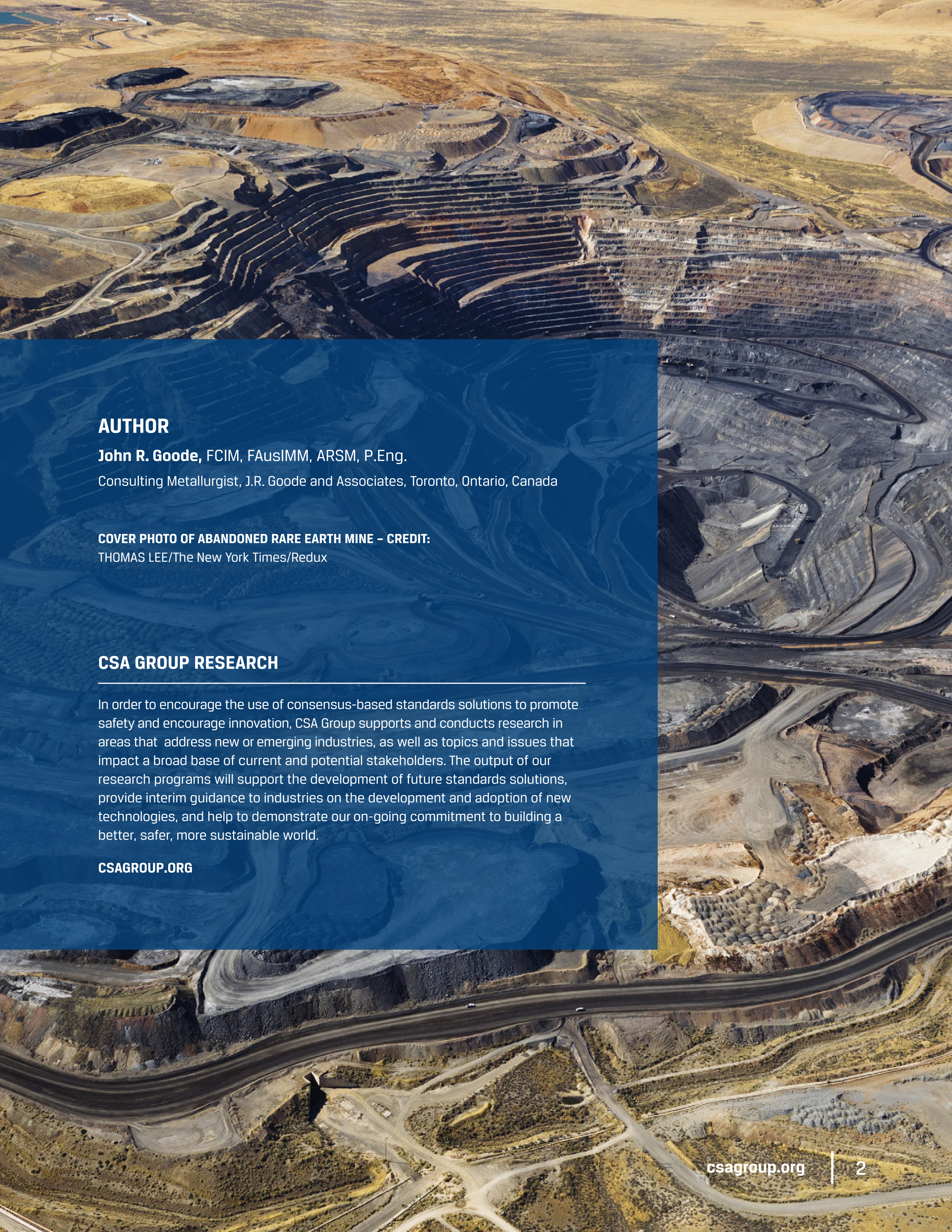
PROVENANCE AND TRACEABILITY OF RARE EARTH PRODUCTS

JUNE 2018



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COVER PHOTO OF ABANDONED RARE EARTH MINE – CREDIT:
THOMAS LEE/The New York Times/Redux

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FOREWORD

Canada has an extraordinary opportunity to responsibly develop its significant resource of Rare Earth Elements (REE) thanks in part to several positive factors including:

- strong mining and REE processing expertise gained both within Canada and Internationally
- an advanced industry with leading-edge technology
- demand for technology relying on REE
- strong Canadian government support for REE developments through a 5-year Canadian REE R&D program with $16.7 million funding
- environmental responsibility expertise and transparency

The Commons Standing Committee on Natural Resources heard evidence during the 41st Parliament that REE mining is an issue important to Canadians. "As an environmentally responsible and conscious country, Canada must set an example for the entire world as it explores those elements on its territory. Canada's mining industry is one of the best regulated industries in the world." (Mr. Andre Gauthier, President and CEO of Matamec Explorations Inc.) *Link to House of Commons RNNR Committee meeting evidence:* http://www.ourcommons.ca/DocumentViewer/en/41-2/RNNR/meeting-15/evidence

In order to develop the present opportunity, Canada, and other countries, would benefit from a level playing field in which all producers accept the importance of environmentally responsible and sustainable production. The elimination of illegal production of REE would help with the required levelling process. Such practices cause environmental devastation and also depresses REE prices such that more responsible producers are not profitable. Elimination of unsanctioned production would enable REE exploration activities to be transformed into profitable production facilities. This will allow Canada to satisfy its own REE needs and even export to help meet global demand.

Illegal and irresponsible extraction of REE would be reduced if there were international standards on traceability just as there are standards for various food commodities, critical aircraft parts, etc. Standards covering other aspects of the REE industry would also facilitate trade and the general development of the industry. Understanding this, Canada, has determined to play an active role in drafting international standards through participation in ISO/ TC298 Rare Earth. A technical committee of Canadian experts has been formed and is supported by CSA Group, Natural Resources Canada, Standards Council of Canada and Canadian Rare Earth Element Network. Through this process consensus can be built among the researchers, regulators, producers, and end-users in Canada and internationally.

This report is intended to start a discussion about the ways in which REE can be traced from mine to manufacturer and what a standard on traceability and provenance for REE might look like.

EXECUTIVE **SUMMARY**

The rare earth elements (REE) are a group of sixteen metallic elements with exceptional chemical and physical properties. With the exception of scandium, the basic chemistry of the REE are very similar and so they are generally found together in nature and are difficult to separate from one another. The separated REE are extensively used in modern life and are key components in permanent magnets used in motors and generators, lighting phosphors, catalysts, ceramics, and other materials.

There is very little REE recycling at this time, with almost all production coming from mining and hydrometallurgical processing. Most ore types require complex processing operations to yield a high-value intermediate mixed REE product. The ionic clay deposits are exceptional and an intermediate product is obtained with relative ease. Intermediate mixed REE products require a difficult separation process to produce individual REE needed by industry.

At this time, 79% of the world's REE are produced in China and 15% are mined in Australia (with hydrometallurgical processing in Malaysia) according to data from USGS (2018). Research from Packey and Kingsnorth (2016) estimates that 40% of global production of praseodymium and neodymium, essential in permanent magnets, are illegally produced. Illegal production leads to environmental damage and depressed prices, and could become more of a problem if not addressed through standards.

ISO/TC 298 Rare Earths has proposed that standards on REE traceability could help ensure that REE are sourced from legitimate operations. This research paper is intended to set the scene for the creation of such standards.

Existing traceability systems were studied to see what is applied in other industries and seek models that would facilitate the creation of a traceability standard for the REE industry. Existing ISO standards cover parts used in the aircraft and space industries, food products, and medical devices. Non-ISO systems have also been surveyed. Several traceability systems are in place to prevent conflict minerals such as tin, tantalum, tungsten, gold ("3TG"), and diamonds from entering the supply chain. Several food, wine, pharmaceutical, medical device manufacturers/users, and luxury goods purveyors have developed traceability systems.

