Lateritic, supergene rare earth element (REE) deposits
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Lateritic, supergene rare earth element (REE) deposits
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Abstract

Intensive lateritic weathering of bedrock under tropical or sub-tropical climatic conditions can form a variety of secondary, supergene-type deposits. These secondary deposits may range in composition from aluminous bauxites to iron and niobium, and include rare earth elements (REE). Over 250 lateritic deposits of REE are currently known and many have been important sources of REE. In southeastern China, lateritic REE deposits, known as ion-adsorption type deposits, have been the world's largest source of heavy REE (HREE). The lateritized upper parts of carbonatite intrusions are being investigated for REE in South America, Africa, Asia and Australia, with the Mt. Weld deposit in Australia being brought into production in late 2012.

Lateritic REE deposits may be derived from a wide range of primary host rocks, but all have similar laterite and enrichment profiles, and are probably formed under similar climatic conditions. The weathering profile commonly consists of a depleted zone, an enriched zone, and a partially weathered zone which overlie the protolith. Lateritic weathering may commonly extend to depths of 30 to 60 m. REE are mobilized from the breakdown of primary REE-bearing minerals and redeposited in the enriched zone deeper in the weathering horizon as secondary minerals, as colloids, or adsorbed on other secondary minerals. Enrichment of REE may range from 3 to 10 times that of the source lithology; in some instances, enrichment may range up to 100 times.

The secondary minerals are generally fine-grained, REE-bearing phases that include secondary phosphates, oxides, clays, and iron and manganese oxides. REE are adsorbed on the clays and iron and manganese oxides. Lateritic REE may be associated with any lithology containing REE minerals, but the most frequently reported lithologies include granites, rhyolites, carbonatites, and various metamorphic rocks. Secondary REE-bearing minerals may occur in bauxites, phosphorites, and weathered hydrothermal replacement deposits.

In the southeastern United States, stream sediments associated with metamorphic rocks in the Piedmont and Blue Ridge terranes contain exceptionally high REE. Rocks in the Piedmont have been subject to intensive lateritic weathering, and the areal extent of the anomalous REE would make large areas permissive for lateritic REE deposits. Currently mined bauxite and kaolin deposits in the Upper Coastal Plain of the southeastern United States may also contain lateritic REE mineralization.

Although reported grades and tonnages for lateritic REE deposits have similar ranges to those of primary hard-rock deposits, the lateritic deposits have important advantages over those of primary deposits. Some advantages include: 1) ease and cost of mining are low with near surface ore (<100 m); 2) soft ore that is easy and cheap to open-pit mine; 3) ease and cost of REE extraction and processing are low; and 4) large areal extent of the deposit defines larger exploration targets and increased options for development. Also, lateritic REE enrichment greatly expands the resource potential by including source lithologies that would be normally be considered to be sub economic.

Glossary

A number of abbreviations regarding rare earth elements are used in both scientific and industry reports which are not always precisely defined. Abbreviations used in this paper include: REE = rare earth elements; REO = rare earth oxides; TREO = sum of REO and yttrium oxide; LREE = light rare earth elements = sum of (lanthanum (La)-europium (Eu)); HREE = heavy rare earth elements = sum of (gadolium (Gd) and lutetium (Lu)) + yttrium (Y); Total REE (TREE) = sum of REE + yttrium (Grauch, 2003, unpublished report).

Introduction

Most current research and exploration efforts for REE deposits are focused on primary hard rock deposits (Lentz, 2010; British Geological Survey, 2011; Mariano and Mariano, 2012). These include REE mineralization associated with carbonatites,
Lateritic, supergene rare earth element (REE) deposits

peralkaline igneous complexes, granites, pegmatites and migmatites (British Geological Survey, 2011; Mariano and Mariano, 2012). Primary minerals in primary deposits may include bastnaesite, monazite, xenotime, eudialyte, allanite, zircon, apatite, and a variety of more uncommon minerals. Extraction and concentration of REE minerals and metallurgical processing to remove and separate the various REE can be difficult and expensive, and the beneficiation for each deposit may be unique.

In contrast to primary deposits, laterites, those soils formed during intense weathering of bedrock under tropical or sub-tropical (i.e., hot and humid) conditions, are important sources of viable economic mineral deposits. Lateritic weathering results in the breakdown of primary rocks and minerals, and concentration of metals such as aluminum, iron, manganese, nickel, gold, phosphorous, and niobium (Freyssinet and others, 2005; Berger and others, 2011). Many occurrences of rocks containing these elements had minerals that were difficult or costly to mine or process to obtain these elements; e.g. nickel in olivine and aluminum in mica, clay, and feldspar. Laterization changes the mineralogy and hence how these elements are situated in relation to the bonding of these minerals. Metallurgical methods, mostly developed during the last 50 years, allow economic recovery of these elements from lateritic minerals. Lateritic weathering increases concentration of these elements above background or sub economic levels to values that are considered to be economic, e.g. aluminous micas or clays are altered to bauxites, olivine may be altered to garnierite, nickel-rich smectite, or nickel-bearing goethite (Freyssinet and others, 2005).

Laterized rocks containing elevated or economic grades of REE have been noted and briefly described in Asia, Australia, Africa and South America (Orris and Grauch, 2002; Berger and others, 2009). Laterized granitic rocks in southeastern China have been the source of most of the heavy REE (HREE) produced since the 1980s and are proposed to contain more than 80 percent of the world’s economic HREE (Chi and Tian, 2008). Generally ignored in the past as relatively unimportant, viable sources of REE, lateritic deposits are now being explored for and developed at perhaps a faster pace than primary hard rock REE deposits.

