



A geological reconnaissance of electrical and electronic waste as a source for rare earth metals



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ABSTRACT

The mining of material resources requires knowledge about geogenic and anthropogenic deposits, in particular on the location of the deposits with the comparatively highest concentration of raw materials. In this study, we develop a framework that allows the establishment of analogies between geological and anthropogenic processes. These analogies were applied to three selected products containing rare earth elements (REE) in order to identify the most concentrated deposits in the anthropogenic cycle. The three identified anthropogenic deposits were characterised according to criteria such as “host rock”, “REE mineralisation” and “age of mineralisation”, i.e. regarding their “geological” setting. The results of this characterisation demonstrated that anthropogenic deposits have both a higher concentration of REE and a longer mine life than the evaluated geogenic deposit (Mount Weld, Australia). The results were further evaluated by comparison with the geological knowledge category of the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) to determine the confidence level in the deposit quantities. The application of our approach to the three selected cases shows a potential for recovery of REE in anthropogenic deposits; however, further exploration of both potential and limitations is required.

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1. Introduction

Metallic raw materials are crucial to modern society: their mobilisation increased almost 19-fold from 1900 to 2005 (Graedel et al., 2012). With remarkable selectivity, people have sought the local concentration of specific raw materials in the Earth's crust to satisfy increasing demand. Considering the lifespan of the planet, the exploitation of these ores¹ is a recent phenomenon, but it increased exponentially during the last two hundred years (Arndt and Ganino, 2012). Once these geological heritages are consumed, they cannot be replaced in any period significant to

human beings (McLaughlin, 1956), since geogenic mineral deposits are the end product of the prolonged formation of local environmental and geodynamic settings (Dill, 2010). Minerals are individual components within rocks that are generally defined according to their chemical composition and crystal structure (Nickel, 2005). They are the starting point for the production of metals such as rare earth elements (REE). REE are considered geochemically scarce² although they are more abundant in the Earth's crust than many other metals (Hoatson et al., 2011; Wäger et al., 2012). Nevertheless, REE are regarded as prominent geological heritage (Hoatson et al., 2011), because they have properties required in current and future technologies and presently cannot be substituted by other metals (National Research Council, 2008; Graedel et al., 2013). The demand for REE is continually increasing (USDOE, 2011), with a high risk of supply disruption (Izatt et al., 2014). For example, the demand of Neodymium–Iron–Boron permanent magnets is expected to increase by 12.5% annually until 2035. The use of phosphors with REE is expected to increase at an annual rate of 8% by 2015. Thereafter, an annual decline by 4.5% is expected until 2035

Abbreviations: EoL, end-of-life; Eu₂O₃, europium oxide; Nd₂Fe₁₄B, Neodymium–Iron–Boron; REE, rare earth elements; REO, rare earth oxides; UNEP, United Nations Environment Programme; UNFC, United Nations Economic Commission for Europe; USDOE, U.S. Department of Energy; EEE, electrical and electronic equipment; WEEE, waste electrical and electronic equipment.

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¹ Ores are accumulations of metals and minerals at a particular location (McLaughlin, 1956).

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² Geochemically scarce metals are those metals, whose crustal abundance is <0.01 weight-% (Skinner, 1979).

(Alonso et al., 2012). Both of these components, magnets and phosphors, are used in electrical and electronic equipment (EEE). This use has led to a rapidly increasing volume of REE deposits in waste electrical and electronic equipment (WEEE) over the last few years (Oswald and Reller, 2011). With current recycling technologies, less than 1% of the applied REE can be recovered (UNEP, 2011, 2013). Accordingly, today REE follow a nearly linear resource flow from design to eventual landfill disposal along the material life cycle (Curran and Williams, 2012) and are at risk of being dissipated³ (Wäger, 2011a). According to Graedel et al. (2011) and UNEP (2010), the material life cycle describes the path of a metal over the various life stages from refining to product manufacturing, to use, end-of-life (EoL), and waste management. Along this path, the metal undergoes several concentration and dilution steps: while refining, the pure metal concentrates, during manufacturing it dilutes slightly and during use the metal dilutes heavily (Wäger et al., 2015). Through recovery, the pure metal is concentrated, else further dilution can occur. To move from a linear to a circular material flow (Curran and Williams, 2012), material recovery needs to be facilitated with minimised dissipative losses (Oswald and Reller, 2011). To enhance material recovery in the future, it is pivotal to shed light on the process chain from mining to waste management (Brunner, 2011; Simoni, 2012; Wäger et al., 2011b; UNEP, 2013). In particular, both mining of the geosphere and anthroposphere require knowledge about mineable deposits (Lederer et al., 2014). In the study presented here, we develop a framework that allows the establishment of analogies between geological and anthropogenic processes. Based on this framework, analogies between mining of the geosphere and anthroposphere are derived for the case of REE and used to identify the most concentrated deposits for three selected EoL products containing REE components. The three identified deposits are characterised and evaluated with “geological” approaches.

2. Geological approaches for characterisation and evaluation of geogenic deposits

In geology, deposits are characterised to provide a basic understanding of ore deposits' formation and the abundance of minerals. A characterisation includes different attributes describing geological features, such as the location, geological provenance, host rock, mineralisation, source and age of mineral and genetic modelling (Hoatson et al., 2011).

On this basis, different classification schemes have been developed that allow a comparison between the different ore minerals (Long et al., 1998). A widely applied scheme is the so-called “genetic classification” of ore deposits. The genetic classification is based on a description of various mineralisation criteria and/or associated geological events, i.e. ore forming processes (Arndt and Ganino, 2012; Hoatson et al., 2011; Pohl, 2011).

In order to evaluate mineral reserves and resources, a globally harmonised and universally applicable classification framework has been developed by international experts from different country-specific classification frameworks: The United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009 classification) (UNFC, 2010). This classification evaluates resources based on three dimensions: socio-economic viability, project feasibility and geological knowledge. Within this framework, the dimension “geological knowledge” encompasses four levels, which assign different levels of confidence to the quantities of a deposit (Table 1). For potential

Table 1

Summary of the category geological knowledge of the UNFC-2009 classification (UNFC, 2010).

Level	G1	G2	G3	G4
Definition	Quantity of known deposits that can be determined with high level of confidence.	Quantity of known deposits that can be determined with moderate level of confidence.	Quantity of known deposits that can be determined with low level of confidence.	Estimated quantity of potential deposits based mainly on indirect evidence.

mining, both mining of the geosphere and anthroposphere require quantities that can be determined with at least low level of confidence, i.e. between levels G1–G3. In contrast, if the quantities are only estimated, respectively cannot be determined with a low level of confidence, no mining can commence. Then level G4 is assigned to the potential deposit.

3. Methodology

3.1. Framework development

To establish and verify the relationship between geological and anthropogenic processes, four consecutive workshops were organised with four experts: two geologists and two resource management researchers from academia. The knowledge generation process commenced by critically analysing, identifying and discussing the processes of the geologic ore deposit formation, i.e. genetic ore deposit formation understanding and its resulting classification. On this basis, mining, processing and the material life-cycle processes were analysed, deconstructed and categorised. This was followed by the development of a commonly agreed overview framework. The initial framework was then independently synthesised and resynthesised. To verify the emerged framework the same experts were re-consulted (Jabareen, 2009).

