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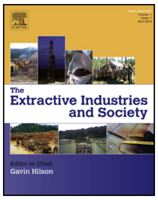

Review article

A historical geography of rare earth elements: From discovery to the atomic age

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ABSTRACT

This article presents a historical geography of rare earth elements from their discovery to the atomic age with a focus on the period between 1880 and 1960 in order to lend greater depth to the growing body of scholarship on the relationship between rare earth elements and global political change. Drawing on archival and field research undertaken in the United States, China, Brazil, and Germany between 2011 and 2014, this article advances the following argument. Rare earth elements, and the production of geological knowledge about them, have entangled with contentious politics since their first industrial applications in the late 19th century. The historical geography of rare earth exploration and extraction is defined by a fundamental tension between the military-industrial necessity of these elements and the hazards associated with their production. This tension played a definitive role in international colonial, Cold War, and atomic politics.

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1. Introduction

The international community was made aware of importance of rare earth elements in 2010, when China allegedly halted exports amidst a territorial dispute with Japan. At the time, China produced 97% of the global supply of rare earths, which are essential for a diverse and expanding array of communications, energy, information, and military technologies. Research and analyses have since proliferated on this important topic (Humphries, 2013; de Boer and Lammertsma, 2013; Wübbeke, 2013; Biederman, 2014; Hurst, 2010; Phua and Velu, 2012; Rauer and Kaufmann, 2015).

In historical terms, the majority of the academic literature focuses on the last decade and a half, while the geographical focus is overwhelmingly on China, Australia, and the United States. This makes sense, as the two largest sources of rare earth elements for the past 50 years have been located in Mountain Pass, California, and Bayan Obo, Baotou, Inner Mongolia, while the mine at Mount Weld in Western Australia has emerged as an important new site. However, some have erroneously attributed China's rare earth

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monopoly to geological determinism: that China possesses more rare earth elements than any other country is a stubbornly popular fiction in contemporary commentary (Wang, 2010; Lin, 2012; Xie, 2013; Yan et al., 2014). While the consensus in the contemporary literature is that China's production quotas and export controls 'politicized' rare earth elements, this article explains that in fact, the political life of rare earths began well over a century ago, with their earliest commercial applications and subsequent expansion of knowledge about their material properties and geological incidence.

The article presents an international historical geography of rare earth elements between 1880 and 1960. It was during this period that applications gradually began to expand as diverse state and commercial interests sought these elements ever further afield in the contentious times defined by colonial, atomic, and Cold War politics. However, it was not until the 1960s, with the rise of the Mountain Pass mine in Southern California that a period of relative calm and stability settled around the production of rare earths. Because the Mountain Pass era (1960–2000) is often positioned as the historical reference point against which contemporary rare earth politics are contrasted, this article focuses on the preceding eras in order to lend greater depth to the small but growing body of scholarship (e.g., Kiggins, 2015) on the relationship between rare earths and international political change over the course of history.

The analytical approach utilized herein is concerned with historical human–environment relations in terms of how past geographies influence those of the present. Such an approach reveals that the 2010 emergence of rare earths as important elements of international politics is more accurately characterized as a *re*emergence after decades of relative calm maintained first by US, and subsequently by China's *de facto* monopolies over mining and processing. Just as rare earths are at the center of several key 21st century geopolitical disputes, a historical geographical analysis reveals that the production of scientific knowledge about these elements has entangled with contentious politics since the end of the 19th century. During the period examined herein, various state and industrial actors undertook to explore and exploit these elements in ways that served broader territorial agendas, which had to contend with imperatives to secure these strategically vital elements while sequestering the hazards generated by mining and processing.

Each theme is explored herein. Section 2 defines the elements and the conditions of their discovery. Section 3 explains the physical properties of rare earth elements as they occur in Earth's crust and introduces the politics of geological knowledge production. The fourth examines the role of rare earths prospecting, research, and extraction in global politics from 1880 to the 1960s. Because developments in the political life of rare earths are diverse and overlapping, the histories are examined as several overlapping periods rather than in discreet chronological sequence. The article concludes its history where most begin: with the rise of US dominance of rare earth production that lasted until the end of the 20th century.

2. Discovery and classification

'In a way,' writes Abraham (2011, 101), 'it begins with semantic confusion.' Rare earths are not rare; the name is much less indicative of their actual qualities than certain assumptions made at the time of their discovery. In 1788, a miner in Ytterby, Sweden, found a strange black rock. It was identified several years later, in 1794, as a new kind of 'earth,' which is an archaic reference for acid-soluble elements (Rowlatt, 2014). It was later found to be a mineral consisting of cerium, lanthanum and yttrium in iron ore. Since such elements had not been found anywhere else, they were presumed to be scarce. Hence the name, *rare earths,* which refers primarily to the 15 elements in the lanthanide series ranging from lanthanum (atomic number 57), to lutetium (number 71). The implication of rarity has legitimated the ruthless pursuit and capture of these elements over the past century, and perhaps that is why the antiquated name persists over a 125 years after this misnomer was identified.[1]

The elements that are included with the lanthanide series in reference to rare earths changes over time: during the race to build the nuclear bomb, thorium and uranium were also referred to as rare earth elements because of their close affiliation and frequent geological coincidence. Currently, scandium and yttrium are also counted as rare earths, although they are found elsewhere on the periodic table: atomic numbers 21 and 39, respectively. Therefore, at present, *rare earths* refers to a group of 17 chemically-similar elements comprising about 17% of all naturally occurring elements (Cardarelli, 2008; Goldschmidt, 1978; Beaudry and Gschneidner, 1974; Liu, 1978).

