analytical skills as outlined in chapter D.4., complemented by an understanding of more sophisticated data management and data manipulation procedures (e.g., standardization, calibration, recalibration, quality checks).

E.5 Data Processing

Focussing on doré also means that sampling and measurement are not as problematic as with heterogeneous materials such as mined gold (flakes, nugget) or amalgamated gold (gold sponge). Consequently, element concentrations may be calculated from the spectra.

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[142] Another hypothetical option to obtain countrywide data and eventually even outreach into the segment of B-traders, could consist of a legal/administrative decree, requesting license payments for trading permits to be paid partly in cash and partly in physical gold. The authors are aware that this is speculative at the current moment. This or similar approaches of non-conventional sampling could - over time - contribute to a countrywide gold database similar to the one in South Africa.

In the first stage of roll-out, all assay data from *comptoirs*, OCC and CEEC (or the laboratories in charge of assaying) must be exported to a regional database collecting spectra from all *comptoirs*. This way, a regional database is set up enabling comparisons of doré compositions in the region.

The data processing in this scenario can be done either in a standalone or in a multiuser system, depending on who maintains the database and how the data entry should take place. It is recommended that an independent organization or official unit is responsible for the database (see above). In addition data collection should be as simple as possible for non-skilled persons.

In the second stage of roll-out, outreaching to A-traders, analysis data (pXRF or pLIBS spectra) acquired by *comptoirs* (including data of purchased gold dust, nuggets and sponge) need to be systematically collected in a country-wide database. Distant geographic locations of *comptoirs* (currently in 4 provinces and in the capital) make a server based DBMS with online data transmission mandatory.[143] The example from the Scenario I with the QR Code ID can be adapted, to uniquely identify *comptoirs* and A-traders.

In a hypothetic further roll-out stage, if outreaching to B-trader level is aimed for and considered enforceable, such a QR-code scheme can be easily extended. In that case the A-trader would upload the spectra of gold purchases from the B-trader, *comptoirs* would upload the spectra of purchases from A-trader, and spectra from *comptoir* exports are collected by OCC and CEEC. The spectrum from the doré is then linked to all upstream traders (and their spectra). In principle, the mix of sources acquired by A-traders should plausibly result in the spectra of the gold purchased by *comptoirs* and the mix of sources of all purchases by *comptoirs* should plausibly result in the compositional characteristics of the gold exported by them.

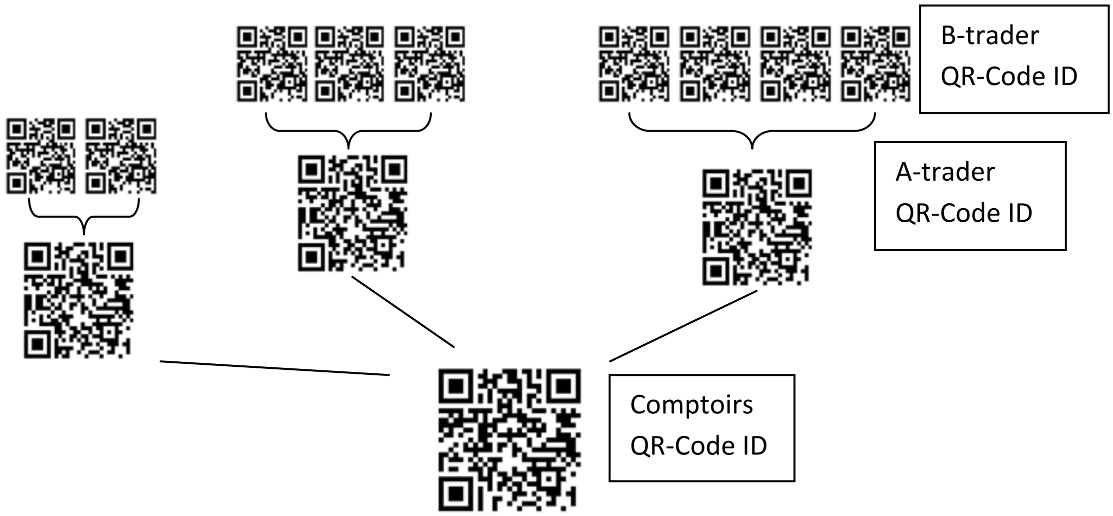

Figure 33: Different levels of documentation the supply chain using QR-Code IDs.

