Field Guide to Mountain Pass, California and the Searchlight District, Nevada

by

G. Nason, G. B. Haxel, and S. Ludington

Guidebook for the

Arizona Geological Society Fall Field Trip

October 8-10, 2004

Compiled by C. Hoag and D. Maher

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October 8, 2004

Dear Field Trip Participant,

Welcome to the 2004 Fall Field Trip of the Arizona Geological Society. This trip will visit the Molycorp Mountain Pass Mine and surrounding region of California followed by a tour of the Searchlight District of Nevada.

We wish to acknowledge the management of Molycorp for permission to visit the mine and processing facilities and to thank Geoff Nason for leading the mine tour. We also gratefully acknowledge the leadership of Gordon Haxel, US Geological Survey in Flagstaff, for sharing his knowledge of rare earth minerals and the fascinating geology in the area surrounding the Mountain Pass Mine, and for coordinating important aspects of the field trip and guidebook. Thanks also to Steve Ludington, US Geological of Menlo Park for sharing his knowledge of the tilted, epithermal, volcanic-hosted vein deposits of the Searchlight District in Clark County, Nevada and for his guidebook contribution.

David Maher, VP Field Trips

Corolla Hoag, Secretary

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Trip Leaders:

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Driving Directions to Campsite

From Nipton, California, drive on CA 164 10.1 miles west to the intersection with Interstate 15. Take I-15 westbound (toward Los Angeles) 5.0 miles, up to Mountain Pass. Exit I-15 at Bailey Road. Immediately turn left and cross southward over the interstate; immediately turn left again onto an old paved road. Reset odometer at the second left turn. Continue east on the old paved road; at ≈ 0.7 miles it turns right (south) and then becomes a dirt road. After going south for ≈ 0.45 miles, the road turns southeast. Stay on this main graded (more-or-less) dirt road, heading generally southeastward; don't turn off onto any of the myriad of mining-district roads. At ≈ 2.5 – 2.6 miles, the road comes to the top of a grade, enters a flattish pediment area, and swings southwestward. At ≈ 3.0 (±0.2) miles, encounter the only major intersection (with another major dirt road). Take the left fork, to the southeast. Proceed ≈ 0.5 miles (to mileage ≈ 3.5 ± 0.2) to an intersection with a minor dirt road, at UTM coordinates E ≈ 0636.130, N ≈ 3922.280 (NAD 27). This critical turnoff: (1) is marked with an asterisk on the map, (2) is right at the join of the Mescal Range and Mineral Hill 7.5' topo maps, and (3) will be flagged. Turn left (east) on this road. Drive ≈ 0.9 miles east to the intersection with a shallow, sandy arroyo that may or may not contain a 4WD road. Turn right (southeast) into/onto this arroyo/road. We will camp in this arroyo, near E ≈ 0637.400, N ≈ 3922.050, amidst friendly juniper trees.
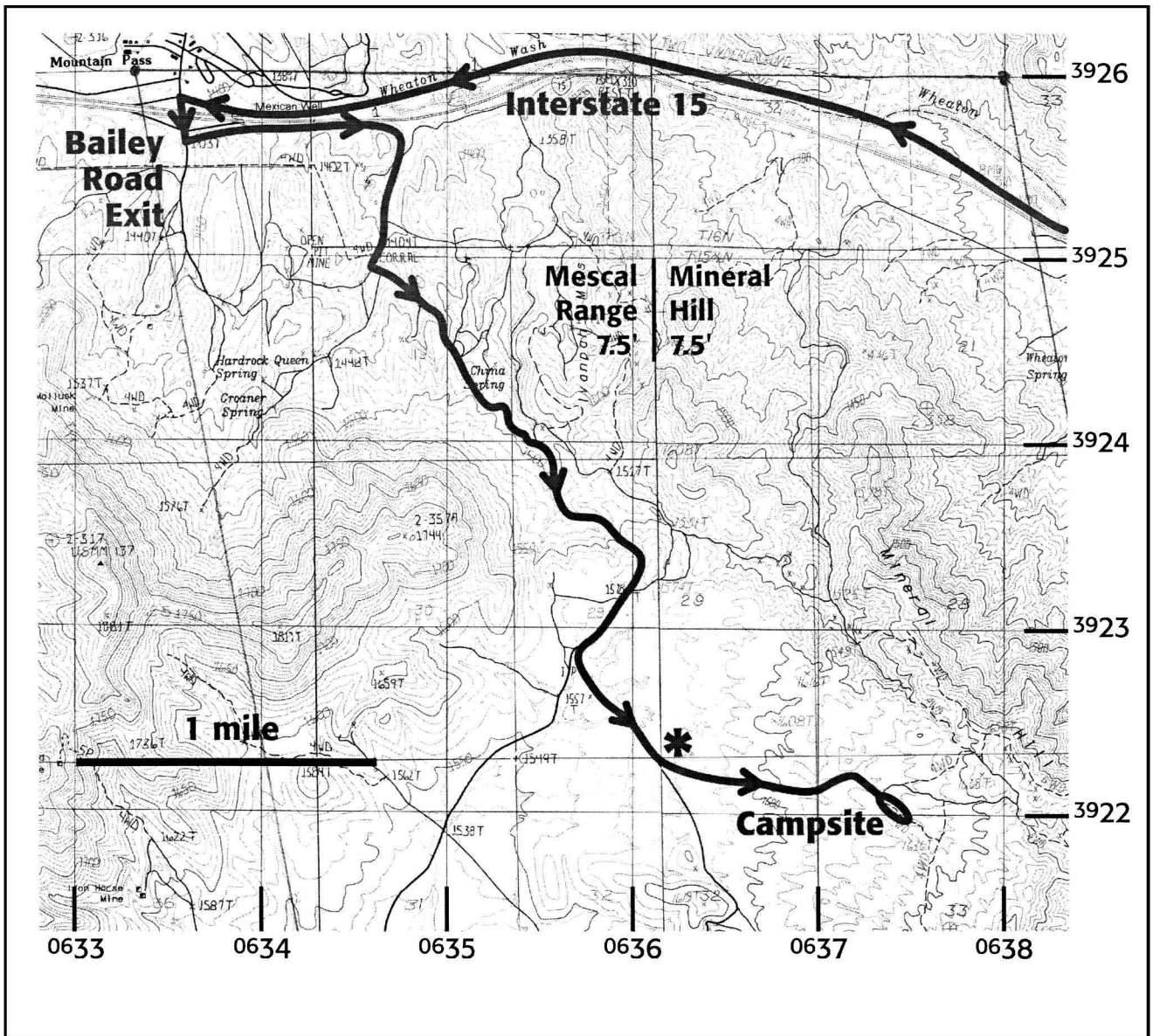
Section 1 Itinerary and Orientation

Friday, October 8

10:30 am Tucson group meets at carpool location; secure vehicles, and load vans. Pass out instructions/guide books. Tucson carpool location is at 3275 W. Ina Rd (parking lot south of office building) near Ina and Shannon.   Another contingent will leave from the University of Arizona in the late afternoon.

11 am Leave Tucson to drive to Primm, Nevada (estimated time 7 hours). Pick up folks in Phoenix, or they will carpool and leave independently from Phoenix.

6 or 7 pm Vehicles arriving from Arizona (Tucson, Phoenix, Flagstaff) rendezvous at Nipton, California. Haxel takes camping contingent to campsite in Ivanpah Mountains, just south of Mountain Pass. Motel contingent proceeds to Primm (State Line), Nevada. Check in to Whiskey Pete's Hotel and Casino on Interstate 15, eat dinner, gas up. Vehicles from Nevada go directly to Primm or camp site (with Gordon's directions).

Saturday, October 9

8 am Field trip reassembles at Mountain Pass (Bailey Road) exit, Interstate 15, California. (~15 miles from Primm).

8-10 am Meet at the Molycorp Mountain Pass Mine (training room). Talk #1 by Haxel: Regional setting, host rocks; character and applications of rare earth elements (Abstract below). Talk #2 by Nason: Mine history, production and processing methods, environmental issues, REE as a commodity; and safety information.

10 am - 3 pm Tour of Mountain Pass mine and plant(s) (not currently in operation): Nason

3 - 4 pm Examine synplutonic shonkinite dikes in shonkinite-syenite stock, "Tors" area, Mountain Pass district, south of Interstate 15: Haxel (see abbreviated abstract below)

4 - 5 pm Overview of Mountain Pass district and region; beer: Nason, Haxel. (2 - 6 pm ?) -- Possible additional stop: Birthday Vein - discovery outcrop.)

5 or 6 pm Return to camp and hotels. Campers cook in camp, and/or drive to Primm for dinner then return to camp.

Sunday, October 10

7:30 am Field trip reassembles at Nipton, California.

8 – Noon Examine base- and precious-metal vein systems, Searchlight district, Nevada: Ludington. (Abstract below.

Noon Field trip disperses. Tucson folks need to hit the road.

Noon - 4? pm Optional stops for folks who may be able to stay longer.

~8 pm Arrive back in Tucson (~6 pm for Phoenix)

TRAVEL DIRECTIONS FROM TUCSON

Tucson-Phoenix-Wickenburg-Kingman-Laughlin-Nipton-Primm

- Travel north on I-10 approx. 120 miles from Tucson to Phoenix.

- Take US 60 approx. 54 miles northwest to Wickenburg.

- Take US 93 north approx. 105 miles to the intersection with I-40.

- Take I-40 west approximately 18 miles to Kingman.

- Take Arizona State Route 68 33 miles to Laughlin at the Arizona/Nevada border. Cross the Colorado River and head west on Nevada State route 163 for another 20? miles to the Nevada/California border.

- At the Nevada/California border, head north on US 95 19 miles to Searchlight.

- Travel west 21.3 miles on California State route 164 (Nipton Road to Nipton at the intersection with I-15.

- Mountain Pass Mine is 16.3 miles west of Nipton on I-15. Directions to camp site to be provided by Haxel.

- To get to the Whiskey Pete's Hotel at 100 W. Primm Blvd., Primm, Nevada, turn north from Nipton on I-15 and travel 20.6 miles to the California/Nevada state line. Take highway exit 1; hotel is visible from the exit.

Tucson to Phoenix 110 miles	1 hour 45 min	
Phoenix to Wickenburg 54.2 miles	1 hour 13 mins	
Wickenburg to Kingman 130.7 miles	3 hours	*6 hrs to this point*
Kingman to Laughlin 33 miles	1 hour	
Laughlin to Searchlight 38.4 miles	1 hour 7 min	
Searchlight to Nipton 38 min	38 min	
Nipton to Primm 20.6 miles	<u>29 min</u>	
	~9 hours	

SAFETY TIPS

- Please observe safe driving practices during the weekend including defensive driving and stopping for rest breaks. All passengers and drivers must wear their seatbelts while the vehicles are in motion.

- Hard hats, safety glasses, close toed-shoes, and long pants are necessary in the Mine. Hard hats and safety glasses will be available at the Mine.

HIGHWAY MAP
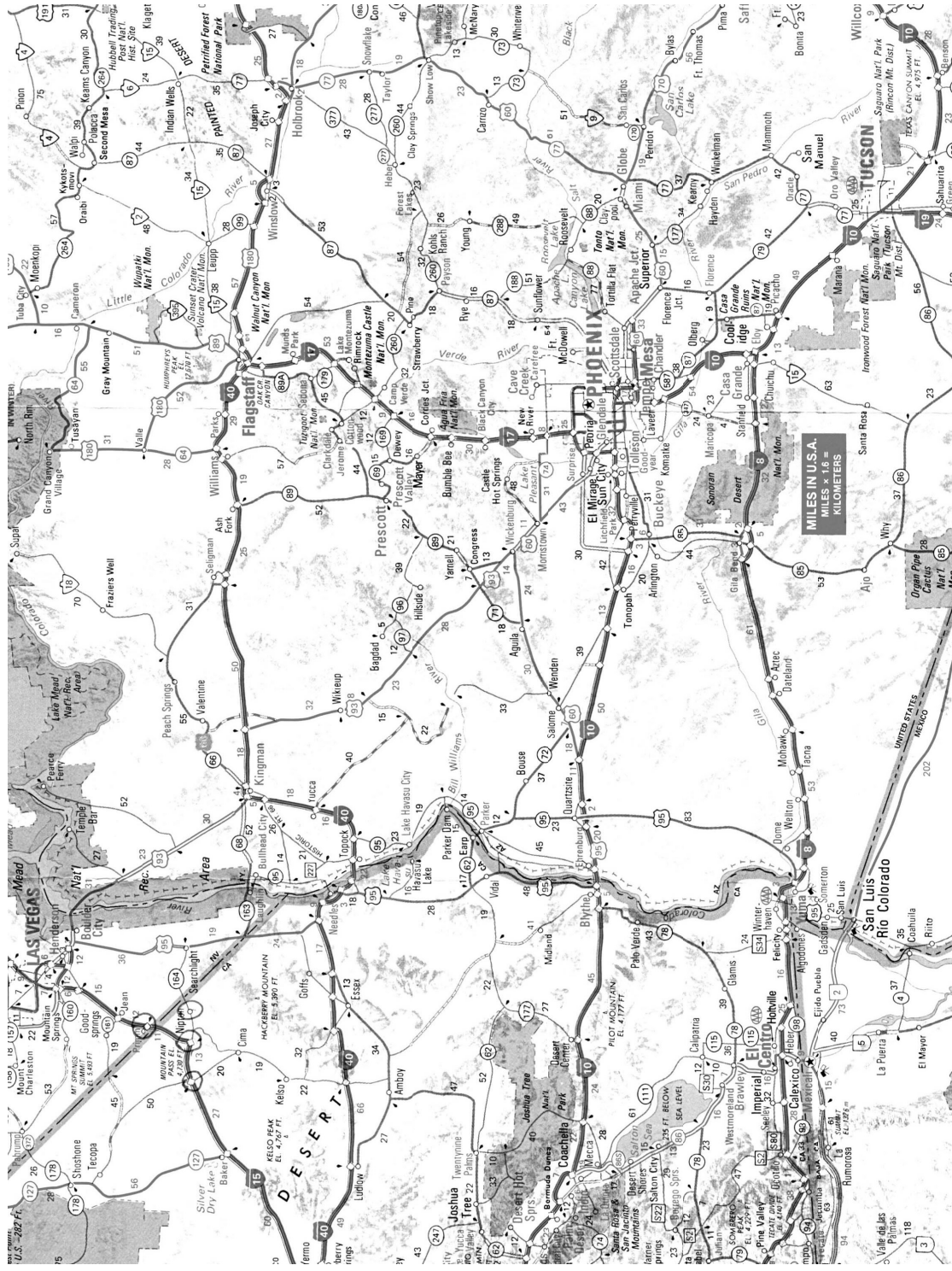
Section 2 Rare Earth Elements – Critical Resources for High Technology

Rare Earth Elements—Critical Resources for High Technology

*H*igh-technology and environ-
mental applications of the
rare earth elements (REE) have
grown dramatically in diversity
and importance over the past four
decades. As many of these ap-
plications are highly specific, in
that substitutes for the REE are
inferior or unknown, the REE have
acquired a level of technological
significance much greater than
expected from their relative obscu-
rity. Although actually more abun-
dant than many familiar industrial
metals, the REE have much less
tendency to become concentrated
in exploitable ore deposits. Conse-
quently, most of the world's supply
comes from only a few sources.
The United States once was largely
self-sufficient in REE, but in the
past decade has become depen-
dent upon imports from China.

Figure 1. *Global rare earth element production (1 kt=10^6 kg) from 1950 through 2000, in four categories: United States, almost entirely from Mountain Pass, California; China, from several deposits; all other countries com-bined, largely from monazite-bearing placers; and global total. Four periods of production are evident: the mon-azite-placer era, starting in the late 1800s and ending abruptly in 1964; the Mountain Pass era, starting in 1965 and ending about 1984; a transitional period from about 1984 to 1991; and the Chinese era, beginning about 1991.*

The rare earth elements (REE) form the
largest chemically coherent group in the
periodic table. Though generally unfamiliar,
the REE are essential for many hundreds of
applications. The versatility and specific-
ity of the REE has given them a level of
technological, environmental, and economic
importance considerably greater than might
be expected from their relative obscurity.
The United States once was largely self-suf-
ficient in these critical materials, but over
the past decade has become dependent upon
imports (fig. 1). In 1999 and 2000, more
than 90% of REE required by U.S. industry
came from deposits in China.

Although the 15 naturally occurring
REE (table 1; fig. 2) are generally similar
in their geochemical properties, their indi-
vidual abundances in the Earth are by no
means equal. In the continental crust and
its REE ore deposits, concentrations of
the most and least abundant REE typically
differ by two to five orders of magnitude
(fig. 3). As technological applications of
REE have multiplied over the past several
decades, demand for several of the less
abundant (and formerly quite obscure) REE
has increased dramatically.

The diverse nuclear, metallurgical,
chemical, catalytic, electrical, magnetic,
and optical properties of the REE have led
to an ever increasing variety of applica-
tions. These uses range from mundane
(lighter flints, glass polishing) to high-tech
(phosphors, lasers, magnets, batteries,
magnetic refrigeration) to futuristic (high-
temperature superconductivity, safe storage
and transport of hydrogen for a post-hydro-
carbon economy).

Some Applications of the Rare Earth Elements

Many applications of REE are character-
ized by high specificity and high unit value.
For example, color cathode-ray tubes and
liquid-crystal displays used in computer
monitors and televisions employ europium
as the red phosphor; no substitute is known.
Owing to relatively low abundance and

high demand, Eu is quite valuable—$250 to
$1,700/kg (for Eu_2O_3) over the past decade.

Fiber-optic telecommunication cables
provide much greater bandwidth than the
copper wires and cables they have largely
replaced. Fiber-optic cables can transmit
signals over long distances because they
incorporate periodically spaced lengths of
erbium-doped fiber that function as laser
amplifiers. Er is used in these laser repeat-
ers, despite its high cost (~$700/kg), be-
cause it alone possesses the required optical
properties.

