Blockchain, Chain of Custody and Trace Elements: An Overview of Tracking and Traceability Opportunities in the Gem Industry

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ABSTRACT: Recent developments have brought due diligence, along with tracking and traceability, to the forefront of discussions and requirements in the diamond, coloured stone and pearl industries. This is a result of consumer demands for detailed information on the provenance of gems, banking requirements aiming to reduce risk, industry and company initiatives seeking to bring greater transparency, and growing government legislation on mineral supply chains. To address this trend, certification mechanisms and technologies (such as blockchain) are being developed to solve inherent traceability challenges. As applied to gems, such standards and associated technology could benefit from the support of existing gemmological approaches (e.g. geographical origin determination) to enhance traceability and transparency measures. Recent initiatives are not just limited to corporate social responsibility reporting and due diligence requirements, but they also embrace supply chain management (including quality control and process improvements)—for example, to correctly identify and disclose treated and synthetic materials throughout the jewellery industry—as well as address consumer demand for provenance information. This article provides an overview of current trends and developments in the tracking and traceability of gems, along with an explanation of the terms used in this context.

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Traceability and transparency—including tracking (from mine to market) and tracing (from market to mine)—of coloured stones, diamonds and pearls is an increasingly important topic in the industry, as shown by recent research and reports (Archuleta, 2016; Walker, 2017; CIBJO, 2018; Human Rights Watch, 2018). The complex and fragmented nature of the global gem industry means that little information is typically available about these supply chains and how specific gem materials are mined, manufactured and sold. Traceability is one way to provide more transparency, and it is argued that by increasing transparency, supply chain issues can be better mapped and understood, ultimately helping to improve the environmental and social impact of a supply chain (Mol, 2015). Consumers are increasingly interested in knowing where and how the materials they consume are extracted and manufactured (Nash et al., 2016; De Angelis et al., 2017; see also Figure 1). Media and non-governmental organisations are placing the gem industry under increased scrutiny regarding the origin and sustainability footprint of various stones (Cross et al., 2010; IndustriALL et al., 2013; Global Witness, 2015, 2016; RESP, 2016). At the same time, some companies want to be proactive so as to mitigate risks and better understand their own supply chains and potential

Figure 1: An artisanal miner in Madagascar holds a treated blue topaz set in a ring. As the gem trade and consumers become increasingly interested in tracing the history and provenance of a gemstone or piece of jewellery, technological solutions and management models need to be developed to respond to these needs. Photo by L. E. Cartier.

sustainable development impact (Bloomfield, 2017). Governments want to improve the management and revenue collected from gem resources, and global governing bodies have highlighted issues such as smuggling and money laundering in recent years (Schroeder, 2010; 'Expert meeting to discuss…', 2013; Financial Action Task Force, 2013; OECD, 2016; Shortell and Irwin, 2017). Both the USA (through the Dodd-Frank Wall Street Reform and Consumer Protection Act) and the EU (through the upcoming Conflict Minerals Regulation in 2021) are requiring that companies carry out due diligence to ensure that the trade in four minerals—tin, tantalum, tungsten and gold—does not fund conflict in certain countries and regions. Although gold is presently the only commodity of concern to the jewellery industry in this context, such regulations could be expanded to diamonds and coloured stones in the future. The jewellery industry has been less scrutinised than other sectors (particularly in terms of legislation) and has been relatively late in responding to some of these concerns in a manner that integrates all materials used in jewellery products.

To further address these issues, a multi-fold approach is required—for example, strengthening specific ethical and sustainability standards and improving resource governance pertaining to the mining, processing and selling of gem materials worldwide (Cartier, 2011; Ali et al., 2017). Documenting the provenance and sources of gems through traceability schemes is one way to increase transparency and provide a supporting mechanism to strengthen the accountability and credibility of sustainability-certification schemes. In this article, we focus on gems (e.g. Figure 2) rather than jewellery as a whole, as track-and-trace in jewellery would also cover more wide-ranging issues such as quality control and inventory management in manufacturing. We briefly address the historic role of provenance in gems and jewellery, and how scientific origin determination of gemstones emerged in recent decades, thereby providing some knowledge about a stone's origin in the absence of a clear paper trail. We then review general concepts of traceability and track-and-trace approaches and how these might apply to gems through a compilation of various industry initiatives. Then, an overview of blockchain technology is given along with examples of emerging projects in the gem industry. A Glossary is included that defines key terms pertaining to provenance, traceability and related topics that are covered in this article. Finally, we conclude with an outlook on traceability, and argue that there is no 'silver bullet', but rather that multiple approaches and technologies are likely to spur greater transparency in the industry.

SIGNIFICANCE OF THE GEOGRAPHICAL ORIGIN OF GEMS

Historical Perspectives

Gems have been coveted by humans for millennia (e.g. Ali, 2009). Traded as precious objects or used for personal adornment, they have long been linked to different symbols and represented as commercial valuables. In some cases, the origin and nature of the minerals unearthed and traded was vital because of historical and spiritual connotations (Raden, 2016).

