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

Laurent E. Cartier, Saleem H. Ali and Michael S. Krzemnicki

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.

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

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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.
A gem formed. In some countries (e.g. Madagascar), gem
deposits may have different geological origins and thus can be separated accordingly (e.g. Ambondromifena
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’
(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).

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**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.

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.

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

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

### 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 (Schwägel, 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).

<table>
<thead>
<tr>
<th>Initiative</th>
<th>Year founded</th>
<th>Target material</th>
<th>Chain of custody model (or model provided)</th>
<th>Strategy</th>
<th>Claim made/aim of initiative</th>
<th>Supply chain segment</th>
</tr>
</thead>
<tbody>
<tr>
<td>World Jewellery Confederation (CIBJO)</td>
<td>1961</td>
<td>Jewellery, metals, diamonds, coloured stones, pearls and coral</td>
<td>Product disclosure</td>
<td>Publish ‘Blue Books’ that cover industry-wide accepted nomenclature for claims made about gems and metals in the jewellery industry</td>
<td>Provide material disclosure guidelines for the jewellery industry</td>
<td>Entire jewellery industry</td>
</tr>
<tr>
<td>Kimberley Process Certification Scheme</td>
<td>2000</td>
<td>Diamonds</td>
<td>Bulk commodity (traceability)</td>
<td>Packages of rough diamonds are certified by exporting governments as conflict free</td>
<td>Diamonds are conflict free</td>
<td>Country of export, only for rough stones</td>
</tr>
<tr>
<td>CanadaMark (Dominion Diamond Mines)</td>
<td>2003</td>
<td>Diamonds</td>
<td>Bulk commodity (traceability)</td>
<td>Diamonds are certified to be of Canadian origin (from Diavik or Ekati mines)</td>
<td>Canadian origin (not tracked back to individual mine)</td>
<td>Diamond industry, from mine to end consumer</td>
</tr>
<tr>
<td>Extractive Industries Transparency Initiative (EITI)</td>
<td>2003</td>
<td>Oil, gas and mineral resources</td>
<td>EITI Standard</td>
<td>Annual EITI Progress Report to disclose information on: contracts and licences, production, revenue collection and allocation, and social and economic spending</td>
<td>Improve transparency in extractives sector</td>
<td>Mining company payments made to governments</td>
</tr>
<tr>
<td>Diamond Development Initiative</td>
<td>2005</td>
<td>Diamonds</td>
<td>Maendeleo Diamond Standards (MDS)</td>
<td>Standards and certification for responsible artisanal small-scale mining (ASM) diamond production</td>
<td>Responsibly mined ASM diamond according to MDS standards</td>
<td>ASM diamond mines (e.g. Sierra Leone)</td>
</tr>
<tr>
<td>Responsible Jewellery Council</td>
<td>2005</td>
<td>Coloured stones, diamonds, gold, platinum and silver</td>
<td>Code of practices and chain of custody (gold only)</td>
<td>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</td>
<td>Responsible practices</td>
<td>Entire jewellery supply chain (coloured stones are currently under review)</td>
</tr>
<tr>
<td>Initiative for Responsible Mining Assurance</td>
<td>2006</td>
<td>Minerals and metals</td>
<td>Independent third-party verified responsible mining assurance system for mining companies</td>
<td>Certify mine-site practices</td>
<td>Certified to follow best practices for mining</td>
<td>Mining companies</td>
</tr>
<tr>
<td>Love Earth (Walmart)</td>
<td>2008</td>
<td>Gold and diamonds</td>
<td>Identity preservation (traceability)</td>
<td>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</td>
<td>Jewellery material components are traceable and comply with Wal-Mart’s responsible sourcing practices</td>
<td>Select mines, refiners, manufacturers and retailers</td>
</tr>
<tr>
<td>OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High Risk Areas</td>
<td>2009</td>
<td>Minerals (including diamonds and coloured stones)</td>
<td>Due diligence guidelines for sourcing of minerals</td>
<td>Provide due diligence recommendations for mineral sourcing</td>
<td>(Not applicable)</td>
<td>Entire supply chain</td>
</tr>
</tbody>
</table>
Table II (continued): An overview of industry initiatives in responsible business practices and traceability programmes (modified from Solomon and Nicholls, 2010).