Specificity is not limited to the more
exotic REE, such as Eu or Er. Cerium, the
most abundant and least expensive REE,
has dozens of applications, some highly
specific. For example, Ce oxide is uniquely
suited as a polishing agent for glass. The

Table 1. Names and symbols of the REE:

La	lanthanum	Tb	terbium
Ce	cerium	Dy	dysprosium
Pr	praseodymium	Ho	holmium
Nd	neodymium	Er	erbium
Pm	promethium	Tm	thulium
Sm	samarium	Yb	ytterbium
Eu	europium	Lu	lutetium
Gd	gadolinium	Y	yttrium
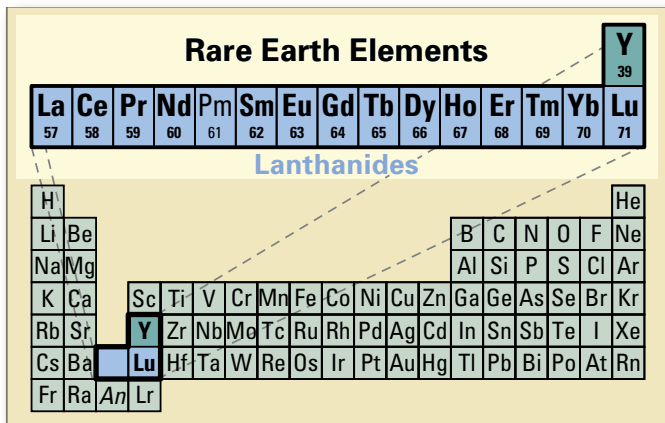
Figure 2. Chemical periodic table delineating the 16 rare earth elements (REE): the lanthanides, La through Lu, plus Y, whose geochemical behavior is virtually identical to that of the heavier lanthanides. Promethium has no long-lived isotopes and occurs naturally on Earth only in vanishingly small quantities. An represents the first 14 actinide elements; Lr is the last actinide.

polishing action of CeO_2 depends on both its physical and chemical properties, including the two accessible oxidation states of cerium, Ce^{3+} and Ce^{4+}, in aqueous solution. Virtually all polished glass products, from ordinary mirrors and eyeglasses to precision lenses, are finished with CeO_2.

Permanent magnet technology has been revolutionized by alloys containing Nd, Sm, Gd, Dy, or Pr. Small, lightweight, high-strength REE magnets have allowed miniaturization of numerous electrical and electronic components used in appliances, audio and video equipment, computers, automobiles, communications systems, and military gear. Many recent technological innovations already taken for granted (for example, miniaturized multi-gigabyte portable disk drives and DVD drives) would not be possible without REE magnets.

Environmental applications of REE have increased markedly over the past three decades. This trend will undoubtedly continue, given growing concerns about global warming and energy efficiency. Several REE are essential constituents of both petroleum fluid cracking catalysts and automotive pollution-control catalytic converters. Use of REE magnets reduces the weight of automobiles. Widespread adoption of new energy-efficient fluorescent lamps (using Y, La, Ce, Eu, Gd, and Tb) for institutional lighting could potentially achieve reductions in U.S. carbon dioxide emissions equivalent to removing one-third of the automobiles currently on the road. Large-scale application of magnetic-refrigeration technology (described below) also could significantly reduce energy consumption and CO_2 emissions.

In many applications, REE are advantageous because of their relatively low toxicity. For example, the most common types of rechargeable batteries contain either cadmium (Cd) or lead. Rechargeable lanthanum-nickel-hydride (La-Ni-H) batteries are gradually replacing Ni-Cd batteries in computer and communications applications and could eventually replace lead-acid batteries in automobiles. Although more expensive, La-Ni-H batteries offer greater energy density, better charge-discharge characteristics, and fewer environmental problems upon disposal or recycling. As another example, red and red-orange pigments made with La or Ce are superseding traditional commercial pigments containing Cd or other toxic heavy metals.
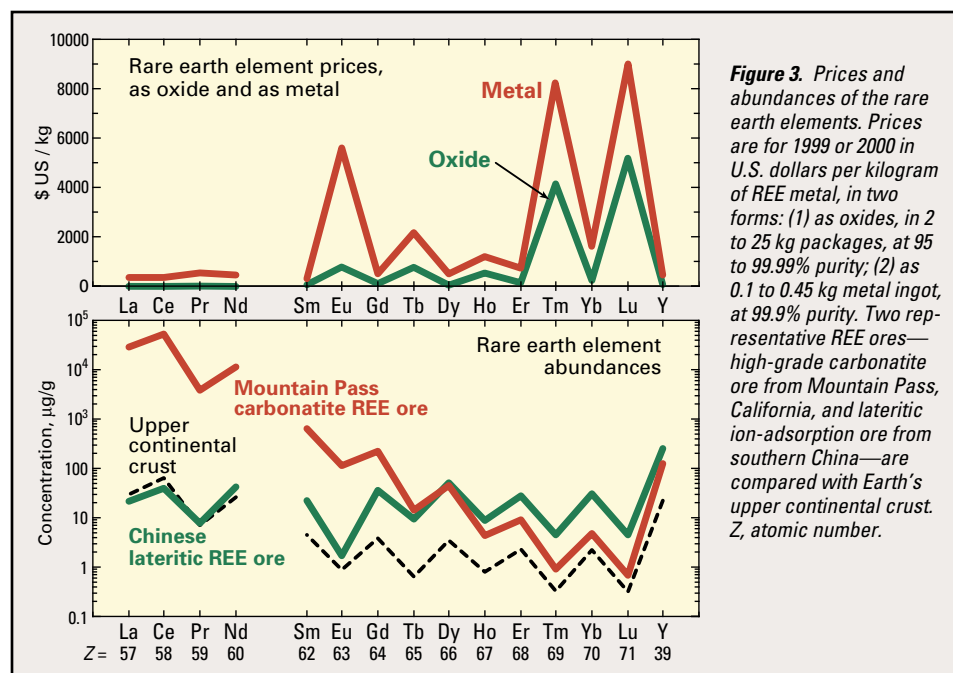
The next high-technology application of the REE to achieve maturity may be magnetic refrigeration. The six REE ions Gd^{3+} through Tm^{3+} have unusually large magnetic moments, owing to their several unpaired electrons. A newly developed alloy, $Gd_5(Si_2Ge_2)$, with a "giant magnetocaloric effect" near room temperature reportedly will allow magnetic refrigeration to become competitive with conventional gas-compression refrigeration. This new technology could be employed in refrigerators, freezers, and residential, commercial, and automotive air conditioners. Magnetic refrigeration is considerably more efficient than gas-compression refrigeration and does not require refrigerants that are flammable or toxic, deplete the Earth's ozone layer, or contribute to global warming.
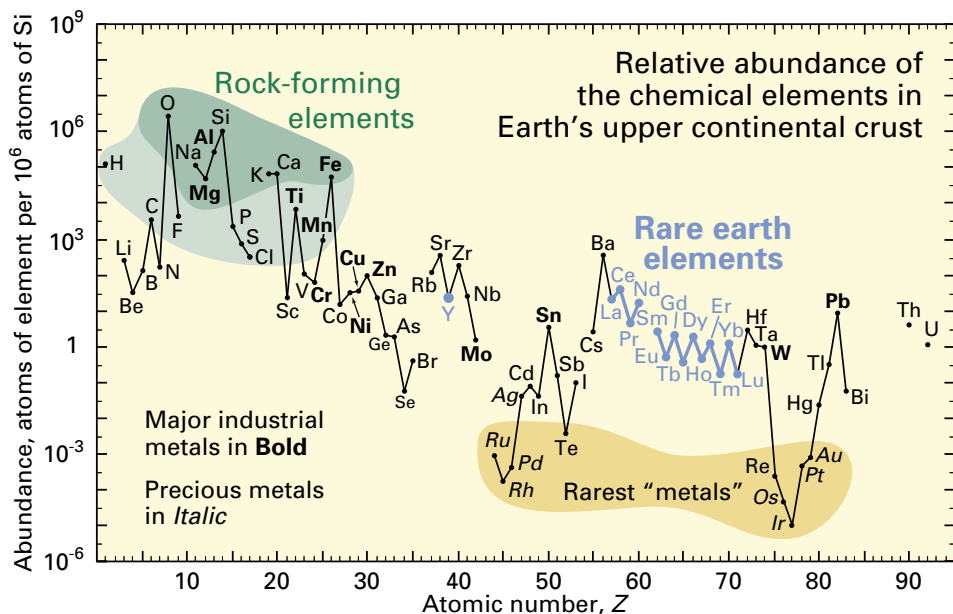
Rare Earth Element Abundances

"Rare" earth elements is a historical misnomer; persistence of the term reflects unfamiliarity rather than true rarity. The more abundant REE are each similar in crustal concentration to commonplace industrial metals such as chromium, nickel, copper, zinc, molybdenum, tin, tungsten, or lead (fig. 4). Even the two least abundant REE (Tm, Lu) are nearly 200 times more common than gold. However, in contrast to ordinary base and precious metals, REE have very little tendency to become concentrated in exploitable ore deposits. Consequently, most of the world's supply of REE comes from only a handful of sources.

Differences in abundances of individual REE in the upper continental crust of the Earth (figs. 3, 4) represent the superposition of two effects, one nuclear and one geochemical. First, REE with even atomic numbers ($_{58}$Ce, $_{60}$Nd, …) have greater cosmic and terrestrial abundances than adjacent REE with odd atomic num-

Figure 3. Prices and abundances of the rare earth elements. Prices are for 1999 or 2000 in U.S. dollars per kilogram of REE metal, in two forms: (1) as oxides, in 2 to 25 kg packages, at 95 to 99.99% purity; (2) as 0.1 to 0.45 kg metal ingot, at 99.9% purity. Two representative REE ores—high-grade carbonatite ore from Mountain Pass, California, and lateritic ion-adsorption ore from southern China—are compared with Earth's upper continental crust. Z, atomic number.

Figure 4. *Abundance (atom fraction) of the chemical elements in Earth's upper continental crust as a function of atomic number. Many of the elements are classified into (partially overlapping) categories: (1) rock-forming elements (major elements in green field and minor elements in light green field); (2) rare earth elements (lanthanides, La–Lu, and Y; labeled in blue); (3) major industrial metals (global production ≥3×10⁷ kg/year; labeled in bold); (4) precious metals (italic); and (5) the nine rarest "metals"—the six platinum group elements plus Au, Re, and Te (a metalloid).*

bers ($_{57}$La, $_{59}$Pr, …). Second, the lighter REE are more incompatible (because they have larger ionic radii) and therefore more strongly concentrated in the continental crust than the heavier REE. In most rare earth deposits, the first four REE—La, Ce, Pr, and Nd—constitute 80 to 99% of the total. Therefore, deposits containing relatively high grades of the scarcer and more valuable heavy REE (HREE: Gd to Lu, Y) and Eu are particularly desirable.

Rare Earth Element Resources

From the discovery of the REE (during the period 1794–1907) through the mid-1950s, a few of the REE were produced in modest amounts from monazite-bearing placers and veins, from pegmatites and carbonatites, and as minor byproducts of uranium and niobium extraction. During this time, the middle and heavy REE generally were available in pure form only in sub-kilogram quantities and were chiefly chemical curiosities.

In 1949, a carbonatite intrusion with extraordinary contents of light REE (8 to 12% rare earth oxides [REO]), was discovered at Mountain Pass, in the upper Mojave Desert, California (fig. 5). The REE at Mountain Pass are hosted chiefly by bastnäsite, (Ce,La,Nd,…)CO$_3$F, and related minerals. By 1966, this single, world-class deposit (owned and operated by Molycorp, Inc.)

had become the paramount source of REE. Early development was supported largely by the sudden demand for Eu created by the commercialization of color television. Mountain Pass, with an average grade of 9.3% and reserves of 20 million metric tons (Mt) REO (at 5% cutoff), remains the only large ore deposit mined solely for its REE content. Mountain Pass ore is very strongly dominated by the light REE (figs. 3, 6). Nonetheless, the large quantities of ore processed and development of solvent-extraction techniques for large-scale separation of individual REE from one another allowed recovery of several of the middle REE. Increased availability led in turn to applications for these formerly exotic elements.

From 1965 through the mid-1980s, Mountain Pass was the dominant source of REE, and the United States was largely self-sufficient in REE. Since 1985, production of REE in China has increased dramatically (fig. 1). Chinese REE production comes chiefly from two sources. The most important is the Bayan Obo iron-niobium-REE deposit, Inner Mongolia. This deposit has geological affinities both to carbonatite REE deposits and to hydrothermal iron-oxide (-Cu-Au-REE) deposits, such as Olympic Dam, Australia, and Kiruna, Sweden. Grades at Bayan Obo are 3 to 6% REO; reserves are at least 40 Mt, possibly considerably more. The second major source

of Chinese REE is ion-adsorption ores in lateritic weathering crusts developed on granitic and syenitic rocks in tropical southern China. These oxide ores are advantageous in their relatively high proportions of HREE (fig. 6) and, especially, in the ease with which they can be mined and the REE extracted.

The number of workable REE deposits, already severely limited by the geochemical properties of the REE, has in recent years also been affected by environmental and regulatory factors. Monazite, the single most common REE mineral, generally contains elevated levels of thorium. Although Th itself is only weakly radioactive, it is accompanied by highly radioactive intermediate daughter products, particularly radium, that can accumulate during processing. Concern about radioactivity hazards has now largely eliminated monazite as a significant source of REE and focused attention on those few deposits where the REE occur in other, low-Th minerals, particularly bastnäsite.

Rare Earth Element Supply Issues

Over the past several years the only domestic source of REE, the mine at Mountain Pass, California, has operated below capacity and only intermittently. Following environmental and regulatory problems with the main wastewater pipeline, the REE separation (solvent extraction) plant was shut down. Mountain Pass currently produces only bastnäsite concentrates and sells separated REE only from stockpiles produced before the shutdown. Even after the regulatory situation has been resolved, however, the long-term viability of Mountain Pass as a supplier of separated REE for high-technology applications is threatened by market factors.

Figure 5. *The Mountain Pass rare earth element mine, Mojave Desert, California, with Clark Mountain (part of the Mojave National Preserve) in the background and Interstate 15 just beyond the hills in the foreground.*
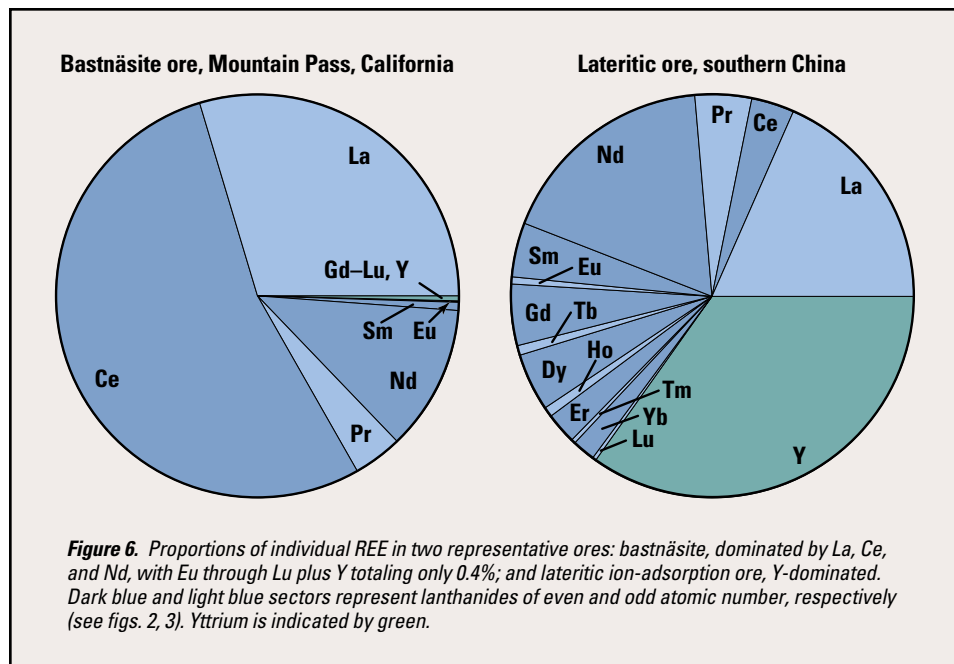
In 1999 and 2000, nearly all (more than 90%) of the separated REE used in the United States was imported either directly from China or from countries that imported their plant feed materials from China. The surprisingly rapid progression from self-sufficiency prior to about 1990 to nearly complete dependence on imports from a single country today involves a number of causative factors. These include much lower labor and regulatory costs in China than in the United States; continued expansion of electronics and other manufacturing in Asia; the favorable number, size, and HREE content of Chinese deposits; and the ongoing environmental and regulatory problems at Mountain Pass. China now dominates world REE markets (fig. 1), raising several important issues of REE supply for the United States:

(1) The United States is in danger of losing its longstanding leadership in many areas of REE technology. Transfer of expertise in REE processing technology and REE applications from the United States and Europe to Asia has allowed China to develop a major REE industry, eclipsing all other countries in production of both ore and refined products. The Chinese Ministry of Science and Technology recently announced a new national basic research program. Among the first group of 15 high-priority projects to be funded was "Basic research in rare earth materials" (Science, Dec. 18, 1998, p. 2171).

(2) United States dependence on imports from China comes at a time when REE have become increasingly important in defense applications, including jet fighter engines and other aircraft components, missile guidance systems, electronic countermeasures, underwater mine detection, antimissile defense, range finding, and space-based satellite power and communication systems.

(3) Availability of Chinese REE to U.S. markets depends on continued stability in China's internal politics and economy, and its relations to other countries.