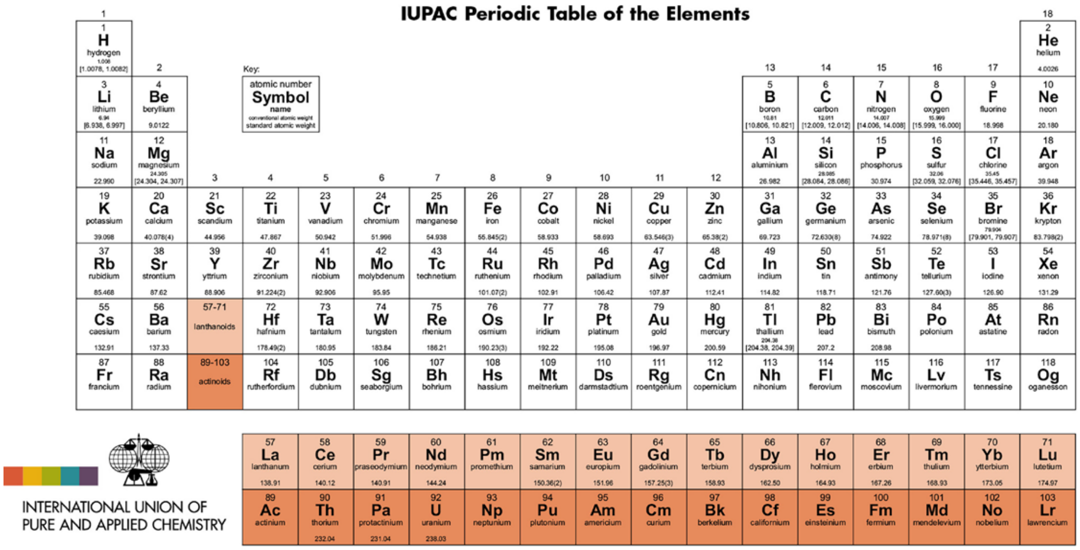
Several provenance schemes, systems that definitively tie a product to a given source, have been proposed or studied for the minerals and food industry. Mineralogy, elemental analyses, and isotopic ratios and added tracer components have been explored.

Lynas Corporation Limited, which produces REE in facilities in Australia and Malaysia has developed a traceability system for its products and provided information. A Chinese group has been testing a REE traceability system, but results are not available.

Details of the REE industry have been examined in an attempt to determine systems that might work. The industry is complex with several different intermediate products moving through the supply chain. However, several practices developed for other industries that could form the basis for an ISO traceability standard have been identified:

- All participants in the supply chain must be officially sanctioned
- Supply chain members must know their counterparties, i.e., the legal entities that are their supplier and customer and the processing and quality control aspects of their operations
- Supply chain members must have the right to make unannounced visits to their counterparty
- Source information must accompany shipments
- Secure packaging should be used as appropriate
- Matrix symbologies or RFID labels should be used to transmit source information
- A secure computerized record-keeping ledger system must be accessible to supply chain members

The inherent properties of intermediate materials in the REE supply chain will probably not be reliable guides to the provenance of a given REE-bearing material. It is possible that added tracers (chemical, radionuclide, or RFID-like devices) could be effective. However, considerable more study is needed concerning the utility of inherent and added provenance indicators.



For notes and updates to this table, see www.iupac.org. This version is dated 28 November 2016.

1 INTRODUCTION

Rare-earth elements

Lanthanoids are defined by the International Union of Pure and Applied Chemistry (IUPAC) as the fifteen elements with atomic numbers of 57 to 71 inclusive, i.e., lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu). The IUPAC defines rare-earth elements (REE) as the lanthanoids plus yttrium (Y) and scandium (Sc). Pm is an unstable element and not found in nature, so in practical terms there are sixteen REE.

Rare-earth elements (REE) are frequently divided into "light" and "heavy" rare earths or LREE and HREE. Definitions of LREE and HREE can vary, but generally Gd and the lighter REE (i.e., La, Ce, Pr, Nd, Sm, Eu, and Gd) are taken as the LREE, and the other REE, including Y, are deemed to be the HREE. REE assays and prices are often expressed on the basis of the oxide – usually abbreviated as REO.

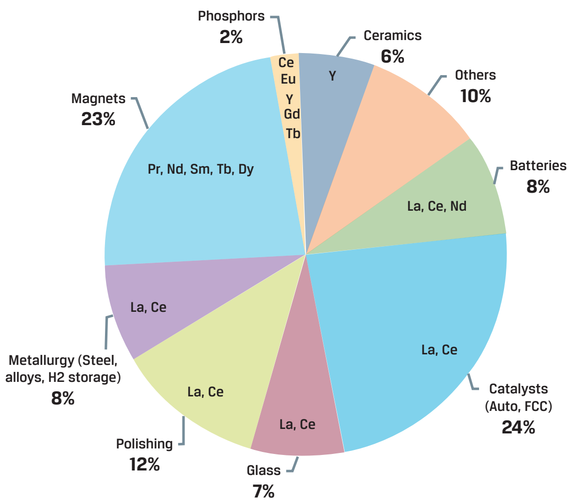
The REE have unique electronic structures that endow members of the group with similar chemical behavior and exploitable optical, magnetic, catalytic, and other properties. These properties of the REE are generally not found in other elements and, to a large extent, there are no substitutes for the REE. As such, the REE are deemed to be "critical" elements by most government agencies.

Uses for rare-earth elements

REE are invaluable and essential components of modern life. Presently the most important uses of REE is in the production of permanent magnets. Some magnets use Sm alloyed with cobalt but most are of the NdFeB type which variously contain Pr and Nd with minor amounts of Dy and Tb. REE are also key ingredients in lighting devices, ceramics, catalysts, and other materials. In most of these applications, REE are used as separated and highly purified metals or compounds. These, and other uses are indicated in Figure 1.

NdFeB permanent magnet production is the most important consumer of REE and in 2016 consumed about 41,000 tons of Nd oxide (Kingsnorth, 2018). However, because of the way in which REE occur in nature, are mined and recovered, the Ce oxide that was co-recovered was about 76,000 tons while the demand was about 53,000 tons. This severe supply-demand imbalance affects several REE and is evident in the very low current prices for Ce, La, Y and several other REE oxides.

FIGURE 1. USES FOR RARE-EARTH ELEMENTS



Graphic produced using percentage data from Roskill 2016

Production of rare-earth elements

A limited quantity of REE are recovered from end-of-life (EOL) products, and some REE are recovered by reprocessing tailings that were generated during uranium production. However, almost all current production comes from either in-situ leaching or mining and beneficiation, followed by hydrometallurgical processing and separation of the REE. The REE processing chain as it now exists is represented in Figure 2.

The beneficiation and hydrometallurgy of REE is generally technologically challenging. The exception is the processing of ionic clay deposits can generally be processed by simple in-situ or heap leach methods, followed by a very simple metallurgical process to produce a REE product suitable for separation. Separating REE from one another is difficult, and the conversion of separated REE to end products such as magnets is also technically challenging.

Current and possible rare-earth operations

The distribution of mine sources of REE in 2017 is shown in Figure 3.

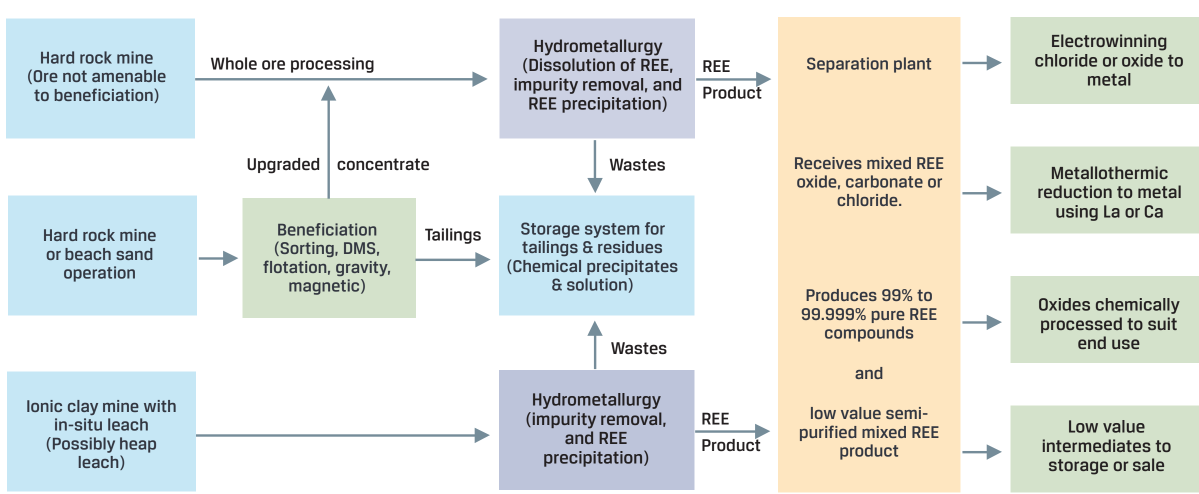
At the present time, about 95% of primary REE production comes from the mining areas shown in insert on page 9 (Goode, 2016 and USGS 2018).