The lateritic deposit at Mt. Weld, Australia is the first of this type to begin production of REE ore during this past year. The current state of knowledge about REE-bearing laterites in southeastern China is more advanced than in other parts of the world, and this is reflected in deposit descriptions that follow.

Besides the lateritic deposits noted in Orris and Grauch (2002) and Berger and others (2009), lateritic alteration is common throughout much of the southeastern United States, the Caribbean, South America, Africa, southern Europe, southern Asia and Australia. Paleo-laterites have been noted in other places of the world not recently subjected to this type of weathering. This review examines the types of data presently available for lateritic REE deposits, briefly describes several known types of lateritic REE deposits (fig. 1), and probable areas and bedrock lithologies in the southeastern United States that may host lateritic REE deposits (Cocker and Grauch, 2012).

Available data

Geology

Compared to primary, hardrock REE deposits, published geologic data for lateritic REE deposits are relatively scarce. In a few instances, such as for Mt. Weld, Australia, earlier drilling for a lateritic phosphate resource (Duncan and Willett, 1990; Lottermoser, 1990) provides a generalized cross-section of the host carbonatite and the lateritic alteration (fig. 2). As development work continues on many REE properties, investor presentations with various types of geologic information, such as that for the Ngulla project (Beazley, 2013) are posted on the internet. Downhole drill data are mainly reported as average percentages of REO contained within certain thicknesses of several meters, and detailed mineralogy, geochemistry or lithology descriptions are commonly absent. TUC Resources (2012) report on the Stromberg REE deposit, Australia, provides cross-sections illustrating the lateritic weathering, distribution of REE and proposed mineralization pathways for this ion-adsorption type deposit (fig. 3). Grauch (2003, unpublished report) provided generalized cross-sections of the upper, weathered ion-adsorption deposits in China (fig. 4). More, somewhat detailed descriptions of these deposits are in Chi and Tian (2008). Overall geology of bauxite and phosphorite deposits are relatively well documented, however there have been few studies that focus on the REE geochemistry, mineralogy, and REE distribution that may occur within these deposits (Wagh and Pinnock, 1987).
Grade and tonnage

Grade and tonnage data are relatively scarce for REE deposits. Earlier, estimated data for REE deposits including mostly lateritic carbonatite deposits were compiled by Orris and Grauch (2002) and Berger and others (2009). Recently reported grade and tonnage data are available on the SEDAR website (http://sedar.com/homepage_en.htm) and listed by companies which are registered on Canadian stock exchanges. Other data may be reported on company websites or on various REE blogs on the internet, such as the ProEdgeWire.com website. Several recent publications, including Long and others (2010), British Geological Survey Natural Environmental Research Council (2011), and Kynicky and others (2012), report grades and tonnages for a number of primary REE deposits and a few lateritic type deposits (table 1). Mt. Weld has the highest reported grade of all REE deposits, and Ngulla has one of the highest overall tonnages of all REE deposits. The published REE grades and tonnage data represent preliminary and incomplete reporting on two or more primary and secondary deposits types not yet fully characterized and data about these deposits do not yet meet the requirements for grade and tonnage modeling (Singer and Menzie, 2010, p. 92-93). From a strictly descriptive perspective, exploration companies are finding and reporting grades and tonnages for lateritic deposits that overlap those found in primary REE deposits (Orris and Grauch, 2002; Berger and others, 2009; Long and others, 2010; British Geological Survey Natural Environmental Research Council, 2011; Kynicky and others, 2012). The sole published grade and tonnage model for REE is for carbonatite-hosted deposits and includes both lateritic and primary deposits (Berger and others, 2009).

Mineralogy

Mineralogy is a key variable in determining the ease or difficulty, and therefore the cost, of processing and extraction of REE. Primary, hard rock deposits with the most abundant REE minerals, those containing bastnäsite, monazite, xenotime, loparite, parasite, and perhaps apatite are more likely to be economical compared with those deposits with eudialyte, allanite, or zircon (Chakhmouradian and Wall, 2012; Mariano and Mariano, 2012). The latter group is more refractory and economic processing of REE from these minerals is not currently possible. Another problem is that many development companies anticipate production of REE concentrates, while end users require finished products in the form of oxides or metals or both (Hatch, 2012). Separation of HREE is more difficult than that of LREE, and few REE separation facilities exist outside of China (Hatch, 2012).

The REE element mineralogy of lateritic deposits is relatively simple compared with primary, hard-rock
Lateritic, supergene rare earth element (REE) deposits. Weathering and breakdown of primary REE-bearing minerals releases the REE as ions in solution. The REE may be adsorbed as hydration cations or hydroxyl hydration cations or they may form secondary phases. Commonly, 30 – 90 percent of the REE in the deposit are (1) as cations in exchangeable sites on clay minerals such as halloysite, kaolinite and on iron and manganese oxides, or as (2) colloids; (3) in secondary phosphate minerals, most commonly monazite and apatite (or florenceite) (Rose and others, 1958); (4) as secondary oxides, such as cerianite (CeO2), containing REE (Morteani and Preinfalk, 1996; Wu and others, 1996); and (5) as residual REE-bearing minerals, including monazite and xenotime (Chi and Tian, 2008). Other REE-bearing phosphates such as gorceixite, rhadophane, and crandallite are reported in some deposits (Morteani and Preinfalk, 1996).