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[143] Cloud based data synchronization can ensure transmission over even extremely weak and intermittent internet connections, sending data packages in chunks. Note: due to sensitivity of data and related security issues, it is not recommended to use public cloud services like Dropbox or similar.

E.6 Issues to be addressed

Proof of concept and need for piloting. Proof that analytical data are useful to validate the plausibility of provenance claims from sub-regional catchment areas must be worked out in a pilot study. The pilot study also has to address the eventuality of a possible large compositional overlap of spectra and quantitative data from different *comptoirs*, resulting from more arbitrary in-country trade relations than assumed under the catchment area hypothesis. In this case it is recommended to evaluate whether a similar “random” distribution also applies at a lower aggregation level (A-traders).

Stage 1 (sampling of doré exported by *comptoirs*) is easy to achieve. It mainly requires analytical equipment for assay labs of OCC and/or CEEC, a DBMS for data processing and the corresponding training of operators.

Stage 2 (outreach to A-traders) is already more challenging. It not only requires equipment, qualified human resources and training for *comptoirs*[144], but also either their voluntary participation based on incentives (e.g. competitive advantages) or a mandatory requirement with corresponding enforcement mechanisms. The approach needs to be clarified and agreed with on political level.

Financial sustainability. If the alternative of external analysis is chosen (independent facility for A-traders to get their gold assayed prior to sales), questions to be addressed relate to long-term financial sustainability. A reliable (and for A-traders trustworthy) entity needs to be identified or established, for which a long-term business plan (government-funded or self-financing) needs to be elaborated.

Potential for further up-scaling. For a hypothetical further outreach to B-traders, the context becomes even more challenging. It not only involves a much larger stakeholder group to be equipped and trained (A-traders), it also raises logistical questions such as internet connectivity in more remote locations, computer literacy and trainability in general with regards to a technology with considerable safety requirements (e.g. use of X-rays).

However, important long term potential is seen in such up-scaling of the scenario: It would (i) help to speed-up the process of populating a country-wide geo-database of gold catchment areas, (ii) add robustness to due diligence processes and hence make sourcing gold from the DRC more attractive to responsible buyers, and it would allow to triangulate gold production volumes and reduce illegal cross-border trade.[145]

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[144] This is apparently a minor challenge, as *comptoirs* reportedly already use XRF equipment for determination of gold fineness (see footnote 93)

[145] Currently some *comptoirs* report only marginal export volumes, some in the range of 2 kg/year (Martin & Taylor 2014) i.e. just as necessary to avoid being considered inactive and losing the license. If activity or inactivity can be monitored for A-trader and B-trader too, and volumes at all level are reported into the system, the accumulated volumes at *comptoir* level become more transparent.

Annex F International Claims of Origin Assessment (GPA Scenario III)

Total official gold exports of DRC in 2015 are reported as 31.8 t. This volume originates almost exclusively from LSM. Together, the three LSM mines contribute to more than 99% of official gold exports.[146] In contrast, out of the estimated 8 to 12 t of gold produced by ASM, only 254 kg are reported as officially exported (Ministère des Mines 2016). Almost 98% of the gold produced by ASM crosses the border without being registered when leaving the country or paying export taxes.[147] The challenge of revenue loss from tax evasion and smuggling of ASM gold pertains not only to the DRC but to many producing gold countries in the Great Lakes Region and elsewhere.