Because of their exceptional magnetic and conductive properties, this family of soft, ductile metals is essential to an expanding array of high-technology applications fundamental to globalized modernity as we know it. There is no single 'rare earth market' to speak of, but rather, multiple markets for the 17 elements with widely divergent availabilities and applications. For example, erbium, which turns pink when oxidized, lends its hue to rose-colored glassware (Hammond, 2000) while also acting as an amplifier in fiber optic cables, which is critical to the functioning of global communications networks (Becker, 1999). The uses of neodymium are likewise wide-ranging. It is used to make permanent magnets in wind turbines, computer hard drives, and electric vehicles (Zepf, 2013), and it is also used to evaluate and predict the severity of volcanic eruptions (DePaolo, 2012). This gives rare earths an air of ineffability—they are seemingly everywhere, but in quantities too minute to quantify compellingly. The nature of their applications, like their geological incidence, is both ubiquitous and dispersed.

3. Geology, territory, and power

Rare earth deposits are borne of intricate geological processes that begin in Earth's mantle. They are formed in comparatively rare alkaline magmas, which possess sufficient iron and magnesium to support the coalescence of rare earths and related elements such as thorium and uranium into minable concentrations.[2] As the magmas go through repeated stages of heating and cooling, a process called fractional crystallization begins in which certain elements solidify as the temperature drops below their melting points. The elements that do not solidify during initial cooling phases are called incompatible elements. The critical feature of alkaline magmas is that the high iron and magnesium content facilitates the formation of relatively stable lattice structures that cradle the incompatible elements which ever-so-slowly solidify into concentrations of rare earth elements, niobium, uranium, and thorium. The material coincidence between rare earth elements

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[1] 'Until the year 1885, though by that time the scientific interest of the group had been fully demonstrated by the discovery of several new elements, it was supposed that the minerals were almost entirely confined to a few scattered localities in Scandinavia and the Ural mountains. In that year Dr. Auer von Welsbach announced his application of the rare earths to the manufacture of incandescent mantles. Immediately there was a great demand for raw material for the preparation of thoria and ceria. The agents of the Welsbach Company visited all the important mining centers of Europe and America, intent on a search which shortly made it clear that the metals of so-called "rare earths" are really quite widely distributed in nature,' (Levy, 1915, 2).

[2] For the sake of simplicity, I am describing the formation of a bastnasite Iron-REE-Th deposit here, such as those found in Bayan Obo, Baotou, Inner Mongolia in China and Mountain Pass, California, in the United States.

and radioactive materials has entangled geological research with multiple political agendas during the period examined herein.

'Politics' and 'the political' are defined according to Lefebvrian spatial theory which maintains that what we are referring to with these terms are social processes dialectically produced through everyday material practice that is invested with dynamic meanings over time and space (Lefebvre, 1991). Therefore the political life of rare earth elements is a product of the actual utilities of their chemical properties, ideas about their significance, and different perceptions of how these material and meaningful properties might serve diverse territorialities over time.

Geology is a science of territoriality. Territoriality refers to the processes and practices through which people claim space as their own in the (un)making of colonial, national, and geopolitical orders. Geological exploration has served as an important tool through which national and colonial powers translated *terra incognita* into vertically organized goods to be exploited in the name of development, security and progress (Braun, 2000; Shen, 2014; Wu, 2010). This work of 'mapping and elucidating specific geological features,' (Zhu and Le Grand, 1999, 292) is at its core a social process informed by the particular times and places in which it occurs (Oldroyd, 1996, 1990; Guntau, 1988). As geological inquiry is influenced by the political contexts in which it takes place, it in turn influences politics: Alatout (2009),Braun (2000) and Rudwick (2014) *inter alia* have shown that the orientation and use of geological knowledge is definitive of identities and politics at local and global scales; while Macfarlane (2003) demonstrated that policy and geology co-evolve in particular political economic contexts. In an analysis of the role of geological rationality in settler colonialism, Braun (2000, 14) argued for a consideration of 'the consequences of the "geologizing" of the space of the nation-state for forms of economic and political rationality, including efforts by the state to compel individual and corporate actors to "do the right thing" in relation to a territory that now had an important sense of verticality.'

