Evaluating Rare Earth Element Deposits

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SUMMARY

There has been a significant growth in exploration activity for rare earth element ("REE") deposits since the firming of prices began in 2003. Numerous deposits have been subject to detailed evaluation, though during this period only one new western-world operation at Mt Weld, Western Australia is in production. One older operation at Mountain Pass, USA, re-opened in 2012 but, due to low rare earth prices, shut down in 2015. Chinese production dominates the world rare earth industry, accounting for approximately 80 - 85% of the world's annual production of ~125,000 tonnes, from numerous deposits in five provinces. It is reported that in excess of approximately 45,000 tonnes per year of total Chinese production is illegal.

Resource estimation of REE presents no special difficulties provided care is taken to avoid over-domaining and definition of domains based on rigid grade-based criteria that are close to the lower reporting cut-off grades. These are likely to result in overstated grades and understated tonnages. Primary and supergene copper resources are natural analogies for the estimation of non-alluvial REE deposits.

Rare earth deposits are typically hosted by carbonatite, alkali- intrusives and supergene-enriched mineralisation developed on REE-enhanced substrate. An important type of heavy-enriched REE mineralisation, first recognised in southern China, has been described as an Ionic Adsorption Deposit ("IAD") and typically is hosted by secondary clays. REE in these deposits are relatively easy to recover using low cost leaching techniques based on lixiviants or eluants consisting of simple electrolytes such as ammonium sulphate and sodium chloride. Current practice in China is to use in-situ leaching ("ISL"), vat or tank leaching or heap leaching to extract the REE.

The Mt Weld deposit, in Western Australia, was put into production after a 30 year exploration history and was only successfully drilled after 1991 once the regolith that hosts the mineralisation had been de-watered. This enabled the recovery of samples that had not suffered from the loss of fines. Its first reported resource estimates in 2002 achieved close reconciliations within a few percent of actual mined material.

In general, cut-off grades used to report resources for many REE deposits of a similar style are unrealistically low and significantly less than those used by the only two recent Western operations. These cut-offs result from over-optimistic assumptions mainly relating to the use of:

- notional values applied to all the REE
- projected metal prices from periods of unstable price hikes and
- unrealistic low costs associated with production and sales.

Key words: rare earth elements, ionic clays, resource estimation, Mt Weld, domaining, cut-off grades.

Introduction

The rare earth elements are usually defined as the 14 lanthanides, from lanthanum (atomic number "Z"= 57) to lutetium with Z = 71 plus yttrium (Z= 39) as shown in Table 1. The prevailing industry practice is to exclude scandium even though it may be included in some chemistry texts. By virtue of its instability, promethium (Pm, Z=61) effectively does not occur in nature. Y has a similar concentration to La and Nd though behaves geochemically like a HREE (eg Dy).

The term rare earth element is commonly abbreviated to "REE" and their oxides to "REO". To avoid confusion, it is wise in reporting REE resources to define whether yttrium is included and to report REO values rather than REE. In this paper, REO includes yttrium oxide and TREO refers to the total sum of the REO.

A commonly used subdivision of the REE consists of the light REE ("LREE") or LREO and the heavy REE ("HREE") or HREO. Common industry usage, which is quite arbitrary, is to define the LREE as consisting of La, Ce, Pr, Nd and Sm and the HREE as Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu plus Y. This grouping may vary with the LREE extended to include Eu and even Gd. The grouping of Sm, Eu and Gd may be referred to as "SEG" and/or middle or medium REE ("MREE"). Nd and Pr have been termed didymium though the mixed oxides of Nd and Pr are now more commonly referred to as "NdPr" in the proportion of approximately 78:22. "Mischmetal" refers to an alloy of various REE such as Ce, La, Nd and Pr.

Table 1. Rare Earth Elements

Element	Atomic Number	Symbol	Atomic Weight	Upper Crustal Abundance (ppm)
Yttrium	39	Y	88.91	22
Lanthanum	57	La	138.91	30
Cerium	58	Ce	140.12	64
Praseodymium	59	Pr	140.91	7.1
Neodymium	60	Nd	144.24	26
Samarium	62	Sm	150.36	4.5
Europium	63	Eu	151.96	0.88
Gadolinium	64	Gd	157.25	3.8
Terbium	65	Tb	158.93	0.64
Dysprosium	66	Dy	162.50	3.5
Holmium	67	Ho	164.93	0.8
Erbium	68	Er	167.26	2.3
Thulium	69	Tm	169.93	0.33
Ytterbium	70	Yb	173.04	2.2
Lutetium	71	Lu	174.97	0.32

(Crustal abundances from Castor and Hedrick, 2006)

REE analyses are usually received in reports from the laboratory as parts per million (ppm) for the individual elements. REO concentrations are then calculated by conversion factors based on the appropriate oxide formulae. REE typically occur in nature in the 3+ state with Eu also occurring in the 2+ state and Ce in the 4+ state. REO pricing is not uniformly based on the 3+ state with mixed oxide formulae for Pr (Pr_6O_{11}) and Tb (Tb_4O_7) and the oxidised state of Ce (CeO_2). Many resource statements mistakenly use a constant conversion based on REE_2O_3.

The gradual firming of prices since 2003 with a spike in 2011 has resulted in considerable exploration activity with numerous deposits having been subjected to exploration and advanced evaluation. This paper provides a background to rare earths and identifies some key issues associated with the evaluation and resource estimation of typical deposits.

Geology and Production

Historically, the REE, along with thorium (Th), were produced mainly from monazite [(Ce-La-Y, Th) PO_4] as by-products from the mineral sands industry (Chakhmouradian and Wall, 2012a). An important source of the world's rare earths' production commenced when the Mountain Pass carbonatite bastnaesite [(Ce-La)CO_3F] operation in California started in the early 1950s. Between 1965 and 1995 it satisfied most of the world's REE consumption. In 2002 Mountain Pass closed due to environmental issues associated with thorium and radon and also low REE prices. Operations resumed in 2012 with mid-2013 production set at approximately 19,000 short tons of TREO per annum with a capacity for 40,000 short tons TREO. Proven and Probable Ore Reserves are stated to be 18.4 million short tons at 7.98% TREO based on a lower cut-off grade of 5.0% (Molycorp, 2012). Unfortunately, the mine closed again in 2015.