At the same time, this practice represents a challenge for significant ASM gold importers such as the United Arab Emirates. Even though these countries may not levy import taxes, they are increasingly concerned about their international reputation and regulatory requirements in the context of due diligence or risks of illicit financial flows. Consequently, import authorities should have a strong interest in verifying the claimed origin of gold shipments. The DRC (or, potentially, any other country for that matter) is considered the “**Provenance**” of this scenario. As, according to GoE (2016), fraudulent or fake documents accompanying shipments from adjacent countries remain an issue, the scenario aims at verifying claims of origin at international export points (mostly airports) from the DRC or other countries of the Great Lakes Region, at transit points, or during the import procedure in key gold trading hubs such as Dubai.

Given the highly aggregated mix of sources at the stage of export and transit points, the scenario is not expected to allow for straightforward identification of an origin (“*sample X is from country Y*”), but to raise a red flag and trigger further due diligence if the compositional characteristics of a sample does not match the claimed origin (“*sample X cannot be from country Y*”). Exceptions, where even a positive confirmation of provenance can be expected are physically segregated volumes of closed pipe supply chains, and gold from LSM operations.

The scenario has a potential for region-wide deployment, but requires inter-governmental coordination at ICGLR level. It has the potential for expanding and integrating export destinations (such as Dubai), with an extra level of inter-governmental coordination.

The number of sampling points required to focus on “out-region smuggling” is closely related with the number of international airports in the ICGLR, and to a lesser extent with border control of roads and waterways. Figure 34 maps the possible main supply routes by air, road and waterways. The number of potentially critical international airports in the DRC and adjacent countries is in the range of 20, the number of border customs in the range of 50.

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[146] Kibali exported 25.0 t, Twangiza 4.9 t and Namoya 1.7 t.

[147] Export taxes are independent from other local and national levies, fees and taxes collected by the State from miners and traders. “Illegal export” therefore does not imply that the gold has been illegally mined and/or ASM does not contribute to government revenues.