Processing and extraction of REE from lateritic deposits has proven to be relatively simple and economic particularly where the REE are in ion-exchangeable sites. The adsorbed REE are leached by ion exchange with inorganic salts in dilute electrolyte solutions. In the early period of REE processing, leaching was with sodium chloride and later with ammonium sulphate (Chi and Tian, 2008) or a weak acid. At the Tantalus ion-adsorption type deposit in Madagascar, metallurgical test recovery rates for leaching with a sodium chloride solution were 37–42 percent TREE, and with an ammonium sulphate (NH4)2SO4 solution, recovery rates were generally 59–76 percent TREE (Gilbertson and Russill, 2013). In China, the most recent method of REE leaching is an in-situ method, where the leachate is introduced into the ground at the upper parts of the deposit and recovered downhill. Approximately 25–30 days are required for the leaching process to be complete (Shajari, 2012). REE are precipitated from the leachate as carbonates or oxalates by addition of ammonium bicarbonate or oxalic acid (Chi and Tian, 2008). REE as colloids have been recovered using a weak acid such as hydrochloric acid (Chi and Tian, 2008).

Depending on the mineralogy, other lateritic deposits may employ an acid leach. Mt. Weld, the only other lateritic deposit in production, is now processing secondary rare earth phosphate minerals by mixing with sulphuric acid and cracking in a rotary kiln to form rare earth sulphates. Solvent extraction separates the REE into groups and elements which are then precipitated as carbonates, hydroxides or oxalates (Lynas Corporation, 2013). The solvents are not identified in the Lynas report; the precipitates may be the same as for the ion-adsorption deposits.

Metallurgical tests of lateritic ore from the Ngulla carbonatite in Tanzania point toward use of a sulphuric acid leach, which has a REO recovery rate of 87 percent (Beazley, 2013). No rotary kiln processing is involved in the processing the bastnäsite iron oxide-rich ore.

**Figure 2.** Sections through the Mt. Weld lateritic REE deposit - A) Present day cross-section (modified from Lottermosser, 1990), and B) Interpreted former weathering profile prior to erosion and deposition of the overlying lacustrine sediments and alluvium. (Glimmerite is characterized as a potassium rich rock composed of ferriphlogopite by Duncan and Willett, 1990).
Some examples of supergene lateritic REE deposits

Mt. Weld, Australia

The Mt. Weld deposit consists of the laterized upper part of a Proterozoic carbonatite. Chondrite normalized La/Lu ratio in the unweathered parent carbonatite is 45–55, and the La/Lu ratio in the laterite rock is 8.7–395.3 (Lottermoser, 1990). Total REE in the unweathered carbonatite ranges from 0.1–0.3 percent (Lottermoser, 1990). Concentrations of secondary apatite occur above an irregular boundary between the laterite and fresh carbonatite. Above the presently irregular top of the laterite and ferruginous cap rock are up to 40 m of lacustrine sediments; these are overlain by about 25 m of alluvium (fig. 2). The ferruginous cap rock and the top of the laterite appear to have been dissected and eroded to form the buried top of the deposit.

Table 1. Grade and tonnage data for some major REE deposits.

<table>
<thead>
<tr>
<th>Deposit name</th>
<th>Country</th>
<th>Source rock</th>
<th>Laterite</th>
<th>Grade</th>
<th>Tonnage (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ngulla</td>
<td>Tanzania</td>
<td>carbonatite</td>
<td>yes</td>
<td>2.24 % REO</td>
<td>170</td>
</tr>
<tr>
<td>Bayan Obo</td>
<td>China</td>
<td>iron oxide-copper-gold (IOCG)</td>
<td>no</td>
<td>6 % TREO</td>
<td>48</td>
</tr>
<tr>
<td>Strange Lake</td>
<td>Canada</td>
<td>alkaline intrusion</td>
<td>no</td>
<td>1.16 % REO</td>
<td>36.53</td>
</tr>
<tr>
<td>Bokan Mt.</td>
<td>United States</td>
<td>vein system</td>
<td>no</td>
<td>0.08 % TREO</td>
<td>30</td>
</tr>
<tr>
<td>Mt. Weld</td>
<td>Australia</td>
<td>carbonatite</td>
<td>yes</td>
<td>7.9 % REO</td>
<td>23.94</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>yes</td>
<td>11.7 % REO</td>
<td>9.7</td>
</tr>
<tr>
<td>Zandkopsdrift</td>
<td>South Africa</td>
<td>carbonatite</td>
<td>no</td>
<td>2.32 % REO</td>
<td>22.92</td>
</tr>
<tr>
<td>Tantalus</td>
<td>Madagascar</td>
<td>granite</td>
<td>yes</td>
<td>1.52 % REO</td>
<td>14.4</td>
</tr>
<tr>
<td>Mt. Pass</td>
<td>United States</td>
<td>carbonatite</td>
<td>no</td>
<td>8.24 % REO</td>
<td>13.6</td>
</tr>
<tr>
<td>Bear Lodge</td>
<td>United States</td>
<td>alkaline complex</td>
<td>no</td>
<td>3.6 % REO</td>
<td>10.7</td>
</tr>
<tr>
<td>Dong Pao</td>
<td>Vietnam</td>
<td>granite</td>
<td>yes</td>
<td>5.22 % REO</td>
<td>7.4</td>
</tr>
<tr>
<td>Araxá</td>
<td>Brazil</td>
<td>carbonatite</td>
<td>yes</td>
<td>5 % TREO</td>
<td>6.34</td>
</tr>
<tr>
<td>Jianghua</td>
<td>China</td>
<td>granite</td>
<td>yes</td>
<td>0.035 % TREO</td>
<td>0.012</td>
</tr>
<tr>
<td>Mabounie</td>
<td>Gabon</td>
<td>carbonatite</td>
<td>yes</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Madeira</td>
<td>Brazil</td>
<td>carbonatite</td>
<td>yes</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Pitinga</td>
<td>Brazil</td>
<td>apogranite</td>
<td>yes</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Stromberg</td>
<td>Australia</td>
<td>altered tuffaceous sandstone</td>
<td>yes</td>
<td>0.43 % TREO</td>
<td>NA</td>
</tr>
</tbody>
</table>

(NA = not available; Mt = million metric tons).