In the early days of gem commerce, only a few sources were known. With expanding global exploration and trade, new and diverse gem deposits were discovered. Traditionally, diamonds were sourced from India (Golconda) and Borneo until the discoveries in Brazil in the 18th century and in South Africa in the 19th century, which revolutionised the diamond industry. Similarly, the emerald sector experienced a surge in the 16th century with the discovery of Colombian deposits by the Spanish (Giuliani et al., 2000). Due to the emotional connection with gem materials from specific localities, knowing the provenance of these gems continued to be of interest for both traders and consumers, and was largely built on a system of trust and experience (Bernstein, 1992; Brazeal, 2017).

Opportunities and Limitations

As the science of gemmology emerged in the early 20th century, and synthetics and treatments became critical research issues, interest grew in carrying out structured investigations on gem materials from different origins to better characterise their properties. For example, Chesley (1942) attempted to correlate spectroscopic features of diamonds to their source localities. Geographical origin determination of coloured stones as we know it today appeared in the 1980s, and at the beginning focused on characterisation of typical microscopic inclusions from a deposit (Gübelin and Koivula, 1986). This was subsequently complemented by chemical and spectroscopic work on gem materials from various localities (Hänni, 1994; Krzemnicki, 2007; Rossman, 2009; Bui et al., 2012; Ogden, 2017), such as the early work on Kashmir sapphires by Hänni (1990). For more than a decade, the use of laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) has provided greater quantitative insight into the trace- and ultra-trace-element composition of gems for fingerprinting their origin (Guillong and Günther, 2001; Rankin et al., 2003; Abduriyim and Kitawaki, 2006a,b). Recent work using GemTOF (SSEF's time-of-flight LA-ICP-MS instrument) in combination with complex multivariate statistical analysis has shown the potential to improve

Figure 2: Emeralds (~0.4–1.0 ct) from various origins: are they natural, treated or synthetic? What is the amount of fracture-filling treatment? What is their country of origin? Can they be traced back to individual mines? What can be said of the conditions in which they were mined and cut? Traceability technologies, represented by the schematic bar code, could help us answer these questions in the future. Photo by L. E. Cartier.

Glossary*

Blockchain: A system for storing data in which groups of valid transactions, called blocks, form a chronological chain, with each block securely linked to the previous one. Originally invented for the digital currency bitcoin, a blockchain is a permanent, unalterable digital file of encrypted transactions that can be distributed in multiple copies across a network of devices linked to the blockchain. Given that every storage device has an exact and updated copy of the ledger, data can be verified and is considered immutable—an important property when transactions are occurring among users that do not know or trust each other.

Chain of custody: Under OECD's 2016 Due Diligence Guidance, chain of custody refers to the document trail recording the sequence of companies and individuals that have custody of minerals as they move through a supply chain.

Code of Practices: The Responsible Jewellery Council (RJC) Code of Practices defines responsible ethical, human rights, social, and environmental practices for businesses in the diamond, gold and platinum-group metals jewellery supply chain. It is being expanded to include coloured stones as well ('RJC to expand…', 2016).

Corporate social responsibility (CSR): 'A management concept whereby companies integrate social and environmental concerns in their business operations and interactions with their stakeholders' ('What is CSR?', 2018).

Disclosure: The release of information by companies required by regulators or requested by business partners in the supply chain.

Due diligence: The act of proactively ensuring that the products sourced and traded by companies within a supply chain conform to national and international regulations. This can include treatment disclosure, banning child labour and money laundering, and a wide range of other issues. For further information, see OECD (2016).

Geographical origin: In gemmological terms, this is commonly understood to be the country of origin of a gem provided as a scientific opinion based on microscopic, spectroscopic and chemical properties of a stone compared to a reference collection of samples and the gemmological literature. Ultimately this is linked to the geological origin of a stone. In some cases, such as rubies from Thailand and Cambodia, geologically similar or identical deposits are found on both sides of the border and thus cannot be separated by country.

Geological origin: The type of geological deposit in which a gem formed. In some countries (e.g. Madagascar), gem deposits may have different geological origins and thus can be separated accordingly (e.g. Ambondromifehy basaltic sapphires and Ilakaka metamorphic sapphires).

Origin determination: Origin determination of gems is an expert scientific opinion on the origin (country) of a stone, based on characteristic inclusions and chemical and spectroscopic features.

Provenance: A (documented) claim made on the origin (e.g. country or mine), source (e.g. recycled, mined, artisanally mined, natural, synthetic), previous ownership (e.g. a historic gemstone or a piece of jewellery formerly in a royal collection) or extraction and processing practices (e.g. conflict free, untreated, responsibly sourced).

Supply chain transparency: The extent to which information about the companies, suppliers, sourcing locations (including mines) and processing conditions (cutting and treatment processes) is available to end consumers and to other companies in the supply chain. There is growing demand for transparency in supply chains, as consumers and companies want detailed information about the origin of products.