(4) Although the present low REE prices caused by abundant supply from China are stressing producers, particularly Mountain Pass, low prices will also stimulate development of new applications. For example, a recent chemistry text notes that "… for many years the main use of lutetium was the study of the behavior of lutetium …" Several promising applications for Lu are known,

Figure 6. Proportions of individual REE in two representative ores: bastnäsite, dominated by La, Ce, and Nd, with Eu through Lu plus Y totaling only 0.4%; and lateritic ion-adsorption ore, Y-dominated. Dark blue and light blue sectors represent lanthanides of even and odd atomic number, respectively (see figs. 2, 3). Yttrium is indicated by green.

but most are precluded by high cost. If the price of Lu were to decrease from many thousand to a few thousand dollars per kilogram (fig. 3), additional high-technology applications of even this least abundant of the REE undoubtedly would follow. How large a role the United States will play in future expansion of REE technology and markets remains an important, but open, question.

The rare earth elements are essential for a diverse and expanding array of high-technology applications, which constitute an important part of the industrial economy of the United States. Long-term shortage or unavailability of REE would force significant changes in many technological aspects of American society. Domestic REE sources, known and potential, may therefore become an increasingly important issue for scientists and policymakers in both the public and private sectors.

———————

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For more information see:
http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/

This fact sheet and any updates to it are available online at: http://geopubs.wr.usgs.gov/fact-sheet/fs087-02/

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WebElements: http://www.webelements.com/

Section 3 Ultrapotassic Mafic Rocks and Rare Earth Element – and Barium-rich Carbonatite at Mountain Pass, Mojave Desert, Southern California: Summary and Field Trip Locality

Ultrapotassic Mafic Rocks and Rare Earth Element- and Barium-Rich Carbonatite at Mountain Pass, Mojave Desert, Southern California: Summary and Field Trip Locality

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Introduction

Mountain Pass is famous for its world-class rare earth element deposit, hosted by a compositionally unique carbonatite stock (Olsen and others, 1954; DeWitt, 1987; Castor, 1990, 1991, 1994; Kilbourn, 1993, 1994; Haxel, in press). This carbonatite contains extraordinary large concentrations of the lighter rare earth elements (La – Gd) and Ba, and is one of the most compositionally extreme, even bizarre, igneous rocks known on Earth. Mountain Pass also features a remarkable suite of silicate alkaline igneous rocks, distinguished by their ultrapotassic character and exceptionally high abundances of F, Th, large-ion-lithophile elements (K, Ba, Rb, Cs), and rare earth elements. Of particular interest are certain phlogopite shonkinite (melanosyenite) dikes that evidently represent the primary, parental silicate magmas at Mountain Pass.

I prepared this informal article to provide petrologic and geochemical background for a field trip to the Mountain Pass district by the Arizona Geological Society in October, 2004. The centerpiece of this trip will be a tour of the Mountain Pass rare earth mine, including the open pit and processing facilities, lead by Geoff Nason of Molycorp, the owner and operator of the mine. Following the mine tour, we will more briefly examine synplutonic shonkinite dikes within a shonkinite-syenite stock, outside the mine property but within the Mountain Pass district. This second field trip locality is described in the final section of the article. We will conclude the field trip by driving up a nearby hill that provides an overview of the entire district.

The Figures that accompany this article, most originally prepared as color slides for talks, are grouped at the end. Table 1 appears after the text and before the Figures. A USGS Fact Sheet (Haxel and others, 2002) summarizing technological applications, abundances, resources, and supply issues of the rare earth elements follows this article.

Geographic and Geologic Setting

The Mountain Pass (MP) district is located in the upper Mojave Desert of southeast California, about 80 km southwest of Las Vegas, Nevada, at elevations of 1,300 – 1,700 m (4,300 – 5,600 feet) (Fig. 1). Interstate 15, connecting Las Vegas and Los Angeles, bisects the district. To the northwest, west, and south, the Mountain Pass district adjoins the Mojave National Preserve.

The crystalline terrane that underlies the MP area is part of the autochthon beneath the basal fault of the late Mesozoic Sevier thrust belt (Hewitt, 1956; Burchfiel and Davis, 1971, 1988; Theodore, in press). Metamorphic and igneous rocks of the MP district comprise two major groups: high-grade gneiss and gneissic pegmatite, of Eoproterozoic age (~1.8 – 1.6 Ga; Wooden and Miller, 1990); intruded by Mesoproterozoic ultrapotassic rocks and carbonatite, which are unmetamorphosed. The alkaline igneous rocks are ≈ 1.4 Ga (DeWitt and others, 1987), several

hundred m.y. younger than and unrelated to their gneissic country rocks. Both groups of Proter-ozoic rocks are widely intruded by Mesozoic or Tertiary andesitic and rhyolitic dikes. Strongly potassic igneous rocks of 1.4 Ga age (but no known carbonatites) occur several other places in the eastern Mojave Desert (DeWitt and others, 1987; Castor and Gleason, 1989; Castor, 1991, 1993; Gleason and others, 1994).

Rare Earth Elements

Rare earth elements (REE; Fig. 2), as generally used in geochemistry, refers to exactly 15 elements: the lanthanides, La through Lu, except for Pm, plus Y (Table 1; Henderson, 1984; Lipin and McKay, 1989; Hedrick, 1988, 1995; Kilbourn, 1993, 1994; Jones and others, 1996; Rossotti, 1998; Orris and Haxel, in press). Promethium is excluded because it has no long-lived isotopes and occurs naturally on Earth only locally and in vanishingly small quantities. The geochemical behavior of Y is virtually identical to that of the heavier lanthanides such as Dy, Ho, and Er (Fig. 2). Though sometimes incorrectly included therein, Sc and Th are not REE. Light REE (LREE) refers to La – Sm; heavy REE (HREE) to Gd – Lu and Y. The symbol *Ln* represents any or all of the lanthanides or REE, depending upon context.

Separation and identification of all fifteen of the naturally occurring REE required more than a century, from 1794 to 1907. Even after nearly all of the them had been discovered, the lanthan-ides remained problematic because they seemed not to fit into the periodic table:

> "In point of respectability your radium family will be a Sunday school compared with the [rare earth elements], whose [chemical] behavior is simply outrageous. It is absolutely demoralizing to have anything to do with them." (B. Boltwood, 1905; quoted in Taylor and McLennan, 1985).

> "The rare earths perplex us in our researches, baffle us in our speculations, and haunt us in our very dreams. They stretch like an unknown sea before us, mocking, mystifying, and murmuring strange revelations and possibilities." (W. Crookes, 1902; quoted in Rayner-Canham, 1996).

These conundrums were finally resolved during the early stages of the development of quantum theory, circa 1910, with the realization that the lanthanides belonged to a previously unknown domain of the periodic table, the f block (Fig. 2).

Primary controls of the behavior, pathways, and distribution of the REE are oxidation state and ionic radius. The REE are predominantly trivalent; only two exceptions occur in Nature (Table 1). In surficial environments, Ce may be partially or largely oxidized to Ce^{4+}, so that its behavior is decoupled from that of the other REE. For example, REE spectra of seawater and many marine authigenic or biogenic sedimentary rocks show pronounced "cerium anomalies" (Fig. 3A). In reduced environments, such as many magmas, Eu frequently is partially divalent. This character-istic accounts for the familiar Eu anomalies in the REE spectra of most igneous rocks. Ionic radii of the trivalent lanthanides decrease gradually from La to Lu (Fig. 3B). As a consequence of this "lanthanide contraction", the LREE are somewhat more incompatible than the HREE.

Cerium is unique among the REE in that both of its oxidation states are readily accessible in aqueous solution, and several of the special applications of Ce exploit this property (Kilbourn, 1992). Principal oxides of the REE are the sesquioxides, Ln_2O_3. In commerce, Ce oxide may be specified as either Ce_2O_3 or CeO_2; and Eu oxide as Eu_2O_3 or EuO. Oxides of Pr and Tb, common-ly nonstoichiometric, contain both Ln^{3+} and Ln^{4+} and are usually designated by the approximate formulas Pr_6O_{11} and Tb_4O_7.

Ultrapotassic Rocks at Mountain Pass

Distribution and petrology

The ultrapotassic silicate igneous rocks at MP form hundreds of dikes and seven stocks (Fig. 1; Olson and others, 1954; Crow, 1984; DeWitt, 1987; Morton and others, 1991; Haxel, in press). The largest stock, adjacent to the carbonatite intrusion that hosts the REE deposit, is about 2 km long by 0.5 wide. The other six stocks, in the southern part of the district, are considerably smaller, ~ 0.1 – 0.5 km in largest map dimension. The rocks that make up these stocks and the numerous dikes range in composition from phlogopite shonkinite (melanosyenite) through amphibole-biotite mesosyenite and leucosyenite to alkali granite. Genetically, the most important of these are the shonkinite dikes, some of which have primitive compositions and evidently represent the parental silicate magmas of the MP district.

The shonkinite-mesosyenite stocks are petrogenetically complex. They are products of fractional crystallization, so each rock represents some mixture of accumulated crystals and residual liquid, in unknown proportions. Furthermore, synplutonic dikes within the Tors shonkinite-syenite stock (Fig. 1) indicate repeated introduction of new magma into the stock during crystallization (see Field Trip Locality below). The dikes are back-intruded by the host shonkinite and syenite, and dike magmas widely mingled and locally mixed with their hosts. So, the dikes are not necessarily compositionally pristine. Given this prolonged history, the bulk or parental composition of the shonkinite-syenite stock is probably not preserved in any single rock. The leucosyenite and granite stocks are potentially even more complicated, as their origin may have involved crustal contamination or assimilation as well as fractional crystallization. These uncertainties can be circumvented by focusing upon the shonkinite dikes, for which parental compositions can be more readily identified. In this summary I emphasize the shonkinite dikes, with little further consideration of the stocks or the syenite and granite dikes.

The shonkinite dikes are medium- to dark-gray, with color indices typically about 40 to 60 percent. They comprise subequal proportions of just three essential minerals: Ba- and Ti-bearing fluor-phlogopite, microperthitic microcline, and augite or aegirine. Some rocks contain accessory quartz; feldspathoids and olivine are absent. Other common accessory minerals include Na-amphibole, plagioclase, apatite (2 – 5 %), and Fe-Ti oxides. Many of the shonkinite dikes at MP have previously been called minette. Although they do resemble minette petrographically, the shonkinites are so different from typical minettes in their major and trace element geochemistry as to render the term inappropriate.

Geochemically, two characteristics of the shonkinite dikes at MP are fundamental: (1) they are magnesian and have high concentrations of compatible elements; (2) they are ultrapotassic and remarkably rich in a number of incompatible elements (Table 2).

Compatible elements and primary magmas

In general, primary magmas are characterized by high MgO, Mg/Fe, and mg (Mg number: Table 2) and by large concentrations of strongly compatible trace elements such as Sc, Cr, Co, and Ni. For tholeiitic, calcalkaline, and ordinary alkaline igneous rocks, typical primitive compositions are MgO ~ 8 percent, mg ~ 0.7, and Ni and Cr ~ 100 – 300 µg/g (Rock, 1991; Nixon and Johnston, 1997). Primary ultrapotassic magmas may have higher slightly lower or higher mg (Foley, 1992; Luhr, 1997). Figure 4 shows the ranges of values of mg and Ni commonly considered diagnostic of primary magmas. By the less restrictive criteria shown, many or most of the

shonkinite dikes at MP could be primary. By even the most restrictive criteria, the five dikes with $mg > 0.70$ and Ni > 300 µg/g have primary compositions.

Four of these five most primitive dikes are members of a diffuse, sparse cluster of dikes in the southernmost part of the MP district (0.1 – 2 km south of the area shown in Fig. 1). These dikes are quite small: 200 – 600 m long, and only 0.25 – 1.5 m thick. Intrusive contacts are entirely sharp, with no evidence of chemical reaction or mechanical interaction (other than simple intrusion) between the dikes and their country rock. Arguably, such thin, isolated dikes cooled quickly because of their high ratio of surface area to volume, and lacked the mass and thermal

Table 2. Representative primary phlogopite shonkinite dike (MP14), Mountain Pass, California {1}.

SiO_2	53.9	Cr	453
Al_2O_3	10.9	Ni	343
Fe_2O_3*	6.43	**Rb**	**368**
MgO	8.64	**Ba**	**8,490**
CaO	6.58	**Th**	**167**
Na_2O	1.11	U	15.4
K_2O	**7.73**	**Th/U**	**10.8**
BaO	**0.95**	Zr	1040
P_2O_5	1.70	Rare earth elements {5}	
TiO_2	1.35	**La**	**476**
Ln_2O_3 {2}	**0.26**	**Ce**	**1,050**
MnO	0.12	**Pr {6}**	**110**
F	**0.969**	**Nd**	**470**
H_2O	0.80	**Sm**	**71.0**
CO_2	0.04	Eu	13.4
Σ {3}	101.	Gd	35.5
		Tb	3.32
mg {4}	0.77	Yb	2.28
K_2O/Na_2O	**7.0**	Lu	0.293
		Y	45
		(La/Yb)$_{cn}$ {7}	**140**

{1} Left column in weight percent; right column in µg/g. Oxides, elements, and ratios whose values are notably elevated are highlighted in **bold**.

{2} $Ln_2O_3 = La_2O_3 + Ce_2O_3 + Pr_2O_3 + Nd_2O_3 + Sm_2O_3$.

{3} Includes SrO and $-O \triangleq F$.

{4} $mg = MgO/(MgO + FeO)$, molar; with weight percent $Fe_2O_3/(Fe_2O_3 + FeO)$ set to 0.2.

{5} Lanthanides determined by INAA; Y by EDXRF.

{6} Pr, not measured, is estimated by logarithmic interpolation between Ce and Nd: $Pr \approx 0.157\sqrt{(Ce \times Nd)}$, with all values in µg/g.

{7} cn: chondrite-normalized (Nakamura, 1974). $(La/Yb)_{cn} = (La/Yb) \times 0.669$.

energy required to assimilate crustal material. Elevated volatile contents (F ~ 1.0 %, H_2O ~ 0.7 %) likewise suggest rapid emplacement and cooling, and therefore minimal crustal interaction. Furthermore, high contents of incompatible elements, 3 – 17 times greater than average upper crust, buffered the dikes against crustal contamination.

The dikes also show no evidence that their magnesian and compatible-element-rich character owes to concentration or incorporation of accumulative material. The dikes are texturally homogeneous, without zoning or indication of crystal concentration by internal mechanical differentiation. They have homogeneous populations of small (0.5 – 2 mm) phlogopite pheno-crysts evenly distributed in a uniform, fine-grained groundmass. Cognate inclusions, megacrysts, or glomeroporphyritic clots that might suggest an accumulative component are absent.

Thus, geochemical data, field relations, and petrographic observations together indicate that the most primitive shonkinite dikes at MP represent primary magmas, derived directly from the mantle and emplaced into the upper crust without significant crustal interaction. Some or many of the other shonkinite dikes also may be primary (Fig. 4).

Incompatible element abundances and ultrapotassic character

The representative composition presented in Table 2 emphasizes the exceptional enrichment in many incompatible element characteristic of the shonkinite dikes at MP. This level of Ba (median ≈ 8,100 µg/g) is extraordinary for a mafic rock, even an alkaline mafic rock. Abundances of three other large-ion-lithophile elements—K, Rb, and Cs—also are remarkably high, as is Th. Concen-trations of F (0.9 – 1.4 %) and LREE and are among the highest known in unaltered silicate igneous rocks (Figs. 5 – 7). In the shonkinites the REE are minor, rather than trace, constituents: LREE oxides total about 0.25 percent, and the concentration of Ce alone is 0.1 percent. These rocks contain twice as much total REE as Mn.

Of the several remarkable geochemical characteristics of the shonkinites, the most genetically significant is their very high K_2O/Na_2O. The vast majority of (unaltered) igneous rocks, ranging from peridotites and basalts to granites and syenites, and including most types of alkaline rocks, have weight percent K_2O/Na_2O ≤ 1.4; virtually all have K_2O/Na_2O < 3.0 (Bergman, 1987). Ultra-potassic rocks are defined as those with K_2O/Na_2O > 4.5 (molar K_2O/Na_2O > 3.0). Ultrapotassic rocks constitute only a minute fraction of igneous rocks on Earth, in terms of either volume or frequency of occurrence. At MP, all of the primary dikes (and nearly all of the other shonkinite dikes) are ultrapotassic, with median K_2O/Na_2O = 5.6.

Petrogenesis, by analogy with lamproites

Three types of ultrapotassic rocks are widely recognized: plagioleucitites, kamafugites, and lamp-roites (Foley and others, 1987; Mitchell and Bergman, 1991). Among these, MP shonkinite is similar only to lamproites (Haxel, in press). Lamproites represent very rare, very small volume magmas that are restricted to Archean cratons and their margins. Lamproites are known from only about 25 localities worldwide, and their total volume is < 100 km^3 (less than that of some single large basaltic or andesitic stratovolcanos). Type localities for these very rare rocks are Leucite Hills, Wyoming and West Kimberley, Australia.

Although the chemical resemblance between MP shonkinite and lamproites is strong, there are a few compositional differences and several significant mineralogical differences (Haxel, 1998). Therefore, the MP shonkinites must be considered lamproite-like, rather than lamproites sensu stricto. Nonetheless, MP shonkinite exhibits most of the distinctive and essential major and trace

element geochemical features of lamproites, and more closely resemble lamproites than it does any other widely recognized suite of igneous rocks.

Lamproites are generated by partial melting of geochemically exceptional mantle, typically in the thick lithospheric keel beneath Archean cratons. The mantle source material, originally fertile lherzolite, underwent major loss of Al, Ca, and Na during Archean extraction of basaltic melt, leaving a depleted harzburgite residuum. This depleted peridotite was subsequently infiltrated by magmas or aqueous fluids that produced vein and metasomatic minerals such as phlogopite, alkali amphibole, clinopyroxene, titanates, and apatite; and introduced incompatible elements, particularly K, Ba, Ti, Zr, P, and LREE. Very infrequent, very localized small-degree partial melting of this re-enriched peridotite generates lamproites. The major elements of the lamproite melt come largely from the harzburgitic component of the source rock, whereas the incompatible elements whose high abundances characterize the lamproite magma are derived from melting or decomposition of the vein and metasomatic minerals.