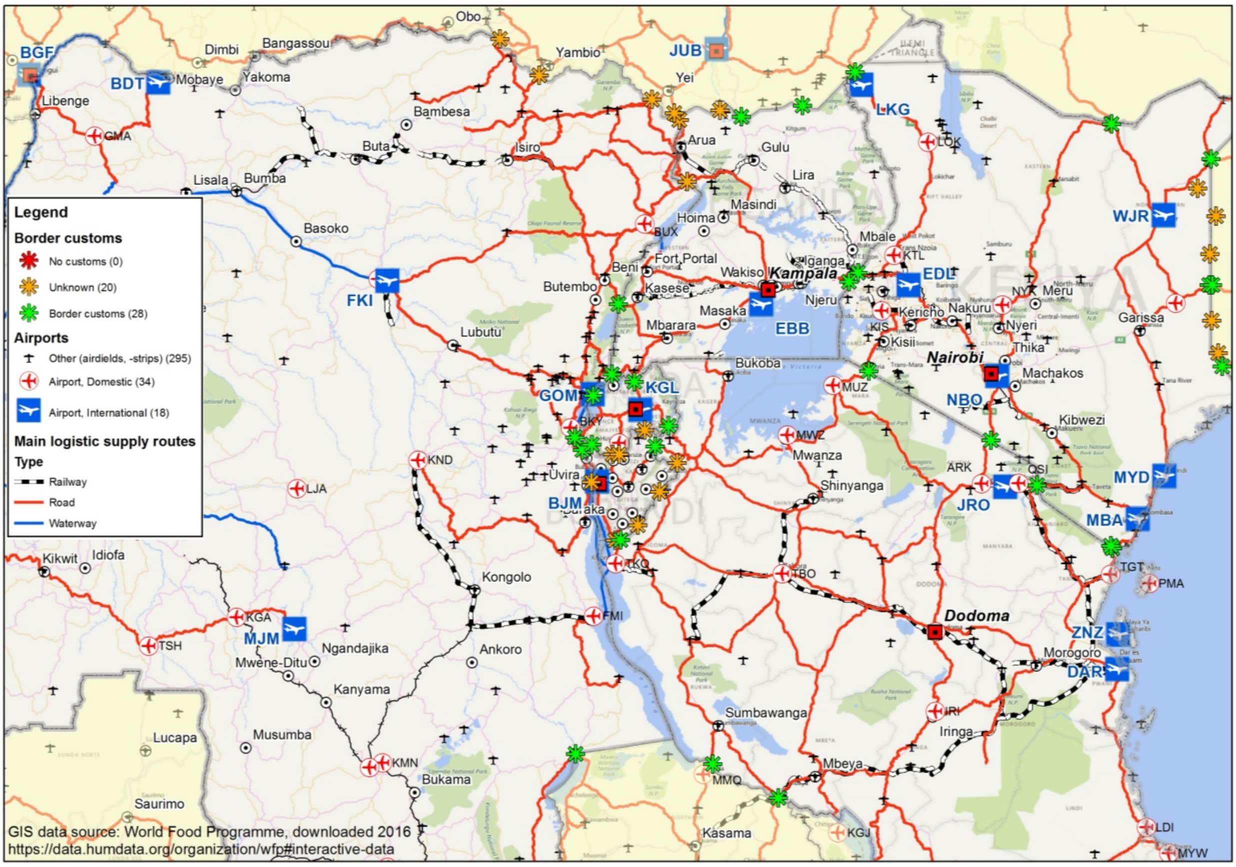

Figure 34: Possible logistic routes and points for border control (airports, roads and waterways). Data source: WFP.[148]

Hypothetically, it might also be possible to create a compositional gold provenance database exclusively from data gathered at import points (without data from producer countries). The underlying assumption is that for truthful declarations of origin, analytical results are consistent in the long term, whereas for pretended claims they vary according to conjunctural opportunities. Systematic sampling of all gold import transactions over an extended period, e.g. at mayor trading hubs for DRC gold such as Dubai, may result in statistically significant patterns of compositional characteristics correlated with plausible provenance declarations. Such an alternative approach to the scenario is however speculative and would require further research to evaluate its feasibility.[149]

F.1 Stakeholders

Target stakeholders of the scenario are export applicants, that is, *comptoirs* and other wholesale trading houses during export, as well as onwards traders in adjacent transit countries (Uganda, Rwanda, Burundi, Tanzania, Kenya) and import authorities within and outside the Great Lakes Region. The number of export applicants or their willingness to cooperate with sample submission is of limited relevance for the feasibility of this GPA scenario given that it would be integrated in official export or import procedures. Obviously, the ability to detect gold smuggling attempts shortcutting the whole

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[148] https://data.humdata.org/organization/wfp#interactive-data

[149] Based on the personal communication of a Swiss-based refiner: "*A certain compositional variation in the compositional characteristics of doré from one provider is considered normal, but analysis results beyond the usual variation automatically triggers a due diligence process*", it is considered possible that refining companies processing DRC gold (currently or in the past) possess data to evaluate this approach.

export process represents a fundamental constraint for the scenario. Including GPA application into better controlled international import procedures, therefore, may be a more effective approach.

The scenario involves other stakeholders as outlined in Table 36 below.

Table 36: Stakeholder Analysis for GPA Scenario III.

	Level of involvement	Effective or prospective role	Possible expectation	Impact
Comptoirs and trading houses	• Medium = **passive GPA target**	• None (subject to control at export point)	• Fear of increased control and taxes	• Increased formal export • Supply chain possibly shifting to countries not participating in regional GPA
Traders in transit countries	• Medium = **passive GPA target**	• None (subject to control at import and export point)	• Fear of increased control and taxes	• Increased formal export • Supply chain possibly shifting to countries not participating in regional GPA
International Refiners	• Medium	• Validation of purchases against sub-regional provenance profile	• Increased certainty of due diligence • Conflict free sourcing	• Reduced reputational risk
Downstream industry	• Low	• Due diligence	• Due diligence	• Reduced reputational risk
State (mining sector)	• Medium	• At policy level	• Improved control of gold trading	• Enhanced control and transparency of EI sector
State(s) (finance sector)	• High	Responsible entities for • **GPA sample collection** • **GPA analytics**	• Increased Government revenues	• Reduction of IFFs
State (local government)	• None	• None	• n/a	• n/a
ODA projects and initiatives	• High	• Technical assistance • Human and financial resources	• Economic development • Peace building and improved human rights situation	• Enhanced impact of programs
Civil society (nat. NGOs) & consulting firms	• Low	Possible service provider for • **GPA analytics**	• Involvement in programs	• Enhanced impact of programs
Civil society (int. NGOs) & consulting firms	• Medium	• Independent assurance schemes	• Synergy with existing programs • Involvement in new programs	• Enhanced impact of programs

