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# An assessment of the potential for transformational market growth amongst the critical metals<sup>†</sup>

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A 'critical metal' is one that has important economic uses, but which also faces supply risks for geopolitical or environmental and sustainability reasons. The constrained nature of critical metals supply means proposed solutions to the problem commonly involve reducing demand and therefore reliance, via recycling, substitution and thrifting. However, most critical metals are presently only small markets and therefore such an approach ignores the potential of transformational market growth to reduce supply risk, by creating large, diverse, transparent markets with multiple sources of primary mine supply, akin to modern base metals markets. Research is therefore required into which critical metals have the greatest potential for such transformational market growth. This study therefore conducts an evaluation of 49 critical metals to determine which are nearest to the combined breakthroughs in discovery, supply and demand that may lead to transformational market growth. The study concludes that 13 markets from the 49 critical metals, being magnesium, silicon, barium, boron, lithium, cobalt, chromium, vanadium, gallium, strontium, cerium, lanthanum and scandium have the highest potential for transformational market growth and thus efforts to resolve supply risk in these markets may be better focussed on overcoming current market constraints and growing these markets, rather than lessening reliance by reducing demand.

**Keywords:** Critical metals, Industrial metals, Mineral economics, Metals supply, Metals demand, Metals discovery, Metals markets, Market growth

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## Introduction

The 2008 National Research Council report 'Minerals, Critical Minerals, and the U.S. Economy' was the first modern paper to define a critical metal, as one which has important end uses, but for which there are concerns over supply security. Following this report, governments and researchers have also compiled other lists of metals which they deemed to be important to their economies,

and where there are concerns over supply security (e.g. Buchert *et al.* 2009; American Physical Society (APS) Panel on Public Affairs and Materials Research Society (MRS) 2011; United States Department of Energy (USDOE) 2011; British Geological Survey (BGS) 2012; Schulz and Bradley 2013; European Commission (EC) 2014). The metals found on these lists are commonly referred to as 'critical metals'.

As the critical metals concept has grown in importance a range of methodologies have arisen for analysing a metal's economic importance and supply risk (Erdmann and Graedel 2011; Graedel *et al.* 2012; Achzet and Helbig 2013; Speirs *et al.* 2013; Bedder 2015; Graedel *et al.* 2015). The definition of criticality employed within these methodologies, i.e. economically important metals exposed to severe supply or environmental risks, means primary mine supply is usually seen to be one of the problems making a metal 'critical'. It is therefore common to suggest solutions to criticality by reducing reliance on the metal and suppressing demand via recycling, substitution or thrifting of use (Buchert *et al.* 2009; EC 2010; APS and MRS 2011; Erdmann and Graedel 2011; USDOE 2011; Graedel *et al.* 2015).

However, critical metals markets are typically also opaque, thinly traded and small markets (Erbenesperger

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et al. 2005; Naumov and Grinberg 2009; Tyrer and Sykes 2013; Sykes et al. 2016). Such a structure makes them vulnerable to supply problems. These markets do not however have to remain small and risky. The history of the metals industry, particularly the aluminium, nickel and uranium industries, suggests that previously minor metal markets can undergo transformational market growth into major industrial metal markets (Street and Alexander 1998; Lynch 2002; Sykes et al. 2016). Such transformational market growth would also reduce supply risk (Sykes et al. 2016), by creating large, diverse, transparent markets with multiple sources of primary mine supply, akin to the modern base metals markets. Though Erdmann and Graedel (2011), the EC (2010) and USDOE (2011) did highlight increasing primary supply as a potential solution, amongst other solutions; the conventional critical metals assessment methodologies do not assess whether the critical metals have potential for market growth that would take them beyond criticality issues. Research is therefore needed to identify which critical metals have the greatest potential for transformational market growth.

Indeed, a number of mining and exploration companies have become increasingly interested in the critical metals markets, particularly the rare earths, anticipating transformational growth of these markets (Tyrer and Sykes 2013; Sykes et al. 2016). In this respect, however, the critical metals' markets have generally disappointed, growing more slowly than the non-ferrous industrial metals and precious metals markets over the last decade (Kelly and Matos 2013; Sykes et al. 2016). This is because the presently small critical metal markets face an economic paradox, with restricted supply dampening demand potential, but a lack of demand in turn suppressing investment in new supply. This suggests that a combination of breakthroughs in minerals discovery and metals supply and demand, creating a market 'tipping point' is therefore required for transformational market growth to occur (Sykes et al. 2016). This paper therefore introduces a framework for assessing the discovery, supply and demand factors to determine which of 49 of the most commonly cited critical metals have the greatest potential for transformational market growth.

Following this 'Introduction', the 'Summary of methodology' section outlines the framework and scoring system used to assess the discovery, supply and demand factors, with a more thorough description found in 'Appendix I: Detailed methodology'. The total scores are compiled and presented in the 'Summary of results' section, with the individual component scores described in full in 'Appendix II: Detailed results'. The 'Discussion, opportunities and recommendations' follows and outlines which metals have the greatest potential for transformational market growth, and where research, commercial and government interventions are likely to be the most impactful. Finally 'Conclusions' are then drawn from these discussions and recommendations.

## Summary of methodology

A brief overview of the study methodology follows, including the selection of metals to study, the scoring system and how the discovery, supply and demand factors were assessed for each metal. More detail on the methodology can be found in Appendix I.

## Selection of metals to study

The metals assessed in the study are listed in Table 1. The list was compiled from several reports on 'critical' metals by the NRC (2008), Buchert et al. (2009), APS and MRS (2011), USDOE (2011), BGS (2012), Schulz and Bradley (2013) and the EC (2014). Cadmium and vanadium were also added to the study at the authors' discretion due to their importance to the battery market (Sykes et al. 2014; USGS 2014, 2015). The critical metals in the study were compared to more familiar metals including aluminium, copper, gold, lead, nickel, tin, titanium and zinc.

## Factors considered in the analytical framework

The analytical framework draws from the observations of Gupta and Krishnamurthy (2005) in explaining why the rare earth metals are not mined in comparable volumes to the base metals, which are similarly abundant in the crust (Rudnick and Gao 2003). Gupta and Krishnamurthy (2005) highlight four factors that are considered to facilitate the growth of metals supply. The first two factors increase the ease of discovering multiple large ore deposits of the metal, whilst the latter two increase the ease with which the metal can be supplied to the market, once the ore deposits have been discovered:

- Discovery
  - (i) Is the metal relatively abundant in the crust?
  - (ii) What is the propensity for the metal to concentrate into discrete mineral deposits within the crust?
- Supply
  - (iii) Are the metal ores easy to extract from the ground (i.e. mine)?
  - (iv) Is it easy to extract the metal from the ores (i.e. process)?

Evidence from Sykes et al. (2016), suggest that to facilitate substantial demand growth, a metal must possess both economically *important* uses, as is usually highlighted in critical metals studies, but also *widespread* uses, as is typical of most major industrial metal markets. As such the two demand factors, making up the fifth and sixth components of the assessment are:

- Demand
  - (v) Does the metal have demand in 'critical' industrial sectors and/or uses?
  - (vi) Is the metal in demand across a range of industrial sectors and/or uses?

The critical metals are then ranked using a simple scoring system, to determine which have the highest potential for transformational market growth. The scoring system is discussed below.

## Scoring system

For each discovery, supply and demand factor the critical metals were assessed for their potential and a simple scoring system was applied:

- *Neutral*: A score of 0.5 is the default score awarded if the information did not indicate strongly whether the factor increased or decreased the economic potential of the metal market. A score of 0.5 was also awarded if there was little or no information on that factor.
- *Positive*: If a factor was considered to increase the potential for a metal to move from a minor critical

**Table 1** The full results of the assessments including crustal abundance (Table A1), propensity to concentrate into mineral deposits (Table A2), ease of mining (Table A4) and processing (Table A5) and both criticality (Table A7) and diversity (Table A8) of demand. Scores total between 0 and 6, with higher scores seemingly indicating a greater potential for that metal to become one of the major industrial metals of the future. The column containing the final scores is highlighted in bold. The table also includes details on the recent production levels, prices and thus approximate market size of the metals to allow for easier comparison of the critical metals with the larger more established industrial and precious metals markets, and therefore some insight into potential production scale and market size of these critical metals. The rows containing the non-critical major industrial and precious metals are highlighted in bold

| Commodity        | Score                              |                                        |                                 |                                     |                                     |                                   | Total      | USGS estimated 2013<br>annual metal equivalent<br>production/thousands<br>tonnes | USGS estimated 2013<br>average metal<br>equivalent price/US<br>\$/tonne | 2013 approximate<br>market value (US\$<br>millions) based on<br>USGS data <sup>1</sup> |
|------------------|------------------------------------|----------------------------------------|---------------------------------|-------------------------------------|-------------------------------------|-----------------------------------|------------|----------------------------------------------------------------------------------|-------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
|                  | Crustal<br>abundance<br>(Table A1) | Crustal<br>concentration<br>(Table A2) | Ease of<br>mining<br>(Table A4) | Ease of<br>processing<br>(Table A5) | Criticality<br>of use<br>(Table A7) | Diversity<br>of use<br>(Table A8) |            |                                                                                  |                                                                         |                                                                                        |
| Antimony         | 0                                  | 1                                      | 1                               | 1                                   | 0.5                                 | 0.5                               | <b>4</b>   | 163 <sup>2</sup>                                                                 | 10 252 <sup>2</sup>                                                     | 1671                                                                                   |
| <b>Copper</b>    | <b>0.5</b>                         | <b>0.5</b>                             | <b>1</b>                        | <b>1</b>                            | <b>0</b>                            | <b>1</b>                          | <b>4</b>   | <b>17 900</b> <sup>3</sup>                                                       | <b>7319</b> <sup>3</sup>                                                | <b>131 010</b>                                                                         |
| <b>Aluminium</b> | <b>1</b>                           | <b>0</b>                               | <b>1</b>                        | <b>0.5</b>                          | <b>0</b>                            | <b>1</b>                          | <b>3.5</b> | <b>47 300</b> <sup>4</sup>                                                       | <b>2088</b> <sup>4</sup>                                                | <b>98 762</b>                                                                          |
| Barium (Barite)  | 1                                  | 0                                      | 1                               | 1                                   | 0.5                                 | 0                                 | <b>3.5</b> | 4998 <sup>5</sup>                                                                | 196 <sup>5</sup>                                                        | 980                                                                                    |
| Germanium        | 0.5                                | 0.5                                    | 1                               | 0                                   | 1                                   | 0.5                               | <b>3.5</b> | 0.15 <sup>6</sup>                                                                | 1 607 000 <sup>6</sup>                                                  | 241                                                                                    |
| Indium           | 0                                  | 1                                      | 1                               | 0                                   | 1                                   | 0.5                               | <b>3.5</b> | 0.77 <sup>7</sup>                                                                | 620 000 <sup>7</sup>                                                    | 477                                                                                    |
| <b>Silver</b>    | <b>0</b>                           | <b>1</b>                               | <b>1</b>                        | <b>0</b>                            | <b>0.5</b>                          | <b>1</b>                          | <b>3.5</b> | <b>26</b> <sup>8</sup>                                                           | <b>765 188</b> <sup>8</sup>                                             | <b>19 894</b>                                                                          |
| Tellurium        | 0                                  | 1                                      | 1                               | 0                                   | 1                                   | 0.5                               | <b>3.5</b> | 0.58 <sup>9</sup>                                                                | 112 000 <sup>9</sup>                                                    | 65                                                                                     |
| Arsenic          | 0.5                                | 1                                      | 0.5                             | 0                                   | 0.5                                 | 0.5                               | <b>3</b>   | 59.4 <sup>10</sup>                                                               | 434 <sup>10</sup>                                                       | 26                                                                                     |
| Boron            | 0.5                                | 0                                      | 0.5                             | 1                                   | 0.5                                 | 0.5                               | <b>3</b>   | 1539 <sup>11</sup>                                                               | 1815 <sup>12</sup>                                                      | 2793                                                                                   |
| Chromium         | 1                                  | 0                                      | 1                               | 0.5                                 | 0.5                                 | 0                                 | <b>3</b>   | 12 064 <sup>12</sup>                                                             | 776 <sup>12</sup>                                                       | 9362                                                                                   |
| Cobalt           | 0.5                                | 0.5                                    | 0.5                             | 0                                   | 1                                   | 0.5                               | <b>3</b>   | 120 <sup>13</sup>                                                                | 27 117 <sup>13</sup>                                                    | 3254                                                                                   |
| Gallium          | 0.5                                | 0.5                                    | 1                               | 0                                   | 1                                   | 0                                 | <b>3</b>   | 0.28 <sup>14</sup>                                                               | 511 000 <sup>14</sup>                                                   | 143                                                                                    |
| Lithium          | 0.5                                | 0                                      | 0.5                             | 0.5                                 | 1                                   | 0.5                               | <b>3</b>   | 35 <sup>15</sup>                                                                 | 26 549 <sup>16</sup>                                                    | 929                                                                                    |
| Magnesium        | 1                                  | 0                                      | 0.5                             | 0.5                                 | 0.5                                 | 0.5                               | <b>3</b>   | 910 <sup>17</sup>                                                                | 2590 <sup>17</sup>                                                      | 2357                                                                                   |
| Mercury          | 0                                  | 1                                      | 0.5                             | 0.5                                 | 0.5                                 | 0.5                               | <b>3</b>   | 1.81 <sup>18</sup>                                                               | 53 623 <sup>18</sup>                                                    | 97                                                                                     |
| Molybdenum       | 0                                  | 1                                      | 1                               | 0.5                                 | 0.5                                 | 0                                 | <b>3</b>   | 270 <sup>19</sup>                                                                | 22 740 <sup>19</sup>                                                    | 6140                                                                                   |
| Niobium          | 0.5                                | 0                                      | 1                               | 1                                   | 0.5                                 | 0                                 | <b>3</b>   | 51 <sup>20</sup>                                                                 | 73 333 <sup>20</sup>                                                    | 3740                                                                                   |
| Iridium (PGM)    | 0                                  | 1                                      | 0.5                             | 0                                   | 1                                   | 0.5                               | <b>3</b>   | 0.006 <sup>21</sup>                                                              | 29 610 837 <sup>22</sup>                                                | 178                                                                                    |
| Osmium (PGM)     | 0                                  | 1                                      | 0.5                             | 0                                   | 1                                   | 0.5                               | <b>3</b>   | 0.1 <sup>23</sup>                                                                | 5 669 231 <sup>24</sup>                                                 | 0.6                                                                                    |
| Platinum (PGM)   | 0                                  | 1                                      | 0.5                             | 0                                   | 1                                   | 0.5                               | <b>3</b>   | 0.192 <sup>22</sup>                                                              | 48 579 778 <sup>22</sup>                                                | 9327                                                                                   |
| Ruthenium (PGM)  | 0                                  | 1                                      | 0.5                             | 0                                   | 1                                   | 0.5                               | <b>3</b>   | 0.02 <sup>21</sup>                                                               | 2 604 210 <sup>22</sup>                                                 | 52                                                                                     |
| Cerium (REM)     | 0.5                                | 0                                      | 0.5                             | 0                                   | 1                                   | 1                                 | <b>3</b>   | 34.2 <sup>26</sup>                                                               | 123 457 <sup>25</sup>                                                   | 4222                                                                                   |
| Scandium (REM)   | 0.5                                | 0                                      | 1                               | 0                                   | 1                                   | 0.5                               | <b>3</b>   | 0.00001 <sup>27</sup>                                                            | 4 352 941 <sup>25</sup>                                                 | 44                                                                                     |
| Silicon (metal)  | 1                                  | 0                                      | 0.5                             | 0.5                                 | 0.5                                 | 0.5                               | <b>3</b>   | 7700 <sup>28</sup>                                                               | 2646 <sup>28</sup>                                                      | 20 374                                                                                 |
| Strontium        | 1                                  | 0                                      | 1                               | 0.5                                 | 0.5                                 | 0                                 | <b>3</b>   | 117 <sup>29</sup>                                                                | 105 <sup>29</sup>                                                       | 12                                                                                     |
| Beryllium        | 0.5                                | 0                                      | 0.5                             | 0                                   | 0.5                                 | 1                                 | <b>2.5</b> | 0.24 <sup>30</sup>                                                               | 460 766 <sup>30</sup>                                                   | 111                                                                                    |
| Bismuth          | 0                                  | 1                                      | 0.5                             | 0                                   | 0.5                                 | 0.5                               | <b>2.5</b> | 7.6 <sup>31</sup>                                                                | 19 180 <sup>31</sup>                                                    | 146                                                                                    |
| <b>Gold</b>      | <b>0</b>                           | <b>1</b>                               | <b>0.5</b>                      | <b>0.5</b>                          | <b>0</b>                            | <b>0.5</b>                        | <b>2.5</b> | <b>2.77</b> <sup>32</sup>                                                        | <b>45 011 045</b> <sup>32</sup>                                         | <b>124 681</b>                                                                         |
| <b>Nickel</b>    | <b>0.5</b>                         | <b>0.5</b>                             | <b>0.5</b>                      | <b>0.5</b>                          | <b>0</b>                            | <b>0.5</b>                        | <b>2.5</b> | <b>2490</b> <sup>33</sup>                                                        | <b>15 018</b> <sup>33</sup>                                             | <b>37 395</b>                                                                          |
| Palladium (PGM)  | 0                                  | 1                                      | 0.5                             | 0                                   | 1                                   | 0                                 | <b>2.5</b> | 0.211 <sup>22</sup>                                                              | 23 662 949 <sup>22</sup>                                                | 4993                                                                                   |
| Rhodium (PGM)    | 0                                  | 1                                      | 0.5                             | 0                                   | 1                                   | 0                                 | <b>2.5</b> | 0.03 <sup>21</sup>                                                               | 35 205 068 <sup>22</sup>                                                | 1056                                                                                   |

(Continued)

Table 1 Continued.

| Commodity             | Score                              |                                        |                                 |                                     |                                     |                                   | Total      | USGS estimated 2013<br>annual metal equivalent<br>production/thousands<br>tonnes | USGS estimated 2013<br>average metal<br>equivalent price/US<br>\$/tonne | 2013 approximate<br>market value (US\$<br>millions) based on<br>USGS data <sup>1</sup> |
|-----------------------|------------------------------------|----------------------------------------|---------------------------------|-------------------------------------|-------------------------------------|-----------------------------------|------------|----------------------------------------------------------------------------------|-------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
|                       | Crustal<br>abundance<br>(Table A1) | Crustal<br>concentration<br>(Table A2) | Ease of<br>mining<br>(Table A4) | Ease of<br>processing<br>(Table A5) | Criticality<br>of use<br>(Table A7) | Diversity<br>of use<br>(Table A8) |            |                                                                                  |                                                                         |                                                                                        |
| Lanthanum (REM)       | 0.5                                | 0                                      | 0.5                             | 0                                   | 1                                   | 0.5                               | <b>2.5</b> | 32.9 <sup>26</sup>                                                               | 117 647 <sup>25</sup>                                                   | 3871                                                                                   |
| Rhenium               | 0                                  | 1                                      | 1                               | 0                                   | 0.5                                 | 0                                 | <b>2.5</b> | 0.053 <sup>34</sup>                                                              | 3 200 000 <sup>34</sup>                                                 | 170                                                                                    |
| Tungsten              | 0.5                                | 0                                      | 0.5                             | 0.5                                 | 0.5                                 | 0.5                               | <b>2.5</b> | 71 <sup>35</sup>                                                                 | 45 397 <sup>35</sup>                                                    | 3223                                                                                   |
| Vanadium              | 1                                  | 0                                      | 1                               | 0                                   | 0                                   | 0.5                               | <b>2.5</b> | 76 <sup>36</sup>                                                                 | 24 605 <sup>36</sup>                                                    | 1870                                                                                   |
| Cadmium               | 0                                  | 1                                      | 1                               | 0                                   | 0                                   | 0                                 | <b>2</b>   | 21.8 <sup>37</sup>                                                               | 1950 <sup>37</sup>                                                      | 43                                                                                     |
| <b>Lead</b>           | <b>0.5</b>                         | <b>1</b>                               | <b>0.5</b>                      | <b>0</b>                            | <b>0</b>                            | <b>0</b>                          | <b>2</b>   | <b>5400</b> <sup>38</sup>                                                        | <b>2072</b> <sup>38</sup>                                               | <b>11 189</b>                                                                          |
| Manganese             | 1                                  | 0                                      | 0.5                             | 0                                   | 0.5                                 | 0                                 | <b>2</b>   | 17 000 <sup>46</sup>                                                             | 576 <sup>47</sup>                                                       | 9792                                                                                   |
| Europium (REM)        | 0.5                                | 0                                      | 0.5                             | 0                                   | 1                                   | 0                                 | <b>2</b>   | 0.38 <sup>26</sup>                                                               | 3 837 209 <sup>25</sup>                                                 | 1458                                                                                   |
| Gadolinium (REM)      | 0.5                                | 0                                      | 0.5                             | 0                                   | 1                                   | 0                                 | <b>2</b>   | 0.66 <sup>26</sup>                                                               | 274 713 <sup>25</sup>                                                   | 181                                                                                    |
| Neodymium (REM)       | 0.5                                | 0                                      | 0.5                             | 0                                   | 1                                   | 0                                 | <b>2</b>   | 20.6 <sup>26</sup>                                                               | 313 953 <sup>25</sup>                                                   | 6467                                                                                   |
| Praseodymium<br>(REM) | 0.5                                | 0                                      | 0.5                             | 0                                   | 1                                   | 0                                 | <b>2</b>   | 7.2 <sup>26</sup>                                                                | 264 706 <sup>25</sup>                                                   | 1906                                                                                   |
| Samarium (REM)        | 0.5                                | 0                                      | 0.5                             | 0                                   | 1                                   | 0                                 | <b>2</b>   | 0.47 <sup>26</sup>                                                               | 137 209 <sup>25</sup>                                                   | 64                                                                                     |
| Yttrium (REM)         | 0.5                                | 0                                      | 0                               | 0                                   | 1                                   | 0.5                               | <b>2</b>   | 9.2 <sup>26</sup>                                                                | 208 861 <sup>25</sup>                                                   | 1922                                                                                   |
| <b>Titanium</b>       | <b>1</b>                           | <b>0</b>                               | <b>0.5</b>                      | <b>0</b>                            | <b>0</b>                            | <b>0.5</b>                        | <b>2</b>   | <b>2639</b> <sup>39</sup>                                                        | <b>1268</b> <sup>40</sup>                                               | <b>3346</b> <sup>21</sup>                                                              |
| <b>Zinc</b>           | <b>0.5</b>                         | <b>0.5</b>                             | <b>0.5</b>                      | <b>0</b>                            | <b>0</b>                            | <b>0.5</b>                        | <b>2</b>   | <b>13 500</b> <sup>41</sup>                                                      | <b>1918</b> <sup>41</sup>                                               | <b>25 893</b>                                                                          |
| Dysprosium (REM)      | 0.5                                | 0                                      | 0                               | 0                                   | 1                                   | 0                                 | <b>1.5</b> | 1.1 <sup>26</sup>                                                                | 1 839 080 <sup>25</sup>                                                 | 2023                                                                                   |
| Erbium (REM)          | 0.5                                | 0                                      | 0                               | 0                                   | 1                                   | 0                                 | <b>1.5</b> | 1.3 <sup>42</sup>                                                                | 293 103 <sup>25</sup>                                                   | 381                                                                                    |
| Ytterbium (REM)       | 0.5                                | 0                                      | 0                               | 0                                   | 1                                   | 0                                 | <b>1.5</b> | 0.00006 <sup>42</sup>                                                            | 511 364 <sup>25</sup>                                                   | 26                                                                                     |
| Thorium               | 0.5                                | 0                                      | 0                               | 0                                   | 0.5                                 | 0.5                               | <b>1.5</b> | 6.7 <sup>43</sup>                                                                | 65 000 <sup>43</sup>                                                    | 436                                                                                    |
| <b>Tin</b>            | <b>0.5</b>                         | <b>0.5</b>                             | <b>0</b>                        | <b>0</b>                            | <b>0</b>                            | <b>0.5</b>                        | <b>1.5</b> | <b>230</b> <sup>44</sup>                                                         | <b>22 267</b> <sup>44</sup>                                             | <b>5121</b>                                                                            |
| Holmium (REM)         | 0                                  | 0                                      | 0                               | 0                                   | 1                                   | 0                                 | <b>1</b>   | 0.00001 <sup>42</sup>                                                            | n/a                                                                     | n/a                                                                                    |
| Lutetium (REM)        | 0                                  | 0                                      | 0                               | 0                                   | 1                                   | 0                                 | <b>1</b>   | n/a                                                                              | 4 545 455 <sup>25</sup>                                                 | n/a                                                                                    |
| Terbium (REM)         | 0                                  | 0                                      | 0                               | 0                                   | 1                                   | 0                                 | <b>1</b>   | 0.4 <sup>26</sup>                                                                | 3 235 294 <sup>25</sup>                                                 | 1294                                                                                   |
| Thulium (REM)         | 0                                  | 0                                      | 0                               | 0                                   | 1                                   | 0                                 | <b>1</b>   | 0.00006 <sup>42</sup>                                                            | n/a                                                                     | n/a                                                                                    |