Sources include: Long and others, 2010; British Geological Survey, 2011; TUC Resources, 2012; Watanabe, 2010; Orris and Grauch, 2002; Berger and others, 2009; Kynicky and others, 2012; Gilbertson and Russill, 2011; LynasCorp, 2012; Pittuck, 2011; and Watanabe, 2010).

Within the supergene zone of the laterite, the major minerals include goethite, hematite, and plumbogummite (Lottermoser, 1990). Minor minerals include secondary maghemite, apatite, calcite, dolomite, hollandite, cryptomelane, kaolinite, montmorillonite, and monazite; primary minerals include magnetite, pyrochlore, zircon, Nb-ilmenite, and Nb-rutile. The underlying residual zone contains...
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apatite and goethite with minor secondary calcite, dolomite, kaolinite, apatite, and hematite; primary minerals include magnetite, calcite and dolomite. Fresh carbonatite includes rocks such as sövite, beforsite, glimmerite and phosphorite (Lottermoser, 1990). Additional secondary and primary minerals are also listed by Lottermoser (1990). Most of the REE and yttrium (Y) are found in secondary monazite, churchite, a hydrous yttrium phosphate, and plumbogummite-group minerals, a group of hydrated aluminophosphates with a varied composition. The monazite, containing most of the LREE, occurs as microcrystalline aggregates on and replacing apatite. Plumbogummite minerals occur as pisolites, overgrowths on manganese minerals, as botryoidal cellular and platy aggregates, and pseudomorphs after apatite and pyrochlore. Churchite, containing most of the HREE, occurs as polycrystalline aggregates and intergrown with plumbogummite (Lottermoser, 1990).

Minor amounts of REE are also found in secondary apatite and cerianite.

Lateritic weathering of the Mt. Weld carbonatite is believed to have occurred during the early- to mid-Tertiary. Low pH fluids, probably acidic meteoric water (Bao and Zhao, 2008) dissolved primary carbonates and REE-bearing phosphates. The REE were mobilized, complexed by carbonate, fluoride, or chloride ions, transported down through the laterite, and began to precipitate where pH conditions increased towards the less weathered carbonatite. The LREE elements were deposited in the upper parts of the supergene zone with the HREE deposited at greater depths (Lottermoser, 1990).

Presently, the Lynas Corporation has mined and stockpiled REO ores adjacent to their open pit. This company has built a processing plant in Malaysia, but has encountered local resistance to begin operations. After legal hurdles have been cleared in November,
2012, Lynas Corp. began to start up their processing plant and will be the first new REE deposit outside of China to produce REO (Berube, 2012).

Numerous other lateritized carbonatites, such as Ngulla, Araxa, Mabounie, and Madeira (see table 1), primarily found in South America and Africa, have been examined for their possible REE resources (Orris and Grauch, 2002; Berger and others, 2009). Laterization of other carbonatites may result in similar enrichment zones, secondary mineralogy, grade and tonnage as described for Mt. Weld. Other outcomes are possible and related to differences in their primary REE mineralogy, total REE content, and proportions of the different lanthanides (Mitchell, 2005).

Stromberg, Northern Territory, Australia

The Stromberg REE deposit (fig. 1) is one of the few known lateritic deposits outside of China with a high percentage of HREE. The presently defined deposit is hosted in gently dipping, permeable sandstones and tuffs interbedded with impermeable siltstones and shales (fig. 3A). The stratigraphic section is broken into a number of east dipping blocks by a series of west-dipping, listric basin growth faults (TUC Resources, 2012). The age of these rocks, structures, and mineralization is not reported.

The weathering profile (fig. 3B) consists of: 1) an upper mottled zone; 2) a silicified zone; 3) goethite-bearing mottled zone; 4) a localized kaolinite-bearing bleached zone; and 5) a ferruginous saprolite with alternating hematite- and goethite-bearing zones overlying saprock (TUC Resources, 2012).

Mineralization is at or near the surface within the weathering profile zones 1-4 (fig. 3B). The REE mineral occurs as very fine-grained xenotime in a mixture of kaolinite and halloysite. Average thickness of drilled mineralization is 6 m @ 1 percent TREO with 95 percent containing the HREE dysprosium and yttrium (TUC Resources, 2012).

The current proposed origin of the primary mineralization is that hydrothermal fluids ascended up a series of reverse faults and deposited REE in the porous tuffaceous sandstone (fig. 3). Subsequent

Figure 4. A. Idealized weathering profile for in-adsorption-type REE deposits. B. Variation of REE in soil profile from Guangdong area (modified from Grauch, 2003, unpublished).
Lateritic weathering remobilized and concentrated the REE down dip from the original mineralization sites as shown in fig. 3A (Bamborough, 2012a, b).