The distinctive geochemistry of the primitive shonkinite dikes at MP indicates that their petrogenesis must be closely analogous to that of the better-known lamproite suite (Haxel, in press). In particular, in both lamproites and MP shonkinite the high concentrations of K and F require that phlogopite is a major constituent of the mantle source (Fig. 5). Following this reasoning, abundances of incompatible trace elements in MP shonkinite can be successfully modeled by a *very* small degree (~0.01 – 0.1 %) of batch partial melting of *highly* enriched (~10 – 40 times chondritic or primitive-mantle) lithospheric mantle. This model suggests that the MP shonkinites are rare or unique rocks because their genesis required the conjunction of two circumstances, both quite rare: existence of exceptionally highly enriched mantle, and ascent of a very-small-volume mantle melt into the upper crust. Most mantle melts of such small volume migrate only a short distance from their source and then refreeze in the mantle. Ascent of shonkinite magma probably was facilitated by its high volatile content.

Rare earth element systematics

REE systematics of the primitive shonkinite dikes at MP further emphasize their singular geochemistry. Among all widely recognized suites of *silicate* igneous rocks, lamproites have the highest concentrations of total REE and the highest degrees of LREE-HREE fractionation (that is, the highest La/Yb ratios) (Cullers and Graf, 1984; Mitchell and Bergman, 1991). (In considering lamproites, I concentrate upon phlogopite lamproites, as this class includes the primary members of the lamproite suite, as well as many other primitive or near-primitive compositions; and de-emphasize olivine lamproites, which are derivative, non-primary rocks: Mitchell and Bergman, 1991, p. 399–400).

Remarkably, the shonkinite dikes at MP display even higher concentration of light and middle REE than most lamproites. In Figure 6, REE spectra for the primitive shonkinites lie along or slightly above the upper part of the range for the classic lamproite provinces. The primitive shonkinites also have greater REE fractionation than most lamproites: $(La/Yb)_{cn} \approx 130 - 140$, in contrast with the lamproite mean of 95 (cn: chondrite-normalized). Examining these relations in another way, Figure 7 shows that La/Yb ratios in the primitive shonkinites overlap with those of some lamproite provinces, but the primitive shonkinites are unsurpassed in their concentrations of Sm (representing the middle REE).

Mountain Pass Carbonatite

Petrology and geochemistry

Figure 8 is a photograph of an exceedingly strange igneous rock—a porphyritic carbonatite from Mountain Pass. The medium-grained groundmass, mostly calcite, surrounds centimeter-size phenocrysts of barite(!). The chemical composition of this strange rock is illustrated in Figure 9. Oxides of Ca and Ba together make up nearly one-half of the rock. Oxides of C and S make most of the remainder. All of the 'normal' rock-forming oxides (SiO_2, Al_2O_3, …) combined constitute only about two percent. The whole-rock content of REE oxides exceeds 11 percent!

Within the MP district, carbonatite forms widely scattered dikes and a single larger intrusion, the Sulfide Queen stock (Fig. 1). Some of the smaller carbonate bodies probably are veins rather than dikes (though this distinction may be in part semantic).

The Sulfide Queen carbonatite stock has a north-south strike length of about 700 m, dips about 40° west, and is roughly 70 m thick (Barnum, 1989). Olson and others (1954) mapped three intergradational units: ferruginous dolomite carbonatite (beforsite), barite-calcite carbonatite (sövite), and silicified carbonatite. The most abundant type, sövite, consists of 40 to 75 volume percent calcite, 15 – 50 percent barite, and 5 – 15 percent bastnäsite (Fig. 8). Bastnäsite, the chief REE ore mineral at MP, has the formula $(Ce,La,Nd,Pr)(CO_3)F$. In some places it is accompanied by parisite, $CaCe_2(CO_3)_3F_2$ (where Ce represent the LREE). Accessory minerals, some sporadic in distribution or uncommon, include other bastnäsite-family REE fluorocarbonate phases, strontianite, celestite, phlogopite, apatite, monazite, thorite, allanite, zircon, pyrite, galena, magnetite, and, hematite.

The MP carbonatite is "One of the most unusual of all carbonatites …" (Heinrich, 1966; Olson and others, 1954; Mariano, 1989a, 1989b):

- The MP carbonatite is associated with saturated to oversaturated (in SiO_2), phlogopite-rich, ultra*potassic* silicate igneous rocks, whereas nearly all other carbonatites are associated with undersaturated, nephelinitic, *sodic* rocks.
- Ca-silicate minerals common in many carbonatites, such as garnet and monticellite, are absent at MP.
- Unlike most, the MP carbonatite is not significantly enriched in the high-field-strength elements P, Ti, and Nb. Apatite and monazite, abundant in other carbonatites, are conspicuously sparse. Ti-Nb phases, such as pyrochlore or perovskite, are absent.
- Concentrations of Ba and LREE are extremely high (Fig. 10); correspondingly, barite and bastnäsite are very abundant.
- Bastnäsite is magmatic, rather than hydrothermal as in most other carbonatites.

Among all terrestrial igneous rocks, carbonatites have the greatest concentrations of LREE and the strongest REE fractionation: typically La ~ 200 – 5,000 μg/g and $(La/Yb)_{cn}$ ~ 100 – 1,000 (Cullers and Graf, 1984; Woolley and Kempe, 1989). Even in comparison with other carbonatites, the LREE enrichment and REE fractionation of MP carbonatite are extraordinary: La = 7,000 – 51,000 μg/g (median 26,000 μg/g) and $(La/Yb)_{cn}$ = 700 – 6,600 (median 3,600) (Fig. 11). Barium (median 14 %) is likewise enriched, by factors ~ 10 – 1,000, relative to most other carbonatites (Figs. 10, 11). Thus, MP sövite is compositionally extreme even for a carbonatite. Figure 12 provides a broader comparison of the REE spectrum of a MP carbonatite with spectra of diverse suites of igneous rocks, ranging from ordinary carbonatites to MORB and alpine peridotite.

Figures 8 – 12 should amply substantiate the statement made in the Introduction that the Mountain Pass carbonatite is one of the most bizarre igneous rocks on Earth.

Origin

Its field relations and extraordinary composition leave no doubt as to the igneous nature of the MP carbonatite. Although Olson and others (1954) conservatively referred to the carbonatite as "carbonate rock", they clearly recognized its igneous character, based upon regional geology, field relations, petrologic evidence, and rudimentary geochemical data (p. 59–63). All subsequent workers have accepted the carbonatite as an intrusive igneous rock. Experiments conducted by Wyllie and others (1996; Wyllie, 1989) further support an igneous origin: "… addition of water to the Mountain Pass carbonatite is all that is required for it to be molten at approximately 543°C and 1 kbar pressure." These experiments also are consistent with the magmatic origin of bastnäsite in the carbonatite.

Available data do not permit a full account of the origin of MP carbonatite. I can offer only a few preliminary ideas, and a concluding speculation. Three related issues need to be considered: genetic relations of carbonatite and ultrapotassic silicate magmas, mantle versus crustal genesis of carbonatite, and the extraordinary enrichment of LREE and Ba in the carbonatite.

Two lines of evidence indicate the independence of carbonate and silicate magmas at MP. First, field relations (Olson and others (1954) show that the two magmas arrived in the upper crust separately. Second, the Sulfide Queen carbonatite is approximately 25 m.y. younger than the main shonkinite and syenite (U-Th-Pb and Ar-Ar ages: DeWitt and others, 1987).

The MP carbonatite seemingly can have originated only in the mantle. Continental crust contains no known reservoir capable of yielding a carbonatite magma. On the other hand, melting of carbonate-bearing peridotite in the mantle to produce carbonatite is well documented (Gittins, 1989; Wyllie and others, 1996; Bell and Tilton, 2002). The Sr isotopic composition of the MP carbonatite ($[^{87}Sr/^{86}Sr]_{initial} = 0.7044$, $\varepsilon_{Sr} = 22$; Powell and others, 1966), though slightly more radiogenic than most carbonatites (Bell and Blenkinsop, 1989), is consistent with mantle genesis. The origin of the MP carbonatite can be examined in greater detail after more isotopic data become available (E. DeWitt, personal communication, 2003).

The extraordinary levels of LREE and Ba could owe to either or both of two factors: a very highly enriched mantle source, or concentration of these elements through prolonged fractional crystallization. Two kinds of evidence favor an unusual mantle source as the most important contributor. First, no much larger body of precursor carbonatite with much lower LREE and Ba than the Sulfide Queen stock is known at MP. Second, several of the most distinctive characteristics of the carbonatite—high LREE, Ba, and F—are shared by the mantle-derived primary shonkinite. The geochemical correspondence between these two very unusual magmas, occurring together in the same small district, surely is no coincidence. I suggest that both originated by melting within the same area or zone of highly anomalous mantle.

This hypothesis requires or implies (1) a mantle source highly enriched in LREE, (2) transport of high concentrations of LREE in a carbonatite melt, and (3) retention of LREE as the magma ascended to the upper crust.

(1) The exceptional abundance of LREE in the primary shonkinite independently indicates a mantle source rich in LREE. In enriched mantle LREE (and Ba) can reside in titanate minerals of the crichtonite group, $A(Ti,Fe,Cr)_{21}O_{38}$, where A can include Ca, Sr, Ba, LREE, K, and others (Jones and Ekambaram, 1985; Jones, 1989).

(2) Experiments with carbonatite melts have established the very high solubility of LREE, ~ 20 – 40 percent, so natural carbonatite magmas are considered efficient scavengers of LREE (Wyllie, 1989; Wyllie and others, 1996).

(3) Retention of LREE in the magma until it ascended to the upper crust evidently is related to the unusually high F/P ratio of the MP carbonatite (Mariano, 1986b; Wyllie and others, 1996). Low P content inhibited early precipitation of monazite and apatite, so LREE remained in solution. High concentration of F then allowed most of the endowment of LREE to crystallize as magmatic bastnäsite and parisite.

Fluorine in the carbonatite magma presumably derives from phlogopite in the enriched mantle that sourced the primary shonkinite magma. This phlogopite evidently was unusually rich in fluorine. Thus, I speculate that the remarkable silicate and carbonate igneous rocks at Mountain Pass might fundamentally reflect a localized fluorine anomaly in the underlying mantle.

Rare Earth Element Deposit

Mountain Pass is a magmatic ore deposit; the Sulfide Queen carbonatite stock is the ore body. This is the only major ore deposit in the world mined solely for its REE content. *Average* ore grade is ≈ 9 percent REE oxides; cutoff grade is 5 percent (Barnum, 1989; Castor, 1990, 1991, 1994; Kilbourn, 1993). Protore grading 2 – 5 percent REE oxides is stockpiled. Stated reserves are ≳ 20 million metric tons (at 5 percent cutoff grade).

Geochemistry

Typical MP REE ore contains about 65 volume percent calcite and/or dolomite; 20 – 25 percent barite, celestite, and strontianite; and 10 – 15 percent bastnäsite, the ore mineral. Concentrations of the individual REE in the ore represent the superposition of two factors, one nuclear and one mineralogical. First, the fundamental baseline for terrestrial geochemical processes is the cosmic abundances of the REE established during nucleosynthesis. REE with even atomic numbers ($_{58}$Ce, $_{60}$Nd, …) have greater cosmic and terrestrial abundances than adjacent REE with odd atomic numbers ($_{57}$La, $_{59}$Pr, …). This fact is a consequence of nuclear physics, transcending chemistry or geochemistry. It is even reflected, imperfectly, in the relative prices of the individual REE (Haxel and others, 2002, Fig. 3).

Second, MP bastnäsite is characterized by extreme preferential enrichment in LREE relative to HREE: $La_{cn} = 6.6 \cdot 10^5$, $Yb_{cn} \approx 20$, and $(La/Yb)_{cn} \approx 37{,}000$ (Fig. 13; Johnson and Sisneros, 1982; Mariano, 1989b; Kilbourn, 1993). Some perspective on these values is provided by comparison with average upper continental crust. In MP bastnäsite Yb is enriched over average upper crust by a factor of 2, whereas La is enriched by a factor of 7,000.

As a consequence of these two factors, Ce alone makes up nearly one-half of the total REE content of the ore, and La constitutes one-third (Fig. 14). The four lightest REE (La, Ce, Pr, Nd) total almost 99 percent. Europium, the most valuable of the REE produced at MP, constitutes only about 0.1 percent of the REE in the ore.

History

The Mountain Pass REE deposit was discovered in 1949 (Hewett, 1954). Development of the mine accelerated in the middle and late 1960s, driven and financed largely by the demand for Eu created by the large-scale commercialization of color television (Evans, 1966). All color cathode-ray tubes utilize Eu in the red phosphor; despite the high cost of Eu, no practicable substitute has

ever been found. For some thirty years, Mountain Pass strongly dominated the world's supply of REE, especially LREE and Eu (Castor, 1990; Haxel and others, 2002). Since the mid-1980s, Chinese production of REE has grown dramatically. Production from China now considerably exceeds that from MP. Chinese deposits, though significantly lower in grade than MP, are huge. Furthermore, some Chinese deposits have elevated concentrations of the less abundant and more valuable HREE. Nonetheless, Mountain Pass remains one of several major sources of light rare earth elements, and the only such source in North America.

Field Trip Locality: Synplutonic Shonkinite Dikes

We will spend an hour or two examining excellent exposures of synplutonic shonkinite dikes within the shonkinite-syenite Tors stock (Fig. 1). The southern one-third of this composite stock is shonkinite (melanosyenite) and mesosyenite. This part of the stock includes phlogopite-rich shonkinite (locally, phlogopite-rock), in some places olivine-bearing, that I interpret as accumulative. Such accumulative rocks, in the Tors stock and others, contain 10 – 17 percent MgO. The northern two-thirds of the Tors stock is mostly mesosyenite and leucosyenite. In some places syenite intrudes shonkinite; elsewhere contacts are gradational. The margins of the stock are locally marked by intrusion breccias. Where we will examine the synplutonic dikes, the rock of the Tors stock is mesosyenite.

The synplutonic dikes display an intriguing and informative variety of shapes, patterns, and textures, collectively indicating that shonkinite magma was intruded repeatedly during solidification of the syenite, and that shonkinite mingled and locally mixed with syenite. Early dikes were extensively back-intruded and disrupted by their syenite host, so that they now form trains of ovoid to amoeboid shonkinite inclusions within the syenite. Later dikes partially maintain their original tabular shapes and locally have fine-grained margins against the host syenite. But, even these younger dikes were locally intruded or veined by syenite or leucosyenite. Most of the shonkinite inclusions and dikes have associated with them irregular, dense to diffuse masses or patches of pegmatoid syenite (some amphibole-rich), gradational outward into normal syenite. This pegmatoid syenite probably reflects nucleation of crystals and/or concentration of volatiles adjacent to the shonkinite bodies. The youngest shonkinite dikes both are crosscut by and crosscut syenoaplite dikes. One provocative outcrop suggests that late shonkinitic magma and aplitic magma coexisted, apparently with minimal mingling, and moved together along the same channel through the syenite of the stock.

The informative and important field relations of synplutonic dikes are not well exposed anywhere else in the Mountain Pass district. **Please don't hammer on and destroy the evidence!** *Take photographs, not rocks. Samples of shonkinite and syenite are readily available nearby from near-source float.*

Acknowledgments

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Table 1. The rare earth elements: the lanthanides, La to Lu, and Y {1}.

Symbol	Name	Z {2}	Number of extant isotopes	Atomic mass	Electron configuration {3} Ln⁰	Ln³⁺	other	Ionic radius (Å) {4}	Concentration (µg/g) Chondrites {5}	UCC {6}	Derivation of name
La	lanthanum	57	2	138.9055	$\odot 4f^0 5d^1 6s^2$	$\odot 4f^0$		1.160	0.329	30.	"to lie hidden" (Greek)
Ce	cerium	58	4	140.115	$\odot 4f^2 6s^2$ {7}	$\odot 4f^1$	Ce^{4+}: $\odot 4f^0$	1.143, 0.97	0.865	64.	The asteroid Ceres
Pr	praseodymium	59	1	140.90765	$\odot 4f^3 6s^2$	$\odot 4f^2$		1.126	0.116	7.1	"leek-green twin" (Greek) {8}
Nd	neodymium	60	7	144.24	$\odot 4f^4 6s^2$	$\odot 4f^3$		1.109	0.630	26.	"new twin" (Greek) {8}
Pm	promethium	61	0	145 {9}	$\odot 4f^5 6s^2$	$\odot 4f^4$		1.093	effectively zero		Prometheus, in Greek mythology the Titan who gave fire to humans
Sm	samarium	62	7	150.36	$\odot 4f^6 6s^2$	$\odot 4f^5$		1.079	0.203	4.5	The mineral samarskite, named for a Russian engineer
Eu	europium	63	7	151.965	$\odot 4f^7 6s^2$	$\odot 4f^6$	Eu^{2+}: $\odot 4f^7$	1.066, 1.25	0.077	0.88	Europe
Gd	gadolinium	64	7	157.25	$\odot 4f^7 5d^1 6s^2$	$\odot 4f^7$		1.053	0.276	3.8	J. Gadolin, Finnish mineralogist, discoverer of Y
Tb	terbium	65	2	158.92534	$\odot 4f^9 6s^2$	$\odot 4f^8$		1.040	0.052	0.64	Ytterby, a Swedish village
Dy	dysprosium	66	7	162.50	$\odot 4f^{10} 6s^2$	$\odot 4f^9$		1.027	0.343	3.5	"hard to obtain" (Greek)
Ho	holmium	67	1	164.93032	$\odot 4f^{11} 6s^2$	$\odot 4f^{10}$		1.015	0.071	0.80	*Holmia*, Stockholm (Latin)
Er	erbium	68	6	167.26	$\odot 4f^{12} 6s^2$	$\odot 4f^{11}$		1.004	0.225	2.3	Ytterby
Tm	thulium	69	1	168.93421	$\odot 4f^{13} 6s^2$	$\odot 4f^{12}$		0.994	0.034	0.33	*Thule*, "most northerly land", an ancient name for Scandinavia (Latin)
Yb	ytterbium	70	7	173.04	$\odot 4f^{14} 6s^2$	$\odot 4f^{13}$		0.985	0.220	2.2	Ytterby
Lu	lutetium	71	2	174.967	$\odot 4f^{14} 5d^1 6s^2$	$\odot 4f^{14}$		0.977	0.0339	0.32	*Lutetia*, Paris (Latin)
Y	yttrium	39	1	88.90585	$[Kr] 4d^1 5s^2$	$[Kr]$		1.019	2.00	22.	Ytterby

{1} Data from Emsley (1998), Shannon (1976), Nakumura (1974), Taylor and McLennan (1985), Greenwood and Earnshaw (1997).