Sustainable development: Defined in 1987 by the Brundtland Commission report as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (Brundtland, 1987, p. 15). This integrates economic, environmental and social pillars.

Tracing: The use of traceability records or an object's properties to identify the origin, attributes or history of a product within the supply chain. In the case of gemmology, this comes down to country-of-origin determination where documents are not available but physical and chemical properties allow for a conclusion of possible country-of-origin. If a gem has been tagged using tracking technology, it can be traced back upstream using this information.

Tracking: The use of traceability records to track an item from its origin to the end consumer through the supply chain. This is often complemented by the use of tracking technology such as radio-frequency identification (or RFID) chips, near-field communication, synthetic DNA implantation, barcodes or other forms of tagging.

Traceability: 'The ability to identify and trace the history, distribution, location, and application of products, parts, and materials' (Norton et al., 2014, p. 6, as per the International Organization for Standardization or ISO).

* Sources: Norton et al. (2014); OECD (2016); RJC (2017); Future of Fish et al. (2018); 'What is CSR?' (2018)

the precision and reliability of origin determinations (Wang et al., 2016).

Thus, today's laboratory reports offer origin opinions for certain coloured stones based on the scientific interpretation of their microscopic, spectroscopic and chemical properties compared to a reference collection of samples and the gemmological literature. Table I lists the gem varieties submitted to labs for origin reports and their common sources. As databases for tested gems grow and further research is carried out, origin determination will likely be extended further to include other gem varieties. Although it is not possible to trace a coloured stone back to a specific mine, origin determination can help validate claims made by companies regarding country of origin. For example, in the context of the now-defunct Tom Lantos Block Burmese JADE (Junta's Anti-Democratic Efforts) Act of 2008 that banned the import of Burmese rubies and jade (Dickinson DeLeon, 2008) into the USA, gemmological methods were useful for providing information to clients.

Origin reports are an important part of today's high-end gem and jewellery markets, where factors such as rarity, branding and provenance are critical to some consumers, investors and traders (Shor, 2013; Ogden, 2017). Rather than providing definitive proof of a stone's source, a country-of-origin report is used in general to support a claim made about the geographical origin of a high-end gemstone (e.g. at auction). This is very similar to expert-opinion reports on ceramics, furniture, paintings and wine (e.g. Spencer, 2004; Bull, 2016). Gemmological origin interpretations can vary in certain cases, and such variations in origin reports may show up between different labs (Gannon, 2004; Ogden, 2017). As accessibility to advanced analytical instrumentation improves, and as databases of documented rough material from different mines become more robust, the scope of geographical origin determination will also expand.

Table I: Selected gem varieties for which geographical origin determination can commonly be performed by gem laboratories.

Gem variety	Commonly identifiable (and commercially relevant) sources
Alexandrite	Africa (Madagascar, Tanzania), Brazil, Russia, Sri Lanka
Cu-bearing tourmaline	Brazil, Mozambique, Nigeria
Demantoid	Madagascar, Namibia, Russia
Emerald	Afghanistan, Brazil, Colombia, Ethiopia, Zambia
Ruby	Afghanistan, Madagascar, Mozambique, Myanmar, Tanzania (Winza), Thailand, Vietnam
Sapphire	Kashmir, Madagascar, Myanmar, Sri Lanka
Spinel	Madagascar, Myanmar, Sri Lanka, Tajikistan, Tanzania, Vietnam
Tsavorite	East Africa (Kenya, Tanzania)

Although considerable research on the origin determination of diamonds was conducted at the turn of the 21st century due to the issue of 'blood diamonds', until now no technique has been found to conclusively identify faceted stones from various origins based on scientific means (Dalpé et al., 2010). As such, it is not possible to determine the country or mine source for a cut diamond of unknown origin through commercially available geochemical, isotopic or spectroscopic methods. The diamond industry has thus had to focus on chain of custody and other mechanisms to support origin claims on sold diamonds (e.g. Table II). This includes the Kimberley Process Certification Scheme, the De Beers Best Practice Principles, the Signet Responsible Sourcing Protocol for Diamonds (D-SRSP) and the Responsible Jewellery Council's consultation for its chain of custody to become applicable to diamonds (RJC, 2017).

Research on pearls has focused on distinguishing natural from cultured and freshwater from saltwater samples, rather than geographical origin determination. However, recent work (Hänni and Cartier, 2013; Meyer et al., 2013; Cartier et al., 2018) has increasingly looked at mollusc species and the potential geographical origin determination of cultured pearls.

TRACKING AND TRACING

Tracking (from origin to market, or forward traceability) and tracing (from market to origin, or backward traceability) conceptualise the path of an item and how it can be identified within a supply chain (Schwägele, 2005). Whereas tracking and tracing describe path direction of goods, traceability is a more overarching term (see Glossary). Various sectors, such as the food and pharmaceutical industries, use both track and trace for different purposes. In such contexts, tracking can locate an item based on specific criteria (e.g. vital when recalling non-compliant items) whereas tracing is the basis for finding the cause of non-compliance (Bechini et al., 2008).