Southeastern Chinese deposits (ion-adsorption type or IAT)

Economic concentrations of REE in lateritic weathered granitic rocks in southeastern China (fig. 1) are commonly referred to as ion-adsorption type or IAT lanthanide deposits (Bao and Zhao, 2008; Chi and Tian, 2008; Kynicky and others, 2012). The term “weathering crust elution-deposited rare earth ores” was recently proposed by Chinese researchers (Chi and Tian, 2008). Most of the more than 214 occurrences and deposits of this type are found in the provinces of Jiangxi, Guangdong, Hunan, and Fujian (Chengyu and others, 1996; Hedrick and Templeton, 1991; Chi and Tian, 2008) and several in Guangxi and Anhui (Clark and Zheng, 1991). These lateritic deposits occur mainly south of 30° north latitude (Yun and Zonghu, 1991; Chi and Tian, 2008).

In Jiangxi Province, currently estimated reserves total 13.5 million metric tons of LREE and 2.13 million metric tons of medium to HREE (Shen, 2013). Mining grades vary between 0.03 and 0.5 % total REO (Chi and Tian, 2008).

In China, REE-bearing laterites have developed on a variety of felsic rocks including rhyolitic lava (Yunhua and Lipu, 1987), granitoids, granitic rocks, biotite – K-feldspar-granite, and K-feldspar granite (Chengyu and others, 1990a, b; 1993; Zhuming, 1987; Yueqing and others, 1981; Chi and Tian, 2008). Some protoliths are enriched in either HREE or LREE with LREE/HREE ratios of about 1 and 8–19, respectively (Bao and Zhao, 2008). Fresh HREE-enriched granites may have concentrations on the order of 80 ppm LREE and 250 ppm HREE+Y. Fresh LREE-enriched granites may have concentrations on the order of 80–600 ppm LREE and 60–150 ppm HREE+Y (Bao and Zhao, 2008). Original TREE grades may range from 0.021 to 0.099 percent (Dianhao and others, 1989; Chengyu and others, 1990a; Bao and Zhao, 2008; Chi and Tian, 2008). Weathering of two-mica granites generally produces yttrium-containing HREE laterites, while weathering of biotite granites and volcanic rocks such as rhyolite and tuff develop Ce-bearing LREE deposits (Chi and Tian, 2008).

The ages of the granitic protoliths range from 548 Ma to about 96 Ma (Chengyu and others, 1990b). The laterites may range in age from modern to at least as old as early Tertiary (Meyerhoff and others, 1991; Samama, 1986). In southeastern China, current climate conditions are humid tropical to subtropical with the mean temperature being 15° C or greater; the annual rainfall is greater than 1,500 mm (Chengyu and others, 1993). Climate conditions similar to the present are thought to have existed throughout development of the laterites (Chengyu and others, 1993; Meyerhoff and others, 1991; Samama, 1986).

The areal extent of individual deposits is not reported, but estimates of the extent of exploited ground as seen from satellite images suggest deposits with lengths up to 4.5 km and widths up to 2 km. The REE mineralized horizons vary in thickness between 0.3 and 20 m (Chuanfu, 1996; Chengyu and others, 1996; Wu and others, 1996). In the Longnan area of Jiangxi Province, China, laterites vary in thickness between several and 30 meters. In adjacent Hunan Province, the exposures of laterite are discontinuous, as they are separated by mountains (Chuanfu, 1994). The laterite deposits are thickest on hill crests and thin dramatically on hillsides as the valley floor is reached (fig. 4). The thickness, lateral extent, and stability of the laterites are a function of bedrock characteristics, landform, vegetation, climatic variations, and tectonic stability (Grauch, 2003, unpublished).

Laterite profiles (fig. 4) are based on physical appearance and consist of: 1) an upper “depleted” soil zone (equivalent to the A horizon); 2) an enriched “totally weathered “ zone (equivalent to the B horizon); 3) sub-weathered zone (weak-weathering zone equivalent to the C horizon); and 4) granitic protolith (Bao and Zhao, 2008). Boundaries between the zones are gradational. These zones in laterized granites roughly correspond to the vertical distribution of the clay mineral assemblage in the <2 micron, clay particle size fraction (Zhuming, 1987; Chengyu and others, 1990a). These mineral assemblages roughly corresponding to the soil horizons consist of: A) kaolinite + halloysite (7Å) ± gibbsite; B) halloysite (7Å) + kaolinite + vermiculite; C) halloysite (7Å) + kaolinite + montmorillonite + mica. The “D zone” is not strictly a soil horizon, but commonly refers to the bedrock. The ore bodies occur within the totally weathered zone (Chuanfu, 1996; Chengyu and others, 1996; Wu and others, 1996; Bao and Zhao, 2008). Similar enrichments of REE are reported in the C zone in weathering profiles of granites in Laos (Sanematsu and others, 2009; Mentani and others, 2010).
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components in residual minerals; 2) residual REE minerals; 3) secondary REE phases including REE-rich colloids; 4) trace components of iron and manganese oxides; and 5) exchangeable cations on clays, and trace components in residual minerals (Chengyu and others, 1993; Zhicheng and others, 1994). Organically complexed REE are a significant component in laterites from the Longnan and Pingyuan areas (Zhicheng and others, 1994). Over 50 percent of the REE is present in the 0.7 mm size range with a grade of 24–32 percent REE (Chi and Tian, 2008). Between 30 and 90 percent of the REE in the laterite reside in exchangeable sites at most ion-adsorption type deposits (Yueqing and others, 1981; Zhuming, 1987; Chengyu and others, 1989, 1990a, 1993; Shaomei, 1991; Chuanfu, 1994, 1996; Chuanxian and others, 1996; Chi and Tian, 2008).