|          |   |   |   |   |     |     |          |                    |                       |     |
|----------|---|---|---|---|-----|-----|----------|--------------------|-----------------------|-----|
| Tantalum | 0 | 0 | 0 | 0 | 0.5 | 0.5 | <b>1</b> | 0.48 <sup>45</sup> | 296 100 <sup>45</sup> | 142 |
|----------|---|---|---|---|-----|-----|----------|--------------------|-----------------------|-----|

<sup>1</sup>Figures subject to rounding.

<sup>2</sup>Source: USGS (2014).

<sup>3</sup>Source: USGS (2014).

<sup>4</sup>Smelter production (2014b).

<sup>5</sup>Based on barium content of 58.8% in barite (BaSO<sub>4</sub>) priced at US\$115/tonne (USGS 2014).

<sup>6</sup>2013 refinery production; price is average of 2013 zone refined (US\$1875/kg) and electronic grade dioxide (US\$1340/kg) prices (USGS 2014).

<sup>7</sup>Source: USGS (2014).

<sup>8</sup>Source: USGS (2014).

<sup>9</sup>Production estimate for 2012, Source: USGS (2015).

<sup>10</sup>Based on arsenic content of 75.8% in arsenic trioxide (As<sub>2</sub>O<sub>3</sub>) priced at US\$0.26/pound (USGS 2014).

<sup>11</sup>Based on boron content of 31.4% in borate (B<sub>2</sub>O<sub>3</sub>) priced at US\$570/tonne (USGS 2014).

<sup>12</sup>Based on chromium content of 46.4% in chromite ore priced at US\$360/tonne (USGS 2014).

<sup>13</sup>Source: USGS (2014).

<sup>14</sup>Source: USGS (2014).

<sup>15</sup>Source: USGS (2014).

<sup>16</sup>Based on lithium content of 22.6% in lithium carbonate priced at US\$6000/tonne, Source: Fox-Davies Capital (2013).

<sup>17</sup>Source: USGS (2015).

<sup>18</sup>Source: USGS (2014).

<sup>19</sup>Source: USGS (2014).

<sup>20</sup>Based on the ~60% niobium content of ferroniobium priced at US\$44 000/tonne (USGS 2014).

<sup>21</sup>Figures for 2012 consumption, Source: USGS (2015).

<sup>22</sup>Source: USGS (2014).

<sup>23</sup>Source: Minor Metals Trade Association (2015).

<sup>24</sup>Calculated from US import values of US\$737 000 divided by imports of 130kg. Source: USGS (2015).

<sup>25</sup>Source: USGS (2015).

<sup>26</sup>Figures for 2008 consumption, based on rare earth content of each: Y (79%), Ce (81%), Pr (83%), La, Tb (85%), Nd, Sm, Eu (86%), Gd, Dy, (88%). Source: Goonan (2011).

<sup>27</sup>General production estimate based on 85% scandium content of scandium oxide, Source: Gillies (2013).

<sup>28</sup>Figures for silicon metal market only i.e. excluding industrial sand etc (USGS 2014).

<sup>29</sup>Based on strontium content of 47.8% in celestite (SrSO<sub>4</sub>) priced at US\$50/tonne (USGS 2014).

<sup>30</sup>Source: USGS (2014).

<sup>31</sup>Source: USGS (2014).

<sup>32</sup>Source: USGS (2014).

<sup>33</sup>Source: USGS (2014).

<sup>34</sup>Source: USGS (2014).

<sup>35</sup>Based on a price of US\$360 per metric tonne unit (mtu) of WO<sub>3</sub> with each mtu containing 7.93kg of tungsten, valuing the contained tungsten at US\$45 397/tonne. Excludes US mine production. There is one mine in California (USGS 2014).

<sup>36</sup>Based on vanadium content of 56% in vanadium pentoxide (V<sub>2</sub>O<sub>5</sub>) priced at US\$6.25/pound (USGS 2014).

<sup>37</sup>Source: USGS (2014).

<sup>38</sup>Source: USGS (2014).

<sup>39</sup>Based on 6 790 000 tonnes of ilmenite containing a minimum of 54% titanium oxide (TiO<sub>2</sub>), thus containing 3 666 600 tonnes of TiO<sub>2</sub> and a minimum of 2 199 960 tonnes of titanium plus 770 000 tonnes of rutile containing a minimum of 95% titanium oxide (TiO<sub>2</sub>), thus containing 731 500 tonnes of TiO<sub>2</sub> and a minimum of 438 900 tonnes of titanium, for a total of 2 638 860 tonnes of titanium (USGS 2014).

<sup>40</sup>Based on price of US\$300/tonne for 6 790 000 tonnes of ilmenite worth US\$2037 million overall, in addition to 770 000 tonnes of rutile priced at US\$1700/tonne and worth US\$1309 million for a total market value of US\$3346 million and an inferred price per tonne of contained titanium of US\$1268/tonne (USGS 2015).

<sup>41</sup>Source: USGS (2014).

<sup>42</sup>Estimates for 2014 production, based on rare earth content of each: Ho, Er (87%), Tm, Yb (88%). Source: Minor Metals Trade Association (2015).

<sup>43</sup>Production estimate for 2012, Source: USGS (2014).

<sup>44</sup>Source: USGS (2014).

<sup>45</sup>Based on tantalum content of 81.9% in tantalum pentoxide (Ta<sub>2</sub>O<sub>5</sub>) priced at US\$110/lb of tantalum oxide content in tantalite (USGS 2014).

<sup>46</sup>Source: USGS (2014) – contained Mn within ores typically around 46–48% Mn.

<sup>47</sup>Manganese ore is typically 46–48% (USGS 2014). 2013 prices are based on an average of US (US\$6.00) and Chinese (US\$5.51) prices, i.e. US\$5.76 per metric ton unit (USGS 2014). A metric ton unit is the price of 1% Mn in the ore, so the price per tonne of a typical 47% ore is US\$270.72 at 2013 prices, i.e. US\$5.76×47 (USGS 2015). This ore is only 47% Mn, so the price per tonne of Mn contained is US\$576. This is multiplied by 2013 world production of 17 000 000 tonnes of contained Mn in ores (USGS 2014) for a market value of US\$9792 million.

metal market to a major industrial metal market it scored 1.

- *Negative*: A score of 0 was awarded if the factor was seen to mitigate against the minor critical metal market becoming a major industrial metal market.

No scores other than 0, 0.5 or 1 were possible in order to retain simplicity. Each of the discovery, supply and demand factors was made up of two sub-factors, resulting a maximum theoretical score of 6. A maximum score would indicate significant potential for this metal to transform from minor to industrial. A score of zero would indicate that the given critical metal had little potential for market transformation.

## Analysing propensity for discovery

### Analysing crustal abundance

The abundance of the elements in the bulk continental crust was drawn from Rudnick and Gao (2003) and Wedepohl (1995). The BGS (2012) considers elements with abundance greater than 100 ppm as low scarcity, between 1 and 100 ppm as medium scarcity and less than 1 ppm as high scarcity. Thus, in this study, elements with a crustal abundance between 1 and 100 ppm are given a score of 0.5, with a score of 1 for greater than 100 ppm, and 0 for less than 1 ppm.

### Analysing element concentration in the crust

Skinner (1976), Gupta and Krishnamurthy (2005) and Graedel et al. (2012) highlight how crustal abundance is not the only important factor in the availability of an element for discovery and subsequent extraction: the ease with which the metal concentrates into discrete mineral deposits is also critical. The differing propensity of elements to concentrate in the crust was first highlighted by Goldschmidt (1937). Siderophiles and chalcophiles are commonly considered to be ore-forming elements (White 2013), as they have a tendency to be concentrated away from the dominant silica (lithophile) crust into discrete deposits by geological heat and pressure. By contrast, lithophile elements are found more diffusely within the crust, which is rich in silica, so lithophiles less commonly concentrate into discrete deposits within the crust. Lithophiles are not commonly considered to be ore-forming elements (White 2013), though they are still nonetheless mined. As an indication of the tendency to form mineral deposits in the crust, rather than remain fairly evenly distributed, in the scoring system, siderophile and chalcophile elements are awarded a score of 1, whilst lithophile elements are awarded a score of 0, using the updated White (2013) version of Goldschmidt's (1937) classification. Some elements are siderophile or chalcophile and lithophile, for which 0.5 is scored.

## Analysing ease of extraction

### Analysing ease of mining

Metals that are mined using scalable hard rock techniques by large, formal companies with access to significant capital are more amenable to mining in large volumes, than metals mined using less scalable techniques such as placer or brine mining, or by capital-poor artisanal or informal miners. The ease of mining assessment is therefore based on whether the industry is dominated by formalised and hard rock mining. A metal which is largely mined both

by formal companies utilising hard rock mines scores 1. If the metal's mining industry is largely informal or else not usually extracted using conventional hard rock mining, 0.5 is subtracted for each of these imposts, making a total subtraction of 1, bringing the score to 0.5 for one incidence and 0 for both incidences. In addition, the presence of a major environmental or socio-political factor that is currently widespread across the mining industry of a particular critical metal reduced the score by 0.5. This further subtraction is in addition to the scoring above for the presence of formalised, hard rock mining. In theory, the cumulative subtractions could total more than 1, but for simplicity only a minimum score of 0 was possible. The relevant chapters of the United States Geological Survey (USGS) Mineral Commodity Summaries (2014) and Minerals Yearbook (2015) were used as the general references, in addition to a few select sources on specific subjects relating to some metals.

### Analysing ease of processing

One potential consequence of metals not concentrating easily into deposits in the crust is that end up frequently being found as by-products and co-products, mitigating against more abundant mining, for both technical and economic reasons (Gupta and Krishnamurthy 2005; Naumov and Grinberg 2009; Alonso et al. 2012; Graedel et al. 2012; Packey 2012; Mudd et al. 2013b; Graedel et al. 2015; Werner et al. 2015). Thus, to analyse the ease of processing a metal the first factor considered is whether the metal is generally mined as a co- or by-product, or as a primary product. If the element is mined mainly as a primary product it scores 1. Similarly, if the element is still most commonly mined as a co- or by-product it scores 0. For commodities where the case is not clear, then a neutral score of 0.5 is awarded. An assessment was also made as to whether a technological constraint or advantage made the metal particularly difficult or straight-forward to process. Harder to process metals had 0.5 subtracted off their initial score (to a minimum of 0), whilst simple to extract metals had 0.5 added to their score (to a maximum of 1). As with mining, additional environmental and socio-political factors may mitigate against the easy processing of a metal and a further 0.5 can be subtracted (to a total minimum score of 0). The relevant chapters of the USGS Mineral Commodity Summaries (2014) and Minerals Yearbook (2015) are again used as the source material, with additional specific sources used as required for specific metals.

## Analysing demand potential

### Analysing criticality of demand

By definition any of the metals appearing in the different 'critical' metal lists of Table A7 are to some measure deemed critical. Some are however more critical than others. A metal which is included in five or more of the seven critical metals lists scores 1 point as it would appear there is widespread agreement the metal is critical. The critical metals which appear in only one to four lists get a neutral score of 0.5, suggesting there is not widespread agreement that this metal is critical. The two 'critical' metals included here at the authors' discretion (cadmium and vanadium) score 0 under this system, reflecting the fact that there is no agreement that these metals are critical. As key comparators, the base and precious metals are

also added to the results in addition to the critical metals list in Table A7. Most of these familiar metals are not considered critical however and do not appear on the critical lists, hence are scored 0.

### Analysing breadth of demand

The final assessment is on the breadth of demand, undertaken using the USGS Minerals Yearbook (2015) and Commodity Summaries (2014), in addition to information from industry associations and other sources. Metals with a broad range of uses are considered to have greater potential for widespread future consumption, as their diversification reduces demand volatility and thus exposure to repeated substitution. For the same reasons that critical metals' supply should be considered in a forward-looking manner, so should demand and substitution. Though a critical metal may currently not have any obvious substitutes, this may not remain the case in the future, particularly if other metal markets grow rapidly and provide other metals to the global economy at much cheaper prices. Substitution is usually a price-property trade-off – a kind of opportunity cost – with substitution occurring when an alternate material can offer the same level of useful properties for a lower overall price. In this case an inferior metal may substitute for a superior metal, if it is significantly cheaper, and thus overall the unit of the relevant useful properties can still be bought cheaper. When substitution is considered in this manner, the current lack of available substitutes making a metal 'critical' becomes relatively less important, whilst the diversity of uses that a metal has, and therefore which it could use to substitute into new markets, resulting in more diverse demand, becomes relatively more important.

In this case, if no specific use makes up more than one-third of current consumption the metal is considered to have broad demand and scores 1. Conversely if more than two-thirds of demand comes from one use then the metal is considered to have very narrow consumption patterns and scores 0. For metals where the main use makes up one-third to two-thirds of demand, consumption is considered to be neither broad nor narrow and thus scores 0.5. Some scores are then further adjusted based on qualitative information. Similarly for metals where quantitative data on consumption are not available, and there is no clear qualitative statement that the metal has particularly broad or narrow consumption then 0.5 is also scored. In this study, demand is preferably assessed on a global level, unless the relevant data are not easily available; in this case, generally the United States or information on a number of major consumer countries or regions is used.

## Summary of results

A summary of the results are included below presenting the total aggregated scores for each of the metals. A more detailed presentation of the results, including scoring for each of the six individual factors can be found in Appendix II.

### Aggregated scores

Table 1 presents the aggregated scores including assessments of crustal abundance (Table A1), propensity to concentrate into mineral deposits (Table A2), describing overall propensity for discovery (Table A3); ease of

mining (Table A4) and processing (Table A5), describing overall ease of supply (Table A6); and both criticality (Table A7) and diversity (Table A8) of demand, making up overall demand potential (Table A9). Table 1 is presented on pages 3–5, whilst Tables A1–A9 can be found in Appendix II. Scores total between zero and six, with higher scores indicating greater potential to become a major industrial metal. Table 1 also denotes recent production levels, prices and thus approximate market sizes of the metals to allow for easier comparison of the critical metals with the industrial and precious metals markets.

### Most potential for transformational market growth

The highest scoring critical metal, antimony, scores four points, equal to copper, one of the most important non-ferrous industrial metals. Antimony, present at 0.2 ppm in the crust, however is considerably rarer than copper, found at 27 ppm in the crust (Rudnick and Gao 2003), so would need to overcome this scarcity should greater future demand arise.

The next group of critical metals scored 3.5 points, the same as aluminium, and include barium (barite), germanium, indium, silver and tellurium. Like antimony; germanium, indium, silver and tellurium are all fundamentally rare in the crust (Wedepohl 1995; Rudnick and Gao 2003), though the large silver market does give an indication of economic potential. Barium (barite) conversely is fairly abundant (Rudnick and Gao 2003) and easy to extract (USGS 2014, 2015) but at present lacks important (NRC 2008; Buchert et al. 2009; APS and MRS 2011; USDOE 2011; BGS 2012; Schulz and Bradley 2013; EC 2014) and diverse (The Barytes Association 2015) economic uses.

### Some potential for transformational market growth

A large number of critical metals score three points including arsenic, boron (borate), chromium, cobalt, gallium, lithium, magnesium, mercury, molybdenum, niobium, silicon (metal), strontium, the platinum group metals: iridium, osmium, platinum and ruthenium, and the rare earth metals: cerium and scandium. The score for these critical metals fall in between aluminium and silver (3.5 points) and gold and nickel (2.5 points). A variety of constraints exist for these metals, with some fundamentally rare in the crust such as mercury, molybdenum and the platinum group metals (Rudnick and Gao 2003), whilst most face extraction constraints in processing (Gupta and Krishnamurthy 2005; Hylander and Meili 2005; King 2005; Veiga et al. 2006; Bradsher 2009, 2013; Gao et al. 2009; Yaksic and Tilton 2009; Kyle 2010; Mudd 2010; Spiegel and Viega 2010; Thomas and Kelley 2010; Cobalt Development Institute 2011; Conflict Minerals Consortium 2012; Grosjean, Miranda, Perrin and Poggi 2012; Kim and Choi 2012; Massari and Ruberti 2013; Packey 2013; Wubbeke 2013; Campbell 2014; Golev et al. 2014; Mudd and Jowitt 2014; Weng et al. 2014; USGS 2014, 2015). Metals such as chromium (International Chromium Development Association 2015), magnesium (NRC 2008; Buchert et al. 2009; APS and MRS 2011; USDOE 2011; BGS 2012; Schulz and Bradley 2013; EC 2014), niobium (Schwela 2012) and strontium (USGS 2014, 2015) however seem more constrained by demand factors.

Like gold and nickel a number of critical metals score 2.5 points, including beryllium, bismuth, rhenium,

tungsten, vanadium, the rare earth lanthanum, and the platinum group metals, palladium and rhodium. Notably palladium and rhodium show less diversity of demand than the other platinum group metals (USGS 2015). Along with the platinum group metals both bismuth and rhenium seem constrained by geological abundance (Rudnick and Gao 2003). Beryllium (USGS 2014, 2015) and lanthanum (Gupta and Krishnamurthy 2005; Bradsher 2009, 2013; Massari and Ruberti 2013; Packey 2013; Wubbeke 2013; Campbell 2014; Golev *et al.* 2014; Weng *et al.* 2014; USGS 2014, 2015) seem processing constrained, whilst tungsten (Rudnick and Gao 2003; NRC 2008; Buchert *et al.* 2009; APS and MRS 2011; Freedman 2011; USDOE 2011; BGS 2012; Bleischwitz, Dittrich and Pierdicca 2012; Schulz and Bradley 2013; White 2013; EC 2014; USGS 2014, 2015; International Tungsten Industry Association 2015) and to a lesser extent vanadium (NRC 2008; Buchert *et al.* 2009; APS and MRS 2011; USDOE 2011; BGS 2012; Schulz and Bradley 2013; White 2013; EC 2014; USGS 2014, 2015) seem to present a complex picture of multiple minor constraints.

#### **Limited potential for transformational market growth**

A number of the rare earth metals (europium, gadolinium, neodymium, praseodymium, samarium and yttrium) in addition to cadmium and manganese score 2 points, alongside industrial metals: lead, zinc and titanium. Broadly all of these metals suffer both processing constraints (Gupta and Krishnamurthy 2005; Bradsher 2009, 2013; Mining Weekly 2012; Massari and Ruberti 2013; Packey 2013; Wubbeke 2013; Campbell 2014; The Economist 2014; Golev *et al.* 2014; Weng *et al.* 2014; USGS 2014, 2015; Assmang 2015) and a lack of diversity in usage (Goonan 2011; USGS 2014; Postle *et al.* 2015), with the two issues related as costly processing inflates prices, reduces availability and thus stunts development of new high volume uses.