Illegal production of rare-earth elements

The prices for REE peaked in mid-2011, at which time, as an example, the Ce price reached 40 times its level in January 2010. Illegal production of REE, that is without a proper government-issued license with the corresponding government oversight and obligations for responsible mining and observing environmental standards, surged at about this time. Such operations were conducted with little or no regard for environmental protection.

Papers by Packey & Kingsnorth (2016) and Kingsnorth (2017) provide estimates indicating that about 40% of Pr/Nd, a key

FIGURE 2. GENERALIZED FLOWSHEET OF RARE-EARTH PRODUCTION



FOUR SIGNIFICANT REE PRODUCTION AREAS

- **Bayan Obo.** Inner Mongolia Autonomous Region, People's Republic of China. Ore is mined from open pits and processed to produce a REE mineral concentrate and an iron ore concentrate. The concentrates are transported to Baotou where they are processed to yield separated and refined REE products and steel respectively. The REE are dominantly LREE including the magnet-making elements Nd and Pr. The HREE content is about 3%.

- **Mianning – Dechang District.** Sichuan Province, People's Republic of China. Ore is mined by open pit methods and REE extracted by beneficiation and chemical processing to yield products that are much like those from Bayan Obo, i.e., dominantly LREE.

- **Southern China.** Jiangxi, Guangdong, Fujian, and Hunan Provinces and Guanxi Zhuang Autonomous Region, People's Republic of China are the locations of a multitude of relatively small ionic clay REE deposits. REE are recovered by simple heap leaching or in-situ leaching operations using a weak salt solution. The leach solution is purified and an intermediate product precipitated which is separated in one of the several separation plants in Southern China. The distribution of the REE in the products varies very widely with some deposits being ~80% HREE, others ~80% LREE.

- **Mount Weld.** Western Australia. Lynas Corporation Limited is open-pit mining the Mt. Weld deposit in Australia. The REE are beneficiated at the mine and shipped to Kuantan in Malaysia for processing through to finished products. The product distribution is very much like those from Bayan Obo, i.e., dominantly LREE with about 5% HREE.

EMERGING PRODUCER

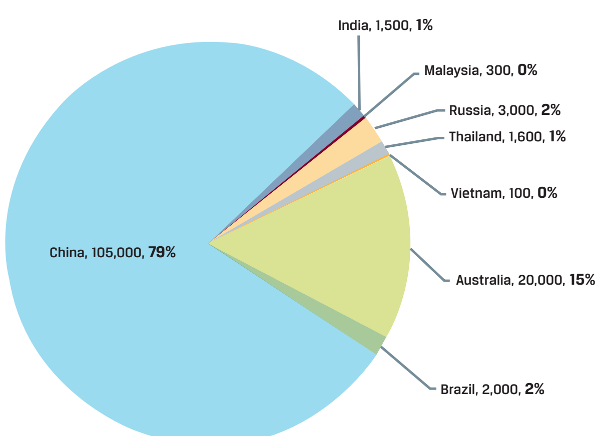
- **Gakara, Burundi.** Rainbow Rare Earths Limited is mining high-grade ore (in-situ grades greater than 47% REO) from open pit mines and intends to produce 5,000 t of concentrate in 2018. The ore will be upgraded to at least 55% REO and shipped to thyssenkrupp in Europe for processing.

PAST PRODUCER

- Molycorp's **Mountain Pass** mine and REE recovery facilities in California, USA commenced operations in about 1950, ceased in 1998 because of high costs and environmental issues, was upgraded and restarted in 2013, then closed in June 2015 because of technical problems and high costs.

A large number of undeveloped REE deposits are known and some could go into production in the near future. Such deposits are located in almost every country with Australia, Brazil, Burundi, Canada, Chile, Greenland, India, Madagascar, Malawi, Myanmar, Namibia, Russia, South Africa, Sweden, Tanzania, Turkey, and Vietnam having well developed projects.

FIGURE 3. 2017 MINE PRODUCTION, TONNES AND % WORLD TOTAL



Graphic uses mass data, excluding undocumented production, from USGS 2018

component in permanent magnets, produced in China was illegally extracted and refined. The Chinese government has provided similar estimates. Packey and Kingsnorth also note that illegal production not only causes environmental damage, but depresses prices to the point that most officially sanctioned production in China, and elsewhere, is unprofitable. Furthermore, illegal mining operations usually practice "high grading" in which only the highest-grade areas of a deposit are extracted and sub-optimal, but most profitable recovery is accepted. This practice often renders the remaining resource uneconomic and therefore wasted.

REE deposits, including the readily exploited ionic clay deposits, are located throughout the world. Whilst most future production will likely be fully sanctioned, it is probable that illegal production will also appear – unless systems are in place to deter such activity.

2 EXISTING TRACEABILITY SYSTEMS

A review of existing traceability and provenance systems could be helpful in establishing a system for REE.

ISO standards

A number of ISO standards cover the traceability of products, including:

- **ISO 21849: 2006 –** Aircraft and space – Industrial data – Product identification and traceability
- **ISO 22005: 2007 –** Traceability in the food chain – General principles and basic requirements for system design and implementation
- **ISO 16741: 2015 –** Traceability of crustacean products – Specifications on the information to be recorded in farmed crustacean distribution chains
- **ISO 12875: 2011 –** Traceability of finfish products – Specifications on the information to be recorded in captured finfish distribution chains
- **ISO 13485: 2016 –** Medical devices – Quality management systems – Requirements for regulatory purposes

Some of the common features of these ISO standards include:

- Traceability from origin to final disposal ("cradle to grave")
- Permanent labeling using bar code or matrix symbologies such as QR code, or RFID (Radio-frequency identification)
- Supply chain members having to know their counterparty (KYC), i.e., their supplier and customer
- Documentation of material as it passes through the supply chain
- Availability of documentation for inspection

Minerals

Several mined commodities, such as diamonds, concentrates of tin, tantalum, tungsten, and gold (last four are commonly dubbed "3TG"), have previously, or are now, obtained in ways that are environmentally damaging, or mined using child labour or exploited to fund armed conflict, or otherwise recovered and sold illegally. Such activities have been documented, commented upon and subject to regulation by several organizations and agencies.

The United Nations (UN) studied the connection between illegal exploitation of mineral resources in the Democratic Republic of the Congo (DRC), funding of armed conflict in the area, and violation of human rights.[1]

In 2014, it issued a Guide to Traceability.[2] The Dodd-Frank Act of 2010 required that US companies exercise due diligence regarding their possible use of DRC-sourced tin, tantalum, tungsten, and/or gold. The Organisation for Economic Co-operation and Development (OECD) has proposed a five-step framework[3] for a due diligence process:

1. Establish strong company management systems
2. Identify and assess risk in the supply chain
3. Design and implement a strategy to respond to identified risks
4. Carry out independent third-party audit of supply chain
5. Report on supply chain due diligence

The China Chamber of Commerce of Metals, Minerals & Chemicals Importers & Exporters (CCCMC) has similar guidelines to those of the OECD.[4] The General Office of the State Council of China (2015) requires that a traceability system focused on "edible agricultural products, food, medicine, rare earth products and other important products" be in place by 2020.