Mining and separation of REO is relatively inexpensive and simple for these deposits. Lateritic REE deposits in China consist of soft material that is easily removed by mechanical excavating equipment or leached in-situ. In the past, leach ponds were constructed on the crests of hills underlain by the REE-bearing laterite or shallow leach wells were dug into the hillsides. Extraction was accomplished by leaching the clays collecting the leachate downslope. This type of extraction has now been banned because of environmental concerns (Kynicky and others, 2012).

Other types of lateritic deposits — bauxites, phosphorites, paleo-laterites

The effects of lateritic weathering that have produced bauxites, phosphorites and paleo-laterites from a wide variety of primary lithologies have commonly been investigated through the use of REE analyses. Recent interest in bauxites, phosphorites and paleo-laterites has increased for their REE potential, but most of these deposits have no reported REE grades or tonnages.

Large bauxite deposits are known to develop on limestone, kaolinite, syenite, and basalt. Most are located in the southern United States, Jamaica, northern South America, southern Europe and southern and central Asia. Bauxites in southeastern United States, Jamaica and southern Europe are known to contain anomalous REE (Stearns and Tieh, 1991; Stearns, 1992; Cocker and Costello, 2003; Logomerac, 1969).

REE are present mainly as cations adsorbed on the clay or diaspore and as cation replacements in diaspore (Wang and others, 2010). Bastnäsite is the main identified REE mineral in bauxite deposits (Mariano, 1989), but crandallite, goyazite, svanbergite-woodhouseite, rhabdophane, florencite, xenotime, churcrite, parisite may also be present (Mordberg, 1999; Laskou and Andreou, 2003; Wang and others, 2010).

Enrichment of REE has been studied in bauxites developed from limestones (karstic bauxites) for many decades. Wang and others (2010) describe Devonian age bauxite in China that contains from 233 to 1,459 ppm TREE, and Liu and others (2010) noted enrichment of TREE of up to 1,800 ppm in bauxites derived from limestones in China. At the lower contact of bauxite developed over limestone at Parhari, Greece, REE concentrations are greater than thousands of ppm (Eliopoulos and Economou-Eliopoulos, 2000). In Jamaica, red mud from bauxite mine waste ponds were reported to contain TREE values from 1,900 to 2,600 ppm (Wagh and Pinnock, 1987). Mariano and Mariano (2012) reported these red muds contain 0.23 to 0.38 percent (2,300 to 3,800 ppm) TREE. Concentrations of REE in bauxite and associated residual red mud occur on basalt in Suriname, also (Logomerac, 1969). In other places where bauxites are not noted, lateritic weathering of basalts has caused enrichment of REE in both laterized basalts and basalts underlying strongly weathered basalts (Sanematsu and others, 2011; Cotten and others, 1995).

Supergene phosphorites from 20 deposits worldwide exhibit a wide range of REE contents according to Zanin and Zamirailova (2009). At the low end are weathered sedimentary rocks with an average of 27 ppm TREE. At the upper end are lacustrine coprolitic phosphorites with 462 ppm mean TREE and weathered igneous rocks with 372 ppm mean TREE (Zanin and Zamirailova, 2009). Examples of phosphorites derived from weathered igneous rocks were discussed earlier in this paper. It is not clear how supergene is defined by Zanin and Zamirailova (2009), and from where in the weathering horizons the samples were collected.

China recently started recovery of REE from the Xinhua sedimentary phosphorite deposit in Guizhou Province, which reportedly contains 1.198 million metric tons TREO (Shen, 2012). Based on the total tons of phosphorite ore, the REE grade would be about 0.0013 percent (or 13 ppm) TREO. The report does not
Lateritic, supergene rare earth element (REE) deposits indicate whether or how much of the REE are primary or secondary.

Some other studies (Gnandi and Tobschall, 2003) indicate a greater enrichment in REE in weathered sedimentary phosphorites in Togo, up to 1,750 ppm (0.18 percent), so weathered phosphorites other than those noted by Zanin and Zamirailova (2009) may also be significantly enriched in REE. Examination of weathered portions of other sedimentary phosphorite deposits may reveal concentrations of REE that may be economically feasible to recover separately from the phosphorite.

Many of the lateritic REE deposits are actually paleo-laterites formed under conditions that existed in the past and not necessarily under present day conditions. These deposits may occur in any part of the world and at any time in the past when and where favorable climatic and geologic conditions existed. Numerous Permian-age bauxite deposits are present in northern Russia that exhibit REE enrichment (Mordberg, 1996, 1999). The weathering that produced the bauxite deposits in the Nanafalia Formation in Georgia and Alabama, noted above, is Paleocene in age. One of the oldest recorded REE enrichments (late Archean, ca 2,760 Ma) is described by Macfarlane and others (1994) in Western Australia. They described greenschist facies metamorphosed weathering profiles consisting of an upper sericite-rich rock and a lower chlorite-rich rock, originally developed on basalt, that show enrichment of LREE 6–9 times that of the underlying parent rock. These examples of paleo-laterites show a considerable range in ages and types of possible lateritic REE deposits.

Southeastern United States

Lateritic supergene REE deposits are possible in the southeastern United States. Lateritic weathering affected sedimentary, igneous and metamorphic rocks from at least the Cretaceous to the present, with strong weathering episodes during the Cretaceous, Paleocene, and Eocene. Extensive bauxite and kaolin deposits in the Upper Coastal Plain may also contain economic concentrations of REE as noted above. Ultisols similar to those in southeastern China are widely distributed in the southeastern United States and some soil samples contain 500 to about 1,000 ppm (0.05 to 0.1 percent) TREE (Stewart, 2012).