3.2. Identification of analogies

The analogies, i.e. similarities or correspondences between elements of the framework, were identified in discussions with the above mentioned experts from geology and resource management (Börjeson et al., 2006). The analogy considered to be most relevant was further elaborated for the case of REE in WEEE, which required a specification both of the crust–surface geochemical cycle and of the product cycle.

3.3. Development of characterisation and evaluation approach for three REE EoL products

To determine the anthropogenic deposit characteristics, typical geogenic deposit characterisation approaches were identified and critically analysed through literature research. To select a meaningful geological deposit characterisation and evaluation, the same experts as within the framework development were consulted (Börjeson et al., 2006).

This consultation led to a critical analysis of the “geological setting” of geogenic deposits according to Hoatson et al. (2011). Overall, the characterisation of the “geological setting” provides a continually narrowing and comprehensive understanding of a geogenic deposit with a focus on its associated minerals and different life-stages. Specifically, to enable this perspective the critical analysis was concluded with a selection of criteria that allow the characterisation of the “geological setting”. These criteria encompass:

³ “Dissipation” is understood as the “dilution” of materials into the anthroposphere in such a way that a material recovery is difficult or impossible (Wäger et al., 2012; Zimmermann and Gößling-Reisemann, 2013). The “anthroposphere” includes the living space created and designed by people (UBA, 2012).

Table 2
Criteria characterising the “geological setting”.

Criteria	Explanation	
	Geological perspective	Product cycle perspective
Location	Short overview of the place of the geogenic or anthropogenic deposit.	
Geological context	The process of the formation of the geological area around the deposit, with focus on identifying potential “host rocks”. An illustration can be included to visualise the formation of the “host rock”.	The process of the formation of the local environment of the deposit, with focus on identifying potential host product group, e.g. laptop. An illustration can be included to visualise the location of the “host rock/product group”.
Host rock	The process of the formation of the rock, which contains the sought resource, to gain an understanding of the forming process to enable discovery of other deposits with the same “host rock”.	The process of building the product component, e.g. laptop screen, which contains the sought resource and potential hazardous substances, to gain an understanding of the matrix forming process, to allow for the discovery of other deposits with the same host product components.
REE mineralisation	The process of concentration and its resulting specification of the existing mineral to obtain a detailed understanding of the formation of the ore to estimate the grade thereof.	The process of past, current and expected concentration of the resource and potential hazardous substances and their resulting specification; e.g. mineralisation of materials in laptop screen, to obtain a detailed understanding of the formation of the resource to estimate the grade thereof.
Age of mineralisation	The period when the deposit was formed, or when the mineral was concentrated. This belongs to a general description of a deposit; it can enable an indication of where other similar deposits were formed during the same period of mineralisation. This is relevant for both local and global deposits.	The period when the deposit was formed and its expected future growth, e.g. formation time of a laptop deposit. This gives a general overview of the age of deposits but also indicates future deposits both locally and globally.
Current status	The current development state of the geogenic or anthropogenic deposit with regard to potential mining, and information on the mine life if available.	

the geographical “location” of the deposit; the “geological context”, instead of the repetitive criteria “geological setting”; the “host rocks”; and the “REE mineralisation” and the “age of mineralisation” (Table 2). The criteria describing “source of REE” and “genetic modelling” were not included. The former is redundant with the specific REE deposit selection and the latter provides a strong congruence with the criterion “host rock”. The characterisation of the “geological setting” concludes with the criterion “current status”. Those criteria that passed this analysis were adapted for mining of anthroposphere.

The selected criteria were first applied to an example geogenic REE deposit as described by Hoatson et al. (2011) and then to three EoL products of anthropogenic deposits: (i) Neodymium–Iron–Boron permanent magnet, (ii) fluorescent lamp with phosphors containing Europium and (iii) fibre optic cable doped with Erbium.

For the evaluation of the anthropogenic deposits, the UNFC-2009 classification (UNFC, 2010) was selected. This classification was critically analysed, and then the category “geological knowledge” was chosen on common agreement between the four experts and the principal investigator (Jabareen, 2009).

4. Results and discussion

4.1. Framework development

The identified framework shows the relationship between the perspectives of the “simplified crust–surface geochemical cycle”, “mining”, “processing” and “product cycle” (Fig. 1). It lays the foundation for establishing analogies between geological and anthropogenic processes.

The framework connecting the geological and anthropogenic cycles can be described as follows:

The simplified crust–surface geochemical cycle adapted from Hoatson et al. (2011) constitutes the foundation of the mining of the geosphere. During this cycle, the “Magmatic rocks” are “altered” and deconstructed by “weathering”, then “transported” and “deposited” as “sedimentary rocks” (Hamblin and Christiansen, 2004). This is followed by a mineralogical

modification of the rock structure through “diagenesis⁴” at low pressure and temperature, and through “metamorphism⁵” at high pressure and temperature, into “metamorphic rocks” (Kornprobst, 2002). These rocks are melted at high temperature and crystallise into “Magmatic rocks” (Bernier and Bernier, 2012). Within the crust–surface geochemical cycle, any rocks can potentially be mined.

Mining is the subsequent process. According to Mudd (2009), the mining site has to be “explored” first, which is followed by an “evaluation”, e.g. after the mineral reserve/resources classification by UNFC (2010). Then, the mining process needs to be “developed” before the “operation” can commence. Lastly, the mine site needs to be “rehabilitated” to its surface original condition (Mudd, 2009).

In processing, “crude ore rocks” are crushed, ground and separated during “mineral processing”, and the concentrated fraction is “smelted” and “refined” to produce the raw material (Wills et al., 2006).

In the product cycle as described by Du and Graedel (2011), the “raw material” is “manufactured” into a “product” which is “used” until it reaches the “end-of-life” stage. Then, through “waste management” raw material can be produced again, which leads into a new product cycle. Within this cycle the processes “manufacturing” and “use” are for a specific purpose: the use of products. Consequently, these products cannot be mined, with the exception of residues and scraps. In contrast, when a product reaches the “EoL product” deposit, it loses its specific purpose and could be mined. This means that for the processes in “waste management”, i.e. starting at the “EoL product” via “waste management” to “raw

⁴ Diagenesis is any physical, chemical or biological change undergone by a sediment after initial deposition and rock formation, excluding surface alteration (weathering) and metamorphism. Such changes happen at relatively low temperatures and pressures and result in transformations to the rock’s original mineralogy and texture (Árkai et al., 2003).

⁵ Metamorphism creates any rock derived from pre-existing rocks by mineralogical, chemical, and/or structural changes, essentially in the solid state, in response to marked changes in temperature, pressure, shear stress, and chemical environment, generally at depth in the Earth’s crust (Hoatson et al., 2011).