Abbreviations: EI: Extractive Industries; IFF: Illicit Financial Flows

F.2 Type of Samples and Sample Collecting Procedures

Type of samples[150]

During in-region cross-border gold trading, doré from the DRC undergoes at least another smelting process to consolidate and homogenize volumes. During this smelting process

- Dorés are further purified (by smelting it the second or third time)

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[150] See chapter 5.4 for further details.

- Dorés may be consolidated and blended with domestic gold or gold from third-country provenance.
- As Uganda and Tanzania count on commercial refiners attending the ASM supply chain, in both countries dorés might be refined or at least pre-refined (nitric acid treatment), eventually jointly with gold from other origin.

All other types of material (dust, flakes, nuggets, sponges) may also be detected at airports; and much more frequently at border controls of roads and waterways. Such material however raises red flags on its own (without need for GPA), as it has not been homogenized into doré for proper assaying as required for legal export.

Consequently, the only GPA-relevant sample type at this stage of the supply chain is **doré**.

Transaction volumes (to be sampled) at cross-border trade (in-region and out-region) are typically in the range of **several kg**.

Sampling procedures

Sampling procedures in the DRC (or elsewhere), particularly in a first stage of roll-out of the scenario and in order to collect data on compositional characteristics of DRC gold, need to cover all gold exported by *comptoirs*. Sampling procedures can be integrated into the already compulsory assaying of export doré bars (see E.2). Additional to the determination of precious metal content of doré bars as required for taxation, minor and trace elements need to be analyzed.

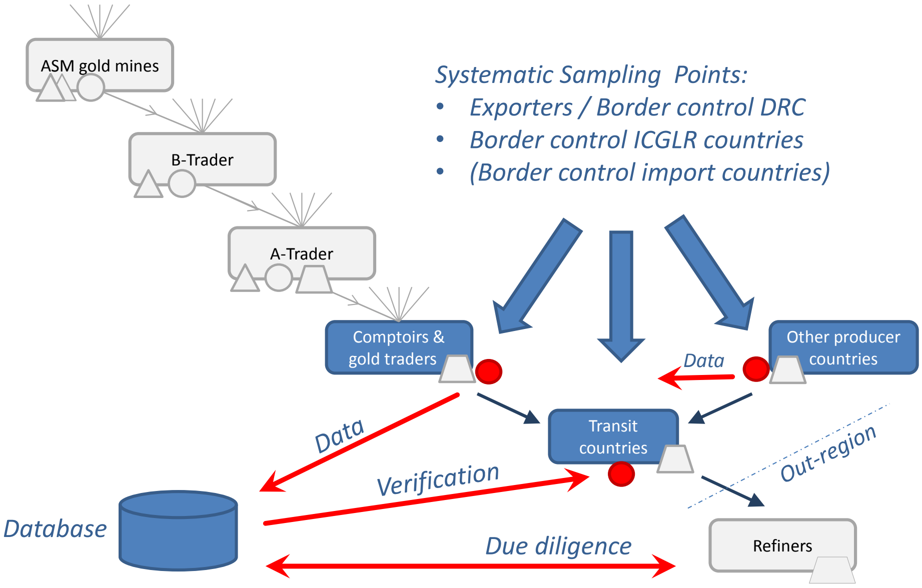

Figure 35: Sampling points for GPA Scenario III.