In the mid-1980s, China started significant production of REE and since 1990 became the dominant world producer. Total Chinese production is thought to be approximately 105,000 tonnes per year ("tpa") TREO (USGS, 2016) with world production totalling approximately 125,000 tonnes. However, one commentator stated that for China in 2016 there was, in addition to 105,000 tonnes of production "to quota" "at least 150,000t of unlawful production" which considerably exceeds figures of approximately 40% of Chinese production being "illegal (Argus, 2017).

The Chinese Bayan Obo deposit is the main world producer of LREE which are dominantly hosted in bastnaesite and monazite, and lesser fluoro-carbonates, within a carbonatite-related hydrothermally replaced dolomitic marble. Niobium (Nb) is a valuable by-product. Tonnages are reported to be 48Mt at 6% TREO and 2.2 million tonnes ("Mt") at 0.13% Nb (Kynicky, et al, 2012.

Since the early 1970s, lateritic deposits, generally 8-10 metres ("m") thick, in southern China have been recognised as being enriched in HREE and constitute an easily recoverable resource (Kynicky, et al, 2012; Chi and Tian, 2008). Various terms have been used to describe this style of mineralisation including "ionic clays", "elution-deposited" ore and "ion-adsorbed" (Chi and Tian, 2008). These REE are derived from secondary processes and are loosely bound via adsorption processes within clay minerals. Although these ores are low grade (eg 0.05-0.2% REO) they are near-surface and have low extraction and processing costs.

Reporting of resource tonnages of this style of REE mineralisation is somewhat ambiguous, with 10Mt suggested as a guide (Kynicky et al, 2012) though Chi and Tian (2012) suggest that "prospective reserves" in Southern China amount to 50Mt

with quoted grades between 0.12-0.19% REO consisting of 57-92% REO in the ionic form (Chi and Tian, 2012). This style of mineralisation has been regarded as unique (Chi and Tian, 2008, p 2) though, as the Tantalus project in Madagascar and the Serra Verde project in Brazil demonstrate, it is likely that similar deposits exist elsewhere.

It is likely that IADs have not been the focus of detailed exploration. One example found by the first author is illustrated in Figure 1 which shows chondrite normalised values for 10 REE within three samples from a tholeiitic pillow lava (Hellman, 1979). Chondrite normalisation is used in reference to rare earths and other elements to smooth out the variable concentrations that arise from the "Oddo-Harkins" effect whereby elements with even atomic numbers above five are more stable and, therefore, more concentrated in the universe, than neighbouring elements in the periodic table with higher odd atomic numbers.
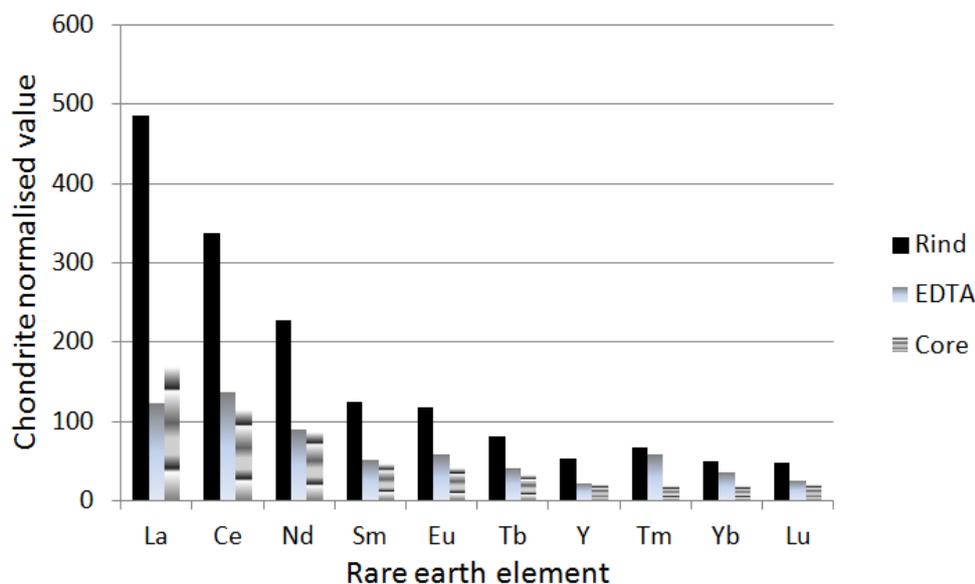

Figure 1. Effect of a chelating agent on loosely bound REE, pillow lava.

This example illustrates the chondrite normalised (Haskin et al, 1968) REE concentrations of the rind and core of a pillow lava compared with the residual concentration after elution with a chelating agent (2% EDTA, using the methods of Roaldset, 1973). These relationships are similar to those described for the southern Chinese ionic clay deposits. In the case of the pillow rind it was suggested (Hellman and Henderson, 1977) that the enrichment in the REE arose due to adsorption processes on layer silicates during seafloor weathering processes. The loosely bound nature of the REE is demonstrated by the effective stripping by EDTA of 63% of the LREE and 48% of the HREE from the rind.

Given that the REE have a demonstrated geochemical mobility (Hellman et al, 1977), exploration targets for secondary rare earth deposits similar to the Chinese ionic clays should be considered in proximity to naturally REE-enriched sources such as alkaline volcanic and intrusive rocks. The Kundybai district in north-west Kazakhstan is possibly a good example of a low grade secondary relatively soluble churchite-dominated HREO deposit (NCCPMRMRK, 2014).