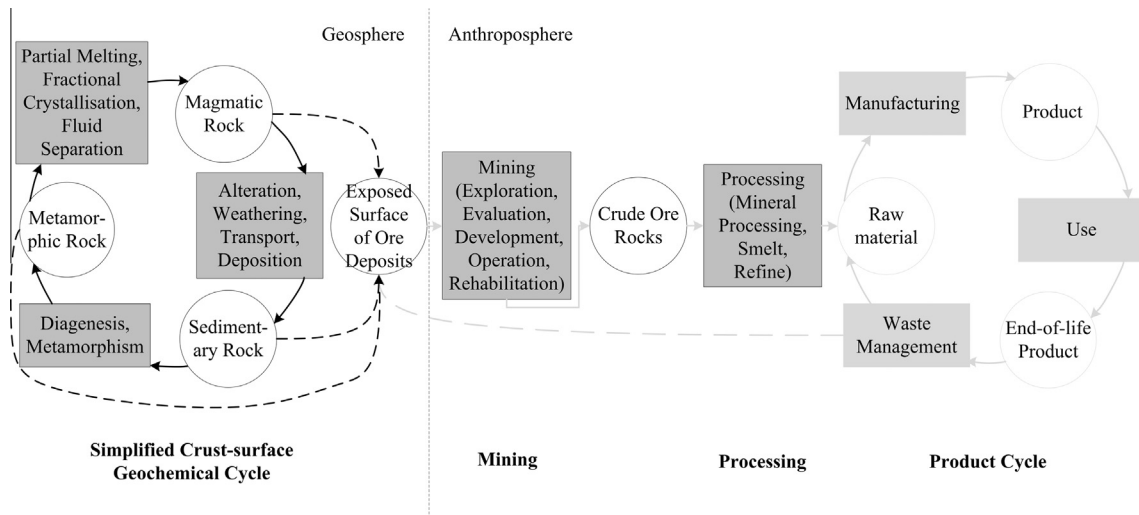


Fig. 1. Basic framework connecting the geosphere with the anthroposphere, represented as processes (boxes), states (circles) and connections between the processes and states (arrows).

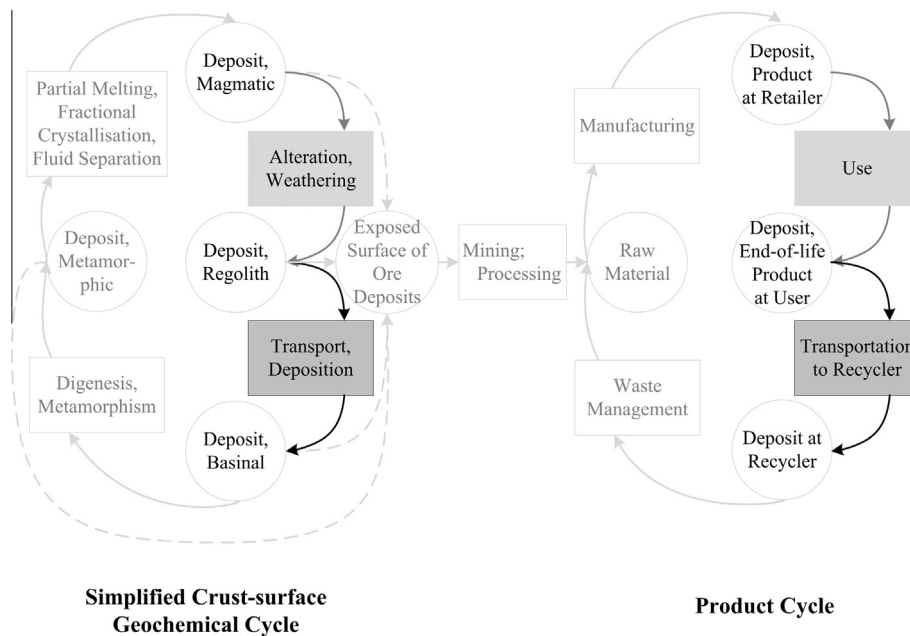


Fig. 2. Specification of the framework connecting the geosphere with the anthroposphere for REE. Processes (boxes) related by analogy are highlighted.

material”, the same principles apply as for genetic deposit understanding and subsequently its classification (Hoatson et al., 2011).

4.2. Identification of analogies

4.2.1. Identified analogies

The experts found the analogy between the processes “alteration, weathering, transportation, deposition” and the process “use”, and their corresponding concentration – dilution profiles for the geogenic and anthropogenic, to be most relevant. Accordingly, this analogy was further elaborated for the case of REE in WEEE, considering the development of the ratio between the total area occupied by a certain amount of geogenic and anthropogenic deposit (measured in specific surface area (m^2/kg)), as a possible representation for the (spatial) concentration–dilution or spread profiles.

4.2.2. Specification of the geochemical cycle and of the product cycle

To further elaborate on the analogy for REE, the crust–surface geochemical cycle had to be specified (Fig. 2). The genetic formation of REE consists of four major mineral-system associated geogenic REE deposits: the “Magmatic⁶”, “Regolith⁷”, “Basinal⁸” and “Metamorphic”. These four deposits differ from the three types of rocks identified in the framework (Fig. 1). The analogy is formed by specifying the process chain from the “Magmatic deposit” via

⁶ Magmatic material comprises a mixture of molten or semi-molten rock, volatiles, solids, dissolved gas and gas bubbles that is found beneath the surface of the Earth (Spera, 2001).

⁷ Regolith is the unconsolidated material, both weathered in place and transported, which overlies consolidated rocks (bedrock) (Hoatson et al., 2011).

⁸ Basinal is a layer of solid, heterogeneous material that comprises a mixture of sedimented rock or sand. It can also form REE containing heavy mineral sand or sea-floor nodules, respectively manganese nodules (Hoatson et al., 2011).

the “Regolith deposit” to the “Basinal deposit”. The main processes between the “Magmatic deposits” and “Regolith deposits” are “alteration” and “weathering” (Fig. 2). The main processes between the followed by deposits “Regolith” and “Basinal associated mineral-system” are “transportation” and “deposition”. The “alteration”, “weathering”, “transportation” and “deposition” processes can either lead to a concentration or a dilution, depending on the circumstances. For example, the existence of a common transportation channel combined with an ideal deposition environment results in spatial concentration, while diverse transportation routes combined with many different options for mineral deposition result in spatial dilution.

Similarly, the product cycle was specified in the three anthropogenic deposits, “product deposit at retailer”, “EoL deposit at user” and “deposit at recycler” and the two processes “use” and “transportation to recycler” between these deposits. The “use” process was identified to correspond to “alteration” and “weathering”, the “transportation to recycler” process to “transportation” and “deposition”. Consequently, the “use” phase is characterised by changes in a local environment with specific boundaries, e.g. using a product in a country. The used products can become concentrated at their EoL (in this paper, this term is used to mean the point at which the last holder no longer has any use for the item). This can lead to the formation of the “EoL deposit”. Such anthropogenic “deposits” are generally formed at each product user. Considering the much larger number of users than manufacturers, scarce metals contained in products are spatially diluted or higher spatial spread (Fig. 3). EoL products can be “transported” and form a “deposit at recycler”. The far smaller number of recyclers compared to consumers result in a spatial concentration or lower spatial spread.