Three rare earths (dysprosium, erbium and ytterbium) and thorium score only 1.5 points, the same as the lowest scoring of the non-ferrous industrial metals, tin. As for the other rare earths, these metals face both processing (Gupta and Krishnamurthy 2005; Bradsher 2009, 2013; Massari and Ruberti 2013; Packey 2013; Tyrer and Sykes 2013; Wubbeke 2013; Campbell 2014; Golev *et al.* 2014; Weng *et al.* 2014; USGS 2014, 2015; Harper *et al.* 2015) and demand (NRC 2008; Buchert *et al.* 2009; APS and MRS 2011; Goonan 2011; USDOE 2011; BGS 2012; Schulz and Bradley 2013; EC 2014; USGS 2014) constraints, but in addition also have mining issues. The mining issues relate to environmental and human rights issues associated with the mining of heavy rare earths in China (Bradsher 2009, 2013; Massari and Ruberti 2013; Packey 2013; Tyrer and Sykes 2013; Wubbeke 2013; Campbell 2014; Golev *et al.* 2014; Weng *et al.* 2014; USGS 2015), and with radioactivity for thorium (USGS 2014, 2015; Weng *et al.* 2014; Harper *et al.* 2015).

Rounding out Table 1, four of the rarest heavy rare earths: holmium, lutetium, terbium and thulium, in addition to tantalum score only 1 point. Not only are these metals rare (Rudnick and Gao 2003), and infrequently found in mineral deposits (White 2013), but they are often difficult to mine and process (Gupta and Krishnamurthy 2005; Bradsher 2009, 2013; Freedman

2011; Bleischwitz *et al.* 2012; Massari and Ruberti 2013; Packey 2013; Tyrer and Sykes 2013; Wubbeke 2013; Campbell 2014; Golev *et al.* 2014; USGS 2014, 2015; Weng *et al.* 2014). All have developed only limited demand to date (Goonan 2011; Schwela 2012).

## **Discussion, opportunities and recommendations**

This section discusses which critical metals have the potential to become major industrial metal markets, including the identification of factors constraining the growth of these markets, and therefore where opportunities for strategic intervention by researchers, companies, professional societies and governments may exist.

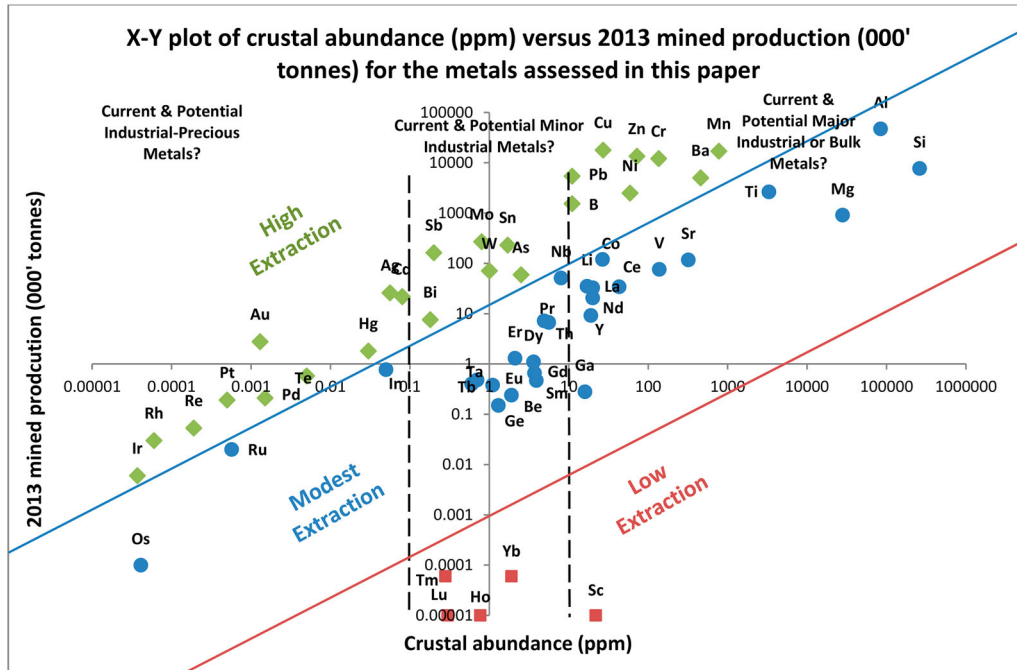
### **Potential future market sizes and values**

Although the critical metals in Table 1 which score the highest can be said to have the greatest potential market transformation, such analysis does not indicate what the potential size of a future metals market could be. As Figs. 1 and 2 demonstrate, although there is a broad correlation between crustal abundance and both mine production and market size, there are metals which are more intensively mined than others. The implication is that breakthrough in mineral discovery, extraction technology or new/increased usage could lead to substantial market growth for a commodity, moving it from one of the least intensively mined commodities in Figs. 1 and 2, to one of the most intensively mined. Thus, in addition to the analysis already covered in this paper, the future market size of a critical metal is defined by two further factors: First the fundamental crustal availability of the metal, meaning that very rare metals cannot support bulk production based markets (Skinner 1976). Second, some metals are nearer their theoretical potential production and market size limits, than other metals so have less growth potential, even if the constraints on the market can be unlocked.

Figures 1 and 2 include approximate estimates of the crustal abundance thresholds for major and minor industrial metals, and 'industrial-precious metals' (very rare metals such as platinum and silver, which nonetheless have industrial uses). It is important to note that the crustal abundance thresholds in these figures differ from those in the crustal abundance assessment summarised in Table A1. That assessment has higher crustal abundance thresholds than the approximate lines in Figs. 1 and 2, as that assessment is just an indicator of whether crustal abundance is a positive, neutral or negative factor in the potential for that metal to form a large industrial metal market. The fact that crustal abundance is a neutral or negative factor does not entirely mitigate against the mass production of that metal if other factors (concentration, extraction, demand, etc.) compensate, with copper being an obvious example. For this reason Figs. 1 and 2 have more lenient crustal abundance thresholds.

#### **Future bulk metals?**

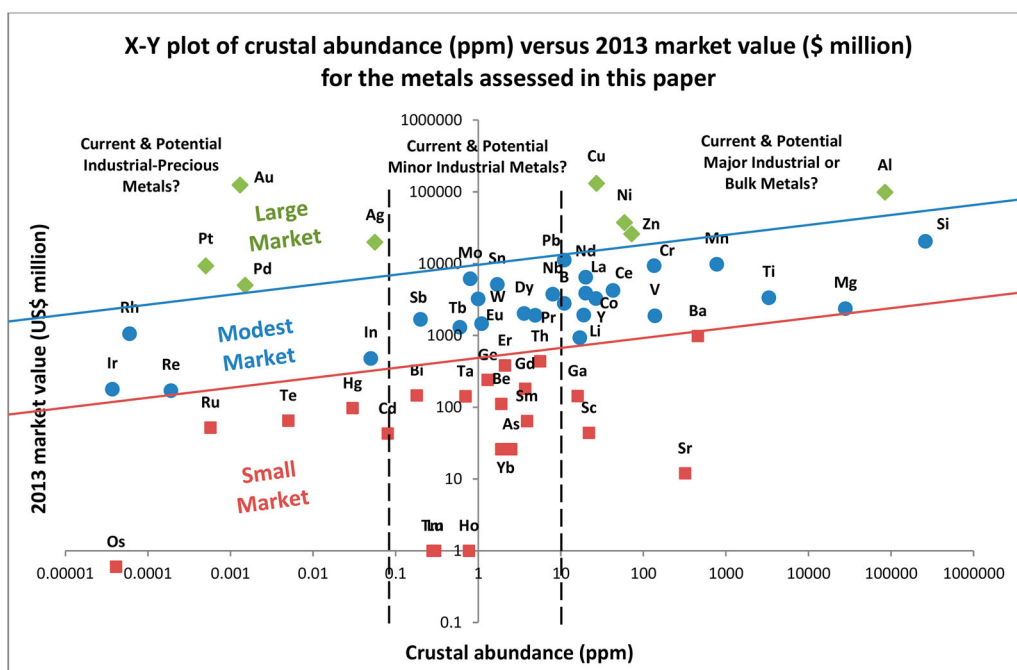
Figure 1 shows that some metals have relatively high extraction rates, including all of the metals of antiquity, thus highlighting the importance of geological availability, via a propensity to concentrate into relatively easy to discover and extract mineral deposits. By this



- 1 X-Y plot of crustal abundance against mined production levels in 2013. The figure gives an indication of how intensively the various metals are mined in comparison to their fundamental crustal availability. To assist with interpretation lines have been drawn subjectively by the authors to demonstrate which metals seem to have a low, modest or high extraction intensity, and which metals are or could be bulk or major industrial, minor industrial or 'industrial-precious' metal markets. The figure suggests that those metals with modest or low extraction rates are somewhat extraction constrained. The fact that a metal does not readily concentrate into mineral deposits is also a constraint in some cases. Data are drawn from Tables 1 and A1

assessment metals such as aluminium and titanium are still only modestly extracted in comparison to their availability, suggesting technical improvements to processing,

and to a lesser extent mining, could significantly increase the scale of these markets. Amongst the critical metals, magnesium is an even stronger example of a modestly



- 2 X-Y plot of crustal abundance against approximate market value for 2013, as calculated by multiplying annual mined production by annual average price. To assist with interpretation lines have been drawn subjectively by the authors to demonstrate which metals seem to have small, modest or large markets in comparison to their crustal abundance, and which metals are or could be major industrial, minor industrial or industrial-precious metal markets. Those metals with modest or small market sizes in comparison to crustal abundance are somewhat demand constrained. The constraint in demand may also relate to geological and technical issues that make the metal scarcer than it should be. Data are drawn from Tables 1 and A1

extracted, but geologically abundant light metal, similar to aluminium and titanium. It is notable that all of these metals suffer from energy intensive processing techniques (Street and Alexander 1998; Gao *et al.* 2009; USGS 2014, 2015), thus these markets would not only benefit from more energy efficient extraction processes, but also dramatic changes in the energy market, which made energy considerably cheaper and more available.

#### **Future major industrial metals?**

A significant number of critical metals also seem to hold the potential to become major industrial metals should their extraction constraints be overcome. Metals such as cobalt, lithium, strontium, vanadium and the more abundant light rare earths: cerium, lanthanum, neodymium and yttrium. These metals are currently produced in volumes of less than 100 000 tonnes per year, but seem to possess the potential to support production levels an order of magnitude or so higher (like copper, nickel, lead and zinc).

In addition, a number of the critical metals appear to have underdeveloped market sizes. The number of metals with a relatively large market (Fig. 2) is fewer than the number of metals produced in relatively large volumes (Fig. 1), when compared to their natural abundance. This suggests a number of these metals are constrained by a structural lack of demand (i.e. they are relatively easy to produce in abundance, but not much value is being attributed to their use). Only aluminium, copper, nickel, zinc, gold, silver, platinum and palladium seem to have relatively large markets compared to their abundance. Thus a number of the critical metals that did not seem to be 'extraction constrained' such as antimony, arsenic, barium (barite), bismuth, boron (borate), cadmium, chromium, mercury, manganese, molybdenum, tellurium and tungsten do seem to be demand constrained. These results from Figs. 1 and 2 seem to correspond with the results in Table 1 that show most of these metals having weaker scores for the demand factors but higher scores for the discovery and/or supply factors. Some of these metals are constrained with good reason, with mercury for example known to be toxic (Hylander and Meili 2005; Kim and Choi 2012), however, a number may present future demand-side opportunities. Barium (barite), boron (borate), chromium and manganese are all naturally abundant enough that they could be extracted in sufficiently large quantities should greater use be required of them. Barium (barite), chromium and manganese are all more abundant in the crust than copper, one of the largest metals markets.

#### **Future minor industrial metals?**

A range of rarer metals could form minor, but nonetheless important industrial markets, perhaps similar to the current tin, tungsten, antimony or molybdenum markets, each with annual production of an order of magnitude of 100 000 tonnes. This group of potential new minor industrial metal markets includes many of the rare earths (dysprosium, erbium, europium, gadolinium, praseodymium, samarium and terbium), but also niobium, tantalum, beryllium and germanium.

#### **Future industrial-precious metals?**

Although metals such as cadmium, indium, mercury, tellurium and the less well known platinum group metals, iridium, osmium, rhodium and ruthenium are fundamentally too rare to support the large scale production of an industrial metal, there are nonetheless a number of valuable 'industrial-precious' metals markets as potential analogues, such as silver, platinum and palladium. These metals have both industrial uses and value ascribed to their precious nature. Whilst many of the critical metals may not possess the immutable and aesthetic qualities of precious metals, increased availability of these metals should nevertheless attract more industrial uses.

#### **Unlocking future critical metal market growth**

Whilst all critical metal markets have their own individualities with respect to discovery, supply and demand constraints, it is worth considering if there are any general themes across these constraints that could be worth broad investigation.

##### **Discovery or geological constraints**

In general lithophile metals seem to remain under exploited in comparison to siderophile and chalcophile metals, the obvious exception being aluminium. Of these metals, barium (barite), boron (borate), chromium, lithium, magnesium, manganese, silicon, strontium and vanadium are abundant enough in the crust to support a major industrial metal market. Rarer metals such as beryllium, niobium, thorium, tungsten and the more common rare earths could probably support minor industrial metal markets analogous in scale to lead or tin.

##### **Supply or extraction constraints**

From a technical perspective, few critical metals seem particularly constrained by mining technology. Far more critical metals face processing issues. The majority of these relate to the fact discussed above that many are still produced as by- or co-products (Gupta and Krishnamurthy 2005; Naumov and Grinberg 2009; Alonso *et al.* 2012; Graedel *et al.* 2012, 2015; Mudd *et al.* 2013b; Werner *et al.* 2015). Further advances in hydrometallurgy that allow the separation of individual metals from complex mineral leach solutions would undoubtedly be of assistance here and would greatly benefit the rare earth metals industry (Gupta and Krishnamurthy 2005; Weng *et al.* 2014), for example.

Whilst several of the critical metals face specific processing issues it is notable that magnesium (Gao *et al.* 2009; USGS 2014, 2015) and lithium (Grosjean *et al.* 2012; USGS 2014, 2015), with the addition of the major industrial metals aluminium and titanium are all reliant on energy intensive processes. In addition, over the long-term the environmental costs of intense energy use may become as or more important than the economic costs of energy use. In general, the importance of environmental constraints on minerals processing is increasingly apparent. Metals such as thorium and mercury are commonly seen as waste elements, but are also becoming increasingly difficult to dispose of into the environment. In some cases not producing the 'waste' elements can be as important as effectively producing the primary product, blurring the relationship between what is defined as a primary product, co- or by-product and waste

(Packey 2012). Rare earth deposits with thorium rich ores would again be an example (Gupta and Krishnamurthy 2005; Weng *et al.* 2014). A number of critical metals may, in fact, remain fundamentally limited in market size due to environmental and health issues. Arsenic, beryllium, bismuth, chromium (USGS 2014, 2015), manganese (The Economist 2014) and mercury (Hylander and Meili 2005; Veiga *et al.* 2006; Spiegel and Viegä 2010; Kim and Choi 2012) are all toxic, whilst silica (to make silicon metal) also presents health issues for miners, via silicosis (Thomas and Kelley 2010).

Finally, tantalum and tungsten (and the industrial metal, tin) would benefit from the resolution of supply chain transparency issues relating to conflict minerals (Freedman 2011; Bleischwitz *et al.* 2012); however, the market growth potential of these markets is more limited.

#### **Demand or economic constraints**

The geological and supply issues highlighted above mean that many critical metals have not yet developed sufficiently diverse end use markets to support sustained and permanent market growth. However quite a few of the critical metals such as barium (barite), boron (borate), chromium, magnesium, manganese, niobium, silicon (metal), strontium and tungsten, seem somewhat underutilised from an economic perspective, according to Fig. 2. Research into new uses for these metals could be fruitful allowing utilisation of what are relatively abundant and cheap resources.

#### **Multi-factor or complex constraints**

What becomes clear from Table 1 is that whilst some metals such as antimony, barium (barite), germanium, indium and tellurium face fewer constraints on market growth, meaning one or two changes in the market factors could trigger major transformations; this is not the case for most critical metals. Most critical metal markets face more complex constraints on growth with geological, technical and economic issues often combining and holding the market back. For example, many of the heavy rare earths are not only constrained by the fundamental crustal rarity (Rudnick and Gao 2003) and the fact that they do not readily concentrate into mineral deposits (Goldschmidt 1937; White 2013), but also that the deposits they do form are currently not amenable to scalable mining techniques (Bradsher 2009, 2013; Wubbeke 2013; USGS 2015), processing is extremely complicated (Gupta and Krishnamurthy 2005; Tyrer and Sykes 2013; USGS 2014, 2015; Weng *et al.* 2014), and where mining does take place it is associated with environmental and human rights issues (Bradsher 2009, 2013; Massari and Ruberti 2013; Packey 2013; Tyrer and Sykes 2013; Wubbeke 2013; Campbell 2014; Golev *et al.* 2014; Weng *et al.* 2014). All of this is in addition to an often narrow range of economic uses (Goonan 2011). Transformational change will therefore not come in these markets unless all these constraints are addressed. Companies entering these markets will therefore need to target efforts towards resolving all of these issues (many of which are related). It is notable, for example, that the recent (re-) entrants into the rare earths market, not only possess world class mineral deposits, but have had to focus heavily on processing technology, downstream integration and to a certain extent creating demand, via research into new uses for

metals such as cerium. Similarly, government research programmes will need to address these issues in an integrated rather isolated manner.

#### **Strategic intervention in critical metals markets**

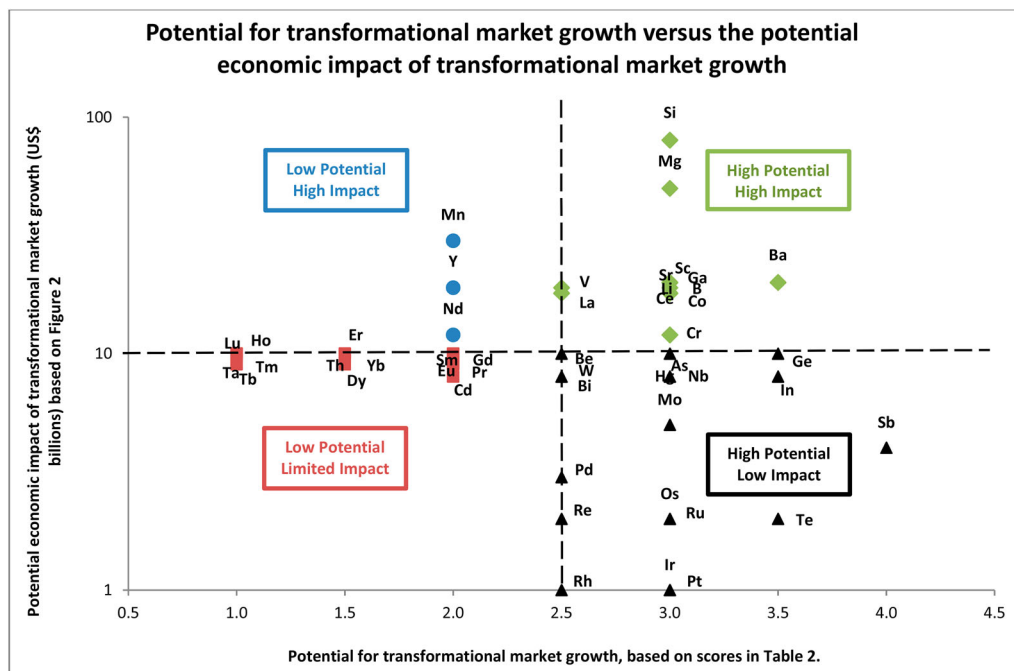
Across the critical metals markets there are those that are not only more or less unconstrained by discovery, supply or demand issues, as represented in Table 1, but also those where the potential market growth has greater or lesser potential as summarised in Fig. 2. From the perspective of companies or governments seeking to intervene in a critical metal market, with the aim of stimulating transformational growth, the ideal target market is one where not only is there high potential for transformational market growth, but also that this growth has high economic impact. This relationship is summarised in Fig. 3. These are the markets where relatively few geological, technical or economic constraints need to be overcome and which the potential future market could be large, as they are sufficiently geologically abundant.

#### **Magnesium, silicon (metal) and barium (barite)**

The three stand-out critical metals in this context are magnesium, silicon (metal) and barium (barite). Advances in processing techniques to make production of the magnesium and silicon metal much cheaper, could have the same transformational impact on these markets as occurred in aluminium in the early twentieth century (Street and Alexander 1998; Lynch 2002; Sykes *et al.* 2016). Along with titanium, which is still somewhat constrained by the Kroll process (USGS 2014, 2015), these light metals all hold the potential to be major future industrial metal markets. It is notable in this context that both silicon (USGS 2014, 2015) and titanium (USGS 2014, 2015) are mainly consumed as pre-metal raw materials (silica sand and titanium oxide), just like aluminium before the invention of the Bayer and Hall-Heroult techniques, when it was still mainly used as alum (Hammond 2015; Sykes *et al.* 2016). Improvements in barium (barite) mining would help this market; however, this metal more than many seems demand constrained, so alternatively could be a target material for research into new uses. Although the market impact would probably be less, boron (borate) is in a similar situation to barium (barite) lacking sufficient variety and importance of end uses, so again maybe a fruitful area for research into new uses.

#### **Lithium, cobalt and the cerium and lanthanum rare earths**

Lithium is another potentially significant future industrial metal market, which could be transformed one of two ways, either via the discovery of higher quality hard rock deposits amenable to conventional mining and processing techniques, or via advances in lithium brine and solar evaporation techniques (Grosjean *et al.* 2012; USGS 2014, 2015). Either way lithium already has a diverse demand base covering some important uses, particularly in battery technology (USGS 2014, 2015). Similarly cobalt and the more common rare earths, cerium, lanthanum and scandium all would benefit from processing improvements. These metals also have ready diverse demand and could plausibly be significant future industrial metal markets. Improvements in the processing of



- 3 X–Y plot of the potential for transformational market growth, based on the scores in Table 1 versus the potential market impact of such growth based on information in Fig. 2. The Y-axis provides an approximate order of magnitude growth estimate for these markets based on how far they fall under the line for a ‘large market’ in Fig. 2. From a strategic perspective commercial, government or research interventions would be best made in the ‘high potential, high impact’ markets in the upper right quadrant. Transformation of these markets may be easier as there are fewer potential constraints on those metals markets, whilst the potential future growth of those markets could be significant, providing substantial economic returns

cerium and lanthanum would also benefit the other co-occurring rare earths, some of which like neodymium and yttrium could also be large markets in themselves, adding a kind of multiplier effect to advancements in this area.