Initial geological surveys of rare earth reserves were undertaken around the globe in the late 19th and early 20th centuries, at a time when multiple competing hegemons sought to rationalize national and colonial territories and take stock of domestic mineral wealth. As discussed in section three, states and firms consistently pursued mining opportunities beyond their borders or in places deemed 'marginal' in order to outsource environmental degradation and preserve domestic reserves, as in the cases of World War II (WWII) Allied Powers (Jones, 1985) and contemporary China (Chen, 2010). Thus the geography of rare earth prospecting and extraction is inseparable from geographies of power and vulnerability: power is exercised in the capacity to make hegemonic claims to the subsoils containing REEs, and power is manifest in the ability to subject some and exempt others from the toxic and radioactive byproducts of mining and processing (Bruce et al., 1963; Hirano and Suzuki, 1996), which, while not fully understood at the turn of the 20th century, were nevertheless recognized (e.g., Otto, 1921). There is a tension, therefore, between securing access to these vital elements and isolating the hazards generated by mining activities.

The international geography of rare earth production is defined by this fundamental tension. There are four main stages where environmental and epidemiological hazards emerge. The first is the mining process, during which certain rare earths, heavy metals such as lead and arsenic, and thorium and uranium are liberated from their subterranean confines. Circulating as windborne dusts and seeping into groundwater, these elements pose health risks to miners and surrounding residents (Mao et al., 2010). Then there is the refining process, where high temperatures and acids are used to separate elements (Hao and Nakano, 2011). The third is waste management from primary processing and beneficiation activities which generate radioactive residues and radon gas, and the fourth concerns disposal of rare-earth containing products for which there has yet to be implemented a comprehensive collection and recycling initiative (Weber and Reisman, 2012; Gullett et al., 2007; Verrax, 2015). All rare earth elements cause organ damage if inhaled or ingested; several corrode skin; five[3] must be handled with extreme care to avoid poisoning or combustion (Krebs, 2006). Because rare earths have a geological coincidence with thorium and uranium, mining can also necessitate a radioactive waste management situation (Bai et al., 2001). Even the most minimal environmental regulation dramatically increases costs of an already capital-intensive enterprise.

Despite contemporary alarmism, scarcity is not the issue. Since British, German, and US interests identified monazite deposits in India and the Americas at the turn of the 20th century, the actual defining issue has been selectively allocating the costs and benefits associated with production. Rare earths are plentiful, occurring between 150 and 200 parts per million (ppm) in Earth's crust, compared to copper at 55 ppm (Long and Van Gosen, 2010). There are currently 799 identified land-based deposits of sufficient concentration to be feasibly mined (USGS, 2013), bringing the total known land-based deposits to over 110 million tons (USGS, 2011), while recent explorations of the Pacific Ocean floor have yielded deposits potentially totaling over one thousand times as much (Pritchard, 2013; Kato et al., 2011). Thus the potential of rare earths to become the next 'elements of conflict' (Ting and Seaman, 2013) is not due to their absolute scarcity or geological concentration in any single place—such as China—but rather to the political life built around them as multiple actors with diverse interests navigate between necessity, cost, and danger.

4. The political life of rare earth elements

Rare earths have entangled with contentious politics, imperialism and militarism since the end of the 19th century. Although rare earths are now essential to the technological infrastructure of modern life as we know it, for nearly a century after their discoveries there was little use for them. From 1788 to 1880, rare earth elements were examined to a limited degree. As Greinacher, (1981, 4) explains, 'A great many learned men with famous names busied themselves with rare earth elements and reported interesting work . . . nevertheless, no applications or industrial usage came out of these efforts'. But from the 1880s onward, rare earth-based technologies began to transform life as we know it, slowly at first, but then with increasing scope, as military and industrial complexes around the world sought to harness their peculiar properties.

4.1. Lighting the night: 1880–1910

The first successful application of rare earths addressed an emergent problem in newly-urbanized industrial zones: how to produce light cheaply and reliably over a large area in order to maintain production after dark, especially during the long winter nights in Northern Europe (Koslofsky, 2011; Bogard, 2013; Ekirch, 2005). Carl Auer von Welsbach's invention of gas mantles (Eliseeva, 2011; Welsbach, 1889) in the 1880s inaugurated the first phase of industrial usage[4] of mixed or simply separated rare earth elements. Although the gas mantle lantern contained only 1% of the rare

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[3] Promethium, gadolinium, terbium, thulium, holmium

[4] Periodized by Greinacher (1981) as lasting from 1891, when Auer von Welsbach was awarded his patent, to 1930, when the properties of rare earth elements began to be used more widely, but before the launch of various atomic research programs during which the properties of rare earth elements were more systematically characterized.

earth element cerium,[5] the production scale was massive for the time. By the 1930s, over five billion had been sold (Niinistö, 1987), providing networks of city lights before the widespread establishment of electrical grids. This was the first of many niche applications of rare earths. Welsbach's first invention engendered the second: gas mantles were difficult to ignite, and large quantities of unseparated rare earth wastes left over from the production of the incandescent mantles were prone to combustion. By blending these rare earth wastes with 30% iron, he developed the alloy called 'mischmetall' that sparked when struck. He patented this as the 'flint stone,' which continues to be used in all manner of ignition switches, from lanterns to cigarette lighters to weapons to automobiles (Krishnamurthy, 2005). Within a few years of mass production, Scandinavian sources for rare earth elements could not satisfy demand. Thus the political life of rare earth elements emerged with the European quest for raw materials in colonial lands in the 1880s, when British and German interests prospected in India and the Americas to feed the expanding gas mantle and flint stone industry.