The Tantalus project area on the Ampasindava Peninsula in Madagascar is an emerging example of the ion adsorption clay-type of rare earth mineralisation found in southern China. Rare earths are enriched in the upper weathered regolith horizons that overlie alkaline intrusives and volcanics and their related veins. Data from 4,412 pits and 359 drill holes were used in 2014 to define Measured, Indicated and Inferred Resources of 628Mt ("Mt" – million tonnes) grading 895 ppm TREO. This estimate is based on a variable cut-off grade between 300 and 500 ppm depending on topography (see SGS, 2014 for details). Preliminary testwork has indicated that either in-situ leaching or heap leaching could potentially be viable extraction methods.

Production of REO from other sources such as Russia, India, Brazil and Malaysia is thought to be not more than approximately 5,000 tpa (Lynas, 2014; Chakhmouradian and Wall, 2012b, p 338). Global demand is approximately 125,000 tonnes REO of which ~65% is consumed by China, ~15% by Japan, ~10% by USA, ~8% by EU and ~4% by others (Arafura, 2014; Lynas, 2014). A total market of 200,000 tonnes TREO is forecast for 2020 (Arafura, 2014).

Resources and Reserves

Unsurprisingly, from 2003, with the firming of rare earth prices, especially since 2009, there are numerous deposits that have been subject to advanced evaluation with reporting of Resource Estimates and Ore Reserves. The considerable variation in grades from various deposits is illustrated in Figure 2. Several of the lower grade deposits plotted in Figure 2 are of the IAD and alluvial type with the ability to sustain very low cut-off grades. It is clear that, if the cut-off grades used for Mt Weld and

Mountain Pass are applied to most of the other primary rare earth resources, there are very few with reasonable chances of economic viability based on prevailing rare earth prices. This, however, does not take into account the possible favourable metallurgical behaviour of particular mineralogies (eg churchite) which may result in low processing costs.

Caution is required in using published tonnage and grade figures from non-Western sources. The Western world largely uses carefully defined terms for Mineral Resources and Ore Reserves that should include a stated cut-off grade(s).
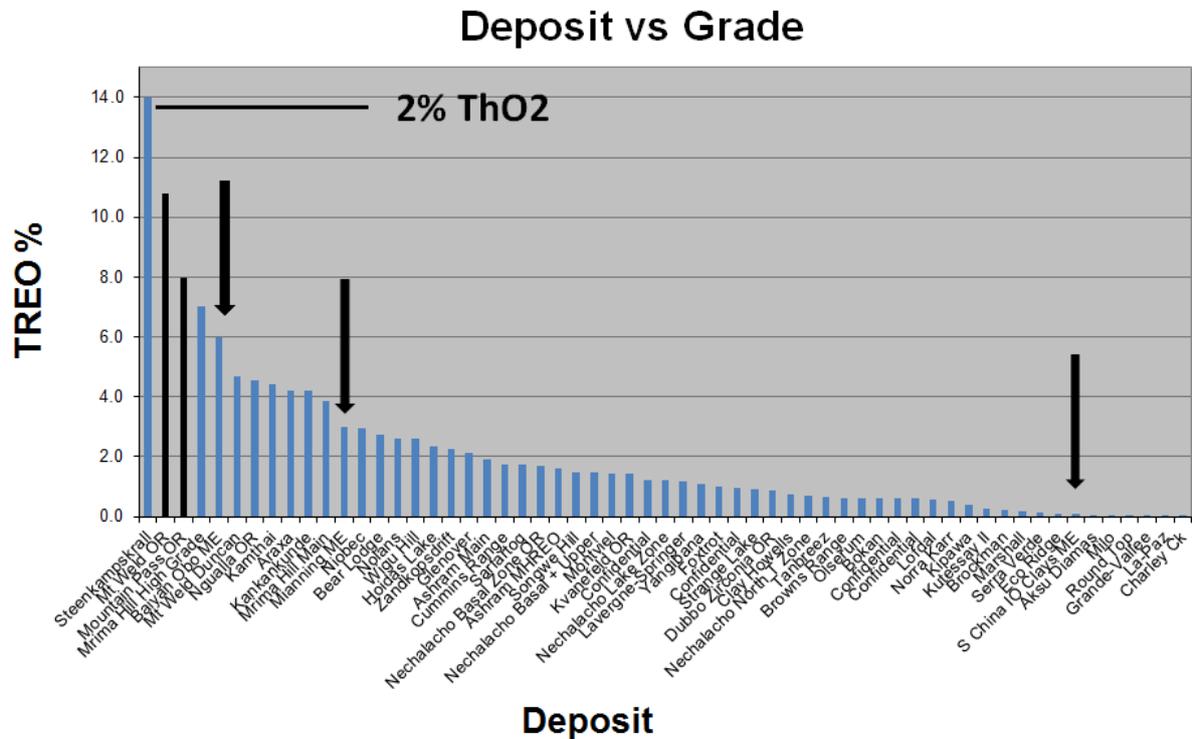

Figure 2. Rare earth deposit grades.
(Solid bars indicate Mt Weld and Mountain Pass and arrows mark Chinese deposits which include one data point for the lower grade Ionic Clay deposits, the high Th from the Steenkamskrall underground historic mine is highlighted)

Assaying

The assay method of choice is typically ICP-MS based on an alkali fusion followed by acid dissolution. Alkali fusion is the preferred primary digestion step in order to ensure "total" results. Extra elements of interest such as Hf, Nb, Sn, Ta, Th, U, W and Zr in addition to the REE may be obtained for an incremental cost. Some laboratories offer "REE packages" that include these elements. Concentrations that report in excess of the quoted maximum range will require re-assay by a more appropriate method. Depending on the style of mineralisation, consideration should be given to assaying Fe, Mn, P and S which are generally determined by ICP-OES.

Complete packages of major, minor, trace and REE are offered by commercial laboratories and have the advantage of providing the ability to characterise the geochemistry of various rock and ore-types. Additionally, such packages are useful when projects reach the stage when measures of acid-consumption and acid-generation may be required as part of the waste-rock and ore characterisation. Metallurgical processing and environmental studies may also benefit from access to multi-element information. Assay techniques that do not achieve complete dissolutions of the matrix should be avoided for resource delineation though they may be appropriate for exploration subject to geochemical orientation studies. It is likely that multi-acid techniques achieve only variable extraction efficiencies unless the REE concentration is controlled by a soluble REE phase.