#### Chromium, vanadium and gallium

Finally, two relatively abundant, by-product ferroalloys, chromium and vanadium represent a problem facing many critical metals – that they are produced as by-products (USGS 2014, 2015). This makes the metals more difficult to process and stunts the economics of these markets. Thus the discovery of high quality primary deposits, via new deposit models or exploration targeting techniques, or improvements in processing techniques would greatly benefit these potentially important markets. Gallium, which is currently captured by proprietary processing technologies (USGS 2014) and strontium which would benefit from mechanisation of processing (USGS 2014, 2015) are both potential significant future metal markets. All of these metals however require greater diversity and intensity of use suggesting these metals would also benefit from research into new uses of these metals.

## Conclusions

This study highlights the importance of analysing critical metal markets in a forward-looking manner, and thus the potential for growing market size as a way to reduce metals criticality, instead of demand reduction solutions such as recycling, thrifting and substitution. Critical metals which hold the potential to grow beyond their

current small, niche markets into major widely-traded, industrial commodities with larger markets would be less vulnerable to some of the supply and demand uncertainties surrounding the current critical metals markets.

The study was undertaken to assess the potential for such transformational market growth across the critical metals. The crustal abundance; propensity to concentrate into mineral deposits; the ease of mining and processing; and the criticality and diversity of demand were assessed for a range of critical metals; along with a number of comparator industrial and precious metals. The methodology was contingent on the assumption that transformational market growth occurs when a number of constraints in minerals discovery and metals supply and demand are overcome together. Critical metals with the fewest constraints mitigating against their abundant discovery, supply and demand were therefore considered to be the closest to transformational market growth and scored the highest.

The study concluded that whilst most critical metals still require a number of breakthroughs for transformative market growth to occur, some did have high potential for such growth. The implication for these markets is that government, research and industry interventions to reduce ‘criticality’ may have the most impact in attempting to increase primary supply, demand and thus the overall market size, rather than reducing demand. The critical metals with the highest potential for transformational market growth are also the ones likely to be of most commercial interest to mining and exploration companies seeking potentially fast-growing metals markets.

The critical metals with the most potential for transformational market growth include magnesium, silicon,

barium, boron, lithium, cobalt, chromium, vanadium, gallium, strontium and the rare earths: cerium, lanthanum and scandium. However, the absolute economic potential for transformational market growth varies amongst these metals. Some of the rarer metals may see transformational market growth in absolute economic terms from presently 'very small' to future 'small or medium-sized' markets, whereas others may see transformational market growth from 'modest-sized' markets to 'very large' markets. Based on the market size of comparatively abundant major industrial metal markets, and the present size of their existing markets, magnesium, silicon (metal) and barium (barite) stand out as having the potential for transformational market growth with a large absolute economic impact, as summarised in Fig. 3.

Most critical metal markets, however, face more complex constraints on growth with geological, technical and economic issues often combining and holding the market back. Transformational change will therefore not come in these markets unless all these constraints are overcome. Governments and researchers will therefore need to address these issues in an integrated, rather than isolated manner, in attempting to overcome metals criticality. Similarly, for companies entering these markets hoping to benefit from rapid market growth, they will need to target efforts towards resolving all of these, often interlocking, issues before they can expect commercial success.

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## Appendix I: Detailed methodology

An overview of the study methodology follows, including the selection of metals to study; the scoring system; and how the discovery, supply and demand factors of each metal are assessed.

### Selection of metals to study

Several reports have been published compiling lists of 'critical' or 'strategic' metals to specific regions, such as the United States (NRC 2008; APS and MRS 2011; USDOE 2011; Schulz and Bradley 2013), United Kingdom (BGS 2012) and the European Union (EC 2014); or specific industries, most commonly energy (Buchert et al. 2009; USDOE 2011). The metals in these reports are summarised in Table A7.

Cadmium and vanadium are also included in this study at the authors' discretion due to their importance to the battery market (Sykes et al. 2014; USGS 2014, 2015). For completion, it is also worth noting that several non-metal minerals also make these lists, but as such are beyond the scope of this study including: carbon (as coking coal and graphite), fluorine (as fluorspar), helium, phosphorus (phosphate rock) and selenium. Similarly, the mineral magnesite for the purposes of this paper is covered by the analysis of the metal magnesium.

In addition, high-level analysis is also conducted where appropriate on some more familiar base metals (copper, lead, nickel, tin and zinc) and light metals (aluminium and titanium), as well as gold to provide comparisons to the critical metals. Silver is included in the list of critical metals, but is also a useful comparator precious metal and is used for both purposes in the study.

### Factors considered in the analytical framework

The framework is based partly on that used by rare earth specialists Gupta and Krishnamurthy (2005) to explain why rare earths are not a major industrial commodity, despite the fact that metals of similar crustal abundance, such as the base metals are major commodities. The Gupta and Krishnamurthy (2005) framework does not however consider demand, yet the historical narrative and case studies of aluminium, nickel and uranium clearly demonstrate the importance of this factor, as does conventional microeconomic theory (Samuelson and Nordhaus 2010). In particular, a major industrial metal, such as aluminium or copper, needs a broad range of uses, in addition to specific important or 'critical' applications (Sykes et al. 2016). Thus the framework used in this paper to assess whether a metal has the potential to be extracted in abundance considers whether the metal:

- Discovery
  - (i) Is relatively abundant in the crust.
  - (ii) Readily concentrates into discrete mineral deposits.

**Table A1** Abundance in the bulk continental crust of the elements assessed in this paper, drawn from Rudnick and Gao (2003) and Wedepohl (1995). The ‘abundance score’ is based on the BGS (2012) scarcity score methodology, where greater than 100 ppm is seen as low scarcity, 1–100 ppm as medium scarcity and less than 1 ppm as high scarcity. In the context of this paper, 1–100 ppm is also used as this corresponds roughly with the range of the base metals, with the scarcest, tin at 1.7 ppm and the most abundant, zinc at 72 ppm. Elements with a crustal abundance between 1 and 100 ppm are therefore given a score of 0.5, with 1 for greater than 100 ppm and 0 for less than 1 ppm

| Element      | Abundance in the bulk continental crust/ppm (Rudnick and Gao 2003) | Abundance score | Element    | Abundance in the bulk continental crust/ppm (Rudnick and Gao 2003) | Abundance score |
|--------------|--------------------------------------------------------------------|-----------------|------------|--------------------------------------------------------------------|-----------------|
| Silicon      | 261 000                                                            | 1               | Erbium     | 2.1                                                                | 0.5             |
| Aluminium    | 84 300                                                             | 1               | Beryllium  | 1.9                                                                | 0.5             |
| Magnesium    | 28 000                                                             | 1               | Ytterbium  | 1.9                                                                | 0.5             |
| Titanium     | 3310                                                               | 1               | Tin        | 1.7                                                                | 0.5             |
| Manganese    | 775                                                                | 1               | Germanium  | 1.3                                                                | 0.5             |
| Barium       | 456                                                                | 1               | Europium   | 1.1                                                                | 0.5             |
| Strontium    | 320                                                                | 1               | Tungsten   | 1                                                                  | 0.5             |
| Vanadium     | 138                                                                | 1               | Molybdenum | 0.8                                                                | 0               |
| Chromium     | 135                                                                | 1               | Holmium    | 0.77                                                               | 0               |
| Zinc         | 72                                                                 | 0.5             | Tantalum   | 0.7                                                                | 0               |
| Nickel       | 59                                                                 | 0.5             | Terbium    | 0.6                                                                | 0               |
| Cerium       | 43                                                                 | 0.5             | Lutetium   | 0.3                                                                | 0               |
| Copper       | 27                                                                 | 0.5             | Thulium    | 0.28                                                               | 0               |
| Cobalt       | 26.6                                                               | 0.5             | Antimony   | 0.2                                                                | 0               |
| Scandium     | 21.9                                                               | 0.5             | Bismuth    | 0.18                                                               | 0               |
| Lanthanum    | 20                                                                 | 0.5             | Cadmium    | 0.08                                                               | 0               |
| Neodymium    | 20                                                                 | 0.5             | Silver     | 0.056                                                              | 0               |
| Yttrium      | 19                                                                 | 0.5             | Indium     | 0.05                                                               | 0               |
| Lithium      | 17                                                                 | 0.5             | Mercury    | 0.03                                                               | 0               |
| Gallium      | 16                                                                 | 0.5             | Tellurium  | 0.005 <sup>1</sup>                                                 | 0               |
| Boron        | 11                                                                 | 0.5             | Palladium  | 0.0015                                                             | 0               |
| Lead         | 11                                                                 | 0.5             | Gold       | 0.0013                                                             | 0               |
| Niobium      | 8                                                                  | 0.5             | Ruthenium  | 0.00057                                                            | 0               |
| Thorium      | 5.6                                                                | 0.5             | Platinum   | 0.0005                                                             | 0               |
| Praseodymium | 4.9                                                                | 0.5             | Rhenium    | 0.00019                                                            | 0               |
| Samarium     | 3.9                                                                | 0.5             | Rhodium    | 0.00006 <sup>1</sup>                                               | 0               |
| Gadolinium   | 3.7                                                                | 0.5             | Osmium     | 0.000041                                                           | 0               |
| Dysprosium   | 3.6                                                                | 0.5             | Iridium    | 0.000037                                                           | 0               |
| Arsenic      | 2.5                                                                | 0.5             |            |                                                                    |                 |

<sup>1</sup>Not included in the Rudnick and Gao (2003) dataset. Figures from Wedepohl (1995) used instead.

- Supply
  - (iii) Has ores which are easy to extract from the ground (i.e. mine).
  - (iv) Has ores from which it is also easy to extract the metal, or other products of economic value (i.e. process).
- Demand
  - (v) Is in demand in ‘critical’ industrial sectors and/or uses.
  - (vi) Is in demand across a range of industrial sectors and/or uses.

**Scoring system**

For each discovery, extraction and consumption factor, each of the critical metals are assessed for their potential. A simple structure for the assessment has been applied, such that each factor is deemed to be neutral, positive or negative in respect of future market transformation potential. The analysis draws from widely available scientific and economic datasets to create a simple Bayesian influenced ranking (Lord et al. 2001; Kreuzer et al. 2009):

- *Neutral*: A score of 0.5 is the default score awarded if the information for the discovery, extraction or consumption factor does not indicate strongly whether the factor increases or decreases the economic potential of the metal (i.e. it is of modest crustal abundance). A score of 0.5 is also awarded (as the default) if there is

little or no information on that factor (i.e. the crustal abundance is not known or disputed).

- *Positive*: If a factor is considered to increase the potential for a metal to move from a minor, ‘critical’ metal market to a major, industrial metal market it scores 1 (i.e. it is very abundant in the crust).
- *Negative*: A score of 0 is awarded if the factor is seen to mitigate against the minor metal becoming industrial (i.e. it is very rare in the crust).

No scores other than 0, 0.5 or 1 are possible in order to retain simplicity. Each of the discovery, supply and demand factors is made up of two sub-factors, resulting a maximum theoretical score of 6. Such a score would indicate significant potential for this metal to transform from minor to industrial. By definition however no ‘minor’ or ‘critical’ metal should score a maximum, as such a score indicates that the metal is already a significant industrial commodity. By contrast, a score of zero is a possible outcome and indicates that any such critical metal has little potential for market transformation.

The scoring system is kept deliberately simple, even though it is likely that some of the discovery, extraction and consumption factors are likely to be relatively more important than others. This is an early-stage, high-level study and further analysis would be required to determine the relative importance of these factors which may in future justify a weighted scoring system. For the time being, in the absence of such objective studies it is best to treat all factors

**Table A2** Propensity of elements to concentrate into ore bodies in the crust. Theoretically, under Goldschmidt's classification (Goldschmidt 1937; White 2013) chalcophile and siderophile elements should more frequently form deposits than lithophile elements. Chalcophile and siderophile elements therefore score 1. Lithophile elements score 0. Elements which show both chalcophile or siderophile, in addition to lithophile properties score 0.5

| Commodity             | Goldschmidt classification in earth's crust (White 2013) | Score | Commodity         | Goldschmidt classification in earth's crust (White 2013) | Score |
|-----------------------|----------------------------------------------------------|-------|-------------------|----------------------------------------------------------|-------|
| Antimony              | Chalcophile                                              | 1     | Chromium          | Lithophile                                               | 0     |
| Arsenic               | Chalcophile                                              | 1     | Lithium           | Lithophile                                               | 0     |
| Bismuth               | Chalcophile                                              | 1     | Magnesium         | Lithophile                                               | 0     |
| Cadmium               | Chalcophile                                              | 1     | Manganese         | Lithophile                                               | 0     |
| Indium                | Chalcophile                                              | 1     | Niobium           | Lithophile                                               | 0     |
| Lead                  | Chalcophile                                              | 1     | Rare earth metals | Lithophile                                               | 0     |
| Mercury               | Chalcophile                                              | 1     | Cerium            | Lithophile                                               | 0     |
| Molybdenum            | Chalcophile                                              | 1     | Dysprosium        | Lithophile                                               | 0     |
| Rhenium               | Chalcophile                                              | 1     | Erbium            | Lithophile                                               | 0     |
| Silver                | Chalcophile                                              | 1     | Europium          | Lithophile                                               | 0     |
| Tellurium             | Chalcophile                                              | 1     | Gadolinium        | Lithophile                                               | 0     |
| Gold                  | Siderophile                                              | 1     | Holmium           | Lithophile                                               | 0     |
| Platinum group metals | Siderophile                                              | 1     | Lanthanum         | Lithophile                                               | 0     |
|                       | Iridium                                                  | 1     | Lutetium          | Lithophile                                               | 0     |
|                       | Osmium                                                   | 1     | Neodymium         | Lithophile                                               | 0     |
|                       | Palladium                                                | 1     | Praseodymium      | Lithophile                                               | 0     |
|                       | Platinum                                                 | 1     | Samarium          | Lithophile                                               | 0     |
|                       | Rhodium                                                  | 1     | Scandium          | Lithophile                                               | 0     |
|                       | Ruthenium                                                | 1     | Terbium           | Lithophile                                               | 0     |
| Cobalt                | Chalcophile and lithophile                               | 0.5   | Thulium           | Lithophile                                               | 0     |
| Copper                | Chalcophile and lithophile                               | 0.5   | Ytterbium         | Lithophile                                               | 0     |
| Gallium               | Chalcophile and lithophile                               | 0.5   | Yttrium           | Lithophile                                               | 0     |
| Germanium             | Chalcophile and lithophile                               | 0.5   | Silicon           | Lithophile                                               | 0     |
| Nickel                | Chalcophile and lithophile                               | 0.5   | Strontium         | Lithophile                                               | 0     |
| Tin                   | Chalcophile and lithophile                               | 0.5   | Tantalum          | Lithophile                                               | 0     |
| Zinc                  | Chalcophile and lithophile                               | 0.5   | Thorium           | Lithophile                                               | 0     |
| Aluminium             | Lithophile                                               | 0     | Titanium          | Lithophile                                               | 0     |
| Barium                | Lithophile                                               | 0     | Tungsten          | Lithophile                                               | 0     |
| Beryllium             | Lithophile                                               | 0     | Vanadium          | Lithophile                                               | 0     |
| Boron                 | Lithophile                                               | 0     |                   |                                                          |       |

as equally important, otherwise the weightings chosen carry the risk of being biased by the analysts' subjective views of what seems important (Kahneman and Klein 2009; Gawande 2010; Kahneman 2011). Such bias becomes prevalent when making forecasts in 'low validity' environments (Kahneman and Klein 2009; Kahneman 2011). In a low validity environment it is difficult to learn via experience, because there is a weak link between the many initial inputs to market dynamics and the one outcome of the eventual future market, thus analysts do not benefit from repeated experience of trial and error in forecasting. Under such a scenario a simple statistical approach that acknowledges the limits of current expert knowledge is preferable (Kahneman and Klein 2009; Gawande 2010; Kahneman 2011).

#### Analysing propensity for discovery

Gupta and Krishnamurthy (2005) suggest two critical high-level components that aid the discovery of metals: (i) their relative abundance in the crust, and (ii) the ease

with which the metals concentrate into discrete mineral deposits.

#### Analysing crustal abundance

The abundance of the elements in the bulk continental crust is drawn from Rudnick and Gao (2003), with the addition of rhodium and tellurium abundances sourced from Wedepohl (1995). Rudnick and Gao (2003) is used by BGS (2012) in their critical minerals assessment to assess the 'scarcity' of various elements. BGS (2012) considers elements with abundance greater than 100 ppm as low scarcity, between 1 and 100 ppm as medium scarcity and less than 1 ppm as high scarcity. The level of medium scarcity (1–100 ppm) corresponds roughly to the range of the base metals, with the scarcest, tin at 1.7 ppm and the most abundant, zinc at 72 ppm. Therefore, in this paper, elements with a crustal abundance between 1 and 100 ppm are given a score of 0.5, suggesting no distinct advantage or disadvantage stemming from their crustal abundance, with a score of 1 for greater than 100 ppm,

**Table A3** The geological constraints on the ability for a metal to be mined in great volumes. Theoretically the metals most amenable to discovery and widespread exploitation would be the abundant chalcophiles and siderophiles, though in reality none occur in this assessment. Conversely, there are some which seem fundamentally geologically constrained being of both low abundance in the crust and showing lithophile behaviour, so likely to be very diffuse in the crust. The non-critical major industrial and precious metals are highlighted in bold

|                                       |          |                                                                                                                                                                                                                                                             |                                                                      |                                                                                                                                                                                                         |
|---------------------------------------|----------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Abundance in the crust >              | High     | <b>Aluminium</b> , barium, chromium, magnesium, manganese, silicon, strontium, <b>titanium</b> , vanadium                                                                                                                                                   | n/a                                                                  | n/a<br>(theoretically the most amenable to discovery)                                                                                                                                                   |
|                                       | Moderate | Beryllium, boron, cerium (REM), dysprosium (REM), erbium (REM), europium (REM), gadolinium (REM), lanthanum (REM), lithium, neodymium (REM), niobium, praseodymium (REM), samarium (REM), scandium (REM), thorium, tungsten, ytterbium (REM), yttrium (REM) | Cobalt, <b>copper</b> , gallium, germanium, <b>nickel, tin, zinc</b> | Arsenic, <b>lead</b>                                                                                                                                                                                    |
|                                       | Low      | Holmium (REM), lutetium (REM), tantalum, terbium (REM), thulium (REM)<br>(theoretically the least amenable to discovery)                                                                                                                                    | n/a                                                                  | Antimony, bismuth, cadmium, <b>gold</b> , indium, iridium (PGM), mercury, molybdenum, osmium (PGM), palladium (PGM), platinum (PGM), rhenium, rhodium (PGM), ruthenium (PGM), <b>silver</b> , tellurium |
|                                       |          | Lithophile                                                                                                                                                                                                                                                  | Chalcophile or siderophile and lithophile                            | Chalcophile and/or siderophile                                                                                                                                                                          |
| Ability to concentrate in the crust > |          |                                                                                                                                                                                                                                                             |                                                                      |                                                                                                                                                                                                         |

suggesting advantage from crustal abundance, and 0 for less than 1 ppm, suggesting disadvantage from crustal scarcity.

#### *Analysing element concentration in the crust*

Gupta and Krishnamurthy (2005), Skinner (1976) and Graedel *et al.* (2012) highlight how crustal abundance is not the only important factor in the availability of an element for discovery in the crust and subsequent extraction; crustal concentration processes are also critical. For example, whilst many of the more familiar elements such as copper and gold readily concentrate into discrete mineral deposits, the rare earths, which are as abundant in the crust do not concentrate as effectively into discrete deposits and remain widely distributed and of more homogeneous concentration (Gupta and Krishnamurthy 2005).

The tendency of different elements to concentrate in the crust was first highlighted by Goldschmidt (1937) who classified the elements into five categories:

*Siderophiles*: with a chemical affinity to iron.

*Chalcophiles*: with a chemical affinity to sulphur.

*Lithophiles*: with a chemical affinity to silicates, and perhaps better described as 'oxyphiles' (White 2013).

*Atomophiles*: elements which are gaseous at the earth's surface.

*Biophiles*: elements commonly found in organisms.

Siderophiles are depleted in the earth's crust, concentrating instead in the iron-rich core. As a result, when they are found in the crust they have a tendency to be concentrated into discrete deposits via geological heat and pressure, 'away' from the silica (lithophile) dominant crust. Chalcophiles are preferentially partitioned into the crust, however, because they are not lithophile, again, there is a tendency for them to be concentrated away from the silica crust, into discrete ore deposits. As a result, both siderophiles and chalcophiles are commonly considered to be ore-forming elements (White 2013). By contrast, lithophile elements are found more diffusely

within the crust which is rich in silica, so less commonly concentrate into discrete deposits. Lithophiles are not commonly considered to be ore-forming elements (White 2013), though clearly they are still mined. For example, the rare earths described above are lithophile (indeed they are 'oxyphile' as described by White 2013, forming very stable oxides in the crust) and therefore found widely in the crust, but rarely in concentrated deposits. By contrast, copper and gold are chalcophile and siderophile, respectively, relatively depleted in the crust but commonly concentrating into discrete mineral deposits.

As an indication of the tendency to form mineral deposits in the crust, rather than remain fairly evenly distributed, in the scoring system, siderophile and chalcophile elements are awarded a score of 1, whilst lithophile elements are awarded a score of 0, using the updated White (2013) version of Goldschmidt's (1937) classification. Prime examples of siderophile elements that are intensively mined (excluding iron itself) include nickel and gold. Similarly copper, zinc and lead are examples of widely mined chalcophiles. Some elements such as gallium are siderophile and/or chalcophile and importantly lithophile, for which 0.5 is scored, based on the combined positive and negative potential for concentration, dependent upon geochemical situation.