<table>
<thead>
<tr>
<th>Initiative</th>
<th>Year founded</th>
<th>Target material</th>
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<th>Strategy</th>
<th>Claim made/aim of initiative</th>
<th>Supply chain segment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamonds with a Story (Rio Tinto)</td>
<td>2013</td>
<td>Diamonds</td>
<td>Identity preservation (traceability)</td>
<td>Australian (Argyle) origin certified as stones are tracked through supply chain</td>
<td>Argyle (Australia) origin</td>
<td>From mine to end consumer</td>
</tr>
<tr>
<td>Signet Responsible Sourcing Protocol for Diamonds (D-SRSP)</td>
<td>2016</td>
<td>Diamonds</td>
<td>Guidelines for responsible diamond sourcing</td>
<td>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</td>
<td>Compliant with D-SRSP</td>
<td>Suppliers to Signet Jewelers</td>
</tr>
<tr>
<td>Emerald Paternity Test (Gübelin Gem Lab)</td>
<td>2017</td>
<td>Coloured stones</td>
<td>Identity preservation and/or bulk commodity (traceability)</td>
<td>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</td>
<td>Support provenance claims made by reading information contained in nanoparticles found in tagged emeralds</td>
<td>From mine to retail, information about a stone can be verified by a lab</td>
</tr>
<tr>
<td>M2M Program (GIA)</td>
<td>2017</td>
<td>Diamonds</td>
<td>Platform for consumers to visualise a diamond’s story from rough to cut</td>
<td>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</td>
<td>Story of the diamond from rough to cut, documented by GIA</td>
<td>A rough diamond submitted by a diamond mining company, tracked all the way through manufacturing and retail via M2M platform</td>
</tr>
<tr>
<td>Tracr (De Beers)</td>
<td>2017</td>
<td>Diamonds</td>
<td>Blockchain traceability</td>
<td>Develop mine-to-finger blockchain for diamonds</td>
<td>Demonstrate traceability of diamonds from mine to finger via blockchain</td>
<td>From mine to end consumer via blockchain</td>
</tr>
<tr>
<td>Diamond Time-Lapse Protocol</td>
<td>2018</td>
<td>Diamonds</td>
<td>Permissioned private blockchain</td>
<td>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</td>
<td>Journey of a diamond can be followed through manufacturing via blockchain and app</td>
<td>Manufacturer and retailer interface as well as a consumer interface</td>
</tr>
<tr>
<td>Provenance Proof</td>
<td>2018</td>
<td>Coloured stones</td>
<td>Blockchain traceability</td>
<td>Mine-to-finger blockchain for coloured stones developed by Everledger and the Gübelin Gem Lab</td>
<td>Demonstrate traceability of coloured stones from mine to finger via blockchain</td>
<td>From mine to end consumer via blockchain</td>
</tr>
<tr>
<td>TrustChain</td>
<td>2018</td>
<td>Gold and diamonds</td>
<td>Permissioned private blockchain</td>
<td>Offer traceability of diamond jewellery via blockchain by working with selected certified miners, certifiers, manufacturers and retailers</td>
<td>Provenance claims for the source of metals and diamonds used in jewellery items</td>
<td>From mine to end consumer via blockchain</td>
</tr>
</tbody>
</table>
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).

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

<table>
<thead>
<tr>
<th>Traceability model</th>
<th>Approach</th>
<th>Level of traceability</th>
<th>Cost</th>
<th>General example</th>
<th>Gem example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identity Preservation or Track-and-Trace</td>
<td>Certified materials and products are physically separated from non-certified materials and products at each stage along the supply chain.</td>
<td>Highest</td>
<td>Very costly</td>
<td>Consumer would know exact farm from which a banana or salad was sourced.</td>
<td>Exact mine-of-origin information is tracked through the supply chain.</td>
</tr>
<tr>
<td>Bulk Commodity or Segregation</td>
<td>Separates certified from non-certified materials but allows mixing of certified materials from different sources. All producers must comply with the certification standards.</td>
<td>High</td>
<td>Costly</td>
<td>An organic chocolate bar that contains cacao beans from various organically certified producers. Another example is Kimberley Process rough diamonds certified as ‘conflict free’.</td>
<td>An aggregation of goods from one company that operates several mines; also useful for gem regions/ countries and could be complemented by gemmological analysis.</td>
</tr>
<tr>
<td>Mass Balance</td>
<td>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.</td>
<td>Low</td>
<td>Slightly costly</td>
<td>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.</td>
<td>Material from different mines (and certified and non-certified goods) can be mixed. Traceability information is lost.</td>
</tr>
<tr>
<td>Book and Claim</td>
<td>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.</td>
<td>Low</td>
<td>Reasonable</td>
<td>Companies wishing to make sustainability claims can purchase certificates (even though their goods may not be certified) that support sustainable production.</td>
<td>A synthetic diamond manufacturer may buy credits and contribute to sustainable mining activities.</td>
</tr>
</tbody>
</table>
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

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**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 $500 \times 500 \mu m$ 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.
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
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 focusing 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.
REFERENCES


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