Older incomplete analyses based on XRF should be verified by re-sampling the pulp residues and re-assaying to achieve better lower limits of detection and to provide actual measurements rather than regressed values.

Instrumental neutron activation analysis (INAA) is a largely matrix-free technique that does not require dissolution by acids. High levels of LREE to >50% La are suitable for INAA although high levels of MREE and HREE are an issue because of the high neutron capture cross section of Gd in particular, and to a lesser extent Sm, Eu and Dy causing self-shielding (Waldron, pers comm). However, INAA of Gd <~3000 – 5000ppm may be possible though the prospective INAA laboratory should be consulted before any samples are submitted to ensure that INAA is suitable for the anticipated REE levels. INAA should be considered as an excellent check-assay method.

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Quality Control (QA/QC)

Chondrite-normalised graphs are useful tools for identifying assaying issues in addition to the usual QA/QC procedures that should involve blind relevant standards, coarse and fine blanks and check assays at a second laboratory. The geochemical similarity of the REE results in high correlation coefficients and scatter plots defining near-perfect straight lines. However, it can be difficult to efficiently examine thousands of assay results for the 15 REE for internal consistency. The factors of Sun and McDonough (1989) have been used for the example in Figure 2 which clearly shows some internally anomalous elevated Eu and Gd. The focus is to identify particular REE that display aberrant behaviour which can then be referred to the laboratory for checking. Positive and negative anomalies for Ce and Eu may be expected in nature due to their variable oxidation states.

The absolute abundances are not critical but rather the relationships within the REE. In this example, Tb and Tm show suspicious elevations compared to neighbouring REE and, as expected, there is an obvious decline in precision towards lower concentrations.
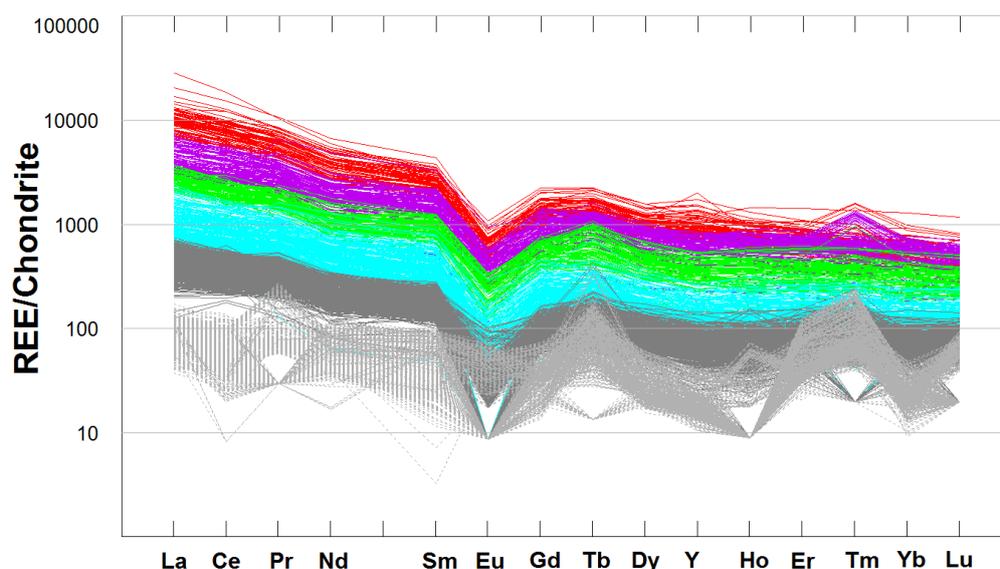

Figure 2. Chondrite-normalised graph of alkaline intrusive-hosted REE deposit.
(Colours highlight various TREO% ranges: >1%, 1-0.5%, 0.5-0.3%, 0.3-0.1%, 0.1 – 0.05% & <0.05%)

Mineralogy and Processing

The early understanding of the phase distribution of the REE is recommended. This can commence with a low-cost mineralogical and petrological study with the aim of identifying the REE-controlling phases and their distribution. Delineation of ore-types such as those dominated by monazite, bastnaesite or eudialyte will assist early metallurgical testing. Rare earth minerals have highly variable metallurgical responses as illustrated in Table 2 (courtesy of C Griffith, ANSTO).

Table 2. Major REE Minerals and Leaching Characteristics

Mineral Groups	Leaching Conditions
Monazite xenotime/churchite	Aggressive conditions - caustic or H_2SO_4
Apatite	Variable - leach+bake, leach with HNO_3
Eudialyte, bastnaesite, ionic clays	Atmospheric leach - mildly acidic, low temperature
Uranium processing	Atmospheric leach - mildly acidic, oxidant required
Columbite/tantalite	Aggressive conditions - very acidic, HF-based
Zircon	Aggressive conditions - chlorination

Even within the major mineral groups there may be significant variation in chemistry and, therefore, in processing response. The name "monazite" encompasses of a number of members including Ce, La, Nd, Sm and Gd-dominant varieties. Churchite, the hydrated yttrium phosphate, may have Nd, Dy and Er-rich varieties. Russian explorers have identified low grade churchite deposits (eg < 0.05% TREO) that are claimed to be easily upgradable by gravity and also soluble in acid which suggests that it is difficult to generalise regarding leaching conditions.

An accurate mineralogical assessment is required to guide sensible ongoing processing test work. The size and density of REE-phases will provide guidance relevant to physical beneficiation and the understanding of the behaviour of possible radio-nuclides. The possible presence of minerals such as zircon will help determine whether Zr may be produced as a discrete by-product. The presence of complex minerals containing a mixture of REE, Ta and Zr may suggest that priority should be placed on zones with simpler mineralogy. It is likely that a specific process will be required for a specific ore-type and that previously established processes for, say, bastnaesite or monazite may not be relevant.