{2} Z = atomic number.

{3} $\odot$ designates the Xe core, $\cdots 4d^{10} 5s^2 5p^6$; [Kr], the Kr core.

{4} In eight-fold coordination, for Ln^{3+}, Ce^{4+}, and Eu^{2+}.

{5} Total lanthanides, 3.47 µg/g; total REE (lanthanides + Y), 5.47 µg/g.

{6} UCC, upper continental crust. Total lanthanides, 146 µg/g; total REE (lanthanides + Y), 168 µg/g; La+Ce+Pr+Nd, 127 µg/g; La+Ce+Pr+Nd+Y, 149 µg/g.

{7} Or $\odot 4f^1 5d^1 6s^2$.

{8} Mixtures of Pr and Nd were once called *didymium* (Di; Greek "twin" or "double"), a term and symbol occasionally found in the older geochemical literature.

{9} Longest-lived isotope, half-life 17.1 a.
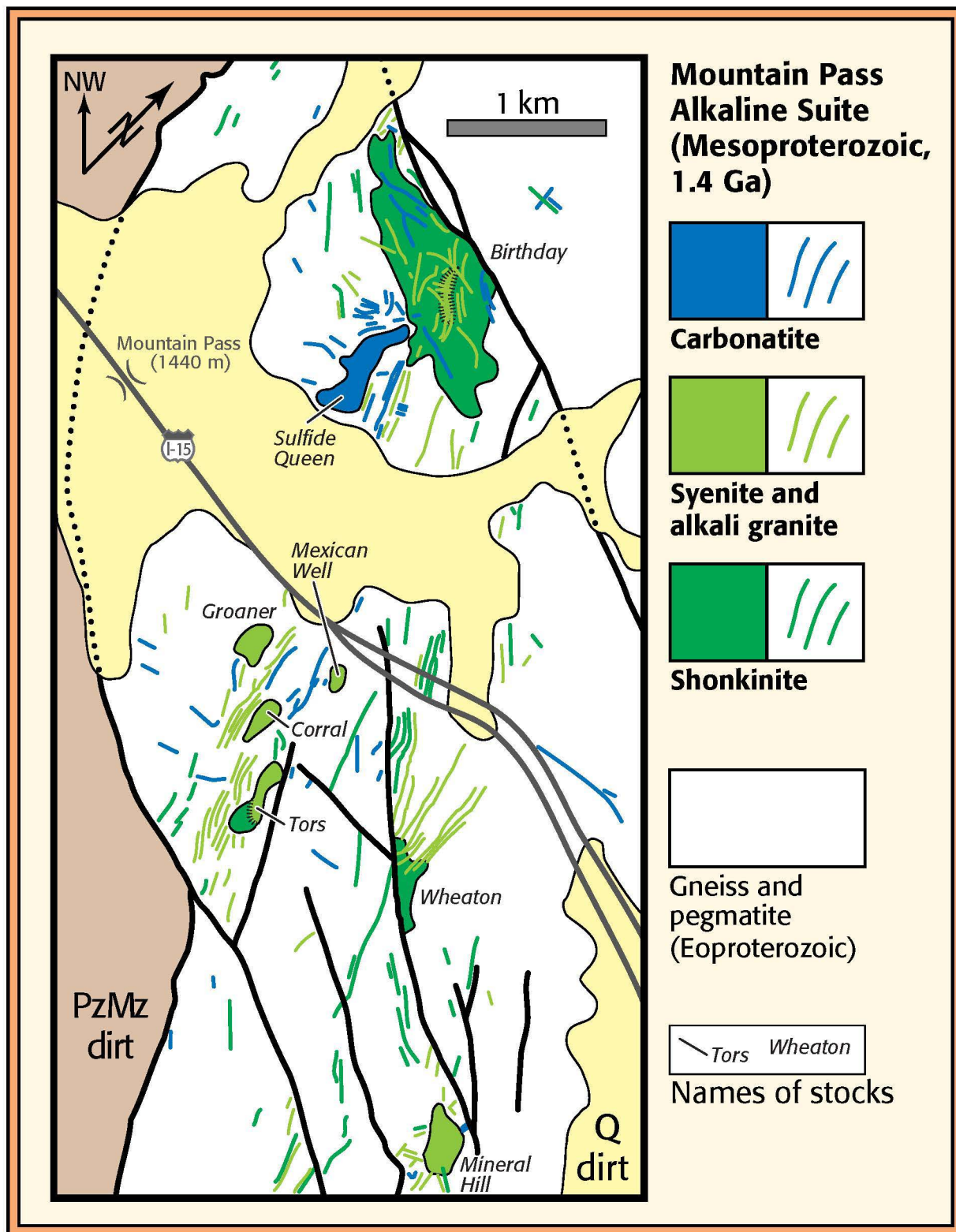
Figure 1. Generalized geologic map of the Mountain Pass rare earth element district, southern California (after Olson and Pray, 1954; Olson and others, 1954; 1.4 Ga age from DeWitt and others, 1987). The district extends 2 – 3 km farther southeast beyond the area shown on this map. Only a representative minority of the hundreds of dikes mapped by Olson and others (1954) are shown. Within the Tors and Birthday stocks, contacts between shonkinite and syneite are gradational. Note that up is northwest.

Figure 2. Chemical periodic table delineating the rare earth elements (REE): the *lanthanides,* La through Lu, except for Pm, plus Y. Promethium is excluded because it has no long-lived isotopes and occurs naturally on Earth only locally and in vanishingly small quantities. In the main periodic table, *An* represents the first 14 actinide elements; Lr is the final actinide.

The rare earth elements

La	lanthanum
Ce	cerium
Pr	praseodymium
Nd	neodymium
Pm	promethium
Sm	samarium
Eu	europium
Gd	gadolinium
Tb	terbium
Dy	dysprosium
Ho	holmium
Er	erbium
Tm	thulium
Yb	ytterbium
Lu	lutetium
Y	yttrium
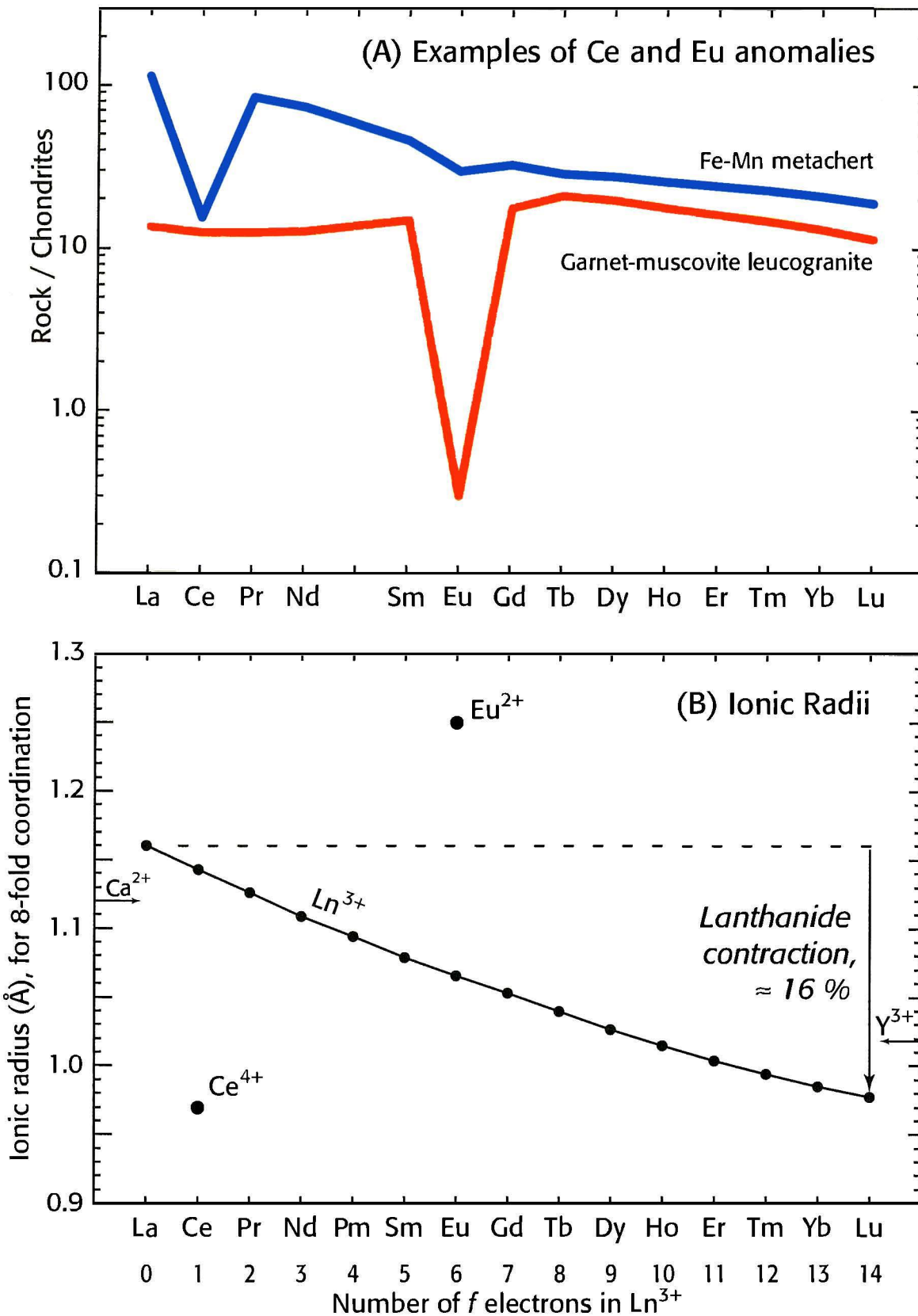
Figure 3. (A) Example of a chondrite-normalized REE spectrum with a Ce anomaly (Fe-Mn metachert, Orocopia Schist, Picacho district, southeasternmost California) and another with an Eu anomaly (garnet-muscovite leucogranite, Baboquivari Mountains, southern Arizona). (B) The lanthanide contraction.