A factor not included in this analysis is secondary geological enrichment processes, often via weathering which act to concentrate metals into discrete deposits; or into higher grade and nearer to the surface; and therefore more economic deposits (Goldschmidt 1937). Currently there does not seem a useful broad geological metric for assessing the general tendency of metals to be concentrates by secondary process. This however would certainly be a useful area to add to future studies.

#### *Analysing ease of extraction*

Although the geological factors of crustal abundance and concentration are important in determining the

**Table A4** The ease with which each metal can be mined, based on whether production is mainly from formalised companies and conventional open pit and underground mines, in addition to the absence of unusual environmental or socio-political problems

| Commodity      | Formalised | Conventional | Notes                                                                                                                                        | Socio-political and environmental problems | Notes                                                                                                                                                                                                                                                                                                         | Total score |
|----------------|------------|--------------|----------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|
| Aluminium      | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                    | 0                                          |                                                                                                                                                                                                                                                                                                               | 1           |
| Antimony       | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                    | 0                                          |                                                                                                                                                                                                                                                                                                               | 1           |
| Barium         | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                    | 0                                          |                                                                                                                                                                                                                                                                                                               | 1           |
| Cadmium        | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                    | 0                                          |                                                                                                                                                                                                                                                                                                               | 1           |
| Chromium       | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                    | 0                                          |                                                                                                                                                                                                                                                                                                               | 1           |
| Copper         | 0.5        | 0.5          | Source: Mudd <i>et al.</i> (2013a), USGS (2014, 2015)                                                                                        | 0                                          |                                                                                                                                                                                                                                                                                                               | 1           |
| Gallium        | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                    | 0                                          |                                                                                                                                                                                                                                                                                                               | 1           |
| Germanium      | 0.5        | 0.5          | Some germanium is recovered from fly ash, but not significant quantities (USGS 2014, 2015)                                                   | 0                                          |                                                                                                                                                                                                                                                                                                               | 1           |
| Indium         | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                    | 0                                          |                                                                                                                                                                                                                                                                                                               | 1           |
| Molybdenum     | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                    | 0                                          |                                                                                                                                                                                                                                                                                                               | 1           |
| Niobium        | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                    | 0                                          | A small amount of niobium may be associated with artisanal tantalum mining in the DRC, though there is no widespread suggestion it is a conflict mineral (Conflict Minerals Consortium 2012)                                                                                                                  | 1           |
| Rhenium        | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                    | 0                                          |                                                                                                                                                                                                                                                                                                               | 1           |
| Scandium       | 0.5        | 0.5          | Mudd and Jowitt (2014; USGS 2014)                                                                                                            | 0                                          | Scandium is not found with the other rare earths and is mined as a by-product of various ores Mudd and Jowitt (2014; USGS 2014)                                                                                                                                                                               | 1           |
| Silver         | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                    | 0                                          |                                                                                                                                                                                                                                                                                                               | 1           |
| Strontium      | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                    | 0                                          |                                                                                                                                                                                                                                                                                                               | 1           |
| Tellurium      | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                    | 0                                          |                                                                                                                                                                                                                                                                                                               | 1           |
| Vanadium       | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                    | 0                                          |                                                                                                                                                                                                                                                                                                               | 1           |
| Arsenic        | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                    | −0.5                                       | Arsenic is toxic and mining can lead to poisoning of local waters (USGS 2015)                                                                                                                                                                                                                                 | 0.5         |
| Beryllium      | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                    | −0.5                                       | Increasing controls are being placed on beryllium handling due to its toxicity (USGS 2014, 2015)                                                                                                                                                                                                              | 0.5         |
| Bismuth        | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                    | −0.5                                       | Bismuth is mainly a by-product of lead mining so has the same problems of toxicity as lead mining (USGS 2014, 2015)                                                                                                                                                                                           | 0.5         |
| Boron (borate) | 0.5        | 0            | Some boron is extracted using brine mining (USGS 2014, 2015)                                                                                 |                                            |                                                                                                                                                                                                                                                                                                               | 0.5         |
| Cobalt         | 0.5        | 0.5          | Some artisanal cobalt mining occurs in the DRC (USGS 2014, 2015)                                                                             | −0.5                                       | Cobalt is occasionally classified as a 'conflict mineral' (Cobalt Development Institute 2011)                                                                                                                                                                                                                 | 0.5         |
| Gold           | 0.5        | 0.5          | Some gold is mined artisanally and in placer but this is no longer the main source of production (Veiga <i>et al.</i> 2006; USGS 2014, 2015) | −0.5                                       | Gold is sometimes cited as a conflict mineral (Freedman 2011; Bleischwitz <i>et al.</i> 2012), whilst artisanal mining is often associated with mercury and cyanide poisoning and social problems (Hilson 2002; Hylander and Meili 2005; Veiga <i>et al.</i> 2006; Spiegel and Viega 2010; Kim and Choi 2012) | 0.5         |

(Continued)

Table A4 Continued.

| Commodity                |              | Formalised | Conventional | Notes                                                                                                                                                            | Socio-political and environmental problems | Notes                                                                                                                                                                                           | Total score |
|--------------------------|--------------|------------|--------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|
| Lead                     |              | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                                        | −0.5                                       | Lead is toxic making extraction technically and legislatively more difficult (USGS 2014, 2015)                                                                                                  | 0.5         |
| Light rare earth metals  | Cerium       | 0.5        | 0.5          | Mining of light rare earth is largely formalised, hard rock open pit mining, though a small amount comes from placer sources (USGS 2014, 2015)                   | −0.5                                       | The mining of rare earths is often associated with radioactivity (Massari and Ruberti 2013; Packey 2013; Tyrer and Sykes 2013; Wubbeke 2013; Golev <i>et al.</i> 2014; Weng <i>et al.</i> 2014) | 0.5         |
|                          | Europium     |            |              |                                                                                                                                                                  |                                            |                                                                                                                                                                                                 |             |
|                          | Gadolinium   |            |              |                                                                                                                                                                  |                                            |                                                                                                                                                                                                 |             |
|                          | Lanthanum    |            |              |                                                                                                                                                                  |                                            |                                                                                                                                                                                                 |             |
|                          | Neodymium    |            |              |                                                                                                                                                                  |                                            |                                                                                                                                                                                                 |             |
| Lithium                  | Praseodymium |            |              |                                                                                                                                                                  |                                            |                                                                                                                                                                                                 |             |
|                          | Samarium     |            |              |                                                                                                                                                                  |                                            |                                                                                                                                                                                                 |             |
| Lithium                  |              | 0.5        | 0            | About half of lithium production comes from brine mining (Erbensperger <i>et al.</i> 2005; Yaksic and Tilton 2009; Grosjean <i>et al.</i> 2012; USGS 2014, 2015) | 0                                          |                                                                                                                                                                                                 | 0.5         |
| Magnesium                |              | 0.5        | 0            | Non-Chinese (and some Chinese) magnesium production often comes from brines, though the total production is minor (Gao <i>et al.</i> 2009; USGS 2014, 2015)      | 0                                          |                                                                                                                                                                                                 | 0.5         |
| Manganese                |              | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                                        | −0.5                                       | Manganese could potentially be related to a degenerative brain dis-order, similar to Parkinson's disease, at the high exposure levels of miners (The Economist 2014)                            | 0.5         |
| Mercury                  |              | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                                        | −0.5                                       | Concerns over mercury toxicity (and its end uses) affect mining (Hylander and Meili 2005; Veiga <i>et al.</i> 2006; Spiegel and Viega 2010; Kim and Choi 2012)                                  | 0.5         |
| Nickel                   |              | 0.5        | 0.5          | Source: Mudd and Jowitt (2014), USGS (2014, 2015)                                                                                                                | −0.5                                       | Ferronickel laterite mining in Indonesia (and South East Asia) has become a shipping safety problem due to the moisture levels of ores (International Nickel Study Group 2012)                  | 0.5         |
| Platinum group metals    | Iridium      | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                                        | −0.5                                       | Platinum mining in South Africa is currently associated with violent union conflict (USGS 2014, 2015)                                                                                           | 0.5         |
|                          | Osmium       |            |              |                                                                                                                                                                  |                                            |                                                                                                                                                                                                 |             |
|                          | Palladium    |            |              |                                                                                                                                                                  |                                            |                                                                                                                                                                                                 |             |
|                          | Platinum     |            |              |                                                                                                                                                                  |                                            |                                                                                                                                                                                                 |             |
|                          | Rhodium      |            |              |                                                                                                                                                                  |                                            |                                                                                                                                                                                                 |             |
| Silicon (metal)          |              |            |              |                                                                                                                                                                  |                                            |                                                                                                                                                                                                 |             |
| Silicon (metal)          |              | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                                        | −0.5                                       | Crystalline silica mining is associated with health problems, such as silicosis (Thomas and Kelley 2010)                                                                                        | 0.5         |
| Titanium (mineral sands) |              | 0.5        | 0            | Titanium is mined heavy mineral sand (ilmenite and rutile) placers (USGS 2014, 2015)                                                                             | 0                                          |                                                                                                                                                                                                 | 0.5         |
| Tungsten                 |              | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                                        | −0.5                                       | Tungsten (as wolframite) is a 'conflict mineral' (Freedman 2011; Bleischwitz <i>et al.</i> 2012)                                                                                                | 0.5         |
| Zinc                     |              | 0.5        | 0.5          | Source: USGS (2014, 2015)                                                                                                                                        | −0.5                                       | The frequent association of zinc with lead, exposes zinc to the same mining environmental risks as lead mining (USGS 2014, 2015)                                                                | 0.5         |

|                         |                                                                                |     |     |                                                                                                                                                                                                                                                                    |      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |   |
|-------------------------|--------------------------------------------------------------------------------|-----|-----|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---|
| Heavy rare earth metals | Dysprosium<br>Erbium<br>Holmium<br>Lutetium<br>Terbium<br>Thulium<br>Ytterbium | 0   | 0   | Most heavy rare earths are still produced by a partly formalised, Chinese private sector, using basic leaching techniques (Bradsher <a href="#">2009, 2013</a> ; Tyrer and Sykes <a href="#">2013</a> ; Wubbeke <a href="#">2013</a> ; USGS <a href="#">2015</a> ) | –1   | The mining of rare earths is often associated with radioactivity (Massari and Ruberti <a href="#">2013</a> ; Packey <a href="#">2013</a> ; Tyrer and Sykes <a href="#">2013</a> ; Wubbeke <a href="#">2013</a> ; Golev <i>et al.</i> <a href="#">2014</a> ; Weng <i>et al.</i> <a href="#">2014</a> ).<br>In addition, the mining of heavy rare earths In China is associated with human rights and environmental problems (Bradsher <a href="#">2009, 2013</a> ; Massari and Ruberti <a href="#">2013</a> ; Packey <a href="#">2013</a> ; Tyrer and Sykes <a href="#">2013</a> ; Wubbeke <a href="#">2013</a> ; Campbell <a href="#">2014</a> ; Golev <i>et al.</i> <a href="#">2014</a> ) | 0 |
| Yttrium                 |                                                                                | 0.5 | 0   | Some yttrium is mined from placers in India and China (USGS <a href="#">2014, 2015</a> )                                                                                                                                                                           | –0.5 | The mining of rare earths is often associated with radioactivity (Massari and Ruberti <a href="#">2013</a> ; Packey <a href="#">2013</a> ; Tyrer and Sykes <a href="#">2013</a> ; Wubbeke <a href="#">2013</a> ; Golev <i>et al.</i> <a href="#">2014</a> ; Weng <i>et al.</i> <a href="#">2014</a> )                                                                                                                                                                                                                                                                                                                                                                                       | 0 |
| Tantalum                |                                                                                | 0   | 0.5 | About half of tantalum mining is artisanal (USGS <a href="#">2014, 2015</a> )                                                                                                                                                                                      | –0.5 | Tantalum (as tantalite) is a 'conflict mineral' (Freedman <a href="#">2011</a> ; Bleischwitz <i>et al.</i> <a href="#">2012</a> )                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 0 |
| Thorium                 |                                                                                | 0.5 | 0   | Thorium is mined from monazite heavy mineral sand placers (USGS <a href="#">2014, 2015</a> )                                                                                                                                                                       | –0.5 | Thorium is radioactive (Weng <i>et al.</i> <a href="#">2014</a> ; Harper <i>et al.</i> <a href="#">2015</a> )                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | 0 |
| Tin                     |                                                                                | 0   | 0   | A significant proportion of tin mining is artisanal and/or placer mining (Kettle <i>et al.</i> <a href="#">2014a, 2014b</a> ; USGS <a href="#">2014, 2015</a> ; Gardiner <i>et al.</i> <a href="#">2015</a> )                                                      | –0.5 | Tin (as cassiterite) is a 'conflict mineral' (Freedman <a href="#">2011</a> ; Bleischwitz <i>et al.</i> <a href="#">2012</a> ; Kettle <i>et al.</i> <a href="#">2014b</a> ; Gardiner <i>et al.</i> <a href="#">2015</a> ).<br>Small scale tin mining is under environmental pressure in China (Kettle <i>et al.</i> <a href="#">2014b</a> ).<br>Placer tin mining in Indonesia is coming under environmental and socio-political pressure (Hodal <a href="#">2012</a> ; Shaikh <a href="#">2014</a> )                                                                                                                                                                                       | 0 |

**Table A5** The ease with which each metal can be processed, based on whether the metal is mainly produced as a by-product, which greatly complicates both the technical and economic aspects of processing and metallurgy. In addition, the presence of known technical processing difficulties and the presence of unusual environmental or socio-political problems are also considered, all as negatives

| Commodity  | Mined mainly as by- or co-product                                                              | Score | Known processing problems                                                                                                                                                                                                                 | Score | Known socio-political or environmental problems                                                                                                                                                                                                                                            | Score | Total Score |
|------------|------------------------------------------------------------------------------------------------|-------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------------|
| Antimony   | No (USGS 2014, 2015)                                                                           | 1     |                                                                                                                                                                                                                                           |       |                                                                                                                                                                                                                                                                                            |       | 1           |
| Barium     | No (USGS 2014, 2015)                                                                           | 1     |                                                                                                                                                                                                                                           |       |                                                                                                                                                                                                                                                                                            |       | 1           |
| Boron      | No (USGS 2014, 2015)                                                                           | 1     |                                                                                                                                                                                                                                           |       |                                                                                                                                                                                                                                                                                            |       | 1           |
| Copper     | No (Mudd <i>et al.</i> 2013a; USGS 2014, 2015)                                                 | 1     |                                                                                                                                                                                                                                           |       |                                                                                                                                                                                                                                                                                            |       | 1           |
| Niobium    | No (USGS 2014, 2015)                                                                           | 1     |                                                                                                                                                                                                                                           |       | A small amount of niobium may be associated with artisanal tantalum mining in the DRC, though there is no widespread suggestion it is a conflict mineral (Conflict Minerals Consortium 2012)                                                                                               |       | 1           |
| Aluminium  | No (USGS 2014, 2015)                                                                           | 1     |                                                                                                                                                                                                                                           |       | Aluminium smelting is very energy intensive creating both cost and environmental issues (Street and Alexander 1998; USGS 2014, 2015)                                                                                                                                                       | −0.5  | 0.5         |
| Chromium   | No – but increasingly a by-product of platinum (USGS 2014, 2015)                               | 1     |                                                                                                                                                                                                                                           |       | Some chromium compounds are very toxic leading to strict environmental and health controls (USGS 2015)                                                                                                                                                                                     | −0.5  | 0.5         |
| Gold       | No (USGS 2014, 2015)                                                                           | 1     |                                                                                                                                                                                                                                           |       | Gold is sometimes cited as a conflict mineral (Freedman 2011; Bleischwitz <i>et al.</i> 2012). Artisanal mining of gold is often associated with mercury and cyanide poisoning (Hilson 2002; Hylander and Meili 2005; Veiga <i>et al.</i> 2006; Spiegel and Viega 2010; Kim and Choi 2012) | −0.5  | 0.5         |
| Lithium    | No (USGS 2014, 2015)                                                                           | 1     | Solar evaporation during lithium processing is lengthy and difficult (Grosjean <i>et al.</i> 2012; USGS 2014, 2015). Research underway to extract it from seawater (Yaksic and Tilton 2009; Grosjean <i>et al.</i> 2012; USGS 2014, 2015) | −0.5  |                                                                                                                                                                                                                                                                                            |       | 0.5         |
| Magnesium  | No (USGS 2014, 2015)                                                                           | 1     | Pidgeon process for magnesium is energy intensive (Gao <i>et al.</i> 2009; USGS 2014, 2015). Research underway to extract it from seawater (USGS 2014, 2015)                                                                              | −0.5  |                                                                                                                                                                                                                                                                                            |       | 0.5         |
| Mercury    | No – though increasingly as a by-product of metal ores (USGS 2014, 2015)                       | 1     |                                                                                                                                                                                                                                           |       | Concerns over mercury toxicity (and its end uses) affect mining (Hylander and Meili 2005; Veiga <i>et al.</i> 2006; Spiegel and Viega 2010; Kim and Choi 2012)                                                                                                                             | −0.5  | 0.5         |
| Molybdenum | Yes – molybdenum is produced as a primary product and a by-product of copper (USGS 2014, 2015) | 0.5   |                                                                                                                                                                                                                                           |       |                                                                                                                                                                                                                                                                                            |       | 0.5         |

|                       |                                                                                                                   |   |                                                                                                                                                      |      |                                                                                                                                                                      |          |
|-----------------------|-------------------------------------------------------------------------------------------------------------------|---|------------------------------------------------------------------------------------------------------------------------------------------------------|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|
| Nickel                | No (Mudd and Jowitt 2014; USGS 2014, 2015)                                                                        | 1 | The processing of nickel laterite ores has remained problematic (King 2005; Kyle 2010; Mudd 2010; Mudd and Jowitt 2014)                              | −0.5 |                                                                                                                                                                      | 0.5      |
| Silicon (metal)       | No (USGS 2014, 2015)                                                                                              | 1 |                                                                                                                                                      |      | Crystalline silica mining is associated with health problems, such as silicosis (Thomas and Kelley 2010)                                                             | −0.5 0.5 |
| Strontium             | No (USGS 2014, 2015)                                                                                              | 1 | Hand sorting is still required at some strontium mines (USGS 2015)                                                                                   | −0.5 |                                                                                                                                                                      | 0.5      |
| Tungsten              | No (USGS 2014, 2015)                                                                                              | 1 |                                                                                                                                                      |      | Tungsten (as wolframite) is a 'conflict mineral' (Freedman 2011; Bleischwitz <i>et al.</i> 2012)                                                                     | −0.5 0.5 |
| Arsenic               | Yes – non-ferrous metal and gold ores (USGS 2014, 2015)                                                           | 0 | Source: USGS (2014, 2015)                                                                                                                            |      | Arsenic is toxic, presenting environmental and health problems near processing sites (USGS 2014, 2015)                                                               | −0.5 0   |
| Beryllium             | No (USGS 2014, 2015)                                                                                              | 1 | Hand sorting is still required at some beryllium mines (USGS 2014)                                                                                   | −0.5 | Beryllium is toxic meaning various environmental controls are in place for the release of beryllium bearing dusts, fumes and mists (USGS 2014, 2015)                 | −0.5 0   |
| Bismuth               | Yes – usually lead, but also fluorspar, tin and tungsten, and occasionally as a primary product (USGS 2014, 2015) | 0 |                                                                                                                                                      |      | Bismuth is usually a by-product of lead mining and processing, presenting the same environmental and health problems as lead (USGS 2015)                             | −0.5 0   |
| Cadmium               | Yes – zinc refining (USGS 2014, 2015)                                                                             | 0 |                                                                                                                                                      |      |                                                                                                                                                                      | 0        |
| Cobalt                | Yes – copper, nickel and platinum, as well as primary ores (USGS 2014, 2015)                                      | 0 | Producing cobalt from nickel–cobalt laterites still faces commercial challenges (King 2005; Kyle 2010; Mudd 2010)                                    | −0.5 | Cobalt is occasionally classified as a 'conflict mineral' (Cobalt Development Institute 2011)                                                                        | −0.5 0   |
| Gallium               | Yes – bauxite and zinc (USGS 2014, 2015)                                                                          | 0 | Key gallium processing technologies are still proprietary (USGS 2014)                                                                                | −0.5 |                                                                                                                                                                      | 0        |
| Germanium             | Yes – zinc and coal fly ash (Fink and Culver-Hopper 1991; USGS 2014, 2015)                                        | 0 |                                                                                                                                                      |      |                                                                                                                                                                      | 0        |
| Indium                | Yes – zinc (Alfantazi and Moskalyk 2003; USGS 2014, 2015; Werner <i>et al.</i> 2015)                              | 0 |                                                                                                                                                      |      |                                                                                                                                                                      | 0        |
| Lead                  | Yes – zinc and occasionally silver and copper (USGS 2014, 2015)                                                   | 0 |                                                                                                                                                      |      | Lead is poisonous presenting environmental and health concerns during processing, particularly smelting (USGS 2014, 2015)                                            | −0.5 0   |
| Manganese             | No, commonly found with iron ores, but not generally mined as a by-product (USGS 2014, 2015; Assmang 2015)        | 1 | Manganese mineralogy can be very complex and laden with iron (Assmang 2015). Ferro-manganese production can be energy intensive (Mining Weekly 2012) | −0.5 | Manganese could potentially be related to a degenerative brain dis-order, similar to Parkinson's disease, at the high exposure levels of miners (The Economist 2014) | −0.5 0   |
| Platinum group metals | Iridium<br>Osmium<br>Palladium<br>Platinum<br>Rhodium<br>Ruthenium                                                | 0 | Yes – PGMs are mined as co- and by-products of each other and occasionally of nickel and copper (USGS 2014, 2015)                                    |      |                                                                                                                                                                      | 0        |

(Continued)

Table A5 Continued.