4.2.3. Synthesis of analogies for selected REE EoL products

Three REE EoL products were selected as case studies for an exemplary application of the analogy on anthropogenic deposits. All products are used in a different local environment, i.e. their

use is either mobile, stationary or inaccessible. The first, Neodymium, is contained in Neodymium–Iron–Boron permanent magnets used in (electrical) cars, which are mobile during their use and at their EoL are “transported” to recyclers at fixed locations for depollution and dismantling. The second, Europium, is contained in phosphors mainly used in fluorescent lamps that are fixed during use and also transported to recyclers for processing. The third, Erbium, is contained in optical fibres used mainly in underground cables.

Fig. 3a–c shows the concentration–dilution profiles for the three case studies addressed. For Neodymium–Iron–Boron permanent magnets and phosphors fluorescent lamps, the concentration decreases from the “deposit at retailer” to the “EoL deposit at user”, while it increases again from the “EoL deposit at user” to the “deposit at recycler”. For underground fibre optic cables, the concentration decreases from the “deposit at retailer” to the “deposit EoL at user”; there is no “deposit at recycler”, because a collection system currently does not exist.

4.3. Development of characterisation and evaluation approach for selected REE EoL products

For each of the three case studies the geological setting was characterised according to the criteria defined in Table 2. For the characterisation, the anthropogenic deposits with the maximal concentration, i.e. lowest spread, of REE EoL products were chosen, i.e. the “deposit at recycler” for the electric car with Neodymium–Iron–Boron permanent magnet and the fluorescent lamp, and the “deposit EoL at user” for the fibre optic cable.

The characterisation of the “geological setting” allows a better understanding of the recycling and disposal phase of an EoL product. In particular, it allows the identification of potential for reducing dissipation of the anthropogenic deposits. It further enables a product-centric perspective, as proposed by UNEP (2013), because the focus of characterising the “geological setting” begins with the product, e.g. electrical car (Table 3).

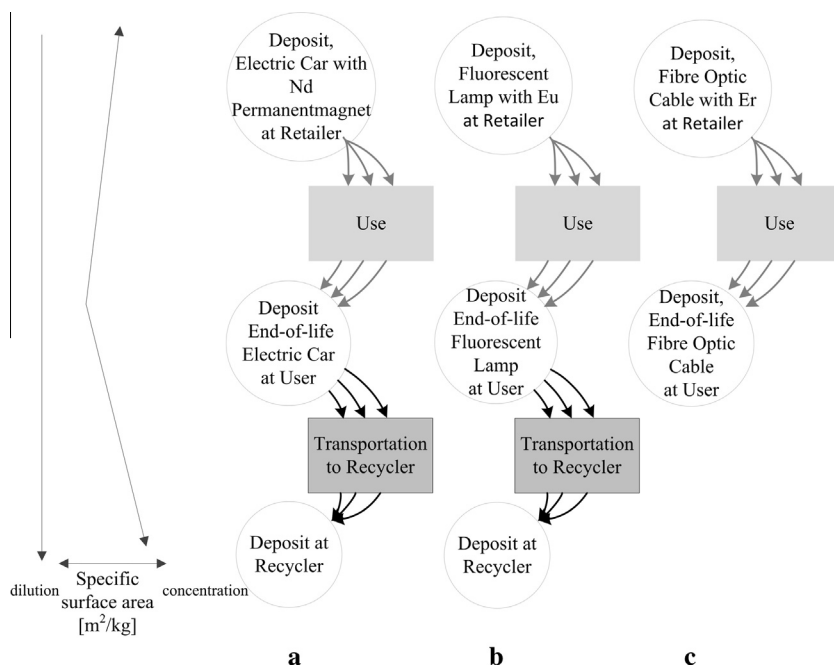


Fig. 3. Concentration – dilution profile for the three case studies addressed (a) electrical car with Neodymium–Iron–Boron permanent magnets; (b) fluorescent lamp with phosphors containing Europium; (c) underground fibres optic cable doped with Erbium.

Table 3

Characterisation of the “geological setting” for geogenic and anthropogenic deposits.