The European Union (EU) has passed a regulation which comes into effect in 2021 to regulate Conflict Minerals as explained on an EU website.[5]

Some specific examples of traceability efforts in the mineral industry include:

Rare earth elements

Lynas Corporation Limited operates a mine and beneficiation plant in Australia. Flotation concentrates are shipped to Lynas facilities in Malaysia for hydrometallurgical processing and separation of individual REE and REE mixtures which are produced as oxides and carbonates. These are sold to companies, generally in China and Japan, for further processing into various commodities including NdFeB magnets.

Lynas has established a traceability system that covers the progress of its magnet-making NdPr oxide from the ore in the mine in Australia, through Malaysia facilities and the several downstream processers, to the final NdFeB product. The system is based on a Lynas-developed traceability log sheet that each of the different downstream processors must complete. Each processor records the incoming batch number and assigns an outgoing batch number and certifies that each batch only contains Lynas material. Unannounced inspections are a part of the system.

The State Council of China requires "the construction of a traceability system for rare earth products" and specifically mentions mining, smelting, separation, product packaging and identification, and management. Several Chinese provinces and autonomous regions with rare earth operations have issued parallel instructions that require systems to be developed by 2020. The China Northern Rare Earth Group, which produces rare earths from the Bayan Obo mine, has started a trial traceability system. Details of the system and results have not yet been reported.

3TG and other minerals

Tantalum is a key component of modern electronics, certain specialty alloys, lenses, and surgical implants. Demand is growing rapidly and in 2016, tantalum concentrates (typically containing 30% Ta_2O_5) commanded a price of about $200/kg of contained Ta205. The DRC and Rwanda account for most of the world's production and a substantial portion of the production is from illegal sources with revenues used to fund conflict. Most of the mining is by artisanal miners using simple washing techniques to concentrate the tantalum and other minerals.

One system that appears to be in effect now, at least at a pilot scale, is operated by the Better Sourcing Program (BSP), which involves local BSP agents at the mine site and providing tamper-proof bags for the products. The bags are tagged, barcoded and scanned as part of an electronic traceability system. An information management system using smartphones keeps track of product movement.

[1] Letter from the United Nations Security Council, November 23, 2009, http://www.un.org/ga/search/view_doc.asp?symbol=S/2009/603&referer=/english/&Lang=E

[2] Business for Social Responsibility United Nations Global Compact, "A Guide to Traceability," 2014, https://www.unglobalcompact.org/library/791T

[3] OECD, "Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas," 2016, https://www.oecd-ilibrary.org/governance/oecd-due-diligence-guidance-for-responsible-supply-chains-of-minerals-from-conflict-affected-and-high-risk-areas_9789264252479-en

[4] CCCMC, "Chinese Due Diligence Guidelines for Responsible Mineral Supply," 2016, http://www.cccmc.org.cn/docs/2016-05/20160503161408153738.pdf

[5] European Commission, "Combatting Conflict Minerals," http://ec.europa.eu/trade/policy/in-focus/conflict-minerals-regulation/

A complementary process is the "Mine to Market Geological Passport" system (Loun, 2016). This was developed by BSP and AVX – a leading producer of tantalum capacitors. The geological passport system relies on knowledge of the unique mineralogy and trace element content of all officially sanctioned mines in a given district. Thus, a check of the mineralogy of a mineral product will confirm that a given concentrate is from a sanctioned source.

Work in the USA (Hark & Harmon, 2014) has investigated "Fingerprinting" of conflict mineral mixtures using LIBS (laser-induced breakdown spectroscopy). Work in Germany (Graupner and Melcher, 2017) has investigated scanning electron microscopy coupled with laser ablation and inductively coupled with plasma mass spectrometry (ICP-MS).

The Australian Nuclear Science and Technology Organisation (ANSTO), working variously with the Lawrence Livermore National Laboratory in the USA and the European Commission, Joint Research Centre, Institute for Transuranium Elements, has developed fingerprinting techniques for uranium concentrates. The method requires elemental, anionic, and, optionally, isotopic analyses on a given sample. The data are then statistically compared with equivalent analytical data for uranium concentrates of known provenance (Keegan et al., 2012; 2014). Other groups (Krajko et al., 2014) have developed similar systems.

The determination of isotopic ratios, using mass spectrometry, as a means of determining provenance has been patented by Hewlett-Packard Development Company, L.P. (US patent 2014/0324347). The patent uses tin as an example but the claims cover all four of the 3TG elements.

The Conflict-Free Sourcing Initiative (CFSI) was established to provide resources to help companies comply with conflict-free sourcing regulations. CFSI has established a "Responsible Minerals Assurance Process" as a standard for the auditing of tin and tantalum smelters. The standard follows guidance in the UN and OECD reports. CFSI has also released a "Conflict Minerals Reporting Template" (CMRT) to facilitate the collection and reporting of information related to the origin of minerals. CSFI urges the ISO approach to management systems and suggests that participants consult ISO 9000, ISO 17000, and ISO 14000 standards. It also requires supply chain members to "Know Your Counter-party" (KYC), exercise due diligence, and be audited on an annual basis. The CSFI approach appears to include tagging of bags of concentrate at the mining site.

Solutions for Hope was founded in 2011 by Motorola and AVX to test the possibility of developing a system to obtain traceability of tantalum from the DRC. The system is described as a closed-pipe supply line from mine through smelters/processors and manufacturers to end user with independent validation throughout the process. This model was adopted by a group comprising the Dutch government, Philips and Motorola to establish the "Conflict Free Tin Initiative" (CFTI). A similar, program has been developed in Colombia and a gold-related initiative is being investigated.

Diamonds

Illegally mined rough diamonds ("Blood Diamonds") have been, and still are being, used to finance conflicts aimed at unseating incumbent governments. As a result of UN investigations and resolutions, several states in Southern Africa formed the Kimberly Process Certification Scheme. Participating countries have the obligation to prevent conflict diamonds entering the market from, or through, their country. This is done through the establishment of self-regulated internal controls and import and export Authorities, the use of tamper-proof packaging, appropriate laws and regulations, and the collection and exchange of production statistics. Several recommended (but not mandatory) procedures include licensing of mines, security measures, and various reporting functions.

Each diamond shipment must be accompanied by a "Kimberley Process Certificate" stating country of origin, identity of exporter and importer, mass of diamonds, and other critical information.

If it agrees, a participating country can be the subject of "review missions" by other participant countries if its self-regulation is deemed suspect in a Plenary meeting.

The Kimberley Process, although a step in the right direction, has been criticized because, while it may reveal the source of diamonds, it does not help prevent human rights abuses that can occur during mineral recovery operations. Furthermore, the effectiveness of a country self-regulating something like diamond mining is questionable.

In 2013, Gemprint Corp. and DNA Technologies announced "Source Veritas" a "Forensic Mine to Market, Chain of Custody" system intended to eliminate trade in blood diamonds.[6] Sanctioned diamond producers would be provided with a spray, containing DNA and an additive that fluoresces under ultra-violet light, to be applied to rough diamonds before shipment. Any diamonds in the supply chain that failed to fluoresce or give a positive DNA test would be deemed illegitimate. The Source Veritas system might work provided that a legitimate receiver of the fingerprinting fluid did not pass, willingly or under coercion, some of the fluid to a non-sanctioned miner.

Food products

Food products can be fraudulently sold as something that they are not, or produced in irresponsible, unethical, or unhygienic ways, or even contain certain additives that are of concern. Instances include the 2008 baby milk powder scandal in which a Chinese manufacturer deliberately adulterated baby milk powder with melamine. The 2013 European horse meat scandal found meat sold as beef actually contained horse meat. Ensuing investigations showed that "beef" often also contained porcine DNA, performance enhancing drugs used in racehorses, and other non-beef components. The food industry has since made significant efforts to better trace the origin of foodstuffs and ensure that adulteration and similar activities are eliminated.