Table II: An overview of industry initiatives in responsible business practices and traceability programmes (modified from Solomon and Nicholls, 2010).

Initiative	Year founded	Target material	Chain of custody model (or model provided)	Strategy	Claim made/ aim of initiative	Supply chain segment
World Jewellery Confederation (CIBJO)	1961	Jewellery, metals, diamonds, coloured stones, pearls and coral	Product disclosure	Publish 'Blue Books' that cover industry-wide accepted nomenclature for claims made about gems and metals in the jewellery industry	Provide material disclosure guidelines for the jewellery industry	Entire jewellery industry
Kimberley Process Certification Scheme	2000	Diamonds	Bulk commodity (traceability)	Packages of rough diamonds are certified by exporting governments as conflict free	Diamonds are conflict free	Country of export, only for rough stones
CanadaMark (Dominion Diamond Mines)	2003	Diamonds	Bulk commodity (traceability)	Diamonds are certified to be of Canadian origin (from Diavik or Ekati mines)	Canadian origin (not tracked back to individual mine)	Diamond industry, from mine to end consumer
Extractive Industries Transparency Initiative (EITI)	2003	Oil, gas and mineral resources	EITI Standard	Annual EITI Progress Report to disclose information on: contracts and licences, production, revenue collection and allocation, and social and economic spending	Improve transparency in extractives sector	Mining company payments made to governments
Diamond Development Initiative	2005	Diamonds	Maendeleo Diamond Standards (MDS)	Standards and certification for responsible artisanal small-scale mining (ASM) diamond production	Responsibly mined ASM diamond according to MDS standards	ASM diamond mines (e.g. Sierra Leone)
Responsible Jewellery Council	2005	Coloured stones, diamonds, gold, platinum and silver	Code of practices and chain of custody (gold only)	RJC members commit to and are independently audited against the RJC Code of Practices, an international standard on responsible business practices for diamonds, gold and platinum-group metals	Responsible practices	Entire jewellery supply chain (coloured stones are currently under review)
Initiative for Responsible Mining Assurance	2006	Minerals and metals	Independent third-party verified responsible mining assurance system for mining companies	Certify mine-site practices	Certified to follow best practices for mining	Mining companies
Love Earth (Walmart)	2008	Gold and diamonds	Identity preservation (traceability)	Traceability of product back to mine (by consumer), with mining company, refiner and manufacturer self-reporting against a set of environmental and social criteria along with third-party audits	Jewellery material components are traceable and comply with Wal-Mart's responsible sourcing practices	Select mines, refineries, manufacturers and retailers
OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High Risk Areas	2009	Minerals (including diamonds and coloured stones)	Due diligence guidelines for sourcing of minerals	Provide due diligence recommendations for mineral sourcing	(Not applicable)	Entire supply chain

Table II (continued): An overview of industry initiatives in responsible business practices and traceability programmes (modified from Solomon and Nicholls, 2010).

Initiative	Year founded	Target material	Chain of custody model (or model provided)	Strategy	Claim made/ aim of initiative	Supply chain segment
Diamonds with a Story (Rio Tinto)	2013	Diamonds	Identity preservation (traceability)	Australian (Argyle) origin certified as stones are tracked through supply chain	Argyle (Australia) origin	From mine to end consumer
Signet Responsible Sourcing Protocol for Diamonds (D-SRSP)	2016	Diamonds	Guidelines for responsible diamond sourcing	Protocol that provides transparency and to assure that all Signet diamonds are sourced through identified and verified sources, over time, through a process of continuous improvement	Compliant with D-SRSP	Suppliers to Signet Jewelers
Emerald Paternity Test (Gübelin Gem Lab)	2017	Coloured stones	Identity preservation and/or bulk commodity (traceability)	Rough stone batches (e.g. emeralds from Gemfields) are marked with unique ID nanoparticles that can be read downstream to provide data on the stones	Support provenance claims made by reading information contained in nanoparticles found in tagged emeralds	From mine to retail; information about a stone can be verified by a lab
M2M Program (GIA)	2017	Diamonds	Platform for consumers to visualise a diamond's story from rough to cut	GIA documents rough diamonds submitted by miner and then each stone is cut and sent back to GIA for grading; GIA confirms that each one is the same stone originally submitted	Story of the diamond from rough to cut, documented by GIA	A rough diamond submitted by a diamond mining company, tracked all the way through manufacturing and retail via M2M platform
Tracr (De Beers)	2017	Diamonds	Blockchain traceability	Develop mine-to-finger blockchain for diamonds	Demonstrate traceability of diamonds from mine to finger via blockchain	From mine to end consumer via blockchain
Diamond Time-Lapse Protocol	2018	Diamonds	Permissioned private blockchain	Show the journey of a diamond to an end consumer via blockchain and app; option for manufacturers to track stock through manufacturing process via blockchain	Journey of a diamond can be followed through manufacturing via blockchain and app	Manufacturer and retailer interface as well as a consumer interface
Provenance Proof	2018	Coloured stones	Blockchain traceability	Mine-to-finger blockchain for coloured stones developed by Everledger and the Gübelin Gem Lab	Demonstrate traceability of coloured stones from mine to finger via blockchain	From mine to end consumer, via blockchain
TrustChain	2018	Gold and diamonds	Permissioned private blockchain	Offer traceability of diamond jewellery via blockchain by working with selected certified miners, certifiers, manufacturers and retailers	Provenance claims for the source of metals and diamonds used in jewellery items	From mine to end consumer, via blockchain