The use of automated microprobe scanners with the ability to provide phase distributions of REE, Ta, Zr, Th and U will considerably aid the understanding of the potential processing options. For example, it may be possible for a relatively acid-soluble churchite deposit grading 0.2% TREO that is amenable to simple gravity upgrade, to be potentially more valuable than a fine-grained monazite deposit grading 5%.

Density

Obtaining a sufficient number of density measurements is especially important in deposits affected by significant weathering. Deposits such as Mt Weld and Ngualla have had supergene enrichment of the rare earths resulting in the host material having considerably lower densities than the primary mineralisation. In the case of Mt Weld, densities of 1.6 - 1.8 t/m^3 were used for the supergene mineralisation in contrast to the value of approximately 2.9 t/m3 for the underlying relatively un-mineralised carbonatite.

The critical part of density determinations is to ensure that the temperature and duration of drying is the same as that for the assaying preparation. Supergene material with high concentrations of layer-silicates and hydroxylated phases may require 12 hours drying.

Appropriate methods for the estimation of densities in a resource block model require far more determinations than are usually obtained. Density should be estimated as a variable and in a similar way to assay grades. This requires quantified geological logging of oxidation preferably on a consistent numerical scale, to ensure that zones of fresh material can be distinguished from partially and totally oxidised zones.

Resource Estimation

There are no special issues relating to the mechanics of the estimation of rare earth elements which appear similar in mineralisation style to primary and supergene enriched copper deposits. A typical process starts with the estimation of TREO along with LREO and HREO to provide an indication of the ratio of HREO to TREO. By-products with possible value or relevance such as Nb_2O_5, Ta_2O_5, ZrO_2 and P_2O_5 should be estimated but not reported unless there is evidence that they will add value. Deleterious elements such as Th and U should be estimated, reported and discussed. Understanding their deportment and distribution should be a priority.

There are many resource estimation issues that are not confined to estimation of REE. The use of an inadequate minimum number of samples is widespread. Blocks classified as Measured or Indicated usually require a minimum of approximately 12 relevant samples within a realistic search distance. In an open pit context, a composite that represents a length of approximately half the bench height is appropriate. Estimates based on less than eight samples or from just one drill hole will result in high risk results. Examples of Measured and Indicated estimates based on only four data points can be found.

Domaining based on the lower cut-off grade invariably results in an over-statement of grade and under-statement of tonnage. An examination of such over-domained models shows imposed continuities that are unrecognised in the natural world. Figure 3 illustrates an example of this approach for tungsten. In this case an artificial high-grade block population has been generated by selecting higher grade samples to estimate into a higher grade domain.

Over-domaining is often a consequence of an approach of "join the dots" whereby individual intercepts are made to join each other from section to section resulting in visually impressive multi-coloured wire-framed shapes that have no basis in reality and have no relevance to the scale of potential mining.

The use of small blocks that are considerably smaller than the drill spacing is often a consequence of over-domaining. Block sizes to less than approximately 1/2 to 1/3 of the drill-hole spacing are, in general, unsuitable for Ordinary Kriging and may result in considerable over-smoothing. This has been recognized for a long time (Vann and Guibal, 1988). Alternative approaches such as Multi Indicator Kriging (MIK) or Uniform Conditioning (UC) estimate distributions of grades of selective mining units (SMUs) within larger panels. A more recent application of UC, localized (multivariate) uniform conditioning (LUC, LMUC), provides results at the SMU scale (Abzalov, et al, 2006; Assibey-Bonsu, et al, 2014).

The use of search distances that significantly exceed the drill spacing will result in impressive tonnages that invariably disappear with more drilling though may be useful in terms of providing an indication of potential tonnages, though not resources, for drill planning.
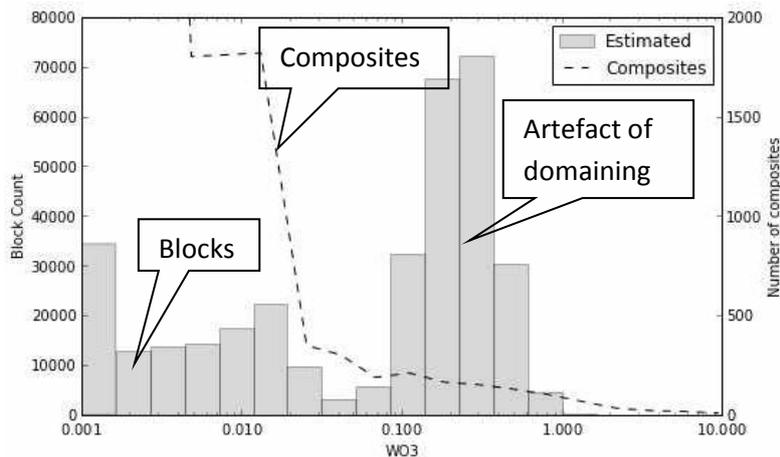
Figure 3. Conflict between populations of blocks and composites due to over-domaining
(Left hand Y-axis is the block count and the right hand Y-axis is the number of underlying composites upon which the estimate is based. The X-axis shows the grade of the variable being estimated (in this case WO₃). Kindly contributed by Mr R Osborn, H&S Consultants).

Appropriate cut-off grades for reporting of resource estimates

Figure 2 highlights the great differences between the grades of the only two non-Chinese producing projects, Mountain Pass and Mt Weld, and most of the rest of the deposits. Of concern is the fact that the lower cut-off reporting grades for these two producers are significantly higher than the reported grades of most of the undeveloped resources.

Choice of the lower cut-off for reporting under codes such as JORC and NI43-101 must support the premise that there are reasonable prospects for eventual economic extraction of the Mineral Resource. Therefore the total costs of development must be considered and a realistic value attributed to all components of the mining, concentration, extraction, separation, purification and market presentation stages of the individual REE products planned for marketing.