| Commodity                           | Mined mainly as by- or co-product                                                                                     | Score                                                                                                                                                                                                   | Known processing problems                                                                                                                                                                                                             | Score | Known socio-political or environmental problems                                                                                                                                                                                                                                                                                                                                                                                                                    | Score | Total Score |
|-------------------------------------|-----------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------------|
| Rare earth elements (exc. scandium) | Cerium                                                                                                                | Yes – REEs are mined as co- and by-products of each other, in addition to other metals and minerals including iron ore, heavy mineral sands and uranium (Gupta and Krishnamurthy 2005; USGS 2014, 2015) | Commercial rare earths processing still not well understood, deposits often require unique processing routes and have complex mineralogy (Gupta and Krishnamurthy 2005; Tyrer and Sykes 2013; Weng <i>et al.</i> 2014)                | −0.5  | The mining of rare earths is often associated with radioactivity (Massari and Ruberti 2013; Packey 2013; Tyrer and Sykes 2013; Wubbeke 2013; Golev <i>et al.</i> 2014; Weng <i>et al.</i> 2014).<br><br>In addition, the mining of heavy rare earths In China is associated with human rights and environmental problems (Bradsher 2009, 2013; Massari and Ruberti 2013; Packey 2013; Tyrer and Sykes 2013; Wubbeke 2013; Campbell 2014; Golev <i>et al.</i> 2014) | −1    | 0           |
|                                     | Dysprosium                                                                                                            |                                                                                                                                                                                                         |                                                                                                                                                                                                                                       |       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0     |             |
|                                     | Erbium                                                                                                                |                                                                                                                                                                                                         |                                                                                                                                                                                                                                       |       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0     |             |
|                                     | Europium                                                                                                              |                                                                                                                                                                                                         |                                                                                                                                                                                                                                       |       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0     |             |
|                                     | Gadolinium                                                                                                            |                                                                                                                                                                                                         |                                                                                                                                                                                                                                       |       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0     |             |
|                                     | Holmium                                                                                                               |                                                                                                                                                                                                         |                                                                                                                                                                                                                                       |       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0     |             |
|                                     | Lanthanum                                                                                                             |                                                                                                                                                                                                         |                                                                                                                                                                                                                                       |       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0     |             |
|                                     | Lutetium                                                                                                              |                                                                                                                                                                                                         |                                                                                                                                                                                                                                       |       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0     |             |
|                                     | Neodymium                                                                                                             |                                                                                                                                                                                                         |                                                                                                                                                                                                                                       |       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0     |             |
|                                     | Praseodymium                                                                                                          |                                                                                                                                                                                                         |                                                                                                                                                                                                                                       |       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0     |             |
|                                     | Samarium                                                                                                              |                                                                                                                                                                                                         |                                                                                                                                                                                                                                       |       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0     |             |
|                                     | Terbium                                                                                                               |                                                                                                                                                                                                         |                                                                                                                                                                                                                                       |       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0     |             |
|                                     | Thulium                                                                                                               |                                                                                                                                                                                                         |                                                                                                                                                                                                                                       |       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0     |             |
|                                     | Ytterbium                                                                                                             |                                                                                                                                                                                                         |                                                                                                                                                                                                                                       |       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0     |             |
|                                     | Yttrium                                                                                                               |                                                                                                                                                                                                         |                                                                                                                                                                                                                                       |       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0     |             |
| Rhenium                             | Yes – copper and molybdenum (USGS 2014, 2015)                                                                         | 0                                                                                                                                                                                                       |                                                                                                                                                                                                                                       |       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0     |             |
| Scandium                            | Yes – various ores including iron, tin, tungsten, nickel, cobalt and uranium (Mudd and Jowitt 2014; USGS 2014)        | 0                                                                                                                                                                                                       |                                                                                                                                                                                                                                       |       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0     |             |
| Silver                              | Yes – more than half of silver is mined as a by-product of lead-zinc, copper or gold mining (USGS 2014, 2015)         | 0                                                                                                                                                                                                       |                                                                                                                                                                                                                                       |       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0     |             |
| Tantalum                            | Yes – some primary, some by-product of niobium and tin (USGS 2014, 2015)                                              | 0.5                                                                                                                                                                                                     |                                                                                                                                                                                                                                       |       | Tantalum (as tantalite) is a 'conflict mineral' (Freedman 2011; Bleischwitz <i>et al.</i> 2012)                                                                                                                                                                                                                                                                                                                                                                    | −0.5  | 0           |
| Tellurium                           | Yes – from copper refining, plus some other base metals though some primary mines in China (USGS 2014, 2015)          | 0                                                                                                                                                                                                       | Tellurium is mainly recovered from slimes during copper refining, the use of which is potentially in decline as relatively more copper is processed via SXEW, than smelting-refining (Naumov and Grinberg 2009; USGS 2014, 2015)      | −0.5  |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 0     |             |
| Thorium                             | Yes – tin, titanium, rare earths and other heavy mineral sands and ores (USGS 2014, 2015)                             | 0                                                                                                                                                                                                       |                                                                                                                                                                                                                                       |       | Thorium is radioactive (Weng <i>et al.</i> 2014; Harper <i>et al.</i> 2015)                                                                                                                                                                                                                                                                                                                                                                                        | −0.5  | 0           |
| Tin                                 | No (USGS 2014, 2015)                                                                                                  | 1                                                                                                                                                                                                       |                                                                                                                                                                                                                                       |       | Tin (as cassiterite) is a conflict mineral (Freedman 2011; Bleischwitz <i>et al.</i> 2012; Kettle <i>et al.</i> 2014b; Gardiner <i>et al.</i> 2015).<br>Human rights and environmental problems have been highlighted in Indonesia (Hodal 2012; Shaikh 2014)                                                                                                                                                                                                       | −1    | 0           |
| Titanium (mineral sands)            | Yes – titanium minerals are co- and by-products of each other and other heavy minerals, i.e. zircon (USGS 2014, 2015) | 0                                                                                                                                                                                                       | Government and private industry recognises the need to find lower cost commercial scale methods of making titanium metal than the Kroll Process (USGS 2014, 2015).<br>Recovery from seawater is under investigation (USGS 2014, 2015) | −0.5  |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |       | 0           |

|                                                                                                                                |                                                                                                                                                  |   |      |
|--------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|---|------|
| Vanadium                                                                                                                       | Yes – usually phosphate, sometimes titanium minerals and uranium, plus some by-product from steelmaking and petroleum refining (USGS 2014, 2015) | 0 | 0    |
| Zinc                                                                                                                           | Yes – lead (USGS 2014, 2015)                                                                                                                     | 0 | –0.5 |
| Zinc is usually mined as co-product with lead, presenting the same environmental and health problems as lead (USGS 2014, 2015) |                                                                                                                                                  |   | 0    |

availability of a metal, they do not fully explain the supply-side story. Firstly, the two simple datasets cannot possibly cover all the geoscientific subtleties of ore deposit formation. Secondly, these datasets do not consider the technological advances that have occurred which may have overcome some of the geological restrictions on the availability of the metal. As the case of aluminium shows, some lithophiles are also mined widely despite the fact that they do not always readily concentrate into discrete deposits within the crust. The next stage of the assessment therefore aims to consider both what is happening practically in the mining industry, which may run counter to the theoretical predictions of geological availability, if the datasets miss a key geological subtlety or if technological advancement for the extraction of that metal has been particularly successful.

Gupta and Krishnamurthy (2005) suggest two critical high-level components that aid the extraction of metals – the ease of removing the ore from the ground (i.e. mining) and the ease of separating the metal from the ore (i.e. processing). Both the ease of mining and ease of processing were analysed and scored for each of the metals and the study, using the methodologies outlined below.

### Analysing ease of mining

Modern mining is based on the economics of scale and technological development (Gordon 1985) that accompany formalised, hard rock mining, either via open pit or underground development. Although, such mining is capital intensive (Maxwell and Guj 2013) it facilitates overall significantly lower operating costs, which in turn allows the extraction of minerals at fundamentally lower costs, hence lower prices, providing lower cost resources to the wider economy and stimulating economic growth. Key enablers for such capital investment include modern, large corporations (Maxwell and Guj 2013) and the formalisation of property rights to creates stable investment conditions (Geenan 2012; Maxwell and Guj 2013). In addition, it seems that hard rock deposits are both generally larger in scale and easier to accurately determine reserves and resources. For example, whilst Indonesia produces as much tin as the major hard rock tin deposits in Peru, China and Myanmar, the production from Indonesia is based on hundreds, or even thousands, of small placer deposits, whilst production in Myanmar and Peru, is currently based largely on one hard rock deposit, and China on a small number of hard rock deposits (Sykes and Kettle 2014; Kettle et al. 2014a, 2014b; Gardiner et al. 2015). Similar, the production forecasts for placer based tin are frequently wrong as the lack of reliable resource information makes such forecasting difficult (Sykes and Kettle 2014; Kettle et al. 2014a, 2014b; Gardiner et al. 2015). In summary, commodities that are mined using hard rock techniques by large, formal companies with access to significant capital are therefore more amenable to mining in large volumes.

The ease of mining is therefore scored on the basis of whether the industry is dominated by formalised and hard rock (either open pit or underground) mining. A metal which is largely mined both by formal companies utilising hard rock mines scores 1. If the commodities’ mining industry is largely informal or else not usually extracted using conventional hard rock mining to facilitate scale economies, 0.5 is subtracted for each of these

**Table A6** The extraction constraints on a metal being mined in large volumes. Those metals which are easiest to mine and process have the greatest potential for large scale extraction, conversely those which are both difficult to mine and process have the least potential for large scale extraction. Some metals are solely mining constrained, whilst others are solely processing constrained, the resolution of this constraint would also make them amenable to large scale production. The non-critical major industrial and precious metals are highlighted in bold

|                         |                                                                                          |                                                                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|-------------------------|------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Mining constraints>     | <i>Mining constrained:</i>                                                               |                                                                                      | <i>Extraction (mining and processing) constrained:</i><br>dysprosium (REM), erbium (REM), holmium (REM), lutetium (REM), tantalum, terbium (REM), thorium, thulium (REM), <b>tin</b> , ytterbium (REM), yttrium (REM) Arsenic, beryllium, bismuth, cerium (REM), cobalt, europium (REM), gadolinium (REM), iridium (PGM), lanthanum (REM), <b>lead</b> , manganese, neodymium (REM), osmium (PGM), palladium (PGM), platinum (PGM), praseodymium (REM), rhodium (PGM), ruthenium (PGM), samarium (REM), <b>titanium (mineral sands)</b> , <b>zinc</b><br><i>Processing constrained:</i> cadmium, gallium, germanium, indium, rhenium, scandium (REM), silver, tellurium, vanadium |
|                         | Boron (borate)                                                                           | <b>Gold</b> , lithium, magnesium, mercury, <b>nickel</b> , silicon (metal), tungsten |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|                         | <i>Not extraction constrained:</i><br>Antimony, barium (barite), <b>copper</b> , niobium | <b>Aluminium</b> , chromium, molybdenum, strontium                                   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| Processing constraints> |                                                                                          |                                                                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |

imposts, making a total subtraction of 1, bringing the score to 0.5 for one incidence and 0 for both incidences.

In addition to the absence of formalised, hard rock mining there are other environmental and socio-political factors which can heavily mitigate against more widespread mining of a metal, especially if the industry is currently very concentrated on one troublesome geographical area (Graedel *et al.* 2015) or troublesome type of deposit. Indeed this is a potential type of criticality which groups such as the European Commission (2014) particularly focus upon. Two of the most prevalent examples of this type are the presence of radioactive ores, which both make the ore technically more difficult to extract and potentially increase the likelihood of local socio-political problems (Weng *et al.* 2014). The second is the ‘conflict minerals’ issue (Tshitereke 2003; Freedman 2011; Bleischwitz *et al.* 2012; Geenan 2012; Kettle *et al.* 2014b) which is restricting the mining of a number of metals in the Great Lakes region of Central Africa, particularly the Democratic Republic of Congo, and has echoes of problems that faced the diamonds industry in the late twentieth and early twenty-first century (Wright 2004).

The presence of a major environmental or socio-political factor that is currently widespread across the mining industry of a particular critical metal reduces the score by 0.5. This further subtraction is in addition to the scoring above for the presence of formalised, hard rock mining. Though in theory the cumulative subtractions could total more than 1, for simplicity only a minimum score of 0 is possible. Negative scores are not possible.

The relevant chapters of the United States Geological Survey (USGS) Mineral Commodity Summaries (2014) and Minerals Yearbook (2015) are used as the general references, in addition to a few select sources on specific subjects relating to some metals.

*Analysing ease of processing*

One potential consequence of metals not concentrating easily into deposits in the crust is that end up most frequently being found as by-products and co-products, and less often as the primary product, mitigating against more abundant mining, for both technical and economic

reasons (Gupta and Krishnamurthy 2005; Naumov and Grinberg 2009; Alonso *et al.* 2012; Graedel *et al.* 2012; Packey 2012; Mudd *et al.* 2013b; Graedel *et al.* 2015; Werner *et al.* 2015). An example of this would be the rare earth metals, which although as abundant in the crust as the base metals, are not mined anywhere near as greater volume. Their co-product status which makes rare earths metallurgy and mineral processing extraordinarily complicated (Gupta and Krishnamurthy 2005; Alonso *et al.* 2012; Tyrer and Sykes 2013; Weng *et al.* 2014). It is impossible to optimise all product streams, so inevitably the recovery and quality of some final metal products are reduced, at the expense of improved quality and recovery of others. The ones that are effectively optimised for, than drive decision making about plant feed, thus, for example, if the price of the now primary product rises, production may be increased, leading also to increased production of the by-product, even if the by-product market is currently over-supplied. Similarly, multiple metal product streams can often lead to cross-contamination of one product with other products, or even build ups of deleterious elements in one product or another. This can result in lower received sale prices, or costly further processing of a product stream to improve product quality. As such, by-product and co-product metals present economic and technical processing challenges, and thus the by-product or co-product nature of a metal can be a partial cause of criticality.

To analyse the ease of processing a metal then the first factor considered is whether the metal is more generally mined as a co- or by-product, or as a primary product. The relevant chapters of the USGS Mineral Commodity Summaries (2014) and Minerals Yearbook (2015) are again used as the source material for determining whether an element is generally mined as a by- or co-product.

If the element is mined mainly as a primary product it scores 1. Similarly, if the element is still most commonly mined as a co- or by-product it scores 0. For commodities where the case is not clear, for example if sometimes it is mined as a primary product and sometimes as a by-product, then a neutral score of 0.5 is awarded.

As with mining, metals that require non-conventional or otherwise difficult techniques for processing may not be produced in as large volumes. Using the USGS

**Table A7** Summary of the metals and minerals included on seven different critical minerals lists, as well as indication of the frequency of appearance by each metal or mineral. Details of whether the metal is included in this study are also included. The more familiar base, precious and light industrial metals also assessed in the study, for purposes of comparison with the less familiar critical metals are also included in the table. The final column refers to the score each of the metals included in the study gains for its 'criticality of use', as explained in the methodology section and discussed in the results section

| Commodity                | Source                |                            |                                 |              |               |                                        |                              | Frequency on<br>'criticality' lists | Included in<br>this paper | Criticality of<br>use score |
|--------------------------|-----------------------|----------------------------|---------------------------------|--------------|---------------|----------------------------------------|------------------------------|-------------------------------------|---------------------------|-----------------------------|
|                          | APS and MRS<br>(2011) | BGS<br>(2012) <sup>1</sup> | Buchert<br><i>et al.</i> (2009) | EC<br>(2014) | NRC<br>(2008) | Schulz and<br>Bradley (2013)<br>(USGS) | USDOE<br>(2011) <sup>2</sup> |                                     |                           |                             |
| Aluminium                |                       |                            |                                 |              |               |                                        |                              | 0                                   | X                         | 0                           |
| Antimony                 |                       |                            | X                               |              | X             |                                        |                              | 2                                   | X                         | 0.5                         |
| Arsenic                  |                       |                            | X                               |              |               |                                        |                              | 1                                   | X                         | 0.5                         |
| Barium                   |                       |                            | X                               |              |               |                                        |                              | 1                                   | X                         | 0.5                         |
| Beryllium                |                       |                            | X                               |              | X             |                                        |                              | 2                                   | X                         | 0.5                         |
| Bismuth                  |                       |                            | X                               |              |               |                                        |                              | 1                                   | X                         | 0.5                         |
| Boron (borate)           |                       |                            |                                 |              | X             |                                        |                              | 1                                   | X                         | 0.5                         |
| Cadmium                  |                       |                            |                                 |              |               |                                        |                              | 0                                   | X                         | 0                           |
| Chromium                 |                       |                            |                                 |              | X             |                                        |                              | 1                                   | X                         | 0.5                         |
| Coal (coking)            |                       |                            |                                 |              | X             |                                        |                              | 1                                   |                           | n/a                         |
| Cobalt                   |                       | X                          | X                               | X            | X             |                                        |                              | 4                                   | X                         | 1                           |
| Copper                   |                       |                            |                                 |              |               |                                        |                              | 0                                   | X                         | 0                           |
| Fluorspar                |                       |                            |                                 |              | X             |                                        |                              | 1                                   |                           | n/a                         |
| Gallium                  |                       | X                          | X                               | X            | X             |                                        | X                            | 5                                   | X                         | 1                           |
| Germanium                |                       | X                          | X                               | X            | X             |                                        |                              | 4                                   | X                         | 1                           |
| Gold                     |                       |                            |                                 |              |               |                                        |                              | 0                                   | X                         | n/a                         |
| Graphite<br>(natural)    |                       |                            | X                               |              | X             |                                        |                              | 2                                   |                           | n/a                         |
| Helium                   |                       | X                          |                                 |              |               |                                        |                              | 1                                   |                           | n/a                         |
| Indium                   |                       | X                          | X                               | X            | X             | X                                      | X                            | 6                                   | X                         | 1                           |
| Lead                     |                       |                            |                                 |              |               |                                        |                              | 0                                   | X                         | 0                           |
| Lithium                  |                       | X                          |                                 | X            |               |                                        | X                            | 4                                   | X                         | 1                           |
| Magnesite                |                       |                            |                                 |              | X             |                                        |                              | 1                                   |                           | n/a                         |
| Magnesium                |                       |                            | X                               |              | X             |                                        |                              | 2                                   | X                         | 0.5                         |
| Mercury                  |                       |                            | X                               |              |               |                                        |                              | 1                                   | X                         | 0.5                         |
| Manganese                |                       |                            |                                 |              |               | X                                      |                              | 1                                   | X                         | 0.5                         |
| Molybdenum               |                       |                            | X                               |              |               |                                        |                              | 1                                   | X                         | 0.5                         |
| Nickel                   |                       |                            |                                 |              |               |                                        |                              | 0                                   | X                         | 0                           |
| Niobium                  |                       |                            | X                               |              | X             | X                                      | X                            | 4                                   | X                         | 0.5                         |
| Platinum group<br>metals | Iridium               | X                          | X                               | X            | X             | X                                      | X                            | 6                                   | X                         | 1                           |
|                          | Osmium                | X                          | X                               | X            | X             | X                                      | X                            | 6                                   | X                         | 1                           |
|                          | Palladium             | X                          | X                               | X            | X             | X                                      | X                            | 6                                   | X                         | 1                           |
|                          | Platinum              | X                          | X                               | X            | X             | X                                      | X                            | 6                                   | X                         | 1                           |
|                          | Rhodium               | X                          | X                               | X            | X             | X                                      | X                            | 6                                   | X                         | 1                           |
|                          | Ruthenium             | X                          | X                               | X            | X             | X                                      | X                            | 6                                   | X                         | 1                           |

(Continued)

Table A7 Continued.

| Commodity                |              | Source                |                            |                                 |              |               |                                        | Frequency on<br>'criticality' lists | Included in<br>this paper | Criticality of<br>use score |                              |
|--------------------------|--------------|-----------------------|----------------------------|---------------------------------|--------------|---------------|----------------------------------------|-------------------------------------|---------------------------|-----------------------------|------------------------------|
|                          |              | APS and MRS<br>(2011) | BGS<br>(2012) <sup>1</sup> | Buchert<br><i>et al.</i> (2009) | EC<br>(2014) | NRC<br>(2008) | Schulz and<br>Bradley (2013)<br>(USGS) |                                     |                           |                             | USDOE<br>(2011) <sup>2</sup> |
| Phosphate (rock)         |              |                       |                            |                                 |              | X             |                                        |                                     | 1                         |                             | n/a                          |
| Rare earth elements      | Cerium       | X                     | X                          | X                               | X            | X             | X                                      |                                     | 6                         | X                           | 1                            |
|                          | Dysprosium   | X                     | X                          | X                               | X            | X             | X                                      | Critical                            | 7                         | X                           | 1                            |
|                          | Erbium       |                       | X                          | X                               | X            | X             | X                                      |                                     | 5                         | X                           | 1                            |
|                          | Europium     | X                     | X                          | X                               | X            | X             | X                                      | Critical                            | 7                         | X                           | 1                            |
|                          | Gadolinium   | X                     | X                          | X                               | X            | X             | X                                      |                                     | 6                         | X                           | 1                            |
|                          | Holmium      |                       | X                          | X                               | X            | X             | X                                      |                                     | 5                         | X                           | 1                            |
|                          | Lanthanum    | X                     | X                          | X                               | X            | X             | X                                      |                                     | 6                         | X                           | 1                            |
|                          | Lutetium     | X                     | X                          | X                               | X            | X             | X                                      |                                     | 6                         | X                           | 1                            |
|                          | Neodymium    | X                     | X                          | X                               | X            | X             | X                                      | Critical                            | 7                         | X                           | 1                            |
|                          | Praseodymium | X                     | X                          | X                               | X            | X             | X                                      |                                     | 6                         | X                           | 1                            |
|                          | Samarium     | X                     | X                          | X                               | X            | X             | X                                      |                                     | 6                         | X                           | 1                            |
|                          | Scandium     | X                     | X                          | X                               | X            | X             | X                                      |                                     | 6                         | X                           | 1                            |
|                          | Terbium      | X                     | X                          | X                               | X            | X             | X                                      | Critical                            | 7                         | X                           | 1                            |
|                          | Thulium      |                       | X                          | X                               | X            | X             | X                                      |                                     | 5                         | X                           | 1                            |
|                          | Ytterbium    | X                     | X                          | X                               | X            | X             | X                                      |                                     | 6                         | X                           | 1                            |
| Yttrium                  | X            | X                     | X                          | X                               | X            | X             | Critical                               | 7                                   | X                         | 1                           |                              |
| Rhenium                  |              | X                     |                            |                                 |              |               | X                                      |                                     | 2                         | X                           | 0.5                          |
| Selenium                 |              | X                     | X                          |                                 |              |               |                                        |                                     | 2                         |                             | n/a                          |
| Silicon (metal)          |              |                       |                            |                                 |              | X             |                                        |                                     | 1                         | X                           | 0.5                          |
| Silver                   |              | X                     |                            |                                 |              |               |                                        |                                     | 1                         | X                           | 0.5                          |
| Strontium                |              |                       | X                          |                                 |              |               |                                        |                                     | 1                         | X                           | 0.5                          |
| Tantalum                 |              |                       | X                          | X                               |              |               | X                                      |                                     | 3                         | X                           | 0.5                          |
| Tellurium                |              | X                     |                            | X                               |              |               | X                                      | Near critical                       | 4                         | X                           | 1                            |
| Tin                      |              |                       |                            |                                 |              |               |                                        |                                     | 0                         | X                           | 0                            |
| Titanium (mineral sands) |              |                       |                            |                                 |              |               |                                        |                                     | 0                         | X                           | 0                            |
| Thorium                  |              |                       | X                          |                                 |              |               |                                        |                                     | 1                         | X                           | 0.5                          |
| Tungsten                 |              |                       | X                          |                                 |              | X             |                                        |                                     | 2                         | X                           | 0.5                          |
| Vanadium                 |              |                       |                            |                                 |              |               |                                        |                                     | 0                         | X                           | 0                            |
| Zinc                     |              |                       |                            |                                 |              |               |                                        |                                     | 0                         | X                           | 0                            |

<sup>1</sup> Elements which score more than 7 on the 'Risk List'.<sup>2</sup> Elements deemed to be 'critical' over the medium term.