As part of a program to define the background geochemistry of major river basins in Georgia, the pre-existing stream sediment geochemical data (n = 7,862) from the U.S. Department of Energy’s National Uranium Resource Evaluation Program (NURE) were contoured using a triangulated integrated network (TIN) program within ArcInfo, the GIS used in this study. Images of two of these maps, for samarium and lanthanum, are reproduced in figure 5. Stream sediment geochemistry may further amplify anomalies present in the source terranes.

Maps for the other analyzed REE, including cerium, europium, dysprosium, ytterbium, lutetium and yttrium, show similar patterns as in figure 5. Three major northeasterly trending belts of anomalous REE are evident on these maps. These REE belts correspond to portions of the Blue Ridge and Inner Piedmont terranes, and to Cretaceous- and Tertiary-age sedimentary rocks of the upper portion of the Coastal Plain.

To determine which rock units may contain background or elevated REE concentrations, all samples that were geographically within rock unit polygons on the digital Geologic Map of Georgia (Cocker, 1999b) were identified with the GIS. Because of sample spacing, drainage patterns, and relatively narrow map patterns of the rock units in the Blue Ridge terrane and the Coastal Plain, these areas were excluded from this analysis. Mean REE values were calculated for samples attributed to each rock unit, and those rock units with the highest mean REE values are listed in table 2. Rock units in this table include various types of sillimanite schist, biotite gneiss and granites as classified on the Geologic Map of Georgia (Cocker, 1999b). The state map has no distinguishing rock unit descriptions and similarly named rock units may be distinguished only by unique map unit symbols such as bg1, bg2, etc. for different biotite gneiss units.

In the Piedmont terrane, regionally elongate, coincident REE anomalies are associated with predominantly metasedimentary aluminous and micaceous schists and felsic biotite gneisses (Cocker, 1996, 1999a). The combination of high concentrations of REE derived from these rock units and extensive lateritic alteration is favorable for the development of lateritic, supergene concentrations of REE over large areas of the southeastern Piedmont. Anomalous REE in stream sediments in the Coastal Plain may be derived from Cretaceous and Paleocene kaolin and bauxite deposits and their enclosing sandstones as noted earlier.

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Figure 5. NURE geochemical maps for lanthanum and samarium in stream sediment samples in northern Georgia and adjacent parts of Alabama and South Carolina (M. Cocker, unpublished). State borders and terranes are approximately located.
Lateritic, supergene rare earth element (REE) deposits

Table 2. Mean values of REE in stream sediment samples geographically associated with major rock units in the Georgia Piedmont. Rock units are from the Digital Geologic Map of Georgia (Cocker, 1996b).

<table>
<thead>
<tr>
<th>Rock unit</th>
<th>La</th>
<th>Ce</th>
<th>Sm</th>
<th>Eu</th>
<th>Dy</th>
<th>Yb</th>
<th>Lu</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sericite schist</td>
<td>483</td>
<td>1,012</td>
<td>143</td>
<td>4.9</td>
<td>50</td>
<td>21</td>
<td>2.3</td>
<td>16</td>
</tr>
<tr>
<td>Mica schist</td>
<td>271</td>
<td>517</td>
<td>42</td>
<td>4.8</td>
<td>23</td>
<td>16</td>
<td>2.1</td>
<td>43</td>
</tr>
<tr>
<td>Garnet mica schist</td>
<td>381</td>
<td>727</td>
<td>43</td>
<td>0.6</td>
<td>106</td>
<td>44</td>
<td>6.5</td>
<td>225</td>
</tr>
<tr>
<td>Sillimanite schist</td>
<td>405</td>
<td>719</td>
<td>72</td>
<td>4.1</td>
<td>28</td>
<td>17</td>
<td>2.3</td>
<td>60</td>
</tr>
<tr>
<td>Sillimanite schist</td>
<td>420</td>
<td>688</td>
<td>84</td>
<td>3.8</td>
<td>50</td>
<td>22</td>
<td>2.9</td>
<td>109</td>
</tr>
<tr>
<td>Sillimanite schist</td>
<td>264</td>
<td>483</td>
<td>52</td>
<td>4.0</td>
<td>34</td>
<td>21</td>
<td>2.2</td>
<td>46</td>
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<tr>
<td>Biotite gneiss</td>
<td>402</td>
<td>755</td>
<td>92</td>
<td>6.4</td>
<td>38</td>
<td>18</td>
<td>2.4</td>
<td>61</td>
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<tr>
<td>Biotite gneiss</td>
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<td>685</td>
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<td>39</td>
<td>21</td>
<td>2.8</td>
<td>46</td>
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<tr>
<td>Biotite gneiss</td>
<td>528</td>
<td>430</td>
<td>57</td>
<td>4.6</td>
<td>29</td>
<td>12</td>
<td>1.5</td>
<td>22</td>
</tr>
<tr>
<td>Non-porphyritic granite</td>
<td>276</td>
<td>524</td>
<td>32</td>
<td>5.4</td>
<td>29</td>
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<td>30</td>
</tr>
<tr>
<td>Undifferentiated granite</td>
<td>253</td>
<td>502</td>
<td>29</td>
<td>4</td>
<td>25</td>
<td>16</td>
<td>1.9</td>
<td>40</td>
</tr>
<tr>
<td>Granite</td>
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<td>382</td>
<td>41</td>
<td>4.6</td>
<td>38</td>
<td>22</td>
<td>1.4</td>
<td>20</td>
</tr>
<tr>
<td>Undifferentiated granite gneiss</td>
<td>253</td>
<td>423</td>
<td>39</td>
<td>3.8</td>
<td>24</td>
<td>19</td>
<td>2.3</td>
<td>48</td>
</tr>
</tbody>
</table>