Criteria/deposit	Mt. Weld, Australia	Neodymium–Iron–Boron permanent magnet	Europium (Eu) phosphors	Erbium (Er) fibre optic cable
Location	Mined deposit with REE in Mt. Weld in Western Australia.	Deposit at recycler of electrical car with Neodymium–Iron–Boron permanent magnet in Switzerland.	Deposit at recycler of fluorescent lamp with Eu phosphors in Switzerland.	End-of-life deposit of fibre optic cable doped with Er in Switzerland.
Geological context	A steeply plunging cylindrical carbonatite complex enclosing REE, which intrudes the central part of the linear graben-like zone. This zone has been overprinted by greenschist facies ^a metamorphism in Yilgarn Craton, Western Australia.	>70 end-of-life vehicle (ELV) recycling sites (Fig. 4) (Blaser et al., 2012). The number of recycling business is increased in urban areas. They sort the vehicle into spare parts and scrap (Blaser et al., 2012).	Four recyclers (Fig. 4) under contract by an independent Swiss Light Recycling Foundation: SLRS (Empa, 2012). The recyclers separate the end-of-life fluorescent lamp into four fractions: aluminium-end-cap, glass chips glass-fraction and distilled phosphors, which last two fractions contain mercury (Hug and Renner, 2010).	Implemented along the road and train network until it reaches a building with elevated concentrations in urban areas and between cities. In urban areas the hotspots occur at roads, businesses hubs and public organisations.
Host rock	The carbonate has been leached and removed by groundwater activity, thus the relict igneous minerals concentrated. The remaining rock encloses phosphates, iron and manganese bearing oxides containing evaluated REE but also the radioactive elements uranium and thorium.	Electrical car motor hosts the Neodymium bearing permanent magnet (Du et al., 2015). The motor is placed at the back or front of a car. Within a motor the Nd can be concentrated at various positions, depending on the design of a motor.	Inside a fluorescent lamp, the Eu and mercury are hosted at elevated mass fractions within the phosphors. In the phosphors, the Eu is homogeneously distributed.	The fibre optic cable is part of underground pipelines and building connections that hosts the Er. It is protected with several layers of slipcovers to prevent cracking but enable bending. The quartz glass is doped with Er (Angerer et al., 2009).
REE mineralisation	The central lanthanide deposit contains in the carbonatite complex (9.88 Mt @ 10.7 weight-% rare earth oxides (REO), 0.85 weight-% Nd, 0.02 weight-% Eu, 0.001 weight-% Er, (Fig. 5). Very high-grade mass fractions of REO in the Regolith result from secondary monazite in polycrystalline aggregates.	By 2030, the Neodymium–Iron–Boron permanent magnet deposit is expected to contain Nd ₂ Fe ₁₄ B 2691t @ 27 weight-% Nd and 15,143t @ 27 weight-% Nd by 2050 (de Haan et al., 2013), (Fig. 5). The amount of magnet depends strongly on the application of the motor.	The distilled phosphors includes Eu as Eu ₂ O ₃ but also the REE: yttrium, lanthanum, cerium, gadolinium, terbium and mercury. In 2011, this deposit contained 22,287t @ 0.6 weight-% Eu (Schüler et al., 2011), (Fig. 5). In 2030, it is expected to contain 76,420t @ 0.6 weight-%.	In 2009, fibre optic cable deposit contained 15,551t (Müller et al., 2013) @ 0.01 weight-% Er (Hering, 2006), (Fig. 5). In 2030, it is expected to contain 95,000t @ 0.01 weight-% Er.
Age of mineralisation	The carbonatite intrusive was part of a local alkaline magmatic event about 2025 million years ago. This carbonate intrusive was concentrated by a Permian glaciation event, which allowed the surface of the rich carbonatite intrusion to be exposed for concentration. This event is understood to have occurred about 65.5 million years ago.	At the end of 2010, the first series of electrical cars with Neodymium–Iron–Boron permanent magnet were introduced into in the mass market. The breakthrough of one million electrical cars produced is estimated to be in 2017 (de Haan et al., 2013). It is estimated these deposits may increase in the future more than 700% (Alonso et al., 2012).	The fluorescent lamp with Eu has been patented in 1973 (Blasse and De Vries, 1973). The demand for Eu is expected to increase during the switch from high-volume halogen fluorescent lamp to compact fluorescent lamp (USDOE, 2011; Binnemans et al., 2013). It is expected that the volume of Eu deposits will increase in the future.	Fibre optic cable with Er was described in 1990 (Suzuki, 1990 in Yoneyama, 1994). The average mine life is expected to be 50 years (Müller et al., 2013) and an exponential application growth at least until 2030 (Angerer et al., 2009).
Current status	Advanced economic deposit including stockpiling of different grade ores in 2011. In 2012 temporary operating license enabled chemical separation in Malaysia to produce the REO (Machacek and Fold, 2014). The mine life is expected to be at least 20 years.	The motors of electrical cars are currently shredded by metallic machineries. The recovery of Neodymium–Iron–Boron permanent magnet is currently under research for reuse and recycling (Schüler et al., 2011). Additionally, there is yet no commercial recovery development (Binnemans et al., 2013).	Currently, the phosphors including Eu is disposed underground with the option for retrieval (Huber and Schaller, 2013). However, in September 2012, Europium recycling facilities commence its operation (Solvay, 2012).	Currently the fibre optic cable is implemented for its use and it is estimated that it is unlikely to develop any recycling by 2030 (Angerer et al., 2009).

^a Greenish rock that is formed under the lowest temperatures and pressure usually produced through regional metamorphism (Encyclopaedia Britannica, 2014).

For the three case studies investigated, the characterisation of the “geological setting” demonstrates that

- There are geogenic REE within Switzerland held as ores in the “host rock” but they will not be economically exploitable (Simoni, 2012) within a reasonable time frame.
- The total quantity of REE in the anthropogenic deposits in Switzerland is much smaller than in a geogenic deposit but with higher mass fraction of raw material, and therefore likely to be more economically viable (Fig. 4).

The quantity and mass fraction of REE within the investigated anthropogenic deposits of Switzerland and within one geogenic deposit Mt. Weld in Australia are,

- Neodymium: 2691t deposit Switzerland @ 27 weight-% and 9.88 Mt central lanthanide deposit Mt. Weld Australia @ 0.85 weight-%;
- Europium: 76,420t deposit Switzerland @ 0.6 weight-% and 9.88 Mt central lanthanide deposit Mt. Weld Australia @ 0.02 weight-%; and

- Erbium: 95,000t deposit Switzerland @ 0.01 weight-% and 9.88 Mt central lanthanide deposit Mt. Weld Australia @ 0.001 weight-%.

Furthermore, the anthropogenic deposits of Neodymium–Iron–Boron permanent magnets and fibre optic cable with Er (Angerer et al., 2009) are expected to grow for at least the next 20 years, which is more than the current estimate of 20 years mine life of the Mt. Weld geogenic deposit (Hoatson et al., 2011). Additionally, mining the REE held in these so-called “anthropogenic deposits” is likely to involve considerably fewer social and environmental impacts than the extraction from the present major mined, geogenic deposits (Alonso et al., 2012). These geogenic deposits often contain accumulations of radioactive thorium and uranium (Hoatson et al., 2011) (see Fig. 5).

Considering the high mass fractions, long mine life and fewer social and environmental impacts with the expected supply constraints of Nd (Roelich et al., 2014) and Eu (USDOE, 2011), which both have limited or no substitution options (Graedel et al., 2013), it is important to develop strategies and a common platform between mining of the geosphere and anthroposphere. Furthermore, for Neodymium–Iron–Boron permanent magnets, the results demonstrate that with the current recycling technology of metallic shredders Nd cannot be recovered (Widmer et al., 2015). Considering the high mass fractions, at present only the Er within the fibre optic cable in Switzerland can be considered as geochemically scarce. Since the Er fibre optic cable applications are expected to increase exponentially (Angerer et al., 2009), the Er will be distributed and consequently diluted further within Switzerland's ground and buildings until after 2030.

The characterisation of the “geological setting” of anthropogenic deposits was demanding. The criterion “host rock” can be valid for different levels of product components. For example, considering an electrical car with Neodymium–Iron–Boron permanent magnets, the “host rock” could apply to the electrical car and

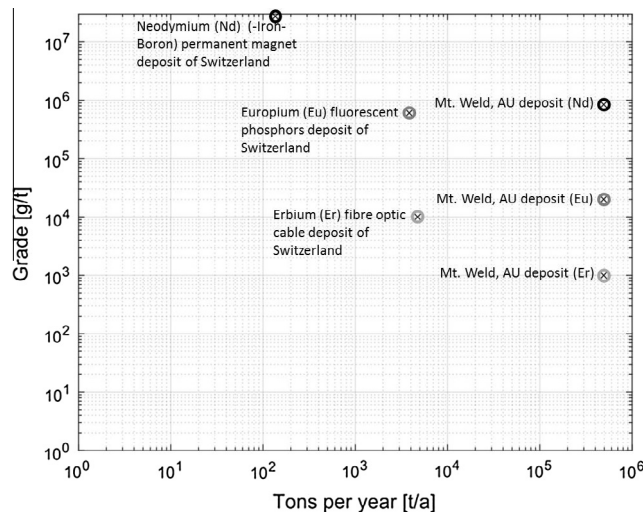


Fig. 5. Grade-tonnage plot of annual REE material resource flows from geogenic and anthropogenic deposits. Corresponding geogenic and anthropogenic deposits shown in the same grey scale (black: Nd case study, grey: Eu case study, light grey: Er case study).