The sites that supplied Welbach's gas mantles and, later, the nuclear arms race, featured monazite sands which are comparatively more abundant, but not as highly concentrated as the rare earth-bearing bastnasites discussed earlier. Monazites, too, have their origins in alkaline magmas. Many igneous and metamorphic rocks produce rare earth-bearing minerals such as monazite and xenotime, which, when weathered, produce the monazite-bearing placers found in the rivers of Idaho and the beaches of Brazil and India. Extracting monazite sands requires shallow surface mining or riverbed dredging as opposed to the blasting and drilling needed for bastnasite mining.

In 1887, a British mining interest began extracting rare earths from the monazite sands on the beaches of North and South Carolina in the US; the operations were soon taken over by the Welsbach Light Company of New York (Levy, 1915). The German Thorium Syndicate and the Austrian Welsbach Company began exploiting monazite placers in Brazil in 1905 and in India in 1909, which drove US production out of business in 1910, except for a brief interlude during World War I (WWI) (Mertie, 1953).

Welsbach's technological and commercial success sparked greater interest in the broader applications of rare earths, which expanded the rare earth industry dramatically and drove the quest for raw materials beyond Europe, to the Americas, colonial India, and China. In the latter decades of the nineteenth and the first half of the 20th century, geological survey teams from Germany, Japan, Soviet Union, and China prospected among the steppe and desert of what was to become, in 1947, the Inner Mongolia Autonomous Region in Northern China. Wu (2010) and Shen (2014) argue that the evolution of geological science in China is inseparable from imperial designs on China's territory and resources. From the 1880s onward, colonial actors in the German Foreign Ministry looked to China to expand their reach with the objective of eclipsing the more extensive British and French empires. The means to do so were overwhelmingly material: diplomatic transmissions from both the Chinese and the German sides were dominated with concerns over mining technology transfer, land use, and mining rights (Wu, 2010). Successive teams came to survey Northern China with the intention of bounding its geological wealth into a larger resource hinterland, whether for Imperial Europe, Imperial Japan, or the USSR. It is worth noting that the industrial orientation of geological survey activities, the cartographic portrayal of mineral wealth and the construction of the infrastructure required to extract it were cited as symbols of progress and modernity for imperialist, nationalist, capitalist and communist interests alike (Davis, 1926). This supports the contention that geological sciences co-evolved with practices of territoriality (Braun, 2000; Winchester, 2009), as opposed to any particular political economic ideology.

4.2. Geology, imperialism, and nation building: 1900–1939

Which elements constitute the category of rare earths has changed over time. Not every rare earth had been identified before WWI. Thorium, uranium, tungsten, platinum and vanadium were grouped with rare earth elements because of their geological coincidence and complementary applications through WWII, while the lanthanide series was grouped with radioactive materials under the euphemism of 'non-ferrous metals' in the global quest to capture raw materials to build atomic bombs (Congress, 1955; Lewis, 1988). During WWI, the pyrophoric properties of rare earths were used in fuses and explosives (Martin, 1915). The English physicist Henry Moseley was the first to confirm, in 1914, that the lanthanide series must consist of 15 members, no more and no less, including promethium, whose existence was not confirmed until 1944. Moseley was the first to hypothesize that rare earth separation might shed light on nuclear fission, but he resigned from his research activities in late 1914 to enlist with the Royal Engineers of the British Army. He was shot in the head in 1915 while serving the British Empire in Turkey; it took three decades for the scientific community to continue where Moseley's research had been interrupted (Asimov, 1982).

The global political turmoil of WWI stimulated the formalization of geological science in China (Zhu and Le Grand, 1999). Competing imperial and nationalist groups surveyed China's terrain with the intention of rationalizing a mysterious empire. China's Geological Society was the first scientific institution established in modern China in 1922 under the Republican government. As Shen (2014, 13) observed: 'any viable understanding of the nation had to suit the twin criteria of protecting Chinese existence and promoting geological activity, and often the boundaries of one effort would shift to accommodate the other.' Early geological research activity in China was characterized by international collaboration and open exchange of information;[6] but there was considerable inequality between Chinese and foreign researchers. The former were cash-strapped and relied on state directives and commissions from mining companies to keep China's Geological Society afloat. The latter were convinced that only an established colonial power could tackle the vast unknown represented by China's geology (Margerie in Wu, 2010, footnote 5) which put Imperial Japan in pride of place because of its control over key infrastructure extending inland from Northeastern and Southeastern China.

To consolidate control over the extractive potential in Northern China, Imperial Japan organized local puppet governments, engaged in prospecting activities and took over heavy industry and munitions factories. In the late 1930s, Japan had almost one third of China under its control, primarily the coastal and northern regions, where the majority of China's government, research, and industry was located (Wu, 2010; Utley, 1937). During the interwar period, Brazil and India supplied the global market—consisting of Europe and North America. Russia was self-sufficient.

Yet in the late 1920s through the 1930s, the Guomindang (KMT) sought to reunify China, integrate China's economy with the world economy, and engage with Euro-American counterparts as equals in international relations. During this time, Germany exerted

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[5] The other 99% was radioactive thorium.