Although traceability in current discussions in the gem and jewellery industry is often understood to mean an object is fully traceable (i.e. an individual gem is uniquely documented and identifiable at each step of the supply chain from mine/farm to market and end consumer), there are four different possible models of product traceability (Norton et al., 2014):

1) Identity Preservation or Track-and-Trace
2) Bulk Commodity or Segregation
3) Mass Balance
4) Book and Claim

The aim of these traceability approaches (see Table III) can be to substantiate sustainability and origin claims made by companies. A more detailed description of this, with examples for diamond and gold jewellery, can be found in Solomon and Nicholls (2010).

Clear guidelines exist for how chain of custody could be put in place in the jewellery industry (RJC, 2012, 2017) and how due diligence for responsible business practices can be carried out (OECD, 2018). Demand for both tracking and tracing within the gem industry is growing, as origin claims need to be verified. In addition, sustainability claims are increasingly being made about gems. In such cases, traceability is equally vital to uphold and validate such claims. In addition to improving chain-of-custody practices and auditing options, technology can provide solutions to verify such claims. Recent efforts have focused on individually marking and separating each stone or cultured pearl so that it can be identified and tracked back to its mine or farm of origin (Hänni and Cartier, 2013; Theodosi, 2017). The ultimate system of traceability should ideally offer a consumer transparent and proven access to the unique and complete story of a gemstone or piece of jewellery, and potentially

Table III: An overview of available traceability models used to support sustainability claims.

Traceability model	Approach	Level of traceability	Cost	General example	Gem example
Identity Preservation or Track-and-Trace	Certified materials and products are physically separated from non-certified materials and products at each stage along the supply chain.	Highest	Very costly	Consumer would know exact farm from which a banana or salad was sourced.	Exact mine-of-origin information is tracked through the supply chain.
Bulk Commodity or Segregation	Separates certified from non-certified materials but allows mixing of certified materials from different sources. All producers must comply with the certification standards.	High	Costly	An organic chocolate bar that contains cacao beans from various organically certified producers. Another example is Kimberley Process rough diamonds certified as 'conflict free'.	An aggregation of goods from one company that operates several mines; also useful for gem regions/countries and could be complemented by gemmological analysis.
Mass Balance	Certified and non-certified materials can be mixed. However, the exact volume of certified material entering the supply chain must be controlled. Claims of 'this product contains X% of certified ingredients' can be made.	Low	Slightly costly	If 20% of the total cocoa purchased comes from fair-trade sources, 20% of a company's chocolate bars made with that mix of cocoa can include the fair-trade certified label.	Material from different mines (and certified and non-certified goods) can be mixed. Traceability information is lost.
Book and Claim	Allows all actors of a supply chain to trade in certificates for certified sustainable materials. Buying certificates allows retailers and manufacturers to claim that their business supports the production of sustainable materials. Claims of 'this product supports the sustainable sourcing and production of essential commodities' can be made.	Low	Reasonable	Companies wishing to make sustainability claims can purchase certificates (even though their goods may not be certified) that support sustainable production.	A synthetic diamond manufacturer may buy credits and contribute to sustainable mining activities.

continue to follow the piece as it is resold and recycled. Although the present consensus is that such a model is not feasible for the entire industry, research shows that many consumers want to know specific information about the origin of, for example, the cultured pearls they purchase (Nash et al., 2016). An integral part of this is marking or tagging—enabling an item to be uniquely tracked—so that it can be linked to the corresponding chain-of-custody document trail. Ultimately, combined approaches are necessary: solely marking a stone or a cultured pearl does not guarantee claims that are made about it; it must be uniquely identifiable in addition to having a chain of custody.

Laser inscription of diamonds has been offered for several years, whereby a logo or a report number is inscribed on the girdle of a stone after cutting. This is done by some natural diamond sellers (e.g. Forevermark) and synthetic diamond manufacturers to document the provenance of such products (Eaton-Magaña and Shigley, 2016). The inscription of a QR (quick response) code can link to further information about a stone that is accessible to consumers (Figure 3). The drawback associated with physically marking gems is linked to the fact that they are processed from rough to cut and thus initial surface markings would disappear. Furthermore, polished gemstones can be re-cut and such markings can be lost or fraudulently used or modified. In cultured pearls, tagging/marking techniques have ranged from inserting radio-frequency identification chips into composite nuclei (i.e. used in beaded cultured pearl production), chemically marking them via their inherent porosity (e.g. with fluorine) or trialling hologram surface markings (Hänni and Cartier, 2013; Segura, 2015). Most recently, in 2017, an 'Emerald Paternity Test' was developed that involves introducing unique synthetic DNA-based, nano-sized particles that can store specific information (e.g. mine location or mining period), which can later be retrieved and decoded in a laboratory (Branstrator, 2018). Clearly, there is no single solution or approach to providing traceability in the gem industry.