Paleocene bauxite deposits found in the Coastal Plain of Arkansas, Alabama, and Georgia contain anomalous REE. Bauxite deposits in Arkansas were derived from weathering of nepheline syenite intrusions. With increased weathering, HREE were enriched in the bauxite, and LREE were enriched at the transition between bauxitized syenite and weathered syenite (Stearns and Tieh, 1991; Stearns, 1992). The LREE were leached by acidic fluids near the surface and deposited at the base of the weathering profile. Bauxite in the Eufaula district in Alabama and the Andersonville district in Georgia was derived from micaceous, kaolinitic clays of the Paleocene Nanafalia Formation. Concentrations of heavy minerals are commonly found within the bauxite and sandstone of that formation (Cocker, 1999a, 2012) and anomalous REE are found in NURE stream sediment samples (Cocker, 1996).

Suggested origin of lateritic deposits

Lateritic weathering may leach potassium, sodium, calcium, and silica from silicate minerals, with concomitant enrichment of the less mobile aluminum, iron, manganese, nickel, gold, phosphorous, and niobium that may be concentrated sufficiently to be economically viable. Lateritic enrichments of these commodities form under fairly similar conditions. Lateritic weathering is a relatively slow process, so long periods of tectonic stability are necessary to develop economic concentrations of these elements. Relief of these deposits is moderate so that runoff of precipitation and physical erosion are minimal. Optimal conditions for lateritic weathering are humid tropical to subtropical climates, similar to current conditions at low to moderate elevations in southeastern China and southeastern United States.

In the laterite deposits in China, pH of the laterite increases downward from 5.8 in the soil zone to 6.5 in the slightly weathered zone (Chengyu and others, 1990a). Braun and others (1993) suggested that pH
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values were less than 6 in the upper parts of a lateritic profile over a syenite and measured a pH of 5.5 in groundwater from a laterite over a gneissic protolith (Braun and others, 1998) in Cameroon. In laterite profiles, Eh values decrease downward (Chengyu and others, 1990a; Braun and others, 1993). Low pH and high Eh indicate an oxidizing, acidic environment for lateritic weathering and leaching of the REE elements in the upper parts of the weathering profile. Increasing pH and decreasing Eh are suggested for precipitation of secondary REE-bearing phosphates, carbonates and oxides. Increasing cation exchange capacity of clays with depth provides sites of the remobilized REE to become adsorbed at depth. In lateritic weathering HREE appear to be more mobile than LREE and these REE may be fractionated with HREE at greater depths (Brown and others, 2003).

The cation exchange capacity of the clay fraction also increases downward from 10.8 to 16.5 meq/100g. Amorphous iron-oxide and possibly manganese-oxide may also provide a significant number of exchange sites (Yong and Zheng, 1993). These oxides and clay mineralogy as well as pH are the primary factors controlling the cation exchange capacity of several different Chinese soils.

Summary and conclusions

Supergene, lateritic deposits may form from a variety of primary lithologies and may contain substantial volumes of economic concentrations of aluminum, iron, manganese, nickel, gold, phosphorous, niobium, and REE. Economic concentrations of both LREE and HREE are found in laterized granites, rhyolites and carbonatites of different compositions. Metamorphic rocks such as schists and gneisses and peralkaline rocks such as syenites that contain anomalous REE and are subjected to lateritic weathering may contain supergene REE in economic concentrations. To a lesser extent, because of the wide variety of source rocks, bauxites and lateritically altered phosphorites may also contain elevated REE that may be in economic concentrations or be recovered as a by-product of other mining activities. Many lateritic REE deposits are actually paleo-laterites which formed under climactic conditions that are not presently active at the location where they are found. Other paleo-laterites may be buried or be recognized as metamorphosed paleosols.

Under climatic and geologic conditions that favor lateritic weathering, REE may be mobilized in the near-surface weathering zone, usually the A zone in soil profiles, and redeposited and concentrated at depth, usually in the B zone. The abundance of REE in laterites is dependent, in part, on the original REE content in the host rock. In laterites formed from different types of granites in China, the enrichment of REE may contain higher LREE, HREE, or a mixture of both types of REE. Also, bauxites derived from different limestones, basalts, kaolins, or syenites may contain different concentrations or distributions of REE. Supergene concentrations of REE are more likely to contain REE grades and tonnages that may be economically viable when the parent lithologies contained elevated REE concentrations.

Lateritic REE deposits have a number of important advantages over hard rock deposits that make them more likely to be developed. Of all REE deposits, Mt. Weld has the highest grade and Ngulla has one of the highest overall tonnages, while many of the ion-adsorption type deposits have lower grades and similar tonnages. In addition, lateritic REE deposits are near-surface (generally less than 100 m), and the ore is relatively soft, thereby making the lateritic deposits amenable to low-cost, open-pit mining. In contrast to hard-rock deposits, the mineralogy of lateritic deposits is relatively simple. REE may be adsorbed on clays, iron or manganese oxides, or colloids, and in others, secondary REE minerals include phosphates, carbonates, and oxides. The minerals are fine-grained foregoing the need for crushing. Extraction of REE and separation of individual REE from these secondary REE-bearing minerals can be relatively simple and inexpensive compared to primary minerals in hard rock deposits.

Supergene enrichment of lower grade REE occurrences conceivably can lead to a large number of unrecognized REE deposits that are economic and more widespread than are currently known. This may result in the discovery that global lateritic REE resources may be much larger than currently recognized. Widespread and unrecognized REE deposits of this type can represent important targets for the exploration and mining sector.
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