[6] Reports from the first year of meetings recount several instances of Japanese, American, Russian and Chinese researchers comparing fieldnotes and perusing each other's notebooks in a period of unusual openness and sharing (Liu, 2009).

arguably the greatest influence among the KMT's governing elite. The KMT's leader, Chiang Kai-shek, viewed Prussian fascism as a model of rapid national development to emulate in order to mobilize and discipline the populace into breathing 'New Life' into the nation,[7] (Kirby, 1984). Looking to revive the domestic German economy struggling the aftermath of WWI and the global slowdown of the Great Depression, Nazi leadership looked to China as both a cheap source of critical resources and an immense potential market for German industry. The two countries brokered a set of barter agreements in which China exchanged raw materials for German military equipment, railroad materials, and industrial equipment. Germany sponsored Chinese students to receive training in Germany; when they returned, many staffed agencies overseeing China's industrial and military modernization (Kirby, 1984). China exported tungsten, antimony, tin, and copper, which were crucial for Nazi Germany's rearmament. Both antimony and tungsten were important predecessors to rare earth elements in the development of modern industry and warfare. Tungsten is an important element of war because it has the lowest coefficient of thermal expansion of any pure metal, so it preceded rare earth superalloys in the construction of airplane engines, tanks, rockets, and other steel alloys (Li, 1955). Antimony was used to build ignition switches, to produce flame retardants, and to harden the lead used in bullets (Butterman, 2004). But tungsten and antimony were heavy and cracked unpredictably, so scientists across Eurasia later turned their attention to rare earths in the search for replacements.

During the second and third decade of the 20th century, Germany provided the majority of China's foreign credit, so the KMT sought to expand the terms of the agreement as much as possible in order to resist Japanese imperialism. Raw materials formed the basis of the agreement, so the KMT leadership worked to expand China's mineral output (Kirby, 1984) and solicited German, Swiss, and Danish experts to explore and map the subsoils of Inner Mongolia and Xinjiang. The international teams of geologists and archeologists, including John Gunnar Andersson and prominent Swiss geographer Sven Hedin, formed the Northwestern Scientific Expedition Team which identified minerals, fossils, and archeological treasures in this 'Western Asian frontier' (Deng, 2007; Hedin et al., 1944). In April 1927, this team of 40 left Beijing by train and traveled to Baotou—then a border outpost before the 'uninhabited' steppe and desert—where they provisioned themselves for the long prospecting journey by mule and camel from Baotou to Alashan tribe in Ejina Banner (Xing et al., 1992). Under these circumstances in July 1927, the geologist Ding Daoheng discovered the resources at Bayan Obo (Ding, 1933) which is now known as 'the rare earth capital of the world.' Although he is now upheld as a national hero for identifying what is still thought by some to be the world's largest rare earth deposit, he was part of a group within the expedition that was entirely focused on identifying iron resources to provision German, Russian, and nascent Chinese industry. The presence of rare earths at Bayan Obo was not demonstrated until 10 years later by the chemist He Zuolin (Zhang et al., 1995).[8] This discovery shaped the nascent communist Chinese industrial geography as the newly established PRC sought to develop nuclear weapons.

4.3. Rare earths and the bomb: 1939–1949

The race to build the atomic bomb reconstituted international rare earth politics along the emergent fault lines of the Cold War. Rare earths were both inputs and outputs of the nuclear war effort. In 1939, the German scientists Hahn and Strassman discovered the neutron-induced nuclear fission of uranium and identified rare earth elements in fission products (Cardarelli, 2008).[9] The US and Germany both drew their rare earth and thorium[10] supplies from India and Brazil until the outbreak of WWII in 1939. Germany then dodged British and Allied embargos before ceasing commercial operations with Brazil[11] and India in late 1940. Russia, meanwhile, extended its own rare earth hinterland into Kyrgyzstan, opening a rare earth–thorium–uranium mine and processing plant in Ak-Tyuz in 1942 (Djenchuraev, 1999) after Stalin received word in April of that year that Allied powers were developing a nuclear weapon (Kojevnikov, 2004). Shortly thereafter, US and British leaders concluded that:

> ' . . . the best future interest of the two countries would be served by a joint effort to seek out and gain control over as much of the world's uranium and thorium deposits as possible; this policy, they reasoned, would ensure their governments ready access to major new resources of inestimable value and would keep these resources out of the hands of their potential enemies. Furthermore, project leaders perceived that, strictly from the viewpoint of national interest, it would be better for the United States to conserve its own apparently limited domestic resources and use whatever raw materials it could acquire from other countries instead.' (Jones, 1985, 293)

Executing this agenda required a survey of unprecedented scope to catalogue international rare earth, thorium and uranium resources. Union Carbide, working in cooperation with the Manhattan Project, assembled a team of approximately 130 geologists, translators, and clerks in New York to search through all available technical literature in any language. In the first six months of 1944, they examined 65,000 volumes and carried out field expeditions in 37 states and 20 countries. They determined that the Belgian Congo, Brazil, and India would provide the most abundant high-quality materials to support the nuclear arms race, with Canadian and Western US minerals as good alternatives (Jones, 1985). The US could not secure supplies in colonial territories without the assistance of the British Empire, while the British Empire had interest in the global intelligence capacities of the US, so they collaborated to extend the atomic hinterlands of both countries into 'areas outside of American and British territory,' (Stimson, 1944 in Jones 1985, 299).