**Table A8 The diversity of demand for the metals in the study. Those in which the main use occupies less than a third of total demand are thought to have a diversified consumption base and score 1. Those where the main use occupies more than two-thirds of demand of thought to have a narrow usage base and score 0. Those where the main demand sector falls between one-third and two-third, or which sufficient quantitative information is not available score 0.5**

| Commodity       | Main end use                                                                                                              | Share of consumption | Notes                                                                                                                                                                                                                                                                                                                                                                                                                                                | Score |
|-----------------|---------------------------------------------------------------------------------------------------------------------------|----------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|
| Aluminium       | Transportation                                                                                                            | 34–43%               | 2006 estimates for North America, Western Europe and Japan (Nappi 2013). Transportation is already a broad category so a full score for diversity of use is awarded                                                                                                                                                                                                                                                                                  | 1     |
| Beryllium       | Industrial and aerospace alloys                                                                                           | 32%                  | Estimates for USA in 2013. Based on sales revenues (USGS 2014)                                                                                                                                                                                                                                                                                                                                                                                       | 1     |
| Copper          | Industrial equipment                                                                                                      | 31%                  | Global estimates for 2013 (ICSG 2014)                                                                                                                                                                                                                                                                                                                                                                                                                | 1     |
| Cerium (REM)    | Glass polishing                                                                                                           | 25%                  | Global estimates for 2008 (Goonan 2011)                                                                                                                                                                                                                                                                                                                                                                                                              | 1     |
| Silver          | Coins and bars                                                                                                            | 21%                  | Global estimated demand in 2013 was 1 186.4 million ounces, of which 105.3 million ounces or 9% was investment demand (The Silver Institute and CPM Group 2014). Industrial fabrication (586.6 million ounces) made up 54% of physical demand (1 081.1 million ounces), but split between a number of sectors, none of which was more than the 245.6 million ounces used to make coins and bars (The Silver Institute and Thomson Reuters GFMS 2014) | 1     |
| Antimony        | Metal products (inc. antimonial lead and ammunition) and non-metal products (inc. ceramics, glass and rubber products)    | 35% (each)           | Estimates for USA in 2013 (USGS 2014)                                                                                                                                                                                                                                                                                                                                                                                                                | 0.5   |
| Arsenic         | Chromated copper arsenide (CCA) preservative for wood                                                                     | Unknown              | Estimates for USA in 2013 (USGS 2014)                                                                                                                                                                                                                                                                                                                                                                                                                | 0.5   |
| Bismuth         | Pharmaceutical chemicals                                                                                                  | 66%                  | Estimates for USA in 2013 (USGS 2014)                                                                                                                                                                                                                                                                                                                                                                                                                | 0.5   |
| Boron (borate)  | Glass additive                                                                                                            | 60%                  | Global estimates for 2012 (USGS 2014, 2015)                                                                                                                                                                                                                                                                                                                                                                                                          | 0.5   |
| Cobalt          | Aircraft gas turbine engine superalloys                                                                                   | 48%                  | Estimates for USA in 2013 (USGS 2014)                                                                                                                                                                                                                                                                                                                                                                                                                | 0.5   |
| Germanium       | Fibre and infrared optics                                                                                                 | 50%                  | Global estimates for 2012 (USGS 2014)                                                                                                                                                                                                                                                                                                                                                                                                                | 0.5   |
| Gold            | Jewellery                                                                                                                 | 45%                  | Global estimates for 2011. Based on 2610 tonnes of fabricated gold, of which 1890 tonnes went into jewellery, plus 1610 tonnes of gold for investment, mainly as gold bars (USGS 2015)                                                                                                                                                                                                                                                               | 0.5   |
| Indium          | Indium-tin-oxide (ITO) thin film coatings for displays, such as LCDs                                                      | 55–85%               | Global estimates for 2012. The wide range of estimates suggests a score of 0.5 based on uncertainty of information (USGS 2014)                                                                                                                                                                                                                                                                                                                       | 0.5   |
| Lithium         | Ceramics and glass                                                                                                        | 35%                  | Global estimates for 2013 (USGS 2014)                                                                                                                                                                                                                                                                                                                                                                                                                | 0.5   |
| Magnesium       | Reducing agent in titanium metal production                                                                               | 34%                  | Estimates for USA in 2013 (USGS 2014)                                                                                                                                                                                                                                                                                                                                                                                                                | 0.5   |
| Mercury         | Catalyst (in coal-based vinyl chloride monomer manufacture, mainly in China, ultimately to make polyvinyl chloride – PVC) | 50%                  | Global estimates for 2013 (USGS 2015)                                                                                                                                                                                                                                                                                                                                                                                                                | 0.5   |
| Nickel          | Austenitic (nickel bearing) stainless steel                                                                               | 60%                  | Global estimates for 2012 (USGS 2014, 2015)                                                                                                                                                                                                                                                                                                                                                                                                          | 0.5   |
| Iridium (PGM)   | Electronic applications (mainly iridium crucibles for making crystal sapphires in turn used in electronics such as LEDs)  | 24%                  | Global estimates for 2012. Only one end use (electronics) is included in the data, so a precise estimate is not possible. Iridium crucible use declined dramatically in 2012 so may have been replaced by another end use as the major consumer (USGS 2015)                                                                                                                                                                                          | 0.5   |
| Osmium (PGM)    | Unknown                                                                                                                   | Unknown              | No data are available on the specific end uses of osmium                                                                                                                                                                                                                                                                                                                                                                                             | 0.5   |
| Platinum (PGM)  | Automobile catalysts                                                                                                      | 40%                  | Global estimates for 2012 (USGS 2015)                                                                                                                                                                                                                                                                                                                                                                                                                | 0.5   |
| Ruthenium (PGM) | Electrical and electronic applications (particularly hard discs)                                                          | 55%                  | Global estimates for 2012 (USGS 2015)                                                                                                                                                                                                                                                                                                                                                                                                                | 0.5   |
| Lanthanum (REM) | Fluid catalytic cracking                                                                                                  | 46%                  | Global estimates for 2008 (Goonan 2011)                                                                                                                                                                                                                                                                                                                                                                                                              | 0.5   |
| Scandium (REM)  | Aluminium alloys for aerospace and sports equipment                                                                       | Unknown              | Estimates for USA in 2013 (USGS 2014)                                                                                                                                                                                                                                                                                                                                                                                                                | 0.5   |
| Yttrium (REM)   | Phosphors (in screens and displays)                                                                                       | 54%                  | Global estimates for 2008 (Goonan 2011)                                                                                                                                                                                                                                                                                                                                                                                                              | 0.5   |
| Silicon (metal) | Silicone                                                                                                                  | 50%                  | Global estimates for 2012 (USGS 2014, 2015)                                                                                                                                                                                                                                                                                                                                                                                                          | 0.5   |
| Tantalum        | Tantalum chemicals                                                                                                        | 36%                  | Global estimates for H1 2011 (Schwela 2012)                                                                                                                                                                                                                                                                                                                                                                                                          | 0.5   |
| Tellurium       | Cadmium-tellurium solar cells                                                                                             | 40%                  | Global estimates for 2012 (USGS 2014, 2015)                                                                                                                                                                                                                                                                                                                                                                                                          | 0.5   |

(Continued)

Table A8 Continued.

| Commodity                | Main end use                                                                                          | Share of consumption | Notes                                                                                                                                                                                                                                                                                                                                                                                               | Score |
|--------------------------|-------------------------------------------------------------------------------------------------------|----------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|
| Thorium                  | Catalysts, ceramics and welding electrodes                                                            | Unknown              | Estimates for USA in 2013 (USGS 2014)                                                                                                                                                                                                                                                                                                                                                               | 0.5   |
| Tin                      | Electronic and electrical solders                                                                     | 50%                  | Global preliminary estimates for 2013 (Kettle <i>et al.</i> 2014b)                                                                                                                                                                                                                                                                                                                                  | 0.5   |
| Titanium (mineral sands) | Titanium dioxide for paints                                                                           | 57%                  | Estimates for USA in 2013. 95% of titanium mineral concentrates were consumed for titanium dioxide. In turn, 60% of these were used in paints (USGS 2014)                                                                                                                                                                                                                                           | 0.5   |
| Tungsten                 | Cemented tungsten carbide (hardmetal) tools                                                           | 54–72%               | Estimates for each of China, Europe, Japan, Russia and USA in 2010 (ITIA 2015). The wide range of estimates suggests a score of 0.5 based on uncertainty of information                                                                                                                                                                                                                             | 0.5   |
| Vanadium                 | Iron and steel alloys (mainly full alloy, 44%, high-strength low alloy, 33%, and carbon, 17%, steels) | 44%                  | Estimates for USA in 2013 (USGS 2014)                                                                                                                                                                                                                                                                                                                                                               | 0.5   |
| Zinc                     | Galvanising steel and metal                                                                           | 50%                  | Global estimates for recent years (International Zinc Association 2015)                                                                                                                                                                                                                                                                                                                             | 0.5   |
| Barium (barite)          | Oil and gas drilling                                                                                  | 80%                  | Global estimates for recent years (The Barytes Association 2015)                                                                                                                                                                                                                                                                                                                                    | 0     |
| Cadmium                  | Ni–Cd batteries                                                                                       | 80%                  | Global estimates for 2013 (USGS 2014)                                                                                                                                                                                                                                                                                                                                                               | 0     |
| Chromium                 | Stainless and heat-resistant steel and superalloys                                                    | 90%                  | Global estimates for recent years (International Chromium Development Association 2015)                                                                                                                                                                                                                                                                                                             | 0     |
| Gallium                  | Gallium arsenide applications in electronics                                                          | 80%                  | Global estimates for 2012 (USGS 2014, 2015)                                                                                                                                                                                                                                                                                                                                                         | 0     |
| Lead                     | Lead-acid batteries (mainly in automotive)                                                            | 85%                  | Global estimate for 2012 (International Lead Association 2015)                                                                                                                                                                                                                                                                                                                                      | 0     |
| Manganese                | Steelmaking (almost all types)                                                                        | 93–94%               | Global estimates for 2010, with around 90% of this total for crude steels, and the rest for specialty steels (Postle <i>et al.</i> 2015)                                                                                                                                                                                                                                                            | 0     |
| Molybdenum               | Molybdenum steels                                                                                     | 70%                  | Global estimates for 2009, totalling engineering steels, 34%; stainless steels, 26%; and tool and high speed steels, 10% (USGS 2015)                                                                                                                                                                                                                                                                | 0     |
| Niobium                  | High strength, low alloy (HSLA) steel                                                                 | 89%                  | Global estimates for 2011 H1 (Schwela 2012)                                                                                                                                                                                                                                                                                                                                                         | 0     |
| Palladium (PGM)          | Automobile catalysts                                                                                  | 67%                  | Global estimates for 2012 (USGS 2015)                                                                                                                                                                                                                                                                                                                                                               | 0     |
| Rhodium (PGM)            | Automobile catalysts                                                                                  | 81%                  | Global estimates for 2012 (USGS 2015)                                                                                                                                                                                                                                                                                                                                                               | 0     |
| Dysprosium (REM)         | Additive to neodymium-praseodymium permanent magnets                                                  | 100%                 | Global estimates for 2008 (Goonan 2011)                                                                                                                                                                                                                                                                                                                                                             | 0     |
| Erbium (REM)             | Glass additives                                                                                       | 86%                  | Specific end use details for erbium are unavailable. Goonan (2011) indicates that of 555 tonnes of 'other' rare earth oxides (i.e. not cerium, lanthanum, neodymium, yttrium, praseodymium, dysprosium, gadolinium, samarium, terbium and europium) consumed in 2008, 480 tonnes (86%) went into glass additives and the rest into 'other' uses. Th actual end uses of erbium could be different    | 0     |
| Europium (REM)           | Phosphors (in screens and displays)                                                                   | 100%                 | Global estimates for 2008 (Goonan 2011)                                                                                                                                                                                                                                                                                                                                                             | 0     |
| Gadolinium (REM)         | Additive to neodymium-praseodymium permanent magnets                                                  | 69%                  | Global estimates for 2008 (Goonan 2011)                                                                                                                                                                                                                                                                                                                                                             | 0     |
| Holmium (REM)            | Glass additives                                                                                       | 86%                  | Specific end use details for holmium are unavailable. Goonan (2011) indicates that of 555 tonnes of 'other' rare earth oxides (i.e. not cerium, lanthanum, neodymium, yttrium, praseodymium, dysprosium, gadolinium, samarium, terbium and europium) consumed in 2008, 480 tonnes (86%) went into glass additives and the rest into 'other' uses. Th actual end uses of erbium could be different   | 0     |
| Lutetium (REM)           | Glass additives                                                                                       | 86%                  | Specific end use details for lutetium are unavailable. Goonan (2011) indicates that of 555 tonnes of 'other' rare earth oxides (i.e. not cerium, lanthanum, neodymium, yttrium, praseodymium, dysprosium, gadolinium, samarium, terbium and europium) consumed in 2008, 480 tonnes (86%) went into glass additives and the rest into 'other' uses. Th actual end uses of erbium could be different. | 0     |
| Neodymium (REM)          | Neodymium-praseodymium permanent magnets                                                              | 76%                  | Global estimates for 2008 (Goonan 2011)                                                                                                                                                                                                                                                                                                                                                             | 0     |
| Praseodymium (REM)       | Neodymium-praseodymium permanent magnets                                                              | 70%                  | Global estimates for 2008 (Goonan 2011)                                                                                                                                                                                                                                                                                                                                                             | 0     |
| Samarium (REM)           | Battery alloys                                                                                        | 73%                  | Global estimates for 2008 (Goonan 2011)                                                                                                                                                                                                                                                                                                                                                             | 0     |
| Terbium (REM)            | Phosphors (in screens and displays)                                                                   | 89%                  | Global estimates for 2008 (Goonan 2011)                                                                                                                                                                                                                                                                                                                                                             | 0     |

|                      |                                                                                  |            |                                                                                                                                                                                                                                                                                                                                                                                                      |        |
|----------------------|----------------------------------------------------------------------------------|------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------|
| Thulium (REM)        | Glass additives                                                                  | 86%        | Specific end use details for thulium are unavailable. Goonan (2011) indicates that of 555 tonnes of 'other' rare earth oxides (i.e. not cerium, lanthanum, neodymium, yttrium, praseodymium, dysprosium, gadolinium, samarium, terbium and europium) consumed in 2008, 480 tonnes (86%) went into glass additives and the rest into 'other' uses. The actual end uses of erbium could be different   | 0      |
| Ytterbium (REM)      | Glass additives                                                                  | 86%        | Specific end use details for ytterbium are unavailable. Goonan (2011) indicates that of 555 tonnes of 'other' rare earth oxides (i.e. not cerium, lanthanum, neodymium, yttrium, praseodymium, dysprosium, gadolinium, samarium, terbium and europium) consumed in 2008, 480 tonnes (86%) went into glass additives and the rest into 'other' uses. The actual end uses of erbium could be different | 0      |
| Rhenium<br>Strontium | High temperature aircraft turbine superalloys<br>Drilling fluids for oil and gas | 80%<br>71% | Global estimates for 2012 (USGS 2015)<br>Figures based on US import estimates in 2013. Based on 21 500 tonnes of minerals, usually celestite – 48% Sr, mainly for use in drilling muds, and 7140 tonnes of compounds, usually strontium carbonate – 59% Sr, split almost equally between pyrotechnics, ceramic magnets, and other uses (USGS 2014, 2015)                                             | 0<br>0 |

Minerals Yearbook (2015) and Mineral Commodity Summaries (2014) an assessment is also made as to whether a technological constraint or advantage makes the metal particularly difficult or straight-forward to process. Harder to process metals can have 0.5 subtracted off their initial score (to a minimum of 0), whilst simple to extract metals can have 0.5 added to their score (to a maximum of 1). As with mining, additional environmental and socio-political factors, for example radioactivity, may mitigate against the easy processing of a metal and a further 0.5 can be subtracted (to a total minimum score of 0).

### Analysing demand potential

Gupta and Krishnamurthy (2005) do not include economic demand factors in their framework, as it is focussed solely on understanding metals extraction. However, as the case studies of aluminium, nickel and uranium show (Sykes et al. 2016), for a metal to become a major industrial commodity, it needs some *important* and *widespread* uses. For example, in the case of aluminium, the metal's low density made it useful in the rapidly growing transport markets of the early twentieth century (Sykes et al. 2016) – an important use, but also its aesthetic (i.e. in monuments), chemically unreactive (useful in kitchenware) and conductive (for electrical cabling) properties made it useful in other areas significantly diversifying and strengthening demand (Street and Alexander 1998; Lynch 2002; Nappi 2013; Sykes et al. 2016). Such diverse demand also makes metals substantially less vulnerable to substitution and therefore more plausible to undergo sustained market demand growth.

Analysing the demand prospects of the wide range of metals included in this analysis is difficult, due to the many product and market factors involved in demand. As such, in line with the other scoring systems, simplicity was the focus, using datasets that are available across the full range of metals and which are straight-forward and transparent to analyse. The methodology is imperfect but does allow for broad screening of a wide range of elements, which can then perhaps lead to more focussed demand studies of particular metals by interested parties at a later date.

As such the two particular areas of demand highlighted above were analysed: first that the metal has some *important* economic uses, so thus could be seen as critical; and second that it has a *diverse* range of end uses, a characteristic of major industrial metals (Sykes et al. 2016), and therefore an indication that the metal has the potential for rapid demand growth. In the final part of the assessment then both the criticality and also the breadth of demand are considered for each metal.

### Analysing criticality of demand

By definition any of the metals appearing in the different 'critical' metal lists of Table A7 are to some measure deemed critical. Some are however more critical than others. A metal which is included in five or more of the seven critical metals lists scores 1 point as it would appear there is widespread agreement the metal is critical. The critical metals which appear in only one to four lists score a neutral score of 0.5, suggesting there is not widespread agreement that this metal is critical. The two 'critical' metals included here at the authors' discretion

(cadmium and vanadium) score 0 under this system, reflecting the fact that there is no agreement that these metals are critical. As key comparators, the base and precious metals are also added to the results in addition to the critical metals list in Table A7. Most of these more familiar metals are not considered critical however and do not appear on the critical lists, hence are scored 0. Although each of the critical minerals studies used in Table A7 were undertaken for different reasons, for example the EU (2014) study is focussed on the European economy, whilst the NRC (2008) study is focussed on the US economy and the USDOE (2011) and APS and MRS (2011) studies are focussed on renewable energy markets, they do at least highlight that the metals that appear on their lists are of concern to some parts of the global economy. The appearance of a metal on multiple lists would therefore seem to suggest that the metal is of concern to multiple parts of the global economy.

#### *Analysing breadth of demand*

The final assessment is on the breadth of demand, undertaken using the USGS Minerals Yearbook (2015) and Commodity Summaries (2014), in addition to information from industry associations and other sources. Metals with a broad range of uses are considered to have greater potential for widespread future consumption, as their diversification reduces demand volatility and thus exposure to repeated substitution. Ideally the study of demand diversity would be forward-looking and highlight the metals with the potential for diverse demand based on multiple useful elemental properties (i.e. magnetism, conductivity, lightness, heaviness, toughness, malleability, ductility, etc.), against those that seem to have a more limited range of useful properties. However, in the absence of such datasets, the presence of broad demand in the present metal market is taken as a proxy indicator of positive substitution into a commodity market, meaning the given commodity is good value for the technical properties it offers in comparison to alternative materials. For this study, demand is preferably assessed on a global level, unless the relevant data are not easily available; in this case generally the United States or information on a number of major consumer countries or regions is used. If no specific use makes up more than one-third of current consumption the metal is considered to have broad demand and scores 1. Conversely if more than two-thirds of demand comes from one use then the metal is considered to have very narrow consumption patterns and scores 0. For metals where the main use makes up one-third to two-thirds of demand, consumption is considered to be neither broad nor narrow and thus scores 0.5. Some scores are then further adjusted based on qualitative information. Similarly for metals where quantitative data on consumption patterns are not available, and there is no clear qualitative statement that the metal has a particularly broad or narrow consumption pattern then 0.5 is also scored.

## Appendix II: Detailed results

A summary of the results presenting the total aggregated scores for each of the metals is described in the results section of the main body of the paper. This includes Table 1 which includes the aggregated scores for each metal. A

more detailed presentation of the results for each of the six individual factors are included across these appendices.