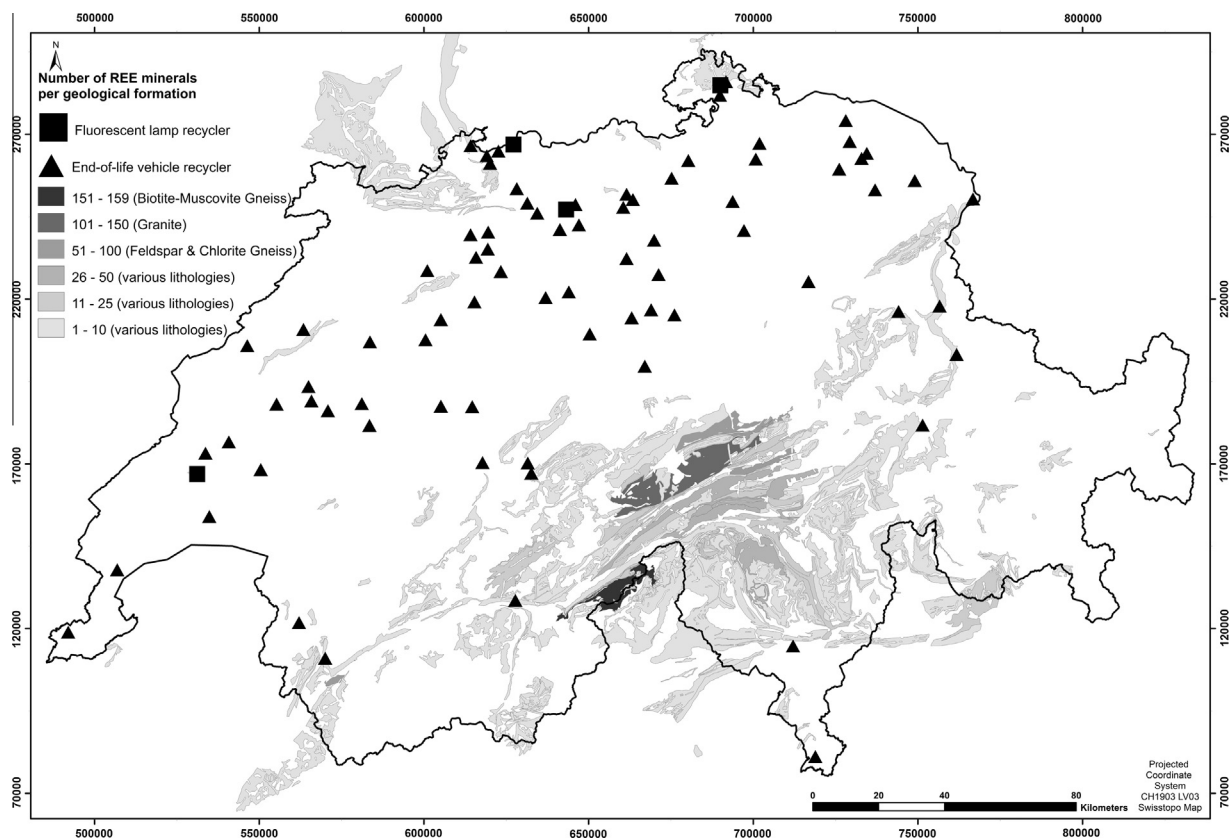


Fig. 4. Simplified illustration of the geogenic and anthropogenic REE deposits in Switzerland. The potential geogenic deposit includes the geological formations that have the highest REE mineral counts (grey nuances with rectangle legend) and the anthropogenic deposits of end-of-life vehicle recycler (Nd, triangles) and fluorescent lamp recycler (Eu, squares) (adapted from Simoni, 2012; SwisscomDirectories, 2012; Empa, 2012).

Table 4

Evaluation of “geological knowledge” of geogenic and anthropogenic deposits, adapted from UNFC (2010).

Criteria	Geogenic deposit Mt. Weld, Australia with REE	End-of-life of electrical car with Neodymium– Iron–Boron permanent magnet	End-of-life fluorescent lamp with Europium	End-of-life optic cable with Erbium
Category	G1	G3	G1	G4
Supporting explanation	Mining has commenced in for stockpiling in 2011 and separation in 2012.	The application is being introduced in the market, thus information of future scenarios including uncertainty is available. Research for recovery is currently being undertaken. No commercial recovery takes place yet.	Information on the future development of the deposit quantity is available. Recovery activities commenced in 2012.	Low information on the precise location of the quantity is available. Currently no research for the recovery is being undertaken.

also to the motor. In such a case, a bottom-up approach was applied. Accordingly, first the “REE mineralisation” was identified, i.e. Neodymium–Iron–Boron permanent magnet, followed by the resulting “host rock”, i.e. motor. To increase the accuracy of characterising the “host rock” or “mineralisation”, it is important to exchange transparent information through the entire “product cycle” from design via manufacturing to waste management. For instance, the implementation of a feedback loop from end-of-life to decision makers is limited (Fakhredin et al., 2013). Information on such matters is critical in determining a comprehensive understanding of “age of mineralisation”, which includes the future growth of a deposit formation. This, in turn is important for identifying the economic viability of a future mine (UNFC, 2010). Hence, key performance indicators are a crucial support for a practical implementation and should be physically-, economic- and environmentally-based as proposed by the UNEP (2013). Moreover, Winterstetter et al. (2015) concluded that future research is required to develop a standardised procedure for characterising any kind of geogenic and anthropogenic deposits. Additionally, it is crucial to develop a common platform for characterising and evaluating geogenic and anthropogenic deposits. Therefore, the characterisation of the “geological setting” and its evaluation of the “geological knowledge” (Table 4) lay a foundation.

Based on this foundation, the evaluation showed that, the Neodymium–Iron–Boron magnets and the fibre optic cables can be considered to be potential deposits for Nd (category G3) and Er, respectively (category G4). The deposit containing Eu is classified as a known deposit of category G1 like the geogenic deposit Mt. Weld. This is a first step in completing the level of proven resources for developing a mining of the anthroposphere mine, as described for mining of the geosphere (USDOE, 2011; Hoatson et al., 2011).

5. Conclusions and outlook

In this study, we have attempted to integrate a geological perspective and approaches into the characterisation and evaluation of anthropogenic metal deposits. Our approach allowed the identification of the most concentrated deposits along the anthropogenic cycle, their characterisation with regard to the “geological” setting, and the evaluation of the confidence level of the deposit quantities for three cases. Not least, the study was able to provide distinct characterisations for the three investigated REEs. However, the present framework is built on a simple representation of the reality, as e.g. raw material losses (for example REE in fibre optic cables left in the underground) are not represented. A possible next step would consist of further differentiating the processes and exploring how far correspondences between the geogenic and anthropogenic cycles can then still be established.