The EU has a regulation (No 1169/2011) that specifies labelling concerning food origin, additives, and other factors. The Codex Alimentarius is a set of international food standards developed jointly by the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) of the UN. It has issued a document entitled CAC/GL 60-2006 "Principles for Traceability/ Product Tracing as a Tool within a Food Inspection and Certification System". Agriculture and Agri-Food Canada has issued the Canadian Food Traceability Data Standard Version 2.0. This voluntary standard applies to the entire supply chain and is based on GS1 and ISO standards. Other legislation have similar standards and requirements.

GS1 is a non-profit supply chain standards organization that, in 1973, developed the barcode standard now used by many industries. Today, GS1 has 112 member organizations and 1.5 million user companies. It is managed by senior representatives of such companies as Alibaba Group, Amazon, Google, and Carrefour. The Global Trade Item Number developed by GS1 is used almost universally and generally presented as a barcode label, but also in RFID. Several GS1 standards are also ISO standards.

[6] Gemprint Corp., "Source Veritas," 2013, http://www.gemprint.com/source-veritas.html

In August 2017, GS1 published its Release 2 of the GS1 Global Traceability Standard – a 55-page document presenting "GS1's framework for the design of interoperable traceability systems for supply chains". The GS1 website includes several implementation guides for traceability of different foodstuffs such as wine, fresh fruit and vegetables, meat and poultry, fish, seafood and aquiculture, and more.

The GS1 system relies heavily on identifying numbers and labels. A Global Location Number (GLN) is assigned to a producer. The product is identified with a Global Trade Item Number (GTIN) and shipping containers receive their own Serial Shipping Container Code (SSCC). Transport, distribution, and retail components of the supply chain are all similarly recorded using bar codes. All transactions are recorded in a database accessible to operators in the chain. In this way, anyone can determine where a product originated, which processing plants it progressed through, how it was shipped, and where it was sold. The product is fully traceable both back to the start of the supply chain and forward to the consumer. Any issues with quality can be quickly and accurately dealt with and recalls effected if necessary.

In 2016, Walmart China, IBM, and Tsinghua University started a trial collaboration to improve food traceability. IBM's blockchain system is used to capture "digital product information such as farm origination details, batch numbers, factory and processing data, expiration dates, storage temperatures and shipping detail." When information is entered into the blockchain, all members of the network must agree on the data after which the record becomes permanent and cannot be changed. Initial tests involved tracing pork products from farm to store appear to have been successful. A similar collaboration between IBM and several US food producers has been announced.[7]

Project Provenance Ltd., a UK-based company, uses blockchain technology as the basis for its traceability services. The company website provides examples of traceability in the fishing industry, coffee, coconuts as well as cotton and alpaca fleece. Matrix symbologies, such as QR codes, and NFC stickers (a form of RFID) are used as unique identifiers. Provenance is also exploring new techniques including Prooftag's Bubble Tag devices and Nano-spirals.

FoodLogiQ is an example of several US companies offering software to manage supply chain issues in the food industry including traceability. Its products are used by several well-known US-based companies including Whole Food Markets, Subway, and Chipotle Mexican Grill. Input to the system is in the form of GS1-type coding.

Several groups are looking at isotope ratios, often combined with elemental analysis, as a means of tracing food provenance. These groups include the University of Utah and IsoForensics[8] and the University of Natural Resources and Life Sciences, Vienna.[9]

Pharmaceuticals and medical devices

Drugs, pharmaceuticals, and medical devices may not be what they are claimed to be despite bearing the name or mark of a reputable manufacturer. Counterfeit medicinal products are a major concern, and in extreme cases, material identified as a therapeutic drug contain no medicinal ingredients at all. Contaminated drugs can be a serious issue as indicated by the 81 deaths in 2008 due to contaminated Heparin produced in China.

Rx-360, an international pharmaceutical supply chain consortium, was formed in 2009. A 2015 document reviews the state of pharmaceutical traceability in Brazil, China, USA, EU, Turkey, South Korea, and Argentina.[10] The systems described varied greatly, with most systems being under development except for Turkey which has had a system working since 2010.

Besides the Rx-360 initiatives, it is clear that the pharmaceutical industry remains concerned as evidenced by the numerous conferences on the subject and several traceability, serialization, and anti-counterfeit systems on offer.

Fake goods

In 2016, the OECD estimated that counterfeit goods were valued at USD 461 billion in 2013 and included clothing, shoes, luxury

[7] IBM, "IBM Announces Major Blockchain Collaboration with Dole, Driscoll's, Golden State Foods, Kroger, McCormick and Company, McLane Company, Nestlé, Tyson Foods, Unilever and Walmart to Address Food Safety Worldwide," 2017 https://www.ibm.com/press/us/en/pressrelease/53013.wss

[8] James Ehleringer and Lesley Chesson, "Determining Geographic Origins of Foods Using Stable Isotope Ratios," http://jifsan.umd.edu/docs/csl10/section2/EhleringerJames_Determining_Geographical_Origin.pdf

[9] Thomas Prohaska, "Food Provenance by Elemental and Isotopic Fingerprint Methods," https://www-pub.iaea.org/iaeameetings/cn222pn/Session2/2-02-IAEA-CN-222-191-Prohaska-Austria.pdf

[10] Rx-360, "Traceability Data Exchange Architecture," 2015, http://rx-360.org/resources/resource-library/traceability-data-exchange-architecture/

> GS1 is a non-profit supply chain standards organization that, in 1973, developed the barcode standard now used by many industries.

items such as handbags, perfumes, replacement parts for automobiles, trucks, aircraft, electronics, and more.[11] An Anti-Counterfeiting Trade Agreement (ACTA) intent on solving the fake goods issue was signed by several countries in 2011, but progress appears to have been limited. Manufacturers are evidently using holograms, RFID, and ever more advanced techniques to identify their products and establish authenticity.

Sports memorabilia can be very valuable, but not if counterfeit. Professional Sports Authenticator has teamed with DNA Technologies to invisibly tag memorabilia with security information that will largely eliminate counterfeiting.

ISO/TC 20 Aircraft and Space Vehicles, has issued numerous standards including ISO 21849:2006 Aircraft and space — Industrial data — Product identification and traceability. The standard refers to permanent product identification using matrix symbologies (such as QR code), linear bar code or RFID tags which facilitate rapid and accurate entry of data into a computerized information management system that allows data exchange.

3. THE RARE EARTH INDUSTRY

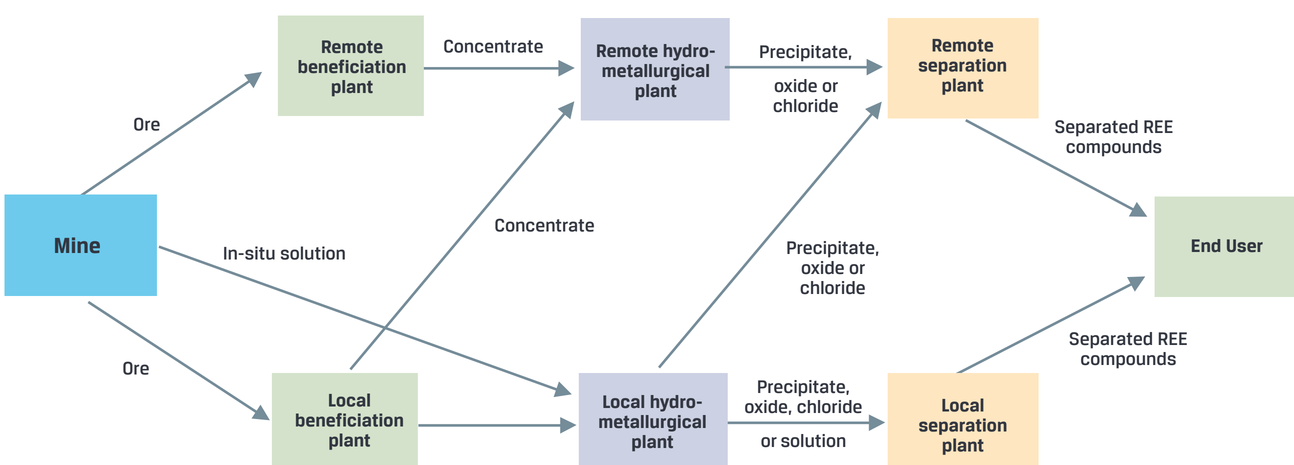
Logistics

REE mines often have their own dedicated beneficiation plant to upgrade the REE content of the rock, their own hydrometallurgical plant, and occasionally a separation plant. However, it is quite common for intermediate materials to be processed in a toll downstream facility that accepts material from more than one source.