Accessing minerals in the Belgian Congo proved difficult for the US. The principle mine of interest, the notorious Shinkolobwe, had

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[7] A euphemism for purging communists and other 'undesirables,' which culminated in the Shanghai Massacre of 1927. See Stranahan (1998) and Grabau (1922), *inter alia*.

[8] Ho Tzao-lin in Wade-Giles spelling.

[9] They, along with several other groups, claimed to have discovered promethium, but definitive proof of its existence was not obtained until 1944 because of the difficulties of separating it from other elements. Promethium is not found on Earth outside of nuclear reactors, but is used to produce batteries that power pacemakers and space crafts as well as to manufacture luminescent paint for watch dials (Krebs, 2006).

[10] 'When thorium 232 captures a slow neutron, it converts to thorium 233. The thorium then disintegrates quickly into protactinium 233, which then decomposes, but more slowly, into uranium 233. Uranium 233 is fissionable by slow neutrons and thus potentially a material for sustaining a chain reaction. Thorium, like uranium, occurs widely in the earth's crust, but similarly not often in sufficient concentration to provide economically workable deposits. Before WWII, it was most commonly used in the manufacture of gas mantles,' (Jones, 1985, 292, footnote 1).

[11] Brazil-Germany relations during the 1930s suggested that Brazil would support Germany in the event of war. President/Dictator Getulio Vargas (1930–1945; 1951–1954) reportedly enjoyed Hitler's company and was sympathetic to Nazi-fascism in the 1930s. Germany was Brazil's second greatest trading partner up to 1940. (Penteado, 2006)

flooded and closed. The mine Director, Edgar Sengier, had returned to London. Sengier reportedly understood the potential of harnessing atomic power and the role his mine could play in it, but did not want to make any commitments to foreign militaries that he might later have to justify to the Belgian Government (Gowing, 1943 in Jones, 1985), unless the US and Britain could make an offer that served the interests of the Belgian Government in exile. In exchange for considerable sums of money, no timetable requirements, new equipment and diplomatic support to the deterritorialized Belgian state, Sengier agreed to re-open the mine to provide uranium to the US beginning in mid-1945 (Helmreich, 1998).[12] In the meantime, the US continued to rely on India and Brazil for thorium and rare earth elements.

India restored independence in 1947; in the post-WWII, postcolonial contests, nuclear weapons were seen as guarantors of sovereign power. Therefore, developing nuclear weapons was a top priority for Prime Minister Jawaharlal Nehru's government (Chengappa, 2000), along with finding a means to relieve the famine (Lawn and Clarke, 2008). The Indian Atomic Energy Act of 1948 identified thorium as a source of atomic energy, thereby naming it a strategic mineral and immediately halting the export of thorium-rich monazite. This embargo seriously disrupted the strategic monazite supply of the US, and coincided with the reorientation of US foreign policy toward containing the spread of Soviet influence and suppressing communist movements in India (Merrill, 1990). India had famine and monazites; the US had grain. The US State Department reframed a proposed US$190 million gift of emergency famine relief as 'Indian Food Crisis—Opportunity to Combat Communist Imperialism,' but US Republican congressmen opposed to international aid reformulated the planned grain transfer as a *quid pro quo*:

> India needs grain immediately; we have the grain. We need strategic materials from India over a period of years; India has those materials. We should make India a loan which can be repaid in strategic materials. (Congressman John M. Vorys quoted in McMahon, 1994, 96)

Nehru refused on the basis that such conditionality violated India's sovereignty. He later relented with the proviso that India would continue to provide strategic materials other than any which could be used for nuclear weapons development, which precluded monazite. Thus the plan to 'bring India closer to the West' backfired, leaving India's Cold War loyalties as well as the monazite issue unresolved (McMahon, 1994) and signaling an end to the rare earths status quo of the colonial era. When Brazilian production failed to make up the difference following the Indian embargo on monazite exports, rare earth and thorium prices rose precipitously between 1948 and 1952 (Mertie, 1953).

This rare earth supply crisis stimulated domestic US geologists, prospectors, and mining firms to set out in search of lucrative deposits in the American West; it was during this time, in 1949, that a uranium prospector discovered the rare earth mine at Mountain Pass, California (Olson, 1954) which would dominate global rare earth production from 1960 to 2000. But in the aftermath of WWII, US Congress opted to slow research and production among rare earth-dependent sectors rather than pursue self-sufficiency despite known domestic abundance (Congress, 1952). Meanwhile, the US State Department worked to source the elements from overseas.