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References

- Alonso, E., Sherman, A.M., Wallington, T.J., Everson, M.P., Field, F.R., Roth, R., Kirchain, R.E., 2012. Evaluating rare earth element availability: a case with revolutionary demand from clean technologies. *Environ. Sci. Technol.* 46, 3406–3414. <http://dx.doi.org/10.1021/es203518d>.
- Angerer, G., Marscheider-Weidemann, F., Lüllmann, A., Erdmann, L., Scharp, M., Handke, V., Marwede, M., 2009. Raw Materials for Emerging Technologies. Fraunhofer ISI, Karlsruhe, ISBN: 9783816779575 3816779573.
- Árkai, P., Sassi, F.P., Desmons, J., 2003. 5. Very Low- to Low-Grade Metamorphic Rocks. British Geological Survey (BGS) Nottingham. <http://www.bgs.ac.uk/scmr/docs/papers/paper_5.pdf> (accessed February 2014).
- Arndt, N.T., Ganino, C., 2012. Metals and Society: An Introduction to Economic Geology. Springer, Berlin; New York.
- Berner, E.K., Berner, R.A., 2012. Global Environment : Water, Air, and Geochemical Cycles. Princeton University Press, Princeton, N.J.
- Binnemans, K., Jones, P.T., Blanpain, B., Van Gerven, T., Yang, Y., Walton, A., Buchert, M., 2013. Recycling of rare earths: a critical review. *J. Clean. Prod.* 51, 1–22. <http://dx.doi.org/10.1016/j.jclepro.2012.12.037>.
- Blaser, F., Widmer, R., Wäger, P., 2012. Application of Rare Technology Metals from Automobile Electricity in Switzerland. Swiss Federal Laboratories for Materials Testing and Research (Empa), Switzerland.
- Blasse, G., De Vries, J., 1973. Low-Pressure Mercury Vapour Discharge Lamp. <<http://www.google.ch/patents/US3748516>> (accessed August 2012).
- Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., Finnveden, G., 2006. Scenario types and techniques: towards a user's guide. *Futures* 38, 723–739. <http://dx.doi.org/10.1016/j.futures.2005.12.002>.
- Brunner, P.H., 2011. Urban mining – a contribution to reindustrializing the city. *J. Ind. Ecol.* 15, 339–341. <http://dx.doi.org/10.1111/j.1530-9290.2011.00345.x>.
- Curran, T., Williams, I.D., 2012. A zero waste vision for industrial networks in Europe. *J. Hazard. Mater.* 207–208, 3–7. <http://dx.doi.org/10.1016/j.jhazmat.2011.07.122>.
- de Haan, P.J., Zah, R., Althaus, H.-J., 2013. Chancen und Risiken der Elektromobilität in der Schweiz. vdf Hochschulvlg AG, Zürich. ISBN: 9783728134875 3728134872.
- Dill, H.G., 2010. The “chessboard” classification scheme of mineral deposits: mineralogy and geology from aluminum to zirconium. *Earth Sci. Rev.* 100, 1–420. <http://dx.doi.org/10.1016/j.earscirev.2009.10.011>.
- Du, X., Graedel, T.E., 2011. Global rare earth in-use stocks in NdFeB permanent magnets. *J. Ind. Ecol.* 15, 836–843. <http://dx.doi.org/10.1111/j.1530-9290.2011.00362.x>.
- Du, X., Restrepo, E., Widmer, R., Wäger, P., 2015. Quantifying the distribution of critical metals in conventional passenger vehicles using input-driven and output-driven approaches: a comparative study. *J. Mater. Cycles Waste Manage.* 1–11. <http://dx.doi.org/10.1007/s10163-015-0353-3>.
- Empa, 2012. Personal Communication with Heinz Böni Empa Lerchenfeldstrasse 5. 9014 St. Gallen, Switzerland.
- Encyclopaedia Britannica, 2014. Greenschist Facies. <<http://www.britannica.com/EBchecked/topic/377777/metamorphic-rock/80338/Greenschist-facies>> (accessed December 2014).
- Fakhredin, F., Bakker, C.A., Huisman, J., Geraedts, J.M.P., 2013. Five perspectives on design for end of life: highlights of a literature review. In: s.n. (Ed.), Proceedings of the EcoDesign 2013 International Symposium, pp. 1–8.