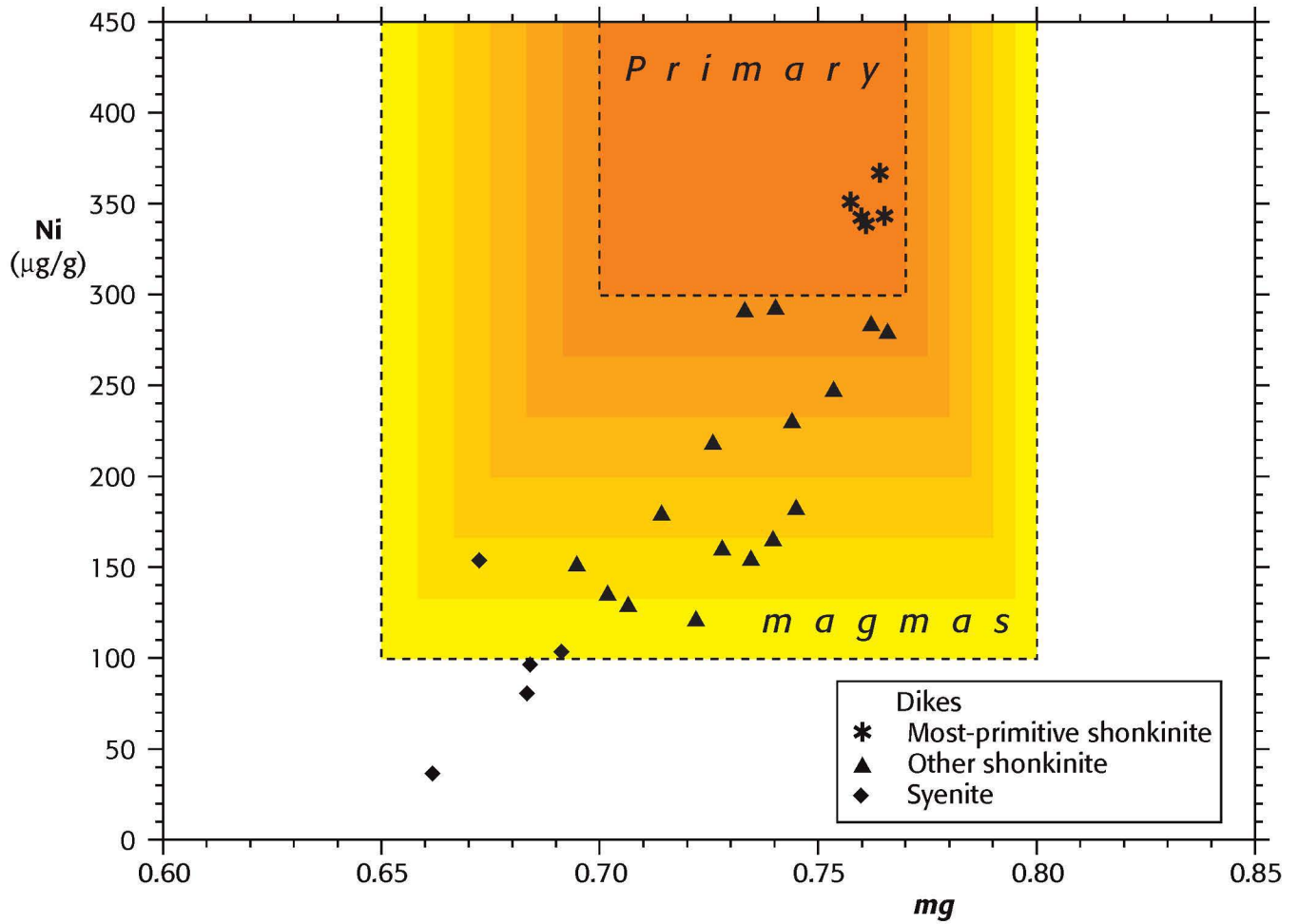
Figure 4. Mg number, *mg* (see Table 2 for definition), and Ni concentration in shonkinite dikes of the Mountain Pass REE district. Orange to yellow rectangles delineate the ranges of values of *mg* and Ni commonly considered indicative of primary, mantle-derived magmas (Sato, 1977; Gill, 1981; Rock, 1991; Tatsumi and Eggins, 1995).
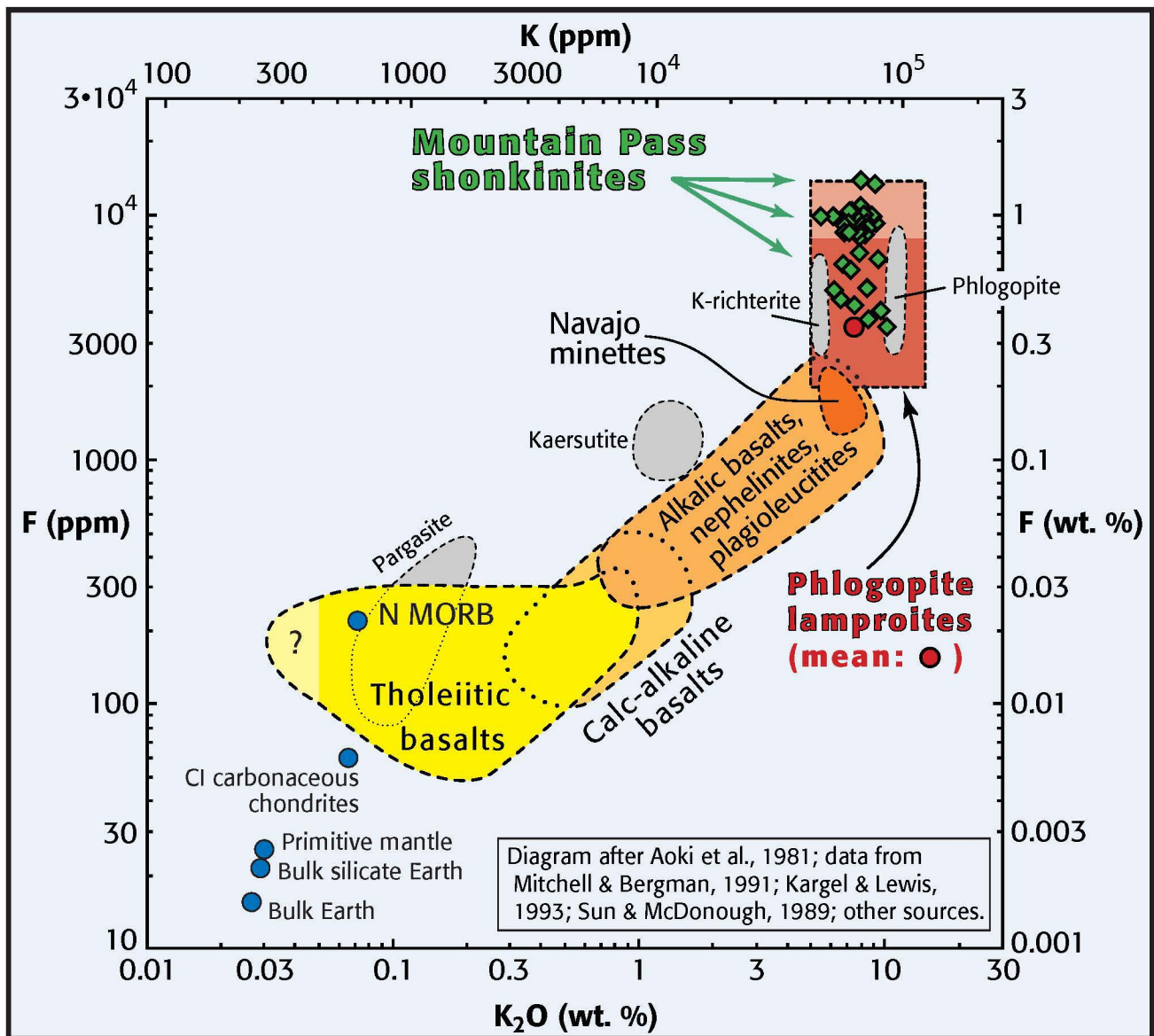
Figure 5. Potassium and fluorine contents of Mountain Pass shonkinites, compared with those of other mafic igneous suites (colored fields), minerals that constitute the principal mantle reservoirs of K and F (gray fields), and several primitive Earth reservoirs or materials (blue dots). Diagram after Aoki and others (1981); with additional data from Mitchell and Bergman (1991), Kargel and Lewis (1993), Sun and McDonough (1989), and several other sources.
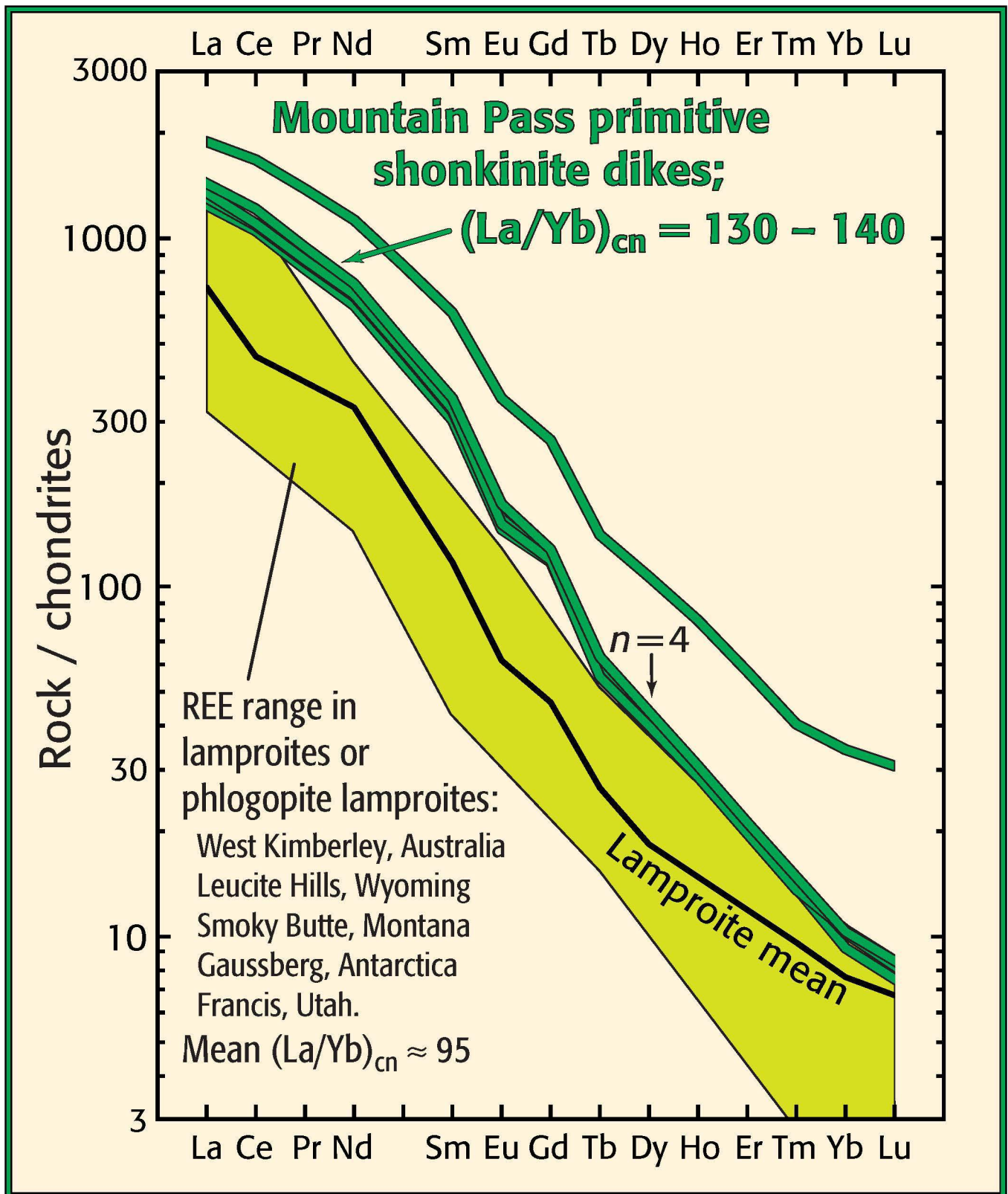
Figure 6. REE spectra of the five most primitive shonkinite dikes (Fig. 4) from Mountain Pass, compared with spectra of lamproites from several classic provinces (Mitchell and Bergman, 1991); chondrite normalized (Nakamura, 1974). The four closely clustered spectra include the sample presented in Table 2. See also Figure 7.
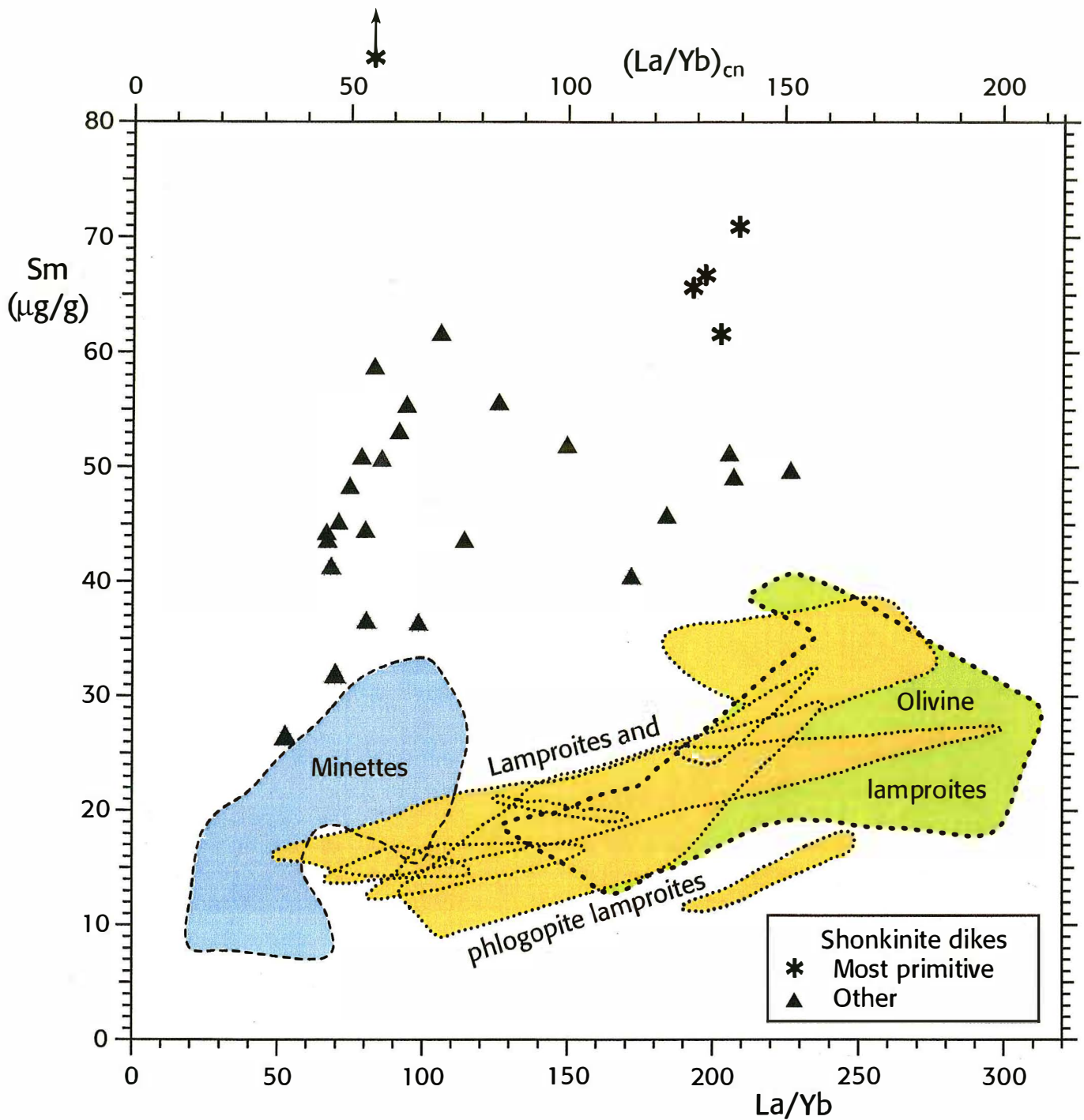
Figure 7. REE systematics of shonkinite dikes from Mountain Pass, compared with those of lamproites and minettes (after Mitchell and Bergman, 1991, Figs. 7.21, 7.23). Samarium represents the middle REE (Fig. 6). The compositional fields in orange encompass phlogopite lamproites or all lamproites from nine provinces, excluding one province considered anomalous by Mitchell and Bergman (1991). The green field represents olivine lamproites from West Kimberley, Australia. One Mountain Pass sample, with Sm = 125 μg/g and $(La/Yb)_{cn}$ = 55, plots above the top of the graph.