Although there are great variations in the geology, mining considerations, mineralogy, concentration technology, infrastructure and potential products of individual rare earth deposits, there are common cost factors in separation of REEs, product presentation and marketing. These latter factors from separation (invariably solvent extraction) to product marketing are generally the major cost centres in any REE development and greatly exceed mining, concentration, transport and other costs. REE separation and refining cost factors are often opaque, usually commercially confidential and outside the experience of resource estimators. Realistic guidance based on informed feasibility-study type considerations, keeping in mind the examples of Mountain Pass and Mt Weld, should be provided to Competent Persons or Qualified Persons who are undertaking the resource estimation.

It is clear that most resources are being reported at too low a cut-off grade. This suggests that the definition of a "resource" should, in many cases, be re-considered taking into account reporting codes such as JORC and NI43-101 which emphasize the "reasonable prospects" test.

In the case of rare earths, unlike a gold resource estimate, the determination of a sensible lower cut-off grade will be an outcome, albeit preliminary, of a number of studies including metallurgical processing, marketing, price forecasting and mining. Synthesis of all this data is probably beyond the experience-base of many authors of typical resource estimation reports. Given that current and projected consumptions of rare earths are between 120,000 and 200,000 tonnes it is clear that only a few operations will be viable without flooding the world's market and impacting price levels.

Some corporate proponents seek to highlight their rare earth deposits by emphasising the high ratio of the generally more valuable HREO to LREO compared with LREO-enriched deposits. These apparently high ratios may, however, be largely due to yttrium being part of the HREO. Yttrium may dominate a particular mix of HREO though its value generally ranks below Pr, Nd, Eu, Tb, Dy, Tm, Yb and Lu. A further consideration is that mining and separating REO from a higher grade LREO deposit may be a more cost-effective source of HREO than low grade, HREO-enriched deposits. For example, Weng et al., (2013) quote two REE deposits with resource grades of 640 ppm and 292 ppm as possible significant resources of the future by virtue of their HREO contents. These deposits, however, will have to compete with established and emerging operations with TREO grades between 10 to 100 times higher.

Economics and Value

Simply totalling the extracted and refined market value of each REE contained in a block of 'ore' will not reflect its true resource value as it is extremely unlikely that all individual REE contained in the block can be extracted and refined at an economic profit. The capital and operational costs invariably preclude production of all REE, particularly small volume demand products and elements such as Tm.

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Commercial production of rare earths is a much more complex and capital-intensive undertaking than many other mineral commodities. In reality, the business is more about chemicals processing and marketing than mining. Final marketing of refined rare earth products follows a long process involving mining, crushing and concentration of ore, followed by cracking, leaching, purification, separation (eg by solvent extraction processes), and final processing to meet specific customer product specifications of purity, contaminants, and physical and chemical form. Even then, the qualification process by each customer for their rare earth material may take weeks and as long as a year. Capital and Operating ("Capex" and "Opex") costs for this whole process greatly impacts the value of REEs in resources and almost invariably exceed the best of pre-production cost estimates.

Assigning a value on resource blocks, essential for pit optimising, requires a number of considerations. Mining and front end processing/concentration costs are the least troublesome. Consideration of processing methods, markets and likely economic products are more difficult. Front end physical concentration is dependant, among other factors, on mineralogy which in turn, influences the cost of cracking (solubilising), separation and refining of specific REEs or their chemical products.

Utilization and demand for REE products is independent of the concentration of individual REEs in any deposit, and marketing factors dictate those that can be economically produced. In a specific deposit, perhaps as little as half the REEs will be the target of commercial production and the rest combined in lower volume or value and less refined products. Each product requires complex chemical processing and refining with its own specific Capex and Opex costs. Depending on the mix of REEs within a specific deposit, separation and refining of individual REEs is market and cost specific.

Case-Study: Mt Weld

The Mt Weld supergene-enriched REE deposit is developed from a carbonatite in the Eastern Goldfields of Western Australia and was discovered in the 1960's. Despite Mt Weld being one of the world's richest deposits, mining only commenced in 2007 with concentrates transported from site in 2011. It took until 2013 for production to commence from a Malaysia-based processing plant. Proven and Probable Reserves (including stockpiles) stand at 9.6Mt at 10.6% TREO based on cut-off grades of 4% TREO for the dominant supergene monazite-rich and the basal apatite material (Lynas, 2017). "Ready for sale" total tonnage of REO for the 2017 Financial Year is 16,000t.

The Mt Weld carbonatite and its thick, complex regolith, lie beneath 20-60m of allochthonous lacustrine clays and overlying sand and gravel alluvium. The immediate region is a featureless sheet-wash plain with ill-defined drainage towards the west and south. The carbonatite was discovered by exploration drilling over a strong, circular magnetic feature revealed by an airborne survey in 1966 (Duncan, 1988). The carbonatite regolith is host to a high grade deposit of REE, in addition to elevated concentrations of Nb, Ta, Ti, Zr and phosphate as mainly apatite.

The deposits have been developed from the essentially weakly mineralized primary carbonatite by groundwater solution of the dominant calcite mineral phase which resulted initially in concentration of residual minerals (mainly granular apatite and magnetite) in a discontinuous layer up to 30 metres thick directly overlying a karstic surface on un-oxidized carbonatite. Subsequent supergene alteration has mobilized soluble elements, particularly phosphorus and REE in the upper parts of the regolith, to re-precipitate as secondary deposits, including the main REE concentrations.

The Mt Weld carbonatite was explored for niobium, uranium, phosphate, rare earths and tantalum by various owners from 1969 until 2007 when mining commenced. REE became the main focus of exploration, processing and feasibility studies from 1988. It was not until 2004 that advances in mineral concentration technology and improved REE market conditions made development of the resources economically feasible.

Preparation of REE resource studies in 2002 struggled with inadequacies in the historical database and compromise of early (pre-1991) reverse circulation Air Core (AC) drilling samples caused by high groundwater flows in largely unconsolidated, fine grained ore. A hydrocyclone de-watering plant employing 130mm and 50mm hydro-cyclones was adequate for sample capture of granular apatite phosphate in the residual mineral zone, recovering 100% of particles >30µm and approximately 50% of >10µm fines from the drilled slurry, but produced potentially compromised recoveries in the very fine grained supergene REE deposit.