- Graedel, T.E., Allwood, J., Birat, J.-P., Buchert, M., Hagelüken, C., Reck, B.K., Sibley, S.F., Sonnemann, G., 2011. What do we know about metal recycling rates? *J. Ind. Ecol.* 15, 355–366. <http://dx.doi.org/10.1111/j.1530-9290.2011.00342.x>.
- Graedel, T.E., Barr, R., Chandler, C., Chase, T., Choi, J., Christoffersen, L., Friedlander, E., Henly, C., Jun, C., Nassar, N.T., Schechner, D., Warren, S., Yang, M., Zhu, C., 2012. Methodology of metal criticality determination. *Environ. Sci. Technol.* 46, 1063–1070. <http://dx.doi.org/10.1021/es203534z>.
- Graedel, T.E., Harper, E.M., Nassar, N.T., Reck, B.K., 2013. On the materials basis of modern society. *PNAS* 201312752. <http://dx.doi.org/10.1073/pnas.1312752110>.
- Hamblin, W.K., Christiansen, E.H., 2004. *Earth's Dynamic Systems*. Prentice Hall, Pearson Education, Upper Saddle River, N.J., ISBN: 0131420666 9780131420663.
- Hering, E., 2006. *Photonik: Grundlagen, Technologie und Anwendung*. Springer, Berlin, ISBN: 3540234381 9783540234388.
- Hoatson, D.M., Jaireth, S., Miezitis, Y., 2011. *The Major Rare-Earth-Element Deposits of Australia: Geological Setting, Exploration, and Resources*. Geoscience Australia, Canberra, ISBN 9781921954023.
- Huber, I., Schaller, S., 2013. *Annual Report 2012 of Swiss Light Recycling Foundation*. Bern.
- Hug, E., Renner, N., 2010. *Study on Mercury Concentrations in Fractions of Fluorescent Lamps Processing*. Roos + Partner AG, Luzern.
- Izatt, R.M., Izatt, S.R., Bruening, R.L., Izatt, N.E., Moyer, B.A., 2014. Challenges to achievement of metal sustainability in our high-tech society. *Chem. Soc. Rev.* 43, 2451–2475. <http://dx.doi.org/10.1039/C3CS60440C>.
- Jabareen, Y.R., 2009. Building a conceptual framework: philosophy, definitions, and procedure. *Int. J. Qual. Methods* 8, 49–62, ISBN: 1609-4069.
- Kornprobst, J., 2002. *Metamorphic Rocks and their Geodynamic Significance: A Petrological Handbook*. Kluwer Academic Publishers, Boston, ISBN: 1402008937 9781402008931.
- Lederer, J., Laner, D., Fellner, J., 2014. A framework for the evaluation of anthropogenic resources: the case study of phosphorus stocks in Austria. *J. Clean. Prod.* <http://dx.doi.org/10.1016/j.jclepro.2014.05.078.w>.
- Long, K.R., DeYoung, J.H., Ludington, S.D., 1998. *Database of Significant Deposits of Gold, Silver, Copper, Lead and Zinc in the United States. Part A: Database Description and Analysis*. US Geological Survey Open File Report. <<http://wrgis.wr.usgs.gov/open-file/of98-206/of98-206a.pdf>> (accessed 15.05.12).
- Machacek, E., Fold, N., 2014. Alternative value chains for rare earths: the Anglo-deposit developers. *Resour. Policy* 42, 53–64. <http://dx.doi.org/10.1016/j.resourpol.2014.09.003>.
- McLaughlin, D.H., 1956. Man's selective attack on ores and minerals. In: *Man's Role in Changing the Face of the Earth*. University of Chicago Press, Chicago, pp. 567–583.
- Mudd, G.M., 2009. *The Sustainability of Mining in Australia Key Production Trends and Environmental Implications*. Monash University, Department of Civil Engineering.
- Müller, E., Widmer, R., Coroama, V.C., Orthlieb, A., 2013. Material and energy flows and environmental impacts of the internet in Switzerland. *J. Ind. Ecol.* 17, 814–826. <http://dx.doi.org/10.1111/jiec.12056>.
- National Research Council, 2008. *Minerals, Critical Minerals, and the U.S. Economy*. National Academies Press, Washington, D.C., ISBN: 0309112826 9780309112826.
- Nickel, E.H., 2005. Definition and classification. In: *Encyclopedia of Geology*. Elsevier, pp. 498–503, ISBN: 978-0-12-369396-9.
- Oswald, I., Reller, A., 2011. E-waste: a story of trashing, trading, and valuable resources. *GAIA – Ecol. Perspect. Sci. Soc.* 20, 41–47.
- Pohl, W., 2011. *Economic Geology: Principles and Practice: Metals, Minerals, Coal and Hydrocarbons – Introduction to Formation and Sustainable Exploitation of Mineral Deposits*. Wiley-Blackwell, Chichester, West Sussex; Hoboken, NJ, ISBN: 9781444336627.
- Roelich, K., Dawson, D.A., Purnell, P., Knoeri, C., Revell, R., Busch, J., Steinberger, J.K., 2014. Assessing the dynamic material criticality of infrastructure transitions: a case of low carbon electricity. *Appl. Energy* 123, 378–386. <http://dx.doi.org/10.1016/j.apenergy.2014.01.052>.
- Schüler, D., Buchert, M., Liu, R., Ditttrich, S., Merz, C., 2011. *Study on Rare Earths and their Recycling*. Darmstadt, Germany.
- Simoni, M.U., 2012. *Rare Earth Elements in Switzerland, Conceptualisation of a Rare Earth Element (REE) Occurrence Knowledge Base as Part of the Swiss Geotechnical Commission Resource Monitoring System*. ETH, Zurich.
- Skinner, B.J., 1979. Earth resources. *Proc. Natl. Acad. Sci.* 76, 4212. <http://dx.doi.org/10.1073/pnas.76.9.4212>.
- Solvay, 2012. *Solvay Launches Its Rare Earth Recycling Activity in France*. Solvay, Brussels.
- Spera, F.J., 2001. Physical properties of magmas. In: Sigurdsson, H., Houghton, B.F. (Eds.), *Encyclopedia of Volcanoes*. Academic Press, pp. 171–190, ISBN: 9780126431407.
- Suzuki, K., 1990. Optical fibre amplifier module. *J. Inst. Electron., Inform. Commun. Eng.* 74, 221–224.
- SwisscomDirectories, 2012. *Car Recycling Locations*. <<http://yellow.local.ch/de/q/Autoverw.html?rid=g79h&where=>>> (accessed September 2012).
- Umweltbundesamt (UBA), 2012. *Glossar zum Ressourcenschutz*. Umweltbundesamt, Dessau-Rosslau, Deutschland. <<http://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/4242.pdf>> (accessed July 2012).
- United Nations Environment Programme (UNEP), 2010. *Assessing the Environmental Impacts of Consumption and Production: Priority Products and Materials*. United Nations, Nairobi.
- United Nations Environment Programme (UNEP), 2011. *Metal Stocks in Society: Scientific Synthesis*. United Nations, Nairobi.
- United Nations Environment Programme (UNEP), 2013. *Metal Recycling: Opportunities, Limits, Infrastructure*. United Nations, Nairobi.
- United Nations Economic Commission for Europe (UNEC), 2010. *United Nations Framework Classification for Fossil Energy and Mineral Resources: 2009*. United Nations, New York.
- U.S. Department of Energy (USDOE), 2011. *Critical Material Strategy*. US Department of Energy, Washington.
- Wäger, P., 2011a. *Scarce Metals – Applications, Supply Risks and Need for Action*. vol. 104, Politeia, pp. 57–66. ISSN 1128-2401.
- Wäger, P., Widmer, R., Stamp, A., 2011b. *Scarce Technology Metals – Applications, Criticalities and Intervention Options*. Swiss Federal Laboratories for Materials Testing and Research (Empa), Switzerland.
- Wäger, P.A., Lang, D.J., Wittmer, D., Bleischwitz, R., Hagelüken, C., 2012. Towards a more sustainable use of scarce metals: a review of intervention options along the metals life cycle. *GAIA – Ecol. Perspect. Sci. Soc.* 21, 300–309.
- Wäger, P.A., Hirschier, R., Widmer, R., 2015. The material basis of ICT. In: Hilty, L.M., Aebischer, B. (Eds.), *ICT Innovations for Sustainability, Advances in Intelligent Systems and Computing*. Springer International Publishing, pp. 209–221.
- Widmer, R., Du, X., Haag, O., Restrepo, E., Wäger, P., 2015. Scarce metals in conventional passenger vehicles and end-of-life vehicle shredder output. *Environ. Sci. Technol.* <http://dx.doi.org/10.1021/es505415d>.
- Wills, B.A., Napier-Munn, T., Wills, B.A., Kruttschnitt, Julius, 2006. *Wills' Mineral Processing Technology an Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery*. Elsevier/BH, Amsterdam, Boston; London, ISBN: 9780750644501 0750644508.
- Winterstetter, A., Laner, D., Rechberger, H., Fellner, J., 2015. Framework for the evaluation of anthropogenic resources: a landfill mining case study – resource or reserve? *Resour. Conserv. Recycl.* 96, 19–30. <http://dx.doi.org/10.1016/j.resconrec.2015.01.004>.
- Yoneyama, K., 1994. Optical Fibre Amplifier Circuit Comprising a Control Circuit for Controlling a Plurality of Excitation Light Sources. <<http://www.google.ch/patents?ei=K-k0UI-tAY2LhQeg2oDgQ&hl=de&id=WREjAAAAEBAJ&dq=%22History%22+AND+Erbium+AND+%22optic+cable%22&q=Erbium#v=snippet&q=Erbium&f=false>> (accessed August 2012).
- Zimmermann, T., Gößling-Reisemann, S., 2013. Critical materials and dissipative losses: a screening study. *Sci. Total Environ.* 461–462, 774–780. <http://dx.doi.org/10.1016/j.scitotenv.2013.05.040>.