Figure 8. Sövite (calcite carbonatite) from the Sulfide Queen stock, Mountain Pass. Abundant, tabular to irregular, light-gray to cream phenocrysts of barite, the largest 1–1.5 cm across, are surrounded by a medium-grained, pinkish-tan to light-salmon matrix composed of calcite, barite, and bastnäsite (all difficult to distinguish in hand specimen). The chemical composition of a very similar sövite is illustrated in Figure 9. The yellowish object in the lower left is a small, altered xenolith. The light-colored area along the lower edge is a percussion (hammer) mark. As printed here, the specimen is imaged approximately actual size.

Bastnäsite‑barite sövite (calcite carbonatite), Mountain Pass, California

CaO

BaO

SrO

$"(Ce,La,Nd)O^+"$

$SiO_2 + Al_2O_3 + FeO + MgO + Na_2O + K_2O + TiO_2 + MnO + H_2O$

SO_3

F^-

CO_2

(Analysis in weight %)
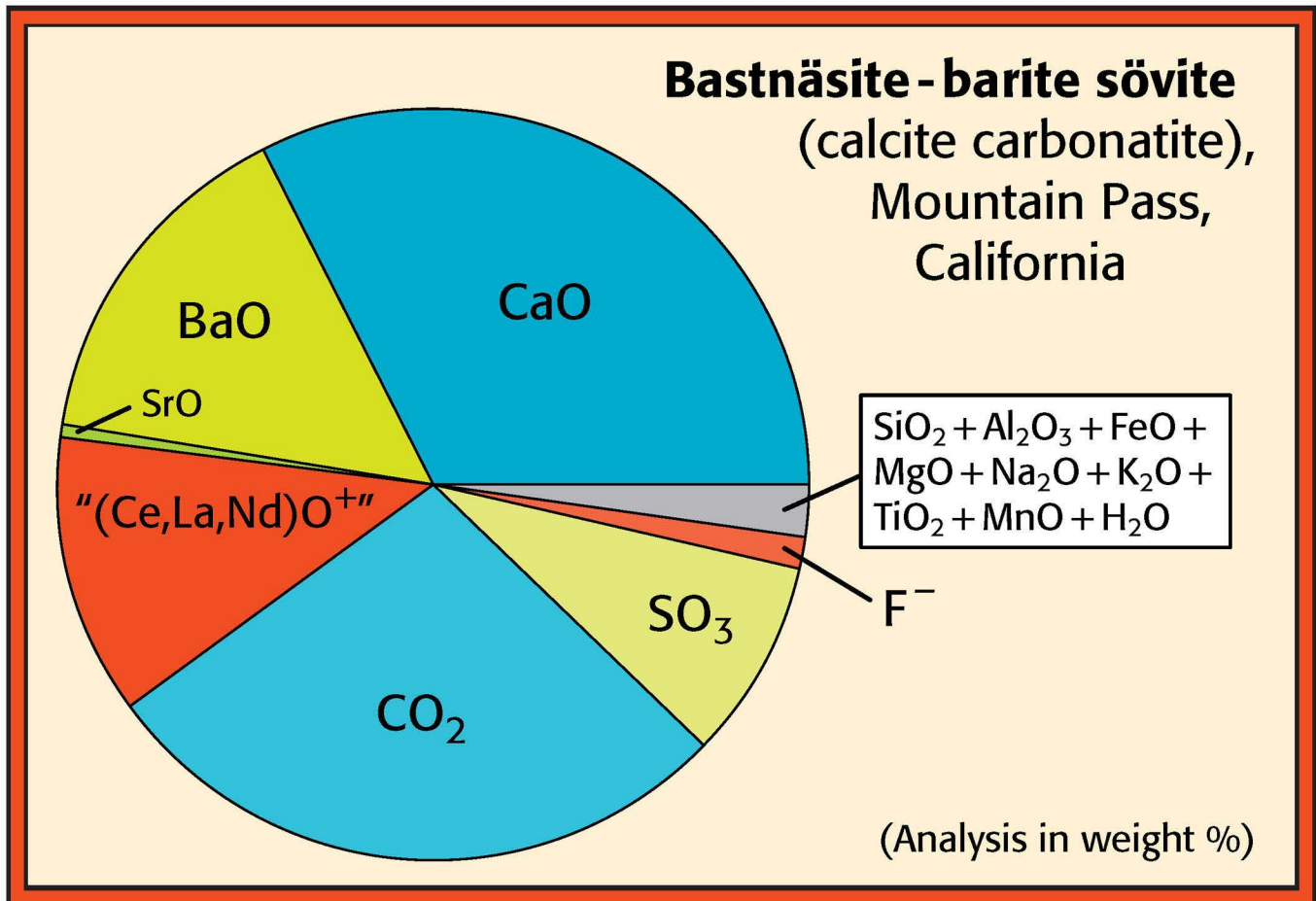
Figure 9. Proportions, by mass, of major and minor constituents of bastnäsite-barite sövite (Fig. 8), Mountain Pass. The black sector labeled "$-F \triangleq O$" represents grams of O equivalent to the grams of F in the analysis. If the analysis were tabulated, this value would be subtracted from the sum of the oxides to yield the analytical total.
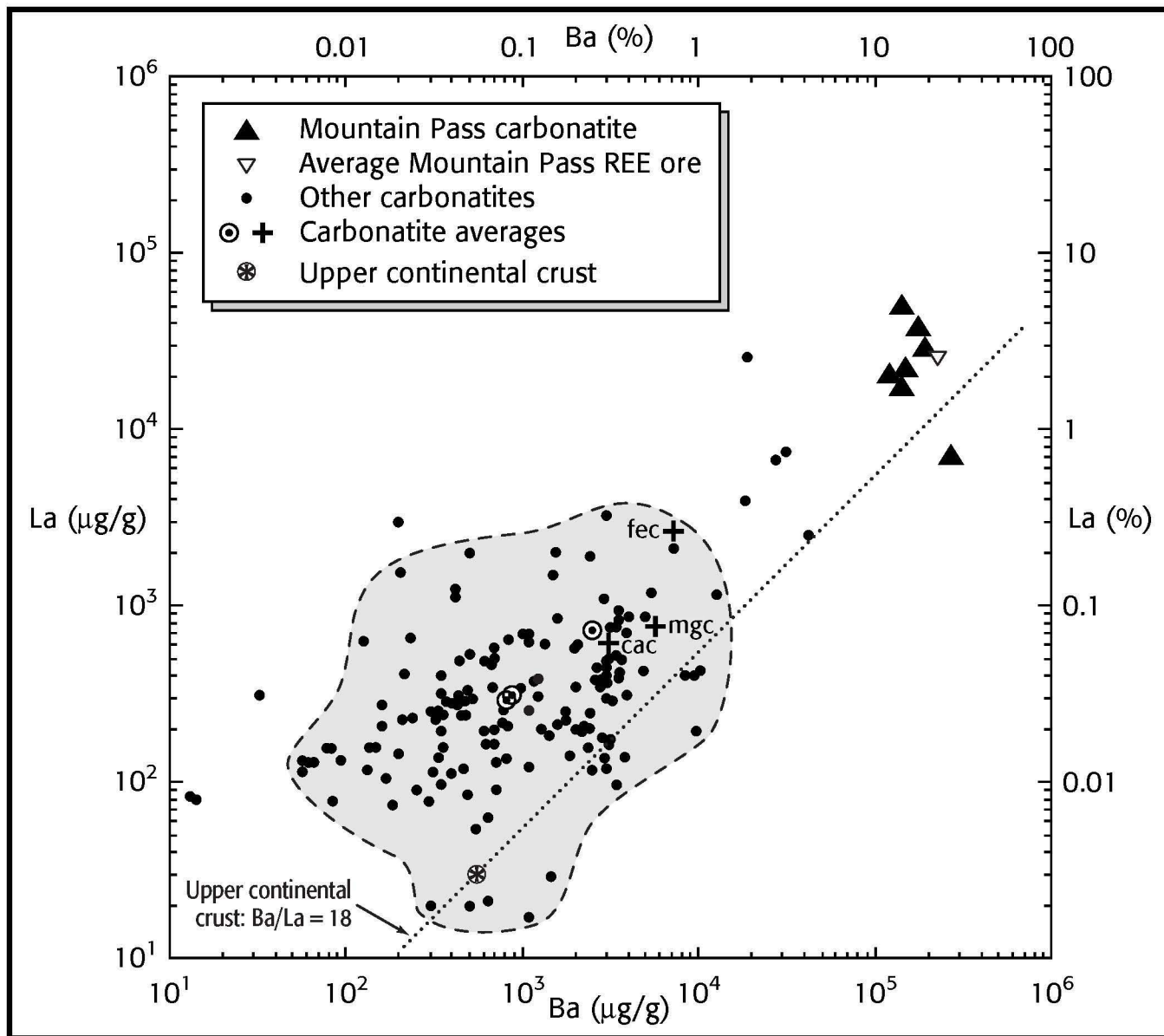
Figure 10. Concentration of Ba and La in the LREE-rich carbonatite at Mountain Pass, California compared with other, ordinary carbonatites. Small dots represent 161 analyses of carbonatites, from five continents (data from Bell, 1989; Nelson and others, 1988; and numerous other sources); 94 percent of these data plot within the shaded area. The two overlapping encircled dots symbols represent the geometric mean and median of these data (excluding Mountain Pass); the third such symbol is the arithmetic mean. The three equant crosses represent the global average composition (presumably the arithmetic mean) of Ca-, Mg-, and Fe-carbonatites (labeled respectively cac, mgc, fec) from Woolley and Kempe (1989). See also Figure 11.
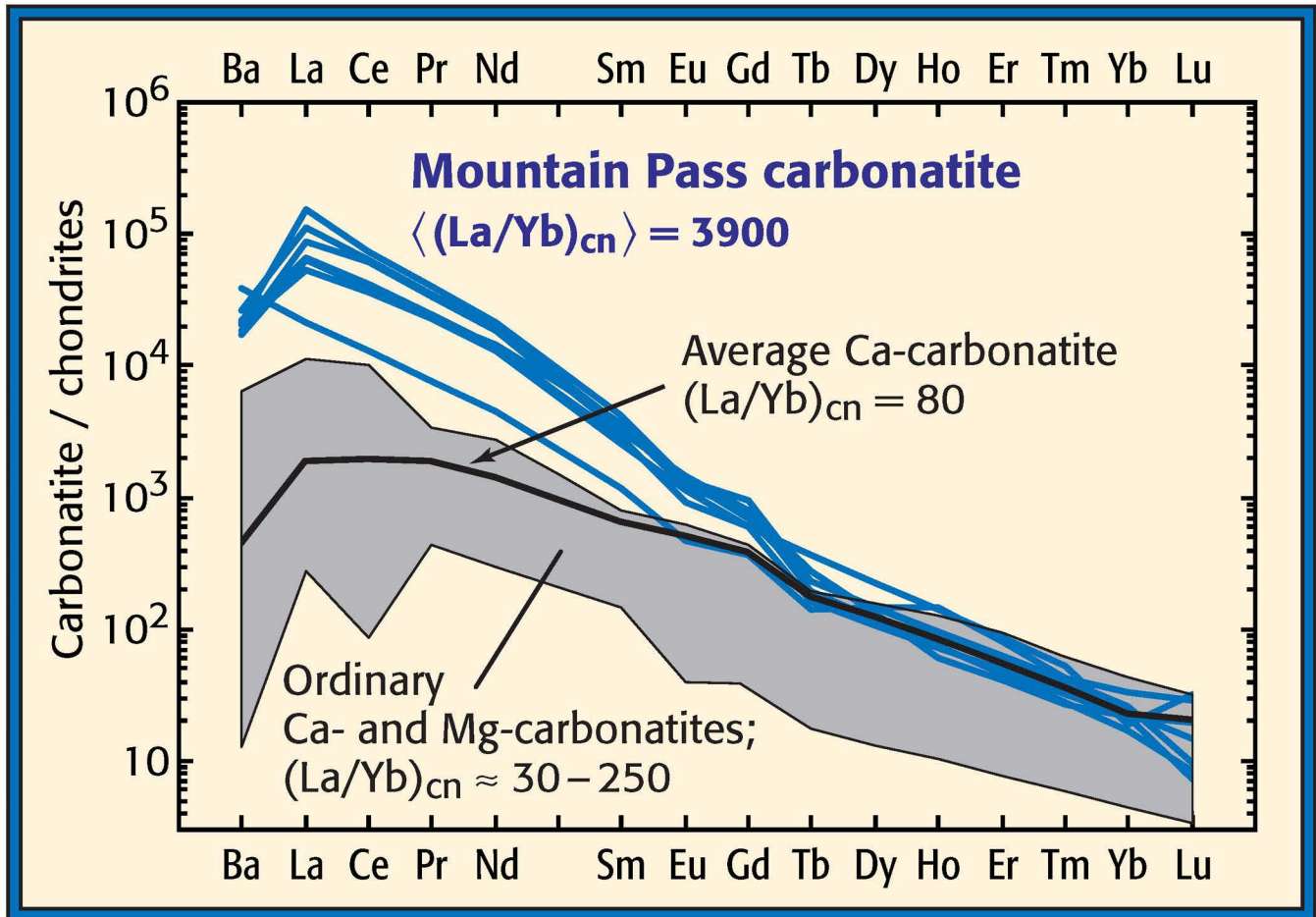
Figure 11. Extended REE spectra (lanthanides plus Ba) of Mountain Pass carbonatite (including one analysis from Johnson and Sisneros, 1982), compared with ordinary carbonatites (Woolley and Kempe, 1989); chondrite normalized (Nakamura, 1974). See also Figure 10.
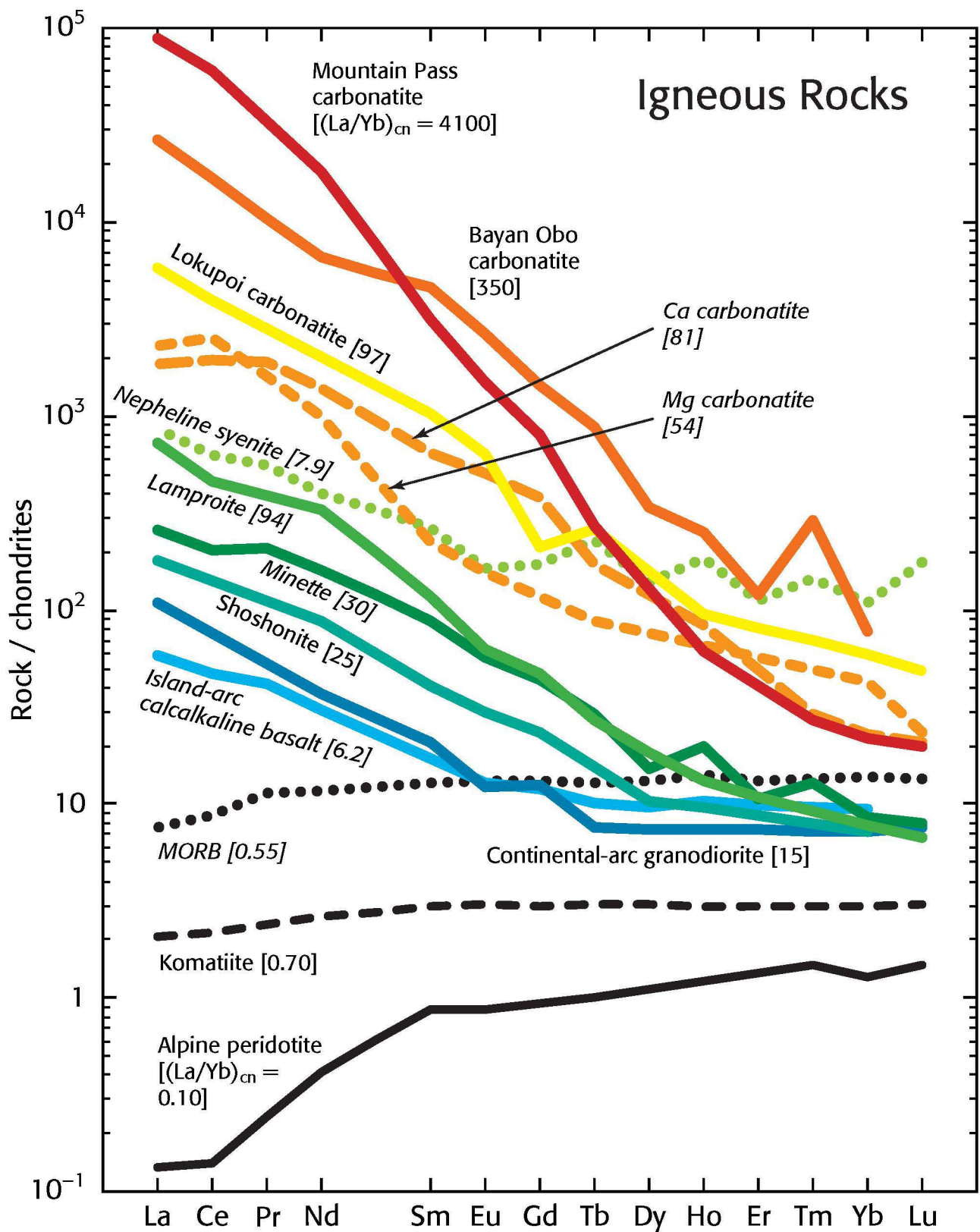
Figure 12. Chondrite-normalized (Nakamura, 1974) REE spectra for average compositions (labeled in *italic*; global unless stated otherwise) or representative compositions (labeled in upright type) of several common suites of tholeiitic and calcalkaline igneous rocks, and several varieties of continental alkaline igneous rocks. Minor irregularities in the HREE portion of some patterns are artifacts owing to analytical difficulties or to averaging of data from analyses reporting different combinations of HREE.
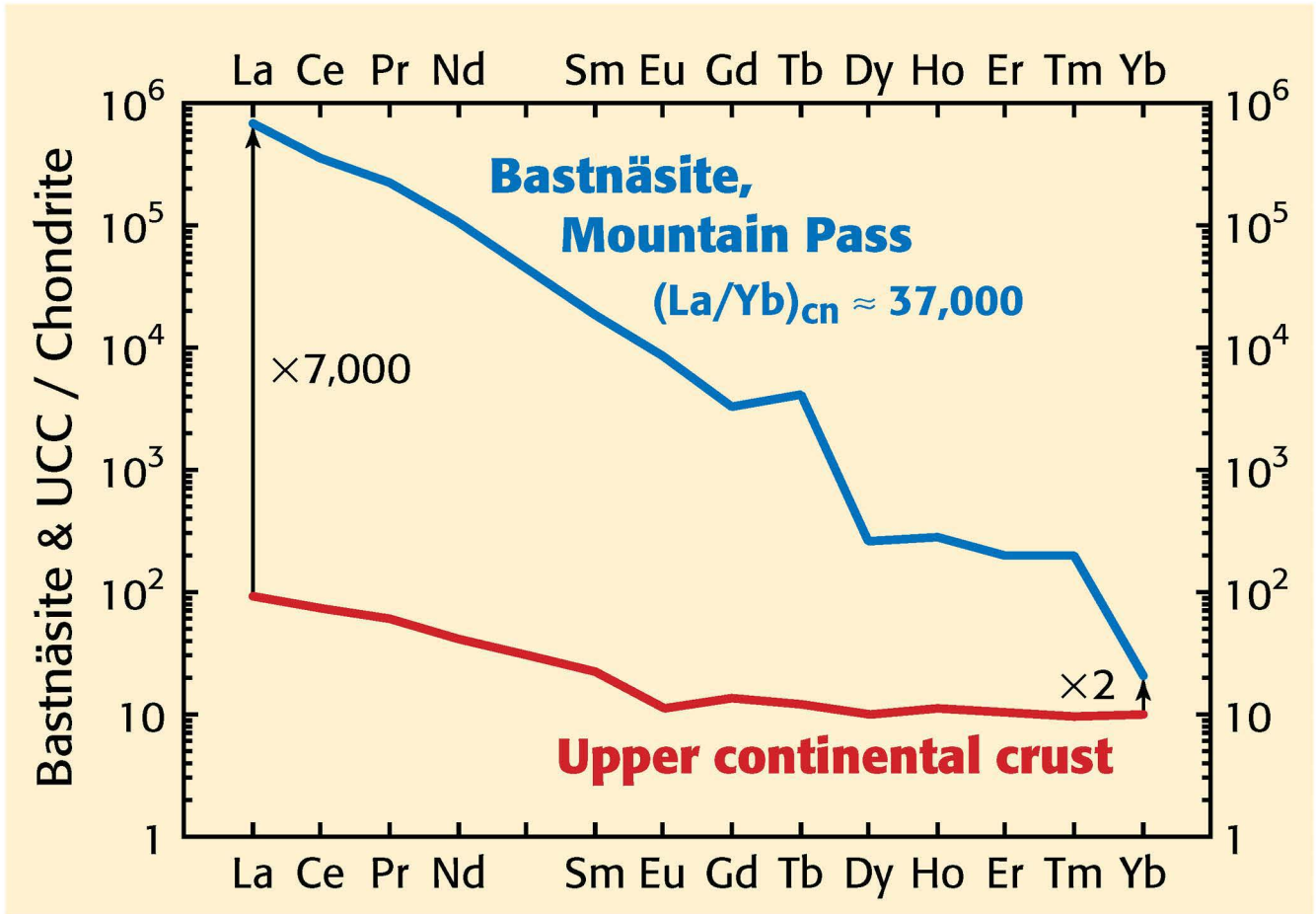
Figure 13. REE spectra of bastnäsite from the Mountain Pass carbonatite (Mariano, 1989b), compared with average upper continental crust (Taylor and McLennan, 1985); chondrite normalized (Nakamura, 1974).
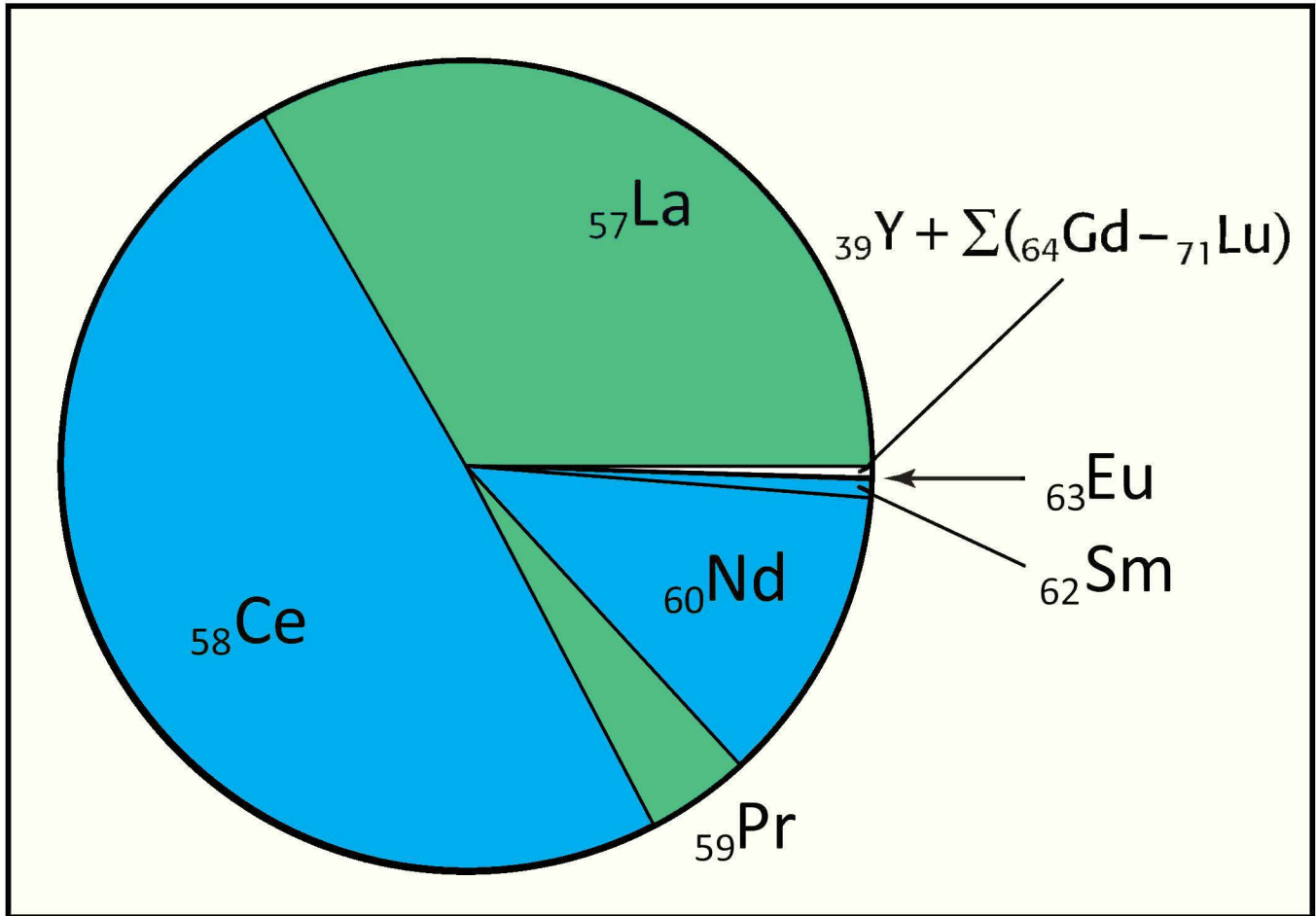
Figure 14. Proportions of individual REE in bastnäsite ore from Mountain Pass (Johnson and Sisneros, 1982; Kilbourn, 1993). Yttrium plus all lanthanides from Gd through Lu total only 0.3 percent, most of which comprises just Y and Gd. Europium makes up only about 0.1 percent of the REE content of the ore. Green and blue sectors represent lanthanides of odd and even atomic number (Z), respectively. The even-Z lanthanides Nd and Sm are adjacent because the intervening odd-Z element, $_{61}$Pm, has zero abundance (Fig. 2, Table 1). See also Haxel and others (2002, Fig. 6).