### **Discovery factors**

#### *Crustal abundance*

The full list of crustal abundances and their scores are included in Table A1.

The critical elements that are sufficiently abundant in the crust that it is seen as a potential advantage in becoming a more widely used industrial metal (i.e. with a crustal abundance of greater than 100 ppm) include: barium, chromium, magnesium, manganese, silicon, strontium and vanadium. None of these metals occurs frequently on critical metals list, so are not generally considered as being amongst the most 'critical' metals.

Critical metals with abundances similar to that of the base metals, between 1 and 100 ppm (therefore scoring 0.5) include: arsenic, beryllium, boron, cobalt, gallium, germanium, lithium, niobium, thorium and tungsten, along with most of the rare earth metals: cerium, dysprosium, erbium, europium, gadolinium, lanthanum, neodymium, praseodymium, samarium, scandium, ytterbium and yttrium (just holmium, lutetium, terbium and thulium are considered too rare). A number of the most frequently cited 'critical' metals sit in this medium abundance category including cobalt, gallium, germanium, lithium and the rare earth metals.

A number of critical metals however seem just too rare to ever become major industrial metals markets, with crustal abundances of less than 1 ppm (and therefore scoring 0): antimony, bismuth, cadmium, indium, mercury, molybdenum, rhenium, tantalum, tellurium, four of the rare earth metals: holmium, lutetium, terbium and thulium and all of the platinum group metals (iridium, osmium, palladium, platinum, rhodium and ruthenium). The presence of the frequently cited 'critical metals': indium, tellurium and the platinum group metals, however, suggested that the markets for these metals may always be relatively constrained, no matter what their importance to the economy.

#### *Crustal concentration*

The full list of scores from the Goldschmidt classification (Goldschmidt 1937; White 2013) are found in Table A2.

A number of the critical metals show chalcophile behaviour in the crust so should concentrate effectively into discrete ore bodies within the crust. These are: antimony, arsenic, bismuth, cadmium, indium, mercury, molybdenum, rhenium, silver and tellurium, in addition to the more familiar metal, lead. Indium and tellurium are the only two widely cited critical metals in this grouping.

Siderophiles should also readily concentrate into discrete ore bodies within the crust. Only three metals are siderophile in the crust: gold, platinum and iridium (one of the other platinum group metals). In addition all of the other platinum group metals (osmium, palladium, rhodium and ruthenium) show both chalcophile and siderophile behaviour in the crust. Although gold is not currently considered a 'critical' metal, the platinum group metals are often considered as such. Again, however, these metals should concentrate readily into discrete deposits within the crust.

A large number of critical metals are however lithophiles, thus will have a lesser tendency to concentrate into discrete ore bodies in the crust. Some of the most frequently cited critical metals are lithophiles, suggesting an inability to concentrate into discrete ore bodies in the crust may be an important constraint which makes metals 'critical'. The lithophile critical metals are: boron, chromium, lithium, magnesium, manganese, niobium, silicon, strontium, tantalum and thorium, and the rare earth metals. The rare earth metals and lithium are amongst the most frequently cited critical metals. However, both aluminium and titanium, which are widely mined are also lithophile, suggesting that this geological constraint can be overcome, though admittedly both these metals are also amongst the most abundant in the crust.

#### *Geological constraints on critical metals*

The results of the crustal abundance and crustal concentration of the elements can be used to create a chart of the most and least geologically constrained metals. In theory the most geologically constrained metals are the scarce lithophiles, whilst the ones with the greatest potential for widespread extraction are the abundant chalcophiles and lithophiles (with iron being the example *par excellence*). Such an assessment is detailed in Table A3.

Understanding the type of geological constraint on a metal is important for governments, researchers or industry attempting to grow a particular metal market. Metals that are fundamentally rare in the crust will always be somewhat 'precious', so attempts to build a large industrial metal market upon their extraction are likely to fail. By contrast, metals which do not easily concentrate into discrete deposits in the crust, but nonetheless are not that fundamentally rare do host the potential to support large industrial metal markets, should the discovery and extraction challenges be overcome. Such metals may be a generally more appropriate for market growth orientated government, research or industry interventions.

It is notable that none of metals in the assessment fall into the theoretically most amenable to discover category (abundant chalcophiles and siderophiles), which is perhaps not surprising as chalcophiles and siderophiles are relatively depleted in the crust. However some of the critical metals in the assessment are either chalcophile or show chalcophile properties sometimes, but are of moderate abundance. These include arsenic, cobalt, gallium and germanium. The familiar widely mined base metals (copper, lead, nickel, tin and zinc), however, also fall into this category, suggesting that these critical metals are not necessarily geologically constrained and could represent potential new large metals markets, should extraction and consumption factors align favourably.

Conversely there are a few critical metals which fall into the theoretically most difficult to discover category, being of low abundance, and lithophile, so likely to be diffusely distributed. These include tantalum, and four of the rare earth metals: holmium, lutetium, terbium and thulium. It seems likely that these metals are fundamentally geologically constrained and supply will therefore always be constrained as a result.

Most of the chalcophile critical metals are however of low abundance: antimony, bismuth, cadmium, mercury, molybdenum, rhenium, silver, tellurium and the platinum

group metals. However, the presence of gold in this group, one of the largest metals markets, suggests that the challenges of finding and mining these metals are not insurmountable. Indeed both silver and the platinum group metals are also substantial metals markets as well.

Similarly, there are a number of abundant lithophile 'critical' metals: barium, chromium, magnesium, manganese, silicon, strontium and vanadium, where the size of the aluminium and titanium markets suggest that once again the challenges of finding and extracting these metals in large volumes can be overcome. Lithium, niobium and most of the rare earths present something of a middle ground in this respect, being moderately abundant lithophiles, with no obvious familiar metals that are widely mined falling into this category as a ready comparator for market potential.

#### **Extraction or supply factors**

##### *Ease of mining*

The scores for the ease of mining are including in Table A4.

There are a number of critical metals that already benefit from a formalised mining sector using conventional mining techniques. These are: antimony, barium (barite), cadmium, chromium, gallium, germanium, indium, manganese, molybdenum, niobium, rhenium, scandium, silver, strontium, tellurium and vanadium. This is good news for gallium, germanium, indium and tellurium all of which are amongst the most frequently cited critical metals.

Some critical metals do not benefit from a conventional mining sector, with boron, as borates (USGS 2014, 2015), lithium (Erbensperger *et al.* 2005; Yaksic and Tilton 2009; Grosjean *et al.* 2012; USGS 2014, 2015) and magnesium (Gao *et al.* 2009; USGS 2014, 2015) all generally extracted via brine mining. It is therefore clear that advances in brine mining would benefit the extraction of lithium, one of the most important critical metals.

Major socio-political and environmental issues afflict several critical metals, which otherwise benefit from formalised, conventional mining sectors, including arsenic, beryllium (USGS 2014, 2015) and mercury (Hylander and Meili 2005; Veiga *et al.* 2006; Spiegel and Viegas 2010; Kim and Choi 2012) which cause toxic pollution. Bismuth is a by-product of toxic lead mining (USGS 2014, 2015), which whilst still a relatively large base metal market has grown the least of these metals over the twentieth century (Kelly and Matos 2013), with the metals toxicity being at least part of the cause of this. Silica mining in particular, but along with mining for all commodities in general is associated with silicosis health problems (Thomas and Kelley 2010), whilst manganese mining is also potentially associated with long-term health problems (The Economist 2014). The mining of light rare earths (which unlike many of the heavier rare earths benefit from a formalised, conventional mining sector) are associated with radioactivity (Massari and Ruberti 2013; Packey 2013; Tyrer and Sykes 2013; Wubbeke 2013; Golev *et al.* 2014; Weng *et al.* 2014). Cobalt, one of the most commonly referenced critical metals, is occasionally mistakenly involved in conflict minerals issues (Cobalt Development Institute 2011), whilst tungsten (as wolframite) is more accurately associated with conflict minerals (Freedman 2011; Bleischwitz *et al.*

2012). The platinum group minerals, again one of the most important groups of critical metals, have recently been vulnerable to severe labour union conflict and political issues in South Africa (USGS 2014, 2015).

Thorium and the rare earth, yttrium (USGS 2014, 2015), are both still largely mined from placers (often together), albeit mainly by formalised Indian companies (Gupta and Krishnamurthy 2005), in addition to being associated with radioactivity (Massari and Ruberti 2013; Packey 2013; Wubbeke 2013; Golev et al. 2014; Weng et al. 2014). Conversely whilst tantalum mining mainly utilises conventional techniques, about half of the mining is still done by artisanal miners (USGS 2014, 2015), in addition to the fact that tantalum is the main source of concern in the conflict minerals trade (Freedman 2011; Bleischwitz et al. 2012).

Finally, the heavy rare earths benefit from neither a formal or conventional mining sector (Bradsher 2009, 2013; Wubbeke 2013; USGS 2015), whilst mining practices are associated with radioactivity (Massari and Ruberti 2013; Packey 2013; Tyrer and Sykes 2013; Wubbeke 2013; Golev et al. 2014; Weng et al. 2014), as well as concerns over human rights abuses and environmental problems (Bradsher 2009, 2013; Massari and Ruberti 2013; Packey 2013; Tyrer and Sykes 2013; Wubbeke 2013; Campbell 2014; Golev et al. 2014). All of the rare earths (except scandium), which are amongst the most commonly cited critical metals, appear to have one or more technical, environmental and socio-political problems in their mining.

#### *Ease of processing*

The scores for the ease of processing are detailed in Table A5.

A number of critical metals appear to be relatively straight forward to process, not generally found to be mined as by- or co-products, and with no known systemic technical, environmental or socio-political problems with processing. These include antimony, barium (as barite), boron (as borate) and niobium; however, none of these rank amongst the critical metals of most frequent concern.

A number of critical metals, which are otherwise mined and processed as the primary product are nonetheless associated with systemic technical problems in processing. For one of the most important critical metals, lithium, solar evaporation during processing is known to be a costly, lengthy process, with large environmental footprint (Grosjean et al. 2012; USGS 2014, 2015). Similarly, the Pidgeon process for making magnesium metal is known to be energy intensive (Gao et al. 2009; USGS 2014, 2015). Manganese ores can be complex (Assmang 2015) and production can also be energy intensive (Mining Weekly 2012). At the extreme in some places strontium ores are still hand sorted, lacking any mechanised processing (USGS 2015).

Similarly, some critical metals, which again are generally mined and processed as the primary product are also associated with major environmental or socio-political issues affecting their processing. Mercury is well known to be toxic (Hylander and Meili 2005; Veiga et al. 2006; Spiegel and Viegas 2010; Kim and Choi 2012), whilst chromium compounds are also very toxic attracting strict environmental and health regulations

(USGS 2015); silica as noted is associated with silicosis based health problems (Thomas and Kelley 2010), with management thereof potentially exacerbated at the processing stage. Similarly, for manganese (The Economist 2014). Finally, tungsten (as wolframite) is associated with the conflict minerals trade (Freedman 2011; Bleischwitz et al. 2012).

Many critical metals, including some of the most important, such as germanium (Fink and Culver-Hopper 1991) and indium (Alfantazi and Moskalyk 2003; Werner et al. 2015), in addition to cadmium, molybdenum, rhodium, scandium, silver and vanadium are still mainly mined as by- or co-products (USGS 2014, 2015), which causes technical and economic issues during processing, whilst the platinum group metals, an important group of critical metals, are essentially by- and co-products of each other (USGS 2014, 2015).

Some of the critical metals that are mainly mined as by- or co-products, also suffer from systemic technical problems, such as cobalt where the processing of nickel-cobalt laterites has long faced technical and economic problems (King 2005; Kyle 2010; Mudd 2010). Many of the key gallium processing technologies are proprietary presenting technical and economic barriers to entry (USGS 2014). Gallium is one of the most frequently cited critical metals. Tellurium, an important critical metal, faces a slightly unusual situation in that because it is recovered from the slimes of copper smelting-refining it is vulnerable to a further increase in the use of solvent-extraction electrowinning (SXEW) processing, at the expense of the conventional smelter-refiner processing route for copper (Naumov and Grinberg 2009; USGS 2014, 2015).

Similarly a number of these by- and co-product critical metals also suffer from systemic environmental or socio-political problems, such as arsenic which is toxic (USGS 2014, 2015) and bismuth which is associated with toxic lead mining (USGS 2015). Tantalum is associated with the conflict minerals trade (Freedman 2011; Bleischwitz et al. 2012). Thorium is radioactive (Weng et al. 2014; Harper et al. 2015).

Although it is generally mined as a primary product, beryllium suffers both technical processing problems, in that it is still sometimes hand sorted (USGS 2014); and environmental and health issues as its dusts, fumes and mists are toxic (USGS 2014, 2015).

Finally, the rare earths, amongst the most important critical metals, face a multitude of processing issues, being mined as by- and co-products of each other, and of other metals, whilst many potential rare earth ore minerals still do not have commercial processing techniques (Gupta and Krishnamurthy 2005; Weng et al. 2014). In addition all are associated with radioactivity (Massari and Ruberti 2013; Packey 2013; Wubbeke 2013; Golev et al. 2014; Weng et al. 2014), and the heavy rare earths mined in Southern China are associated with human rights and environmental issues (Bradsher 2009, 2013; Massari and Ruberti 2013; Packey 2013; Tyrer and Sykes 2013; Wubbeke 2013; Campbell 2014; Golev et al. 2014).

#### *Extraction constraints on critical metals*

It is notable that far more critical metals are processing constrained than mining constrained, as highlighted in

**Table A6.** Only boron (borate), which is mined via brines, is solely, somewhat mining constrained, whereas a large number of critical metals are primarily processing constrained: cadmium, germanium, gallium, indium, rhenium, silver, tellurium, vanadium and the rare earth scandium. The silver market is however relatively large for a metal market suggesting some potential exists for these metals despite the processing problems.

In general though most of the critical metals are mining and/or processing constrained including arsenic, beryllium, bismuth, cobalt, manganese, the rare earths cerium, europium, gadolinium, lanthanum, neodymium, praseodymium and samarium; and all of the platinum group metals, which are all mining constrained, but very processing constrained. The fact that the more familiar industrial metals titanium (mineral sands), lead and zinc, however also fall into this group means that significant markets can still develop for these extraction constrained metals. A number of critical metals however fall into the most highly constrained categories for both mining and processing, which includes tantalum, thorium and a number of the rare earths: dysprosium, erbium, holmium, lutetium, terbium, thulium, ytterbium and yttrium. Tin however also falls into this grouping so nonetheless some market volume potential does exist for these metals, though it is notable that the tin market is the smallest of the London Metal Exchange (LME) markets.

By contrast some critical metals have no extraction constraints, including antimony, barium (barite) and niobium, a category the giant copper market also falls into. A number of critical metals fall into a mid-point group being partially mining and processing constrained, including lithium, magnesium, mercury, silicon (metal) and tungsten, alongside the larger gold and nickel markets. Similarly some critical metals are only processing constrained whilst not being mining constrained, including chromium, molybdenum and strontium, a situation similar to aluminium.

## Demand factors

### Criticality of demand

The frequency with which the metals appear on the 'critical lists' of the seven main critical minerals reports (NRC 2008; Buchert *et al.* 2009; APS and MRS 2011; USDOE 2011; BGS 2012; Schulz and Bradley 2013; EC 2014) is recorded in Table A7.

Five of the rare earths feature on all seven lists, suggesting general agreement that these metals are exposed to critical economic sectors. These are dysprosium, europium, neodymium, terbium and yttrium. The rest of the rare earths are not on the short USDOE (2011) list, so along with indium and the platinum group metals appear on six of the lists, with the exception of erbium, holmium and thulium, which along with gallium appear on five lists. Cobalt, germanium, lithium, niobium and tellurium feature on four lists.

There is much less certainty around other metals, with tantalum featuring on three lists; antimony, beryllium, magnesium, rhenium and tungsten on two lists each; and all of arsenic, barium (barite), bismuth, boron (borate), chromium, mercury, manganese, molybdenum, silicon (metal), silver, strontium and thorium only featuring on one list, suggesting limited agreement on whether they are economically critical.

Cadmium and vanadium do not feature on any of the reference lists as these were included at the authors' discretion, due to their exposure to the fast-growing battery sector (Sykes *et al.* 2014; USGS 2014, 2015).

### Diversity of demand

The diversity of demand for the metals assessed in this study is included in Table A8, which details the main end use for each metal and its overall share of demand.

To a certain extent, critical metals almost by definition have a narrow range of uses as they are very important to a few critical sectors, as such only a few have a main end use that is less than one-third of total demand. These include beryllium, silver and the rare earth, cerium, however only cerium is generally acknowledged to be an important critical metal.

Most of the critical metals have a main end use between one-third and two-thirds of total demand suggesting some diversity of consumption, including antimony, arsenic, bismuth, boron (borate), cobalt, germanium, indium, lithium, magnesium, mercury, silicon (metal), tantalum, tellurium, thorium, tungsten, vanadium, four of the platinum group metals: iridium, osmium, platinum and ruthenium; and three of the rare earths: lanthanum, scandium and yttrium. Some of the more important critical metals discussed above feature in this group including cobalt, germanium, indium, lithium, tellurium, the four platinum group metals and the three rare earth metals.

A number of the critical metals however have very narrow usage profiles, with the main use making up more than two-thirds of demand. These include barium (barite), cadmium, chromium, gallium, manganese, molybdenum, niobium, rhenium, strontium, two of the platinum group metals: palladium and rhodium; and most of the rare earths: dysprosium, erbium, europium, gadolinium, holmium, lutetium, neodymium, praseodymium, samarium, terbium, thulium and ytterbium.

Chromium (International Chromium Development Association 2015), manganese (Postle *et al.* 2015), molybdenum (USGS 2015) and niobium (Schwela 2012) are all ferroalloys critical to the steel industry; similarly rhenium is mainly used in aerospace superalloys (USGS 2015). Palladium and rhodium are mainly used as automotive catalysts (USGS 2015). Both barium, as barite (The Barytes Association 2015), and strontium (USGS 2014, 2015) are relied upon primarily in the oil and gas drilling industry. Both cadmium (USGS 2014) and the rare earth samarium (Goonan 2011) are mainly used in battery production. Gallium is mainly consumed as gallium arsenide in electronics (USGS 2014, 2015). The rare earths dysprosium, gadolinium, neodymium and praseodymium are mainly used in the manufacture of permanent magnets; europium and terbium in the phosphor industry; and erbium, holmium, lutetium, thulium, ytterbium are mainly consumed by the glass industry (Goonan 2011). Some of the most important critical metals fall into this undiversified group including gallium, the two platinum group metals and the twelve rare earth metals.

### Demand potential for critical metals

Table A9 summarises the demand potential for the various critical metals and comparative non-ferrous industrial and precious metals. Whilst most metals start out with just a few critical uses, which triggers significant

**Table A9** The demand constraints stopping a metal being consumed in large volumes. Whilst most metals start out with just a few critical uses, for demand to expand to large scales the metal needs to find a broad range of uses. Inevitably the criticality of the metal then begins to fade. Such metals like aluminium and copper in the bottom right of the table are examples of this. Arguably the metals that are both critical and already have a fairly broad range of uses are on their way to the sort of large, scale broad demand of an industrial metal. Cerium, a rare earth, would be the best example in this case. The non-critical major industrial and precious metals are highlighted in bold

|                     |                                                                                                                                                                                                                                                                                                                                                                                                                  |                                                                                                                                                                                                                                                                                                                                                       |                                                                                                                                                            |
|---------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Criticality of use> | <i>Critical demanded metal:</i> dysprosium (REM), erbium (REM), europium (REM), gadolinium (REM), gallium, holmium (REM), lutetium (REM), neodymium (REM), palladium (PGM), praseodymium (REM), rhodium (PGM), samarium (REM), terbium (REM), thulium (REM), ytterbium (REM)<br>Barium (barite), chromium, molybdenum, niobium, rhenium, strontium<br><br><i>Metal with limited demand:</i> cadmium, <b>lead</b> | Cobalt, germanium, indium, iridium (PGM), lanthanum (REM), lithium, osmium (PGM), platinum (PGM), ruthenium (PGM), scandium (REM), tellurium, yttrium (REM)<br><br>Antimony, arsenic, bismuth, boron (borate), magnesium, mercury, silicon (metal), tantalum, thorium, tungsten<br><b>Gold, nickel, tin, titanium (mineral sands), vanadium, zinc</b> | <i>Metal with critical and diverse demand:</i> cerium (REM)<br><br>Beryllium, <b>silver</b><br><br><i>Broadly demanded metal:</i> <b>aluminium, copper</b> |
|                     |                                                                                                                                                                                                                                                                                                                                                                                                                  | Breadth of use>                                                                                                                                                                                                                                                                                                                                       |                                                                                                                                                            |

demand growth for demand to then expand to large scales the metal needs to find a broader range of uses. At this point, inevitably the criticality of the metal then begins to fade as it becomes more widely available. Aluminium and copper in the bottom right of Table A9 are examples of this.

Metals that are both critical and already have a fairly broad range of uses may be on their way to developing the large-scale broad demand of an industrial metal. Cerium, a rare earth, in the top left of Table A9 would be the best example in this case. Beryllium (like silver) also already has a diverse usage base. A number of other commonly considered critical metals are however slowly diversifying their usage base suggesting in the longer term that they may grow into more significant markets. These metals are cobalt, lanthanum, platinum and palladium, which already have somewhat significant

demand, and germanium, indium, lithium, tellurium, the rare earths scandium and yttrium, plus some of the other platinum group metals, iridium, osmium and ruthenium.

Many of the critical metals are however still reliant on a very narrow range of albeit critical uses. Although investors frequently highlight that such metals possess the potential to grow rapidly from a small base due to these new critical uses, such metals are also vulnerable to substitution and rapid market decline, especially if their prices increase without concurrent increases in supply. The metals in this category need to diversify their usage base before they can become major industrial metals. These metals include gallium, palladium and most of the rare earths: dysprosium, erbium, europium, gadolinium, holmium, lutetium, neodymium, praseodymium, rhodium, samarium, terbium, thulium and ytterbium.