Waste Management xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

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

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ARTICLE INFO

*Article history:*
Available online xxxx

*Keywords:*
Geogenic deposit
Anthropogenic deposit
Geological classification
Resource classification
Rare earth element
Waste electrical and electronic equipment

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, Switzerland). 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 (UNFC) 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 its potential and limitations is required.



## 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 ores[1] 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 scarce[2] 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; $Eu_2O_3$, europium oxide; $Nd_2Fe_{14}B$, 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).

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

http://dx.doi.org/10.1016/j.wasman.2015.03.038
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(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 dissipated[3] (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 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 mining,

**Table 1**
Summary of the category geological knowledge of the UNFC 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 |

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 resynthesized. 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).