Section 4 Molycorp Mountain Pass Mine
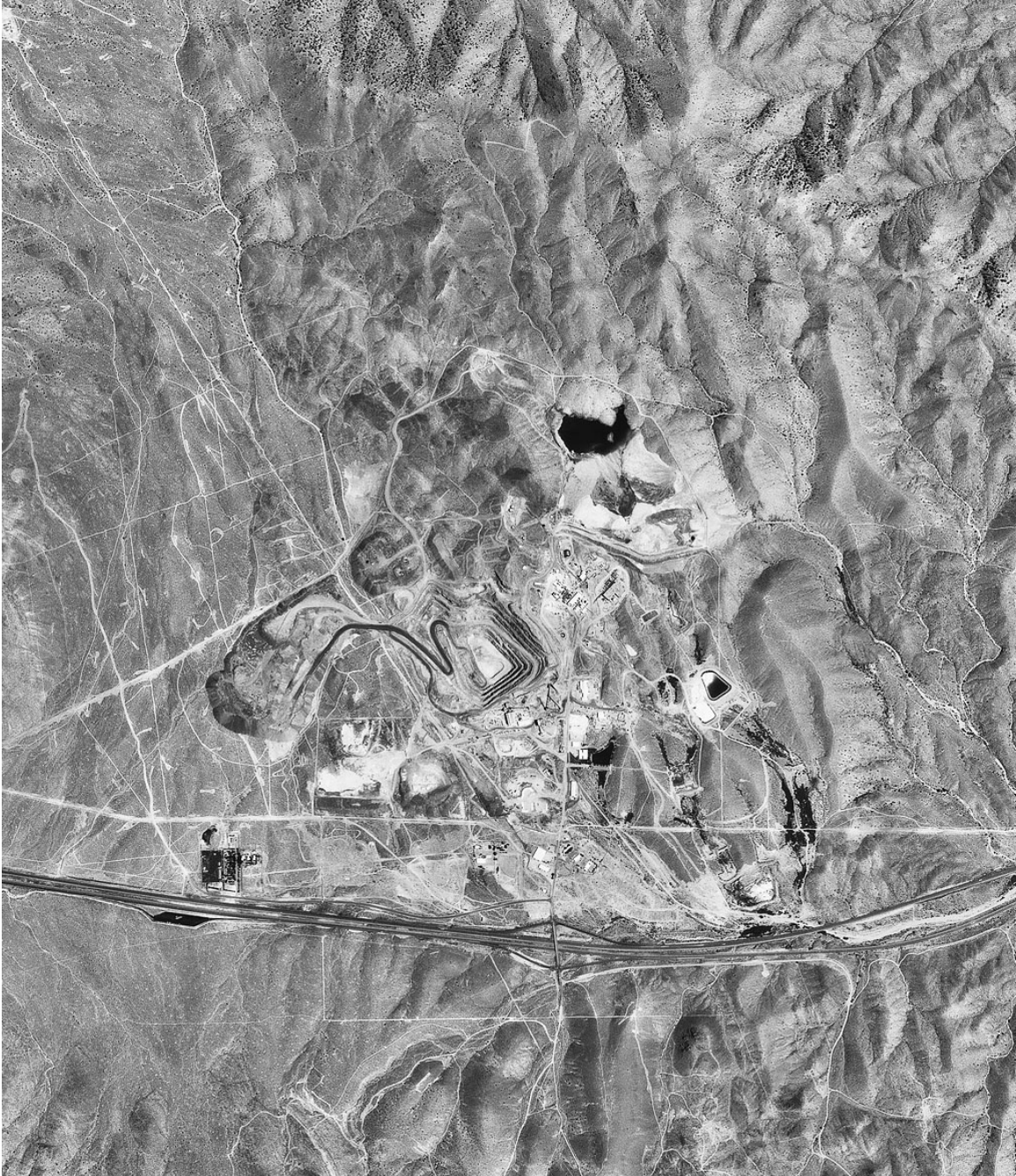
Figure 1 Aerial photograph of the region surrounding the Molycorp Mountain Pass Mine prepared by Kevin Horstman.

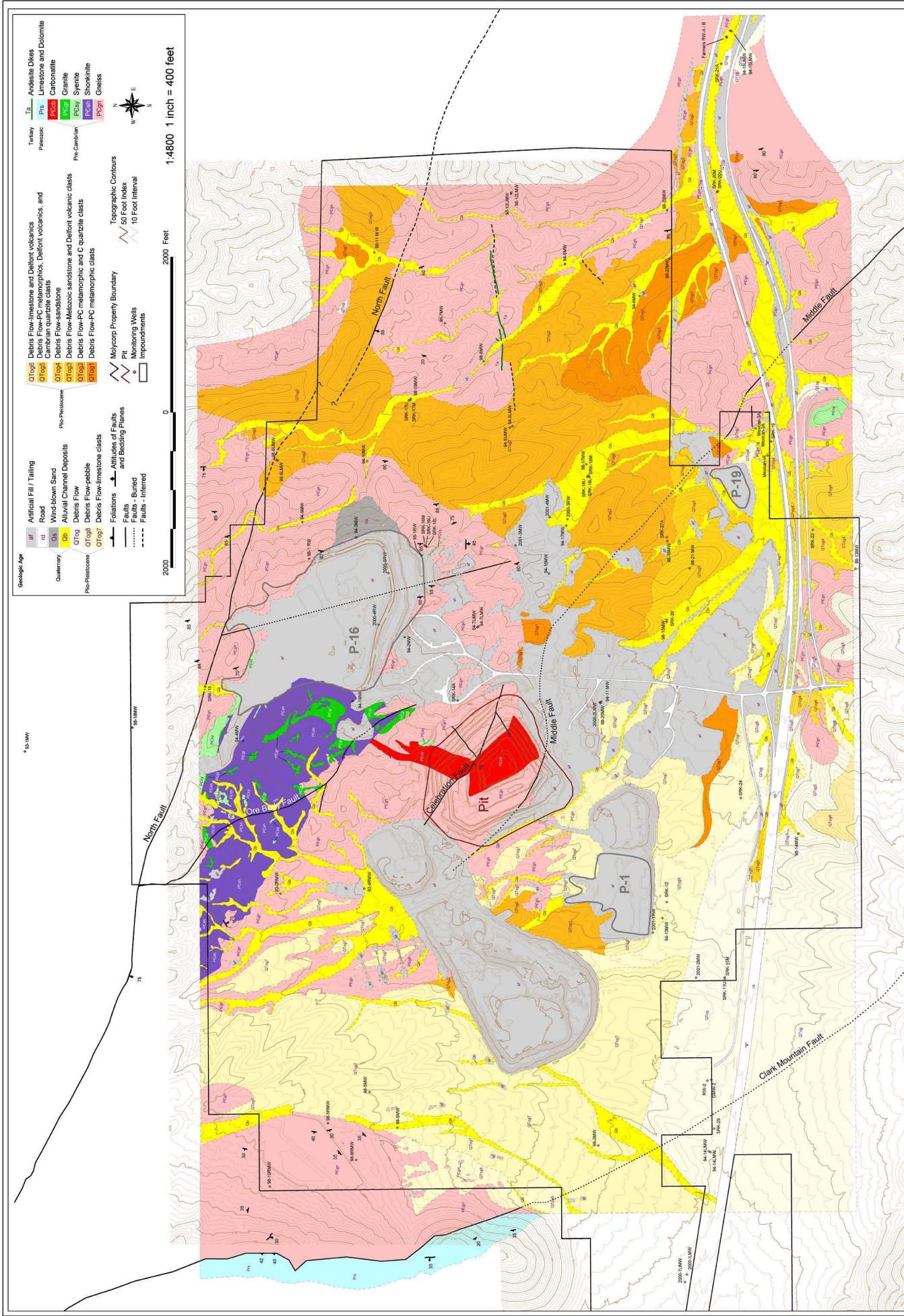**Figure 2 Aerial photograph of the Molycorp Mountain Pass Mine**

Figure 3.6-2. Geologic setting for Mountain Pass Mine site.

Generation
Date:
12/3/02

Geomega

The following information is from the Molycorp Web Site (Lanthanides) at www.molycorp.com.

LANTHANIDES

Capabilities at Mountain Pass range from extracting the ore out of the ground to producing high-grade lanthanide oxides. Surface mining methods are used to produce 2000 tons of crushed ore per day. The mill reduces the crushed ore even further in preparation for the froth flotation operation that yields bastnasite - a widely consumed mineral feedstock containing the natural ratio of lanthanide elements.

Although separations facilities are currently suspended, Molycorp has the capability to isolate the individual lanthanides through our beneficiation facilities. This results in high purity, high value products used in a wide variety of applications. We ensure product quality through the use of our state-of-the-art analytical lab.

MOUNTAIN PASS, CA - HISTORY

The discovery of lanthanide (rare earth) mineralization between Clark Mountain, a dominant peak in northeastern San Bernardino County, California and Interstate Highway 15 (formerly US 91 and before that the Arrowhead Trail) occurred in April of 1949. It is noteworthy that a Clark Mining District was organized in 1885, although it was mainly concerned with silver mining. Between 1900 and 1920 many small lead, zinc, copper, gold and tungsten mines were started and some production recorded. The Sulphide Queen gold deposit, adjacent to the Mountain Pass lanthanide ore-body, was discovered in 1936.

In spite of considerable mining exploration in the Clark Mountain area before 1949, the presence of lanthanide metals was not suspected until Herbert Woodward, later a metallurgist for Molycorp, and his partner Clarence Watkins, discovered a heavy, light brown mineral on mining claims they had located nearly a mile north of the Sulphide Queen gold mine. Specimens of the mineral were taken to Boulder City, Nevada, where the Bureau of Mines mineralogist identified them as bastnasite, a fluor-carbonate mineral containing the cerium group of lanthanide metals.

The United States Geological Survey confirmed the bastnasite discovery and made a public announcement in November 1949. Molycorp became interested and bought these claims in February 1950. Meanwhile, the Survey was mapping the entire Mountain Pass area in detail. During the course of this work, an enormous lanthanide deposit was found. Much of this deposit was found on the Sulphide Queen claims which Molycorp subsequently purchased.

All of this prospecting and property acquisition led to the development and utilization of the Mountain Pass ore-body and its present eminence as one of the few deposits of its kind mined solely for lanthanides. It is presently a major supplier of lanthanide products throughout the world.

Many uses of lanthanides were developed after Molycorp demonstrated they would be commercially available for years to come. Now, researchers are developing new and exciting lanthanide-based products to power your car, clean the air, enhance communications, and more.... to bring us tomorrow's technology today.

MOUNTAIN PASS, CA - MINERALOGY

Our Mountain Pass mine is one of those locations on earth where a fortuitous combination of geology and chemistry has brought the lanthanides together in a goodly concentration. Among the inorganic elements, several with similar properties are grouped together and collectively called the "lanthanides". The chemist's periodic table places them in a special position.

The Mountain Pass lanthanide ore deposit contains about 40% calcite, 25% barite, 10% strontianite, 12% bastnasite, 8% silica and minor amounts of other minerals.

Our mineral bastnasite contains seven lanthanides that are either concentrated or recovered at Mountain Pass, although others are present. The distribution of lanthanides is as follows:

ELEMENTS   Lanthanide Oxide Equivalent (LnO)

| ELEMENTS	Lanthanide Oxide Equivalent (LnO)
Cerium (Ce)	49.0%
Lanthanum (La)	33.0%
Neodymium (Nd)	13.0%
Praseodymium (Pr)	4.0%
Samarium (Sm)	0.5%
Gadolinium (Gd)	0.2%
Europium (Eu)	0.1%
Others	0.2%
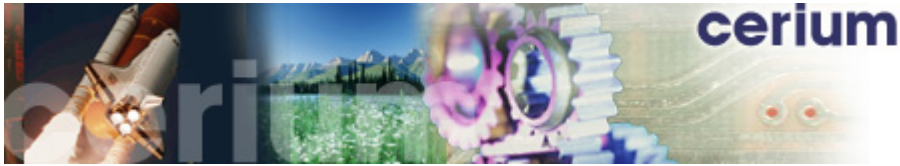
CERIUM

Cerium, the second element in the lanthanide series, is the most abundant and is chemically characterized by having two stable, readily accessible valence states, III and IV.

Cerium is an evironmentally critical component in the manufacture of pollution-control systems for automobiles and oil refineries. TV's and computers rely on cerium to help produce high quality parts. The US Space Shuttle program is dependent on engineering ceramics containing cerium.
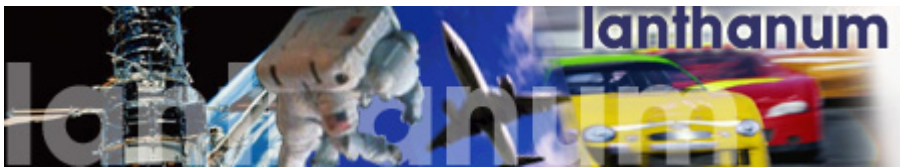
LANTHANUM

The first member of the lanthanide series is recovered from the bastnasite mineral by solvent extraction. Lanthanum is a strategically important lanthanide due to its activity in catalysts needed to create fuel for vehicles and aircraft. This lanthanide also is key to energy providing alloys used everyday in fuel cells and batteries. Electric vehicles may one day consume large quantities of lanthanum for power storage.

NEODYMIUM

Your cell phone, portable CD player, computer, or sound system would not exist in their current form without the use of strong permanent magnets made possible by neodymium. Today, more and more electronics applications realize the benefits of NdFeB permanent magnets that allow for the miniaturization of a variety of technologies.

PRASEODYMIUM

Praseodymium forms about 4% of the lanthanide content of bastnasite. Vibrant yellow ceramic tiles and glasses most likely contain Praseodymium as much of this lanthanides use is in coloring pigments. Certain premium quality mirrors and lenses also depend on Praseodymium.

EUROPIUM

Excitation of the Europium atom, by absorption of electrons or by UV radiation, can result in changes in energy levels that create a visible emission. Almost all practical uses of europium utilize this luminescent behavior. Europium provides the perfect red color in televisions and computer screens around the globe.

OTHER LANTHANIDES

Most of the remaining lanthanides fall into the group known as the "heavies". Dysprosium is a popular heavy that helps to make electronic components smaller and faster. Erbium can be found as an amplifier for fiber optic transmission. Many data storage devices utilize Gadolinium. Alloys containing Samarium are used in high temperature stable permanent magnets that help make many devices smaller and more powerful. Terbium helps give us energy efficient fluorescent lamps.

MINING OPERATIONS

Mountain Pass, California is one of the few places on earth, and currently the only Western resource, where geology and chemistry came together to form an economically mineable lanthanide (rare earth) ore-body.

The Precambrian bastnasite ore deposit is 250 feet thick, has a strike length of 2300 feet, and dips into the ground at a 40 degree angle. Surface mining techniques have been employed since inception of commercial lanthanide operations in 1951. Mining is carried out with 85 ton haul trucks and 13 cubic yard front end loaders. Geological projections, ore-body mapping, blast hole cutting assays, and metallurgical testing provide necessary input to ensure consistent, on-grade ore production. A stripping ratio of approximately 8 tons of waste per ton ore yields an 8.5% ore grade feed to the mill.

Today, approximately 50 years after inception of mining at Mountain Pass, the pit you see measures about 1500 feet in diameter and 500 feet deep.

MILLING OPERATIONS

Ore is hauled to a crushing plant, reduced to less than 3/8 inch in size, and fed to the ball mill where grinding liberates the mineral grains prior to froth flotation. The flotation operation concentrates the bastnasite ore from an initial 8.5% to a 60% Lanthanide Oxide (LnO) product. An enriched 70% LnO product is produced after flotation with a hydrochloric acid leach which dissolves the carbonate gangue. The bastnasite concentrates are thickened, filtered, and dried for shipment or sent to our separations facilities for further recovery operations.

SEPARATION OPERATIONS

Molycorp has the capability of producing lanthanide concentrates as well as high purity products in several forms. The separations facilities are temporarily suspended subject to the resolution of waste water disposal issues.

Bastnasite is selectively leached to separate the insoluble cerium fraction from the other lanthanide elements. The cerium product is washed to remove any contaminants, then filtered and dried prior to packaging according to customer specifications.

The dissolved lanthanides proceed through impurity removal steps, then to solvent extraction cells where a collector preferentially extracts the heavier elements and rejects the lighter fraction. The heavier fraction is separated at our Europium recovery facility where Europium is extracted as a high purity oxide. The lighter fraction may be precipitated, thickened, filtered, dried and packaged as lanthanum concentrate or further purified via solvent extraction to produce high purity lanthanum, praseodymium, or neodymium products.

LABORATORY OPERATIONS

Highly trained and experienced professional analytical chemists staff our ISO 9002 certified, state-of-the-art analytical laboratory. We utilize measurement systems including inductively coupled plasma (ICP) -atomic emission, ICP-mass, fusion disc X-ray fluorescence, and atomic absorption and UV-visible spectrometers.
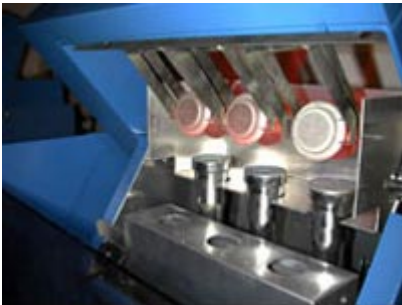
Our chemists perform traditional bench-scale wet chemical