Know Your Source: Due Diligence, Chain of Custody and CSR

Several factors have spurred the jewellery industry to increasingly document its supply chains, including globalisation, greater reporting to shareholders by major groups due to 'conflict mineral' legislation, the need to reduce risk in order to secure financing, and pressure from the media and non-governmental organisations on issues such as 'blood diamonds' or 'dirty gold' (Bloomfield, 2017). It is widely argued that through increased transparency and knowledge of its supply chain, a company can better manage its risks and identify business opportunities (Carter and Rogers, 2008). In this context, chain of custody, a widely used concept in supply chain management, has become a pillar of reporting and verification in the industry (see Table II for various examples). The creation of the Responsible Jewellery Council (RJC) in 2005 further reinforced this trend with its strong focus on chain of custody to track and validate codes of practices by stakeholders (Solomon and Nicholls, 2010). To exemplify this trend further, Signet, a major American retail group, introduced its D-SRSP initiative in 2016 that vendors must adhere to if they want to be suppliers to Signet Jewelers (Bates, 2016).

The Organisation for Economic Cooperation and Development (OECD) recently developed the guidelines followed by companies seeking to respect human rights and avoid contributing to conflict through their mineral sourcing decisions and practices; these guidelines now

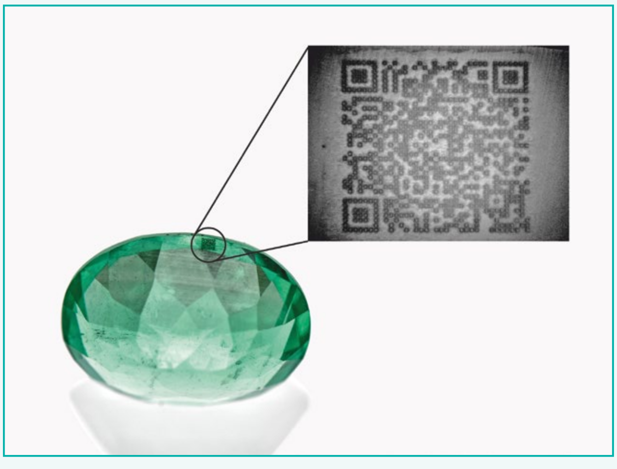

Figure 3: A tiny QR code can be inscribed on a gemstone during chemical analysis with GemTOF instrumentation (Wang and Krzemnicki, 2016). The QR code shown here measures 500 × 500 μm and has been inscribed on the girdle of an emerald weighing 2.5 ct. The material ablated during the inscription of the code is used to measure trace-element concentrations that are evaluated for determining country of origin. The code can be read (after magnification) using a QR reader on a smartphone, and gives the user access to various types of information on the stone. Composite photo by H. A. O. Wang and V. Lanzafame, SSEF.