Process water extraction by the nearby Granny Smith Goldmine from 1991 onward greatly improved sample integrity and, with the use of 1000 litre bulker bags, close to 100% sample recovery was achieved. A study of 617 closely-paired samples from pre-dewatering and post-dewatering drilling revealed a 6% overstatement of TREO from the earlier drill holes. Consequently, 142 AC drill holes were excluded from estimation of Measured and Indicated resources and the Measured and Indicated Resources completed in 2002 were based on 194 valid AC drill holes and 6 diamond drill holes though Inferred Resources utilised the lower quality historical AC data (Figure 4).
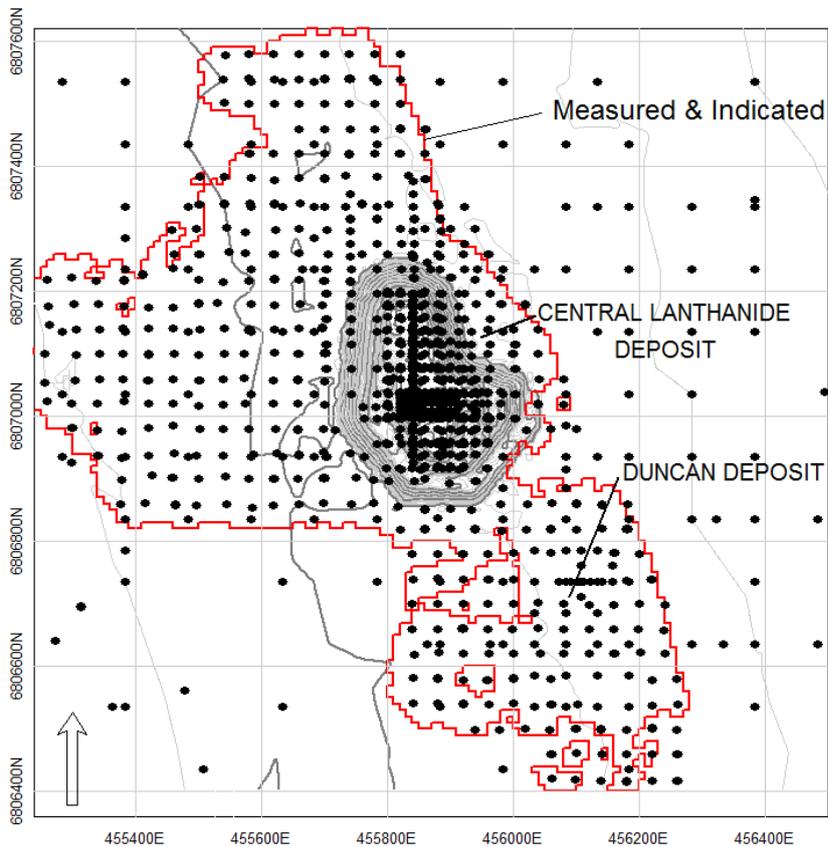
Figure 4. Mt Weld, drilling plan for the 2008 resource estimate
(Drill holes (solid dots), location of pit over CLD and outline of Measured and Indicated Resources)

Densities used for the bulk of the mineralisation were 1.6 with 1.9 for the deeper basal apatite. The overlying sediments have densities between 1.6 and 2.4. Limited density data from the carbonatite average 3.0.

A geological model was assembled consisting of definition of the overlying sediments and a subdivision of the mineralised regolith into nine units and a number of sub-units that had specific rare earth mineral characteristics such as crandallite clays, monazite siltstone, limonitic monazite-rich zone, residual apatite and manganiferous regolith (Figure 5). Indicator Kriging was used to characterize the mineralised regolith. The block model had dimensions 10x10x3m and had 12 defined lithologies.

Ordinary Kriging was used to estimate grades and a confidence classification developed based on proximity to data and number of data points. Measured and Indicated categories were generated from searches of 30x30x6m and 45x45x9m, respectively with a minimum of 12 and a maximum of 32 data points (3m composites). Inferred blocks were based on a 60x60x12m search with 8 to 32 data. Only post-1991 RC data were used for Measured and Indicated. No sub-cells were used.
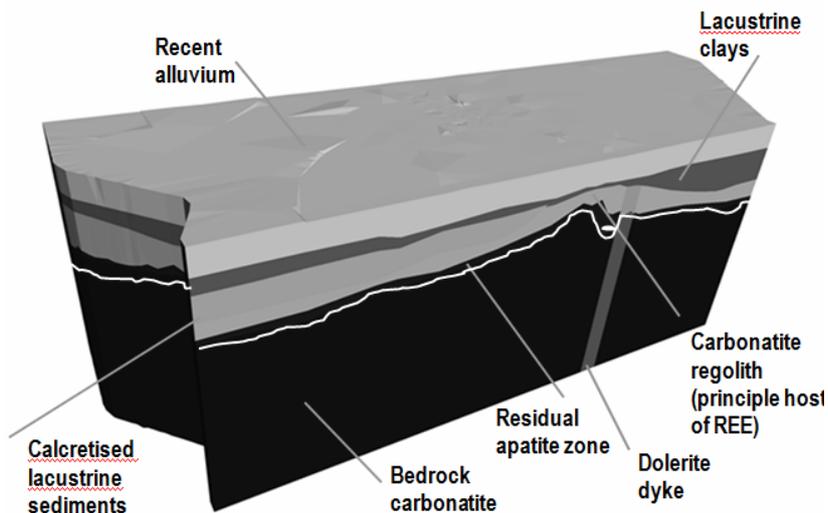
Figure 5. Mt Weld, conceptual 3D perspective

In 2002, the first rare earth resource for Mt Weld to be reported under the prevailing JORC Code was released. The Measured, Indicated and Inferred resources for the Central Lanthanide Zone ("CLD") were, at a 4.0% TREO cut-off, 7.7Mt at 11.9% TREO for 920Kt contained TREO. Subsequently in 2008 after infill and extensional drilling (Figure 4) this increased to 8.6Mt at 12.3% TREO for 1056Kt contained TREO. Since 2008, reporting has been at a 2.5% TREO cut-off. Current estimates stand at 14.7Mt at 8.8% TREO (1.3Mt contained TREO) for the CLD (Lynas, 2017). Following the recognition of the HREO-enriched "Duncan Deposit", to the south-east of the CLD, an additional resource was defined at 8.2Mt at 4.7% TREO based on a 2.5% TREO cut-off (38.9Kt contained TREO). A recent drilling program designed to define the limits of the residual apatite zone (Figure 5), that could not be adequately tested by previous air-core drilling, will likely lead to revisions to the current resources and reserves (Lynas, 2017a). Significant depth extensions to the mineralisation are likely.