4.4. Revolutions and the Cold War: 1949–1960

On the eve of the 1949 Communist revolution that inaugurated the People's Republic of China, the US Department of State was in negotiations with China's soon-to-be-exiled KMT Government to collaborate in geological 'exploration of China for minerals of importance in the atomic energy programs of the two governments' (Stuart, 1948, 740). The US Atomic Energy Commission and affiliated private firms sought to secure low-cost monazite sands outside of India, while the KMT hoped that guaranteeing high volume sales to the United States would help generate foreign exchange which then could be used to purchase the necessary equipment to develop its own nuclear program (Stuart, 1948, 748). In exchange, the US Department of State arranged for Chinese scientists to receive training in the United States.[13] This agreement, which was all but approved in late November 1948, never reached fruition as the People's Liberation Army defeated the KMT south of Baotou, driving them out of the hinterland, forcing their surrender in the Northeast, and retaking Beijing. Shortly thereafter in 1949, the KMT Government fled to Taiwan with the Sino-American survey documents for Chinese uranium and allied minerals, where they would be kept safe from the 'unauthorized' hands of the Chinese communists (Stuart, 1948, 751). But the geologists, by and large, stayed on the mainland and contributed their expertise to Communist China's military-industrial development. They maintained that 'governments might come and go, but geological knowledge would always benefit the nation, so the development of a geological enterprise was inherently patriotic' (Shen, 2014, 186).

The modernization of war and industry as we know it was realized in part through the discovery of new applications of rare earth elements. The Molybdenum Corporation of North America began operating in Mountain Pass, California in 1952, but did not achieve full production until 1960. However, monazite sands from the South African Steenkampskraal mine alleviated shortages between 1952 and 1960.[14] In the first half of the decade, researchers across Eurasia were developing rare earth superalloys to use in the steel production process to transform the skeletal system of modernity from heavy, rust-prone and brittle to stronger, lighter, and more durable (Morena, 1956; Kent, 1953), and to make the weapons of war more precise, long-range, and devastating (Bungardt, 1959; Hickman, 1955). Rare earths are the key to developing materials that remain stable in temperatures as high as 1500 degrees Celsius, the sorts of temperatures needed for rockets and long-range missiles. Soviet Union researchers experimented with nickel-based rare earth alloys beginning in 1950 in order to move away from the high-temperature instability of iron-based alloys used during WWII. Soviet experts shared their discoveries with Chinese researchers; trial alloys were being developed in China by 1956 (Jiang, 2013) as a necessary step in China's quest to develop its own aircraft and ballistic missiles. In both the first and second five year plans of the People's Republic of China, developing these technologies was of utmost importance, not just because they signaled unequivocally the establishment of a modern

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[12] These records, based on US National Archives, conflict with the findings reported in Adam Hochschild's in *King Leopold's Ghost: A Story of Greed, Terror, and Heroism in Colonial Africa*: 'With the start of the Second World War, the legal maximum for forced labor in the Congo was increased to 120 days per man per year. More than 80 percent of the uranium in the Hiroshima and Nagasaki bombs came from the heavily guarded Congo mine of Shinkolobwe' (Hochschild, 1999,279).

[13] Xu Guangxian, considered the father of China's Rare Earth Industry, went to Washington University in St. Louis to conduct graduate work in chemistry in 1946. He finished his PhD at Columbia University and returned to China with the outbreak of the Korean War in 1951, and went to work on China's nuclear program in 1956. During the Cultural Revolution in 1969, he and his wife were accused of being KMT spies and were placed in a labor camp until 1972. After their rehabilitation, he went to work on rare earth separation.

[14] A crucial piece of Cold War-era rare earth production is almost entirely absent from scholarship on the history and politics of rare earths. During the 1950s, the South African Steenkampskraal mine eased global monazite supply pressures until the Mountain Pass facility reached full production capacity in 1960. The relationship between local politics of extraction, the consolidation of the Apartheid State, and the global rare earth economy during this decade merits further inquiry.

industrial society, but also because these were viewed as the essential tools to bring about world socialist revolution.

In Baotou, a comprehensive Sino-Soviet industrialization program was under way in order to transform the ores at the Bayan Obo mine into steel, machinery, and weapons. Beginning in 1951, the Baotou Iron and Steel complex was reportedly the flagship project of a massive aid portfolio of 149 Soviet development projects in China. Both Mao and Stalin intended to convert the windswept steppes of Inner Mongolia into a military-industrial heartland that could provision both Republics in the struggle against capitalism and Western imperialism. But the relationship was tricky: China supplied the Soviet Union with uranium and complied with Soviet military requests to set up communications and military bases throughout Northern China in exchange for the training and technology transfer necessary to support a Chinese nuclear weapons program. The Chinese counterparts were disappointed at what they viewed as Soviet withholding of nuclear expertise (CMO, 1958), and by the mid-1950s were pursuing their own nuclear agenda outside of the Sino-Soviet Plan (Gobarev, 1999).

Indeed, the chemical and conceptual symbiosis drove advances in rare earth and nuclear research on opposite sides of the globe through the mid-20th century. Frank Spedding's discovery of ion exchange for rare earth separation at University of Chicago proved crucial to figuring out how to isolate uranium in the 1940s. In 1956, the 'father of China's rare earth chemistry,' Dr. Xu Guangxian, left his teaching and research position at Peking University to support China's effort to build nuclear weapons in Baotou. In his memoirs, he explained that his expertise in rare earth metal extraction and separation transferred well to his new focus on radiation chemistry within which he specialized in nuclear fuel extraction (Jia and Di, 2009).