The ionic clay deposits are far more readily developed than the other types of deposit since they can usually be exploited using in-situ leaching methods, which produce a REE-bearing solution that is readily processed in adjacent hydrometallurgical plants to make a chemical precipitate containing 90% REO.

Figure 4 indicates how materials can move from the mine to the end user through various intermediate steps. In some cases, brokers facilitate the marketing and movement of intermediate products.

FIGURE 4. POSSIBLE MOVEMENT OF REE FROM MINE TO END-USER



[11] OECD, "Trade in Counterfeit and Pirated Goods," 2016, https://www.oecd-ilibrary.org/governance/trade-in-counterfeit-and-pirated-goods_9789264252653-en

TABLE 1: REE PRODUCTS IN THE PRODUCTION CHAIN

PARAMETER	ORE	MINERAL CONCENTRATE	HYDROMETALLURGICAL PRODUCT	SEPARATED REE COMPOUNDS
Production process	Usually open-pit mining; ionic clay ores are not mined but processed (leached) in-situ	Usually very complex & recovery often low ((60%) if high-grade concentrate (>40% REO) targeted	Usually complex, expensive & environmentally challenging; ionic clay relatively simple	A complex, sophisticated process; high capital & operating costs; can be environmentally challenging
Physical appearance	Coarse to fine rock particles	Generally, a sand-like material but can be ~25 mm rocks	Usually a calcined oxide or precipitate but can be a crystalline salt	A fine powder, colour varies depending on which REE and compound
Particle size	Initially ~1000 mm, can be crushed to be ~25 mm	Usually ~50 mm but most often ~1 mm	Generally ~1 mm powder but salt can be coarse	Generally ~1 mm powder
Typical shipment mass	Usually moved in truckloads of 20 to 200 t	20 to 200 t	1 to 50 t	Very variable depending in which REE
Packaging	Rarely packaged unless very high grade then bulk bags	Bulk shipment or, more often, 1 t bulk bags; loose or in containers	Often 1 t bulk bags; loose or in containers	Bulk bags or lined fibre drums depending on material and quantity shipped
Range of REO* content	Usually <10% often <2%	Often <5% REO, >40% for exceptional deposits	Usually >90% REO	Usually >99% REO
Range in value, $/t material	LREE – $240 to $1,200 HREE – $600 to $3,000	LREE – $600 to $4,800 HREE – $1,500 to $12,000	$11,000 for LREE to $27,000 for high HREE product	$1,500 ($CeO_2$) to $432,000 ($Tb_4O_7$)

*Rare Earth Oxide

Characteristics of REE products

The main intermediate products in the REE supply chain are described in Table 1. The value of materials in the table are the in-place value of the REE using prices of refined and separated oxides for Q1 2019 as projected by Roskill (2017). The LREE deposits containing very low levels of Tb and Dy, such as Mountain Pass, have a "basket" value for the mixed rare earths of about $12/kg REO while an ionic clay deposit high in HREE, especially Tb and Dy would have a basket value of about $30/kg.

The real value of REE in the several materials of Table 1 only reaches the full basket value when the REE have been separated. Present separation costs and market prices are such that La, Ce, Y, and several HREE will not return a net revenue so the actual value of the REE in the hydrometallurgical product is significantly lower than the basket value. Similarly, the value of the REE in the ore and the beneficiated ore will be the basket value in the hydrometallurgical product, less the cost of upstream processing.

Certain conclusions can be drawn from the above characteristics:

- Nowhere in the REE supply chain is there a material to which a label could be readily affixed – until after separation and further processing has yielded solid materials such as magnets.
- Ore and lower-grade mineral concentrates are of such mass, value, and physical attributes that secure packaging, as used to ensure traceability in some industries, is not practical.

Opportunities for illegal production

An analysis of the sort of opportunities available for illegal production of the REE can help identify areas where traceability might or might not work, and what materials need to be traced.

High-grade ore

Very high-grade ore, similar to that found at the Gakara deposit, could be illegally mined and injected into the legitimate supply chain as ore or after simple hand sorting or similar upgrading process. With such material, mining and beneficiation plants would be unobtrusive and could escape surveillance. Such high-grade material (>50% REO) could be accepted by any hydrometallurgical plant geared to process similar minerals. However, such high-grade deposits are unusual and illegal ore production from such deposits is not very high.

Average grade ore

To convert an average ore into something of commercial value, it is necessary to have a hydrometallurgical processing plant. Hydrometallurgical plants are expensive to build and operate and especially if the feedstock is of low grade – say <10% REO. Therefore, lower grade ores need a beneficiation plant as well as a hydrometallurgical plant to produce something that can be processed into a product of value.

For an amenable ore, a simple beneficiation plant would not be too costly and relatively small in size. If such a mine and beneficiation complex could produce a concentrate containing, say, 40% REO, and there was a hydrometallurgical plant prepared to purchase and process such material then a viable operation might be established – with or without official sanction. It is likely that artisanal mining and beneficiation has been a problem in some areas and is probably happening at this time.

Ionic clay REE deposits

Ionic clay REE deposits are very low grade (typically about 0.1% REE) but readily leached. Although ionic clay deposits often contain high levels of Ce, they are usually present as relatively insoluble cerianite along with any thorium that might have been in the original minerals. Therefore, the intermediate product from most ionic clay deposits are low in Ce and relatively high in Pr and Nd (magnet-making materials) and often particularly high in HREE. Leaching can be done very unobtrusively using in-situ methods in which existing vegetation remains in place and a simple system of pipes is used to distribute the leach solution. Given the low cost of production, high value of the product, and ease of concealing the operation, illegal production of intermediate material is very possible. Indeed, it is likely taking place now and will continue in the future. Packey & Kingsnorth (2016) present similar arguments.

All that would be needed for an illegal ionic clay operation to function is a complicit separation plant that would accept the intermediate mixed rare earth product and turn it into marketable material.

Presently, most ionic clay production facilities are located in China. However, such deposits are also found in Myanmar, Laos, Vietnam, Africa, and South America. There is no record of REE being produced from such deposits, but illegal production might be taking place or could be in the future.

Possible provenance indicators

Some mineral industries have investigated the possibility of using indicator minerals or elements to tie a given material to a given source. For a provenance indicator system to work, the ore from a given mine would have a unique characteristic that would persist in the downstream products, i.e., mineral concentrates, intermediate mixed REE products, and separated products derived from the mine. Other mines would have different indicator minerals or different levels of important indicators. Possibilities are discussed below.

Mineralogy

Mineralogical study of ore and concentrates has been applied in determining provenance of some mineral concentrates and might be useful in indicating that a given REE-bearing sample originated in a given deposit. Unfortunately, there is limited data on this subject and it is not clear if this would be an effective approach in the REE industry. Furthermore, mineralogy would be of no use in identifying the source of a mixed REE intermediate product, which is always the result of chemical processing that erases any mineralogical signature in the originating ore or concentrate.

REE distribution

The distribution of REE within a given mineral concentrate or mixed intermediate product deposit might serve as an indicator of the origin of the material. However, available evidence suggests that the distribution will vary with time, depending in

part, on where mining operations actually take place. Figure 5 shows the REE distribution within leach solutions taken from a single ionic clay deposit and illustrates how the distribution of individual REE within the in-situ leach (ISL) product can change with sample location and time.