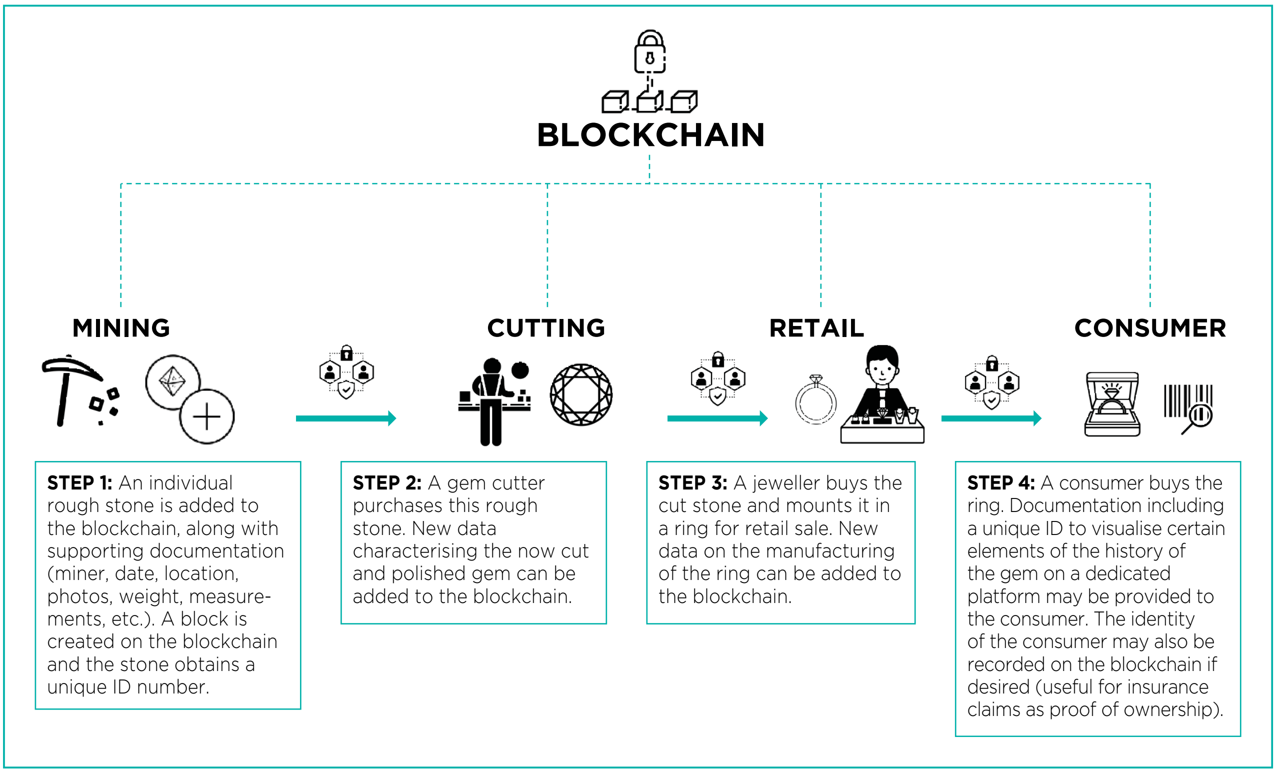

Figure 4: This generalised example of a blockchain serves to illustrate how information can be documented on a single gem's journey from mining to cutting and onward to retail and eventually the end consumer. After the stone is mined, the trade and transfer of ownership are validated at each step by both parties involved and recorded immutably to the blockchain. Illustration by L. E. Cartier.

apply to all minerals (OECD, 2016). Lombe et al. (2015, p. 15) in turn outlined due diligence and chain of custody in the following terms:

> Firstly, social and environmental risks are typically a product of an operator's behavior or environment, so knowing who has handled the material and where is an integral part of risk assessment and management. Secondly, tracking and traceability provide evidence to a company or auditor that a claim being made about a mineral (e.g. country of origin, sustainability dimensions, conflict free, etc.) is in fact true.

Traceability concerns and solutions are, thus, a natural, complementary extension to due diligence and chain of custody, depending on the context.

Blockchain Revolution: How Can It Be Applied to Gems?

Blockchain is a digitally distributed ledger technology that can support chain of custody through a system that makes documentation tamper-proof and, potentially, provides new opportunities for traceability in the highly complex and fragmented sectors of diamonds, coloured stones and pearls (e.g. Figure 4). Data added to the blockchain (e.g. by mobile phone, tablet or computer) at each recorded transaction step are verified, ownership is attributed, and the information is time stamped, encrypted, and stored permanently in a distributed and decentralised manner, providing an immutable record that is formed of a single, yet shared, source of information about a gem's journey from source to end consumer. As such, blockchain can be used to document the origin and path of a gem from mine to market, as well as verify ownership (and potentially possession, e.g. when a gem is out on memo). Blockchain technology has particularly grabbed the attention of the art world as a way to authenticate artwork back to its artist, and to record ownership and authenticity of artwork along a permanent and potentially anonymised chain of custody (O'Neill, 2018).

In blockchain, there are four types of ledgers: traditional (centralised), permissioned private, permissioned public and distributed permissionless public (Jeppsson and Olsson, 2017). A permissioned blockchain is a shared database that requires users to obtain permission before reading or writing to the chain. In permissionless blockchains, anyone can join. The rules in a blockchain are defined by the users, who can be either a private consortium (e.g. TrustChain) or public users. These rules are enforced as 'smart contracts' by computer software. Any computer that connects to the blockchain is called a node. The energy consumption of blockchain networks (documented to be very high in public ones such as

Figure 5: (a) Artisanal diamond miners sift gravels on the Sewa River in Sierra Leone. **(b)** A mixed parcel of rough diamonds from Sierra Leone was produced by such diggers. Programmes such as the GemFair initiative aim to bring certified responsibly produced artisanal diamonds to market, and complement this with blockchain to document the path of the diamonds. Photos by L. E. Cartier.

bitcoin using proof-of-work protocols; see O'Dwyer and Malone, 2014; Orcutt, 2017) must be taken into consideration when deciding what kind of ledger is selected and how it is managed and organised.

A so-called smart contract is software stored in a blockchain that automatically moves digital assets between accounts if pre-required conditions (collaboratively defined by the blockchain's users) are met, and it cannot be unilaterally changed (Iansiti and Lakhani, 2017). Smart contracts are being increasingly explored as solutions for ownership authentication and automatic validation of trades (Kim and Laskowski, 2018). They can potentially provide a huge gain in efficiency (especially with regards to demonstrating compliance and know-your-customer procedures), and they are one of the main reasons why blockchain is being widely investigated as a means of traceability and in logistics (Shrier et al., 2016). Depending on the type of blockchain, users may have transparent insight into the business rules by which the transactions are completed. Therefore blockchain can provide transparency to the regulators and other users who require it, while still providing the privacy and the specific views into the ledger that are relevant for each different type of user. This is an important factor for the gem and jewellery industry, which demands verified, but often anonymised, chain-of-custody solutions.