5. Conclusion: critical reflections on the 1960s and beyond

Indeed, the nuclear arms race depended on rare earths—both the elements and the separation techniques—which defined the tense decades of the mid-twentieth century prior to the rise of the US as the primary producer of rare earth elements from the 1960s to 2000. Following China's first nuclear weapons test in 1964, central government leaders ordered a reorganization of the country's research and development programs for rare earth and other non-ferrous metals. Xu Guangxian's work on isolating uranium was crucial to his discovery of the Cascade Theory of Countercurrent Extraction, which revolutionized rare earth production and greatly increased the global rare earth supply in the 1970s. Until this point, China exported raw materials and imported separated and refined rare earths (Deng, 2009). Although the US dominated global production, Xu's discovery marked the beginning of China's technological superiority in the rare earth sector, which was recognized in the early 21st century (Fifarek et al., 2008).

The improvements in rare earth separation techniques in the 1960s and 1970s reduced the cost of europium, which enabled the mass production of red phosphors for color televisions. The color revolution in television signaled the beginning of the proliferation of rare earths into household life through consumer electronics. The acceleration of innovations in information technology enabled by the elements of the lanthanide series through the 1970s and 1980s conceptually decoupled rare earths from radioactive elements such as uranium and thorium, which likewise shifted the politics of prospecting and production away from those characterizing the early nuclear age.

Applications in television and information technology in the mid-1960s piqued scientific interest in the physical, rather than chemical, properties of rare earth elements. It was their exceptional magnetic and conductive properties that enabled an impressive miniaturization of computing devices. Without rare earths, our computers would still be the size of a classroom instead of the size of a smartphone: global political, economic, social, and information networks would look very different if not for this crucial development. The petroleum industry took notice, and started using rare earths as petroleum cracking[15] catalysts in 1964. Over the course of the next decade, this drove annual domestic consumption in the US alone from 2000 to 10,000 tons annually.

In the period between the atomic and the digital age, US government analysts stated that 'if rare earths were to become unavailable, the effect on our present standard of living would not be catastrophic because, in most applications, the rare earths are merely replacing materials that are less effective for the particular purpose' (Adams and Staatz, 1973, 548). But with the rise of digital economies, the increasing importance of satellite communications to the daily functions of global political economy, security, and scientific progress, the situation has definitively changed. To wit: in 2013, the US House of Representatives passed H.R. 761 (2013, 2), which declared the availability of rare earths to be 'essential for economic growth, national security, technological innovation, and the manufacturing and agricultural supply chains.' These changing political ideas about rare earths reflect the changing uses of rare earth elements over the past four decades. Because rare earth-enhanced technologies are essential to the hardware of modern life as we know it, their political significance differs now from the era examined in the body of this article: then, rare earths were crucial to small groups of highly specialized lighting, glassware, and weapons researchers and manufacturers. Now, rare earths matter for everybody.

Given the multifarious applications of rare earth elements, global consumption may seem relatively small by comparison: 120,148 tons in 2014 (Castilloux, 2014). This is because of the nature of most of their applications. Rare earths are added to other metals to make them stronger, lighter, or more conductive. They are described as 'spice' metals in Germany, as the 'MSG of industry' in China, and the 'vitamins' of modern industry in Japan (Zepf, 2013; Klinger, 2011; Koerth, 2012; Dent, 2012). Their relatively low annual consumption, their contemporary importance, and their fairly common geological incidence illustrates the fact that rare earth politics are driven by structural, rather than actual, scarcity.

This article has presented a broad historical geography of rare earth elements between 1880 and 1960 with an emphasis on the political economic contexts in which sites of extraction were sought, identified, and opened. While rare earths are neither rare nor overwhelmingly concentrated in any single country, their strategic necessity coupled with their geological coincidence with radioactive materials generated contentious politics as imperial, national and Cold War regimes dealt with the conflicting imperatives to secure these resources while sequestering the harmful effects of their production. This dynamic continues to characterize the international geography of rare earth prospecting and mining. In order to mitigate the devastating environmental harm wrought by rare earth production in China, the central government resolved to change the country's position in the global division of labor by becoming a net importer (Chen, 2011), while the recently revived mine in Mountain Pass, California continues to sub-contract portions of the beneficiation processes to places with more lax environmental and labor laws (Molycorp, 2012). Meanwhile, the contemporary race to identify and exploit new rare earth reserves in remote places such as Greenland, Afghanistan, and the Pacific sea bed has challenged environmental

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[15] Cracking describes the process by which heavy hydrocarbons are broken down into light hydrocarbons to produce gasoline, diesel, and jet fuel.

conventions from local to international scales as states and firms struggle to isolate production from centers of accountability while simultaneously hoping to capture the perceived geopolitical capital generated by controlling a portion of the global rare earth supply. Geology, as a science of territoriality, laid the foundation on which these historical dramas unfolded, and remains operative today in the dynamic geographies and politics of rare earth elements.

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