The first phase of mining commenced in 2007 and was completed in May 2008 with 773Kt of high grade ore placed in stockpiles at TREO grades between 8% and 26%. Grade control drilling at 10x10m underpinned this exercise and allowed reconciliation with the 2002 and February 2008 estimates which were based on coarser drilling patterns of approximately 20m spacing for Measured Resources, 30m-40m spacing for Indicated and 40m-80m for Inferred.

Reconciliations based on mining guided by a 10x10m grade control drilling pattern resulted in a 1.5% higher tonnage and 1.1% more grade than the 2002 estimates. An overall reconciliation for contained REO metal was +3%. Comparison of the 2008 model with the grade control model resulted in 2.2% higher tonnage and 1.1% less grade with an overall increase of 1.1% REO metal.

Mount Weld Production

The REE mix for the Mt Weld CLD is approximately 45% Ce, 25% La, 25% Nd/Pr and 5% HREO. First stage concentration is approximately three-fold to ~35% TREO. Second stage processing is in Malaysia and was designed and constructed to produce a mix of oxides and carbonates (Table 3). Total ready for sale production of REO for the financial year 2017 is 16,003 tonnes (Lynas, 2017b) with anticipated levels as predicted in 2014 given in Table 4.

Table 3. Mt Weld Product Summary (Phase 1+2)

Product	Anticipated Tonnage/year	Major Applications
Ce carbonate, oxide	5,200	Automotive catalytic converters ("autocat"), NiMH batteries, Chemical Catalysis, UV cut
La carbonate, oxide	2,700	FCC, NiMH batteries
Ce / La and Ce / La / Pr carbonate, oxide	8,000	Polishing, NiMH batteries
Nd / Pr oxide, Nd oxide and Pr oxide	5,400	Magnet, NiMH batteries, Autocat
SEG + Heavy Rare Earths	960	Lighting, Magnets
Total	**22,000**	

((Lynas Corporation, 2014); FCC = fluid cracking catalysts; NiMH = nickel metal hydride where "M" is Nd/Pr; "UV cut" is ultra-violet transmissivity inhibition in polished glass; tonnage/year is a Lynas projection)

Evaluation Issues

Capex for a project similar to the Mt Weld operation, with production of 22,000 tpa REO products, are likely to exceed US$800M. Longer time frames to full production than estimated in feasibility studies can be expected. Capital, financial, technical expertise and marketing constraints, will make it extremely difficult for new-comers to the industry, so much so that it is unlikely that new deposits will be developed along the Mt Weld model. It is more likely that new producers will develop mines and concentrator plants to provide one of the established separation plants in China or in the West. Depending on many factors, this is likely to entail a price of concentrate delivered to the processor of a maximum of about 70% of the theoretical product value (M Vaisey, pers comm.).

Other factors affecting evaluation of in-situ resources that require special consideration for rare earth projects include:

- Availability of infrastructure and transport for advanced treatment plants
- Process energy, technical expertise, reagents
- Ease of concentration; may require novel flotation techniques and reagents
- Ease of extraction/refining, see Table 2
- Mix of REO
- Radioactivity, this may inhibit or preclude transport options for part- or unprocessed ores and concentrates
- Public relations skills in terms of overcoming concerns about the environmental effects of REE mining and processing

A corollary of this discussion is that the quotation of "in-ground value" should never be attempted in the public sphere and is likely to be misleading and inaccurate.

Equally hazardous is the use of forward projected prices. For example, in March 2011, Lynas (2011, p5) forecast a 2014 TREO price between approximately US$90/kg and US$130/kg for the Mt Weld mineralisation compared with the March 2014 quarter notional value of US30/kg and realised price of US$22.63/kg REO. Avalon Rare Metals Inc, in July 2011, calculated its projected basket price for the Nechalacho concentrate for 2015 at US$46.33/kg. The then (2011) basket price was US$153.83/kg which was discounted to take into account likely decreases in realised prices.

Some cut-off grades are expressed in terms of value to take into account by-products of potential value such as Ta, Nb & Zr. If this approach is used, it is recommended that practitioners also report the resources and/or reserves on the basis of TREO values to facilitate comparison with previous statements and possible future revisions and also to help comparison with other deposits. The use of value cut-offs should be used with caution to avoid over-optimistic assumptions of realized value of the TREO as well as possible by-products resulting in inflated tonnages and metal contents.

The basis of published cut-off grades used for reporting resources and/or reserves should be documented by Competent Persons and Qualified Persons. Examples are common in which inadequate details are provided for the price assumptions of individual REO, whether all the REO have been used to derive a basket price and variable metallurgical recoveries.

Conclusions

The significant growth in exploration activities directed at delineating rare earth resources has resulted in a plethora of low grade deposits that, in general, have grades that fall well below even the lower reporting cut-off grades of the only two recent Western producers, Mountain Pass and Mt Weld though in some cases, production costs may be much lower and, therefore, lower cut offs justified. Early in the evaluation process there should be a study of the phase distribution of the REE to help understand the recoverability and ease of processing of the various ore types. The value of a deposit will be governed by both the distribution of the individual REE and the host minerals. It is likely that relatively soluble "ionic clay" type deposits are more widespread than is currently realised. Although of lower grade, these may prove considerably more attractive than higher grade deposits containing REE-bearing minerals that require aggressive leaching conditions and high capital costs.

Acknowledgments

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