Blockchain is especially suitable for complex industries (Jansson and Peterson, 2017), and different variations of blockchain have been proposed for diamonds (Abeyratne and Monfared, 2016; Wall, 2016), diamond trading ('Singapore Diamond Investment Exchange…', 2017), jewellery (Irrera, 2018), art (O'Neill, 2018), coloured stones (Branstrator, 2018), minerals (RCS Global, 2017) and many other luxury products (Meraviglia, 2018). The Kimberley Process Certification Scheme has investigated blockchain as a solution for its system of warranties (Sulayem, 2016). The company Everledger recently developed the Diamond Time-Lapse Protocol ('Everledger announces…', 2018) to highlight the individual journey of a diamond that can be followed by a consumer through a smartphone application.

However, a blockchain is only as strong as the data supplied, because blockchain only verifies the data and not the event itself. Therefore, it does not replace robust standards in the supply chain (requiring external validation of data and production practices along with audits). However, it has the strong potential to reinforce claims by providing an immutable record of a product's history that can be verified (through the blockchain), and these data are secured using cryptography. A range of properties and information can be recorded in the blockchain, including: weight, quantity, photos, videos, certification/audits, reports, mine of origin, ownership at each step of the supply chain, workers who handle the material at each step, grade, and other factors. Blockchain clearly has enormous potential in the gem and jewellery industry, but more research is required to understand how the efficiency and transparency it can provide can best be put to use, and whether industry-wide consensus is possible or necessary. Further research is also required to understand how all levels of the supply chain (including artisanal miners) can benefit from traceability opportunities that blockchain technology could provide.

The recent launch of De Beers' GemFair programme with the Diamond Development Initiative (Sanderson, 2018) provides insight into how some key characteristics can be recorded in a blockchain. The programme involves a highly localised partnership with civil society groups in areas of artisanal and small-scale mining (Figure 5), with photographic evidence and verification mechanisms at the digging pit itself. De Beers is also investing heavily in developing a blockchain platform for tracking its diamonds more broadly, and in due course plans to link that platform with GemFair (Sanderson, 2018).

OUTLOOK—WHAT'S NEXT?

The informal and highly fragmented nature of some parts of the gem industry makes full transparency a complex and challenging undertaking. Sorting and aggregation steps in supply chains—in which goods may be sorted in terms of quality rather than origin—may further complicate this endeavour (see Figures 6 and 7). Regulatory requirements and consumer demands for supply chain integrity and knowledge of provenance will push the industry to find solutions. Due diligence and chain-of-custody requirements will continue to grow and, as such, all levels of the trade will need to find solutions to address these traceability and transparency challenges. This may also provide newfound opportunities if, for example, synthetics and treated stones can be separated more clearly from natural/untreated material in the supply chain based on traceability information to verify the ownership and authenticity of gem materials at all stages.

Technological solutions such as blockchain and various tagging methods will become increasingly important as complementary responses to improve chain of custody and provide increased transparency in the supply chain. Blockchain and other tracking methods can also provide much more data and information that are increasingly important to consumers and regulators. Importantly, gemmological science can continue to provide much-needed assistance regarding claims of origin (geographical and whether a gem is natural or synthetic) and whether or not a gem has been treated. A gem's inclusions and their location within the stone can be used to help verify its identity, as well as provide gemmological data that can later be compared to existing chain-of-custody information. The current focus on full mine-to-market traceability may not be as realistic as it has been shown for other sectors, nor may the market necessarily want or require it. For example, rather than focussing all efforts on uniquely tracking a stone from its individual mine, tracing gem materials from specific regions that can be verified through gemmological means may prove to be an alternative and complimentary model (Cartier, 2017).

Country-of-origin determination is not a stand-alone traceability solution, but it offers independent verification of claims made about a gem's locality. This model has also been explored for tin, tungsten and tantalum (coltan) supply chains via the analytical fingerprint method (Schütte et al., 2018). Gemmology can complement and supplement the claims and documentation made by more standard traceability approaches that are inspired from other industries. The informal and highly fragmented nature of the coloured stone industry is likely to place stronger reliance on innovations in traceability rather than common tracking techniques that are more feasible for gold, diamonds and other commodities.

Figure 6: At a processing facility in Hunan, China, freshwater cultured pearls are aggregated from different farms and sorted according to various characteristics. Such processing on the basis of quality rather than source poses a challenge for traceability. Photo by L. E. Cartier.

Figure 7: At an amethyst-cutting workshop in Jaipur, India, rough material is generally purchased and sorted by size and quality rather than according to specific sources. The cutting and polishing of gems is an under-researched bottleneck for traceability. Photo by L. E. Cartier.

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