Sampling procedures outside the DRC need to follow the same standardized protocol in order to produce comparable results. This imposes some logistic limitations to the choice of applicable analytical methods. Sampling (e.g. by customs or airport authorities, and particularly of hand-carried gold) needs to be expedite and if possible instant, to avoid security risks of keeping large volumes of gold in custody.

Agreement on standardized sampling procedures at transit- and export points requires inter-governmental coordination at ICGLR level. This also applies if cooperation on supply chain transparency is sought after in coordination with import countries. It further involves harmonization of sampling procedures with refiners, to ensure that the GPA scenario becomes meaningful for practical supply chain due diligence.

F.3 Analytical Methods

Gold is usually exported as doré. Thus, chemical composition and eventually inclusion assemblages must be analyzed. Time is an important issue here, especially when export hubs (airports, customs) are involved, thus necessitating instant results.

F.4 Laboratory Equipment, Personnel Resources and Skills Required

Portable XRF instruments offer highest speed (a few minutes per analysis). If connected to a network, data can be instantly analyzed. This requires a powerful database and special software (spectra comparison software and quantitative analysis software). The system needs to be automated, thus probably requiring similar or even lower skills from operating personnel than Scenario I or II (local or national). At least one responsible person per unit must be in charge of the decision-making process at all times (opening hours, shifts).

F.5 Data Processing

XRF spectra are collected and stored in a database. For being fast and practicable only a multiuser system for the database is recommended for this scenario. Clients with different permissions have access via web interface to the database. Additional modules for the online statistical evaluation of an unknown spectrum from a doré can be integrated. If the origin of the hand-carried doré is in agreement with the declaration, a green flag mechanism applies, otherwise further investigations of the provenance may be triggered. This consideration only works with a linked reference database from gold analyses and an intergovernmental cooperation. Multivariate statistical tests may be applied if instant access to the database is granted and if appropriate software tools have been defined and made available for fast and easy use.

F.6 Issues to be addressed

Proof of concept and need for piloting. Similar as in Scenario II (GPA of gold produced in the DRC), proof that analytical data are useful to validate the plausibility of provenance claims must be worked out in a pilot study. This test is considered passed if piloting of Stage 1 of the scenario produces meaningful results. Further piloting is then necessary to research differences in compositional characteristics of gold from other producer countries in the region. At the highly aggregated level of doré bars for export, certain compositional overlap of spectra and quantitative data from border regions of neighbor countries must be expected.

Regionally coordinated effort. The scenario requires considerable intergovernmental coordination and will only unleash its potential if all regional producer and transit countries participate. The ICGLR is seen as the most appropriate platform for its implementation.

As high-level political consensus is needed for the scenario, it can only be brought to the table after testing and piloting in the DRC proved that gold from different catchment areas (or even from different *comptoirs*[151]) can be clearly distinguished based on compositional characteristics. This requires that prior to considering this scenario, stage 1 of the scenario must have been successfully implemented. It would then require that similar robust evidence is generated for all gold producing countries of the region.

Assessment of evasion risks. Experience has shown that as soon as one country in the regions increases border controls or raises taxes, gold trading routes shift rapidly (ARM 2014b; Blore 2015b). Effectiveness of the scenario with regards to its potential to curb contraband trade needs to be carefully assessed prior to opt for this scenario.

Robust international conflict minerals frameworks. Most likely, the scenario unleashes its full potential only, if buyers have open access to the database and start to use it as a tool for routine due diligence: gold declared to originate from any country of the GLR has to match the compositional characteristics of the claimed provenance. Such an approach has to involve particularly buyers in Dubai, the currently predominant destination for illegally exported gold from the DRC. To achieve that gold mismatching the claimed provenance is consistently rejected, robust international treaties and protocols need to be in place. The EU conflict minerals framework agreed on June 16, 2016 is one more step in this direction.

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[151] As postulated in BGRM report (Augé et al. 2015)

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