Furthermore, the distribution of the REE from a given operation can be modified by changes to the plant processes. For example, Ce can be excluded from the product using an oxidation step or the LREE can be isolated by double-sulphate precipitation.

The distribution of REE within several different deposits are presented in Figure 8 using published data compiled by TMR. Figure 6 suggests that while some deposits with low La and Ce content might have unique REE distributions, most deposits have very similar distributions. The data indicate that REE distribution is not a good tool for determining the provenance of a given REE sample.

Elemental and anion analysis

The contents of elements or anions can be used to establish the provenance of uranium concentrates (Keegan, et al., 2012, 2014; Krajko, et al., 2014). Coltan can be rapidly analyzed using portable instruments based on LIBS technology (Applied Spectra, 2011; Hark et al., 2016). Portable X-ray fluorescence (XRF) could also be used for elemental analysis.

Other elements, such as U, Th, P, Nb, Zr, Sc, are often found in REE deposits. There is limited data on the occurrence of such elements in different deposits so it is difficult to comment on the usefulness of elemental analysis as a provenance tool. Furthermore, these elements would only be found in significant levels in the ore or mineral concentrate. The hydrometallurgical plant is designed to eliminate such elements so intermediate REE products could not be traced using simple chemical analysis.

Only three anions (Cl, SO4, and NO3) might be found in intermediate mixed REE products so anion analysis would not be a useful provenance indicator – especially since intermediate REE products are often calcined, which would eliminate anions.

At this juncture, it seems that elemental analysis might be useful for ore and mineral concentrates but could not contribute to traceability of intermediate and separated products.

Isotopic ratio

Isotopic ratios have been tested as a means of assisting in determining the provenance of uranium concentrates. Keegan et al. (2014) used $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$. Krajko et al. (2014) used $^{143}Nd/^{144}Nd$. Hewlett-Packard has patented isotopic analysis as a means of determining the origin of 3TG products. Isotopic

FIGURE 5. PERCENTAGE DISTRIBUTION OF INDIVIDUAL REE IN IN-SITU LEACH PRODUCT

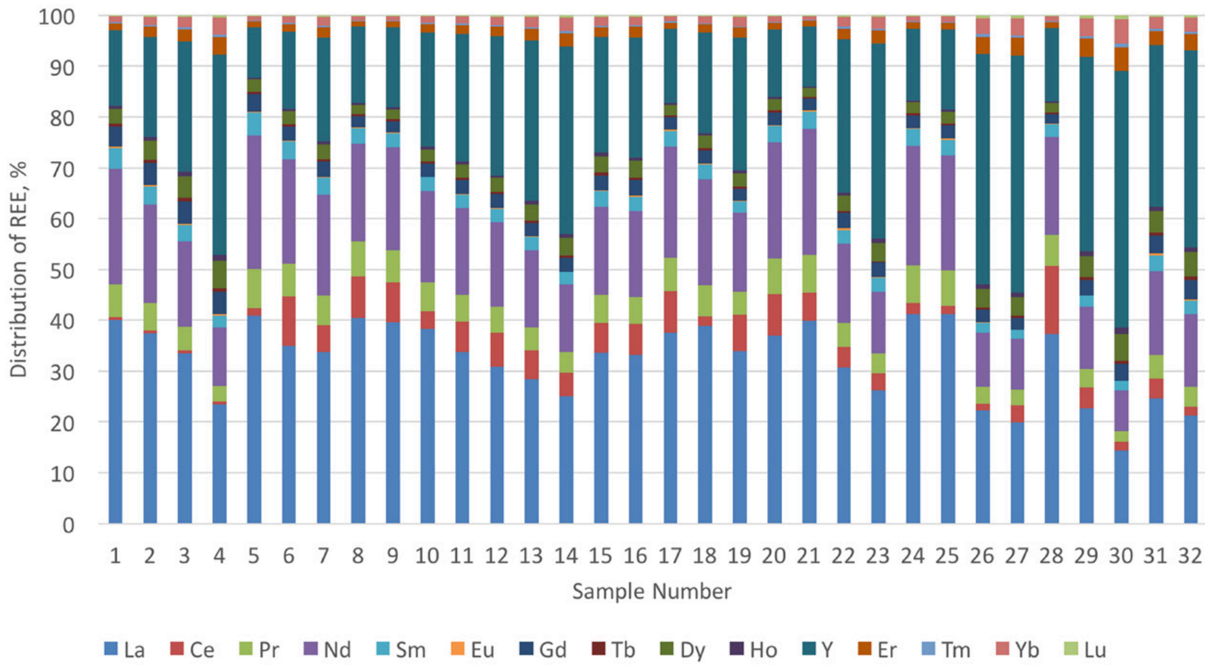
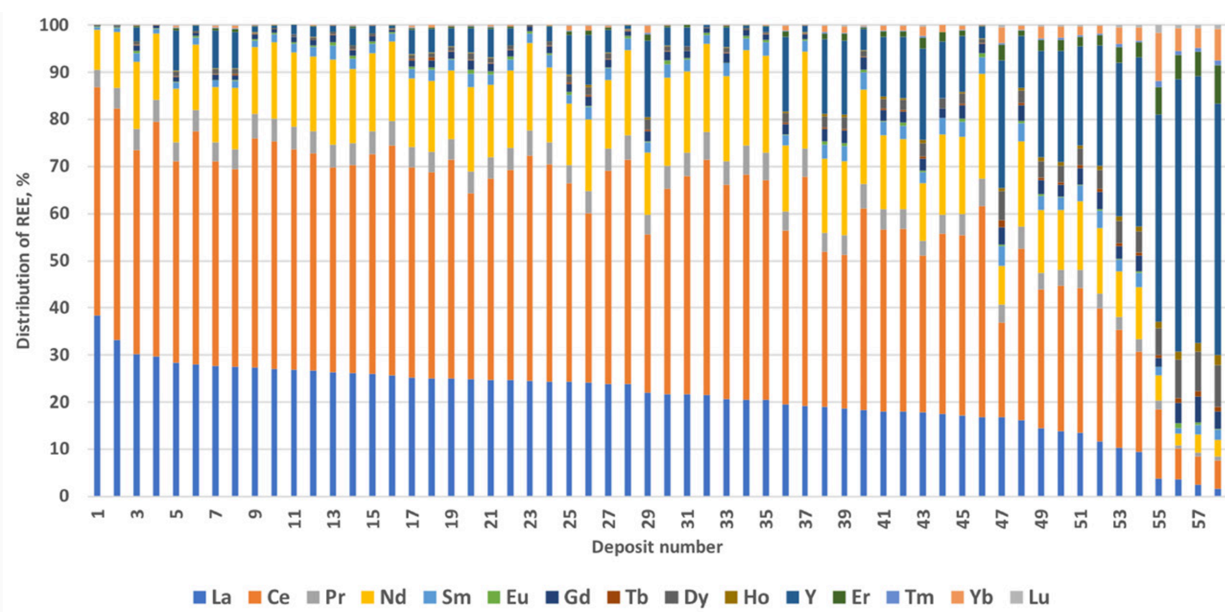


FIGURE 6. REE DISTRIBUTION IN DIFFERENT DEPOSITS



Graphic produced using data compiled by TMR from published reports.

analysis has also been proposed to assist in the traceability of food. However, the discrimination is coarse and the technique appears to be largely a method of defining the geographic origin of materials.

Determining isotopic ratios is a sophisticated and expensive operation. At this time, there is no indication that isotopic analysis could be usefully employed as a REE provenance tool.

Added tracers

It might be practical to add something unique to a REE-bearing material that could be detected in a forensic situation. This is done, or proposed, using fluorescent material and DNA with diamonds and luxury goods. Other possible methods include the addition of hardened RFID, such as something like the Metso SmartTag, into packaged shipments. Another possibility might be the addition of unique chemical or radioactive material to a shipment that could be readily detected if needed but would not interfere with processing.

In operation, unique tracer substances or devices would be issued to each sanctioned mine or processing plant in the supply chain for addition to each package of product. If a suspect shipment was intercepted, the absence of the tracer would strongly suggest that the shipment was illegal.

Significant research would be needed to identify suitable tracer materials or devices that were low cost, non-disruptive to existing process routes, and that could not be faked.

4. ELEMENTS OF A REE TRACEABILITY SYSTEM

There are several components used in the traceability systems developed for other industries that may be considered for REE, as presented and discussed below:

- **Packaging** – It is not applicable to ore because of mass and physical size of material, could be used for mineral concentrates and downstream products.
- **Secure packaging** – It is proposed for Coltan but would not be practical for REE except for low volume, high value separated products.
- **Labeling** – If something is packaged, it could be labeled. There are several formal/commercial systems that could be used such as the GS1 barcode or the QR code or RFID.
- **Know-your-counterparty** – It is something that could be done in the REE industry and would help allow tracing of products through the supply chain.
- **Unannounced inspections** – A participant in the supply chain could visit his counterparties to verify that his source (especially) or customer was compliant.
- **Information transmittal and sharing** – Material moving through the supply chain is documented such that others in the supply chain can examine the history of the material. Machine readable labelling (such as QR code) would help convey information and blockchain type of ledger might be used.

Provenance methods, which definitively tie a product to a source, can be a part of a traceability system – either as an integral part of the system or as a forensic tool to determine if a suspect material has an origin as is claimed. Provenance tools might include:

- **Mineralogy** – It is indicated as a viable provenance indicator in some industries but there is no data to indicate the value in the REE industry. In any event, mineralogy is lost after a hydrometallurgical product has been made.
- **REE distribution** – There is limited evidence that this method would help since within-source variability is likely to be high.
- **Non-REE analyses** – This might be useful for ore and mineral concentrate but of limited value for downstream products.
- **Isotopic ratio** – There is no evidence that this technique would be effective.
- **Added tracer** – It might be possible to add a unique tracer device or compound to a shipment of ore, mineral concentrate, or intermediate mixed rare earth product that could be detected during a forensic investigation but would not affect processing operations.

An assessment of the relevance of the above parameters to provenance and traceability in the REE industry are as summarized in Table 2. Colour codes have been used to

> In operation, unique tracer substances or devices would be issued to each sanctioned mine or processing plant in the supply chain for addition to each package of product. If a suspect shipment was intercepted, the absence of the tracer would strongly suggest that the shipment was illegal.

TABLE 2: TRACEABILITY SYSTEM COMPONENTS AND RELEVANCE TO REE INDUSTRY

PARAMETER	ORE	MINERAL CONCENTRATE	HYDROMETALLURGICAL PRODUCT	SEPARATED REE COMPOUNDS
Packaging	Generally not done or possible	1 t bulk bags possible for higher grade concentrate	Often 1 t bulk bags	Bulk bags or lined fibre drums
Secure packaging	Generally not done or possible	Applicable to bulk bags	Applicable to bulk bags	Applicable
Label on package	Not applicable	Applicable to bulk bags	Applicable to bulk bags	Applicable
Know-your-counterparty	Readily done	Readily done	Readily done	Readily done
Unannounced inspections	Readily done	Readily done	Readily done	Readily done
Information transmittal and sharing	Readily done	Readily done	Readily done	Readily done
PROVENANCE INDICATORS				
Mineralogy	Possibly useful	Possibly useful; probably different to ore	Not applicable	Not applicable
REE distribution	Possibly useful	Possibly useful; could be different to ore	Possibly useful; could be different to ore and mineral concentrate	Not applicable if separation plant has multiple feeds
Non-REE elemental analysis	Possibly useful	Possibly useful; probably different to ore	Probably useless since non-REE removed	Not useful
Anions	Not applicable	Not applicable	Limited usefulness	Not useful
Isotope ratio	Possibly useful	Possibly useful; probably different to ore	No information; could be useful	No information; could be useful
Added tracer	Possibly useful	Possibly useful	Possibly useful	Possibly useful

indicate the usefulness of a given parameter with orange indicating limited value, grey indicating likely a high value, and green indicating uncertainty.

The matrix in Table 2 suggests that key components of an ISO-based traceability system intended to eliminate illegal production and processing of rare earth products must include the following features:

- Members in the supply chain must be officially sanctioned to undertake certain operations, e.g., mining, beneficiation, hydrometallurgical processing, separation, or downstream processing.
- Members must know their counterparty and only deal with counterparties that are legally sanctioned members of the supply chain.
- Unannounced inspections – Parties in the supply chain should have unfettered rights to arrive at an upstream facility, observe activities, and verify that their material is appropriately sourced.
- Information transmittal and sharing – Data concerning a shipment of REE accompanies the shipment of material as it moves down the supply chain.

- In the case of mineral concentrates, the intermediate products of a hydrometallurgical plant, and separated products, the above components could be complemented by:
  - Secure packaging – Bags or other containers that could be sealed to prevent the addition of illegal material.
  - Labels on the package – Identification of the material, the mass, the source, the composition, etc. could be done using barcode or QR code or by using an RFID device.
- A computerized management system – It should be accessible to all operators in the supply chain. A blockchain system might be preferred since it is difficult to tamper.

Analytical means of verifying the provenance of a rare earth compound would be useful. However, there is insufficient information to determine if the inherent properties of REE materials in the supply chain can provide provenance indicators. An evaluation program would be needed to determine within-source variability and between-source uniqueness. This could be an expensive project.

The use of added tracer devices or compounds is a possibility but a great deal more work would need to be done to confirm this.

The Lynas system of traceability for its NdPr oxide and manner in which it generates a mine to magnet record appears to be effective and incorporates several of the elements listed above. It warrants further study and consideration as a model that has wider application within the REE industry.

The system under trial in Baotou, China is of great interest and further information could help point the way to a workable system.

5. CONCLUSIONS

The rare earth industry is complex with many players along the supply chain and various high-value, intermediate products that can take various routes through the supply chain before reaching the consumer. Given the complexity, there is a real possibility of illegally produced material entering the supply chain. The indications are that the illegal production of REE has created significant environmental damage and depressed market prices such that legitimate production is not profitable.

Traceability and provenance practices and proposals of other industries have been reviewed. The following common elements could be included in traceability standards for the REE industry:

- All participants in the supply chain must be officially sanctioned.
- Each supply chain members must know their counterparts, i.e., the legal entities that are their supplier and customer.
- Supply chain members must have the right to make unannounced visits to their counterparty.
- Source information must accompany shipments.
- Secure packaging shall be used as appropriate.
- Matrix symbologies or RFID labels must be used to transmit source information.
- A computerized record-keeping ledger system accessible to supply chain members is essential.
- Traceability and provenance systems should not create an excessive financial or administrative burden on supply chain participants.

Provenance indicators inherent to REE-bearing materials, such as mineralogy, REE distribution, and elemental and isotopic analyses could play a role directly within the traceability system or as forensic tools to determine if material came from a given source. At this juncture there is insufficient data to determine if inherent characteristics are sufficiently stable and unique for this approach to be helpful.

In another form of provenance determination, unique tracers could be added to REE-bearing material by a legitimate producer which would then serve to verify that the REE shipment was legitimate. The unique tracer might be a compound of some form with a unique chemical or radionuclide signature or a hardened RFID.

Inherent and added provenance indicators need additional research to determine their usefulness.

A standard on traceability and provenance is not an end in itself. The real endpoint is reached when an entity within the REE supply chain is certified as being compliant with the standard. The entity's customers can then be assured that the product came from a fully sanctioned source. As is normal, an independent certification body would determine an entity's compliance with the standard.

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ACKNOWLEDGEMENTS

The author significantly benefited from the input provided by fellow members of the ISO/TC 298 Rare Earths Canadian Mirror Committee and by members of the ISO/TC 298 Rare Earths Australian Mirror Committee. Input by ISO/TC 298 Mirror Committee members in Russia and the United States of America are also recognized. The guidance of CSA staff is gratefully acknowledged. This document partially contains the views and ideas provided by others but the content contained herein is that formulated by the author and may not necessarily reflect the complete views, opinions or positions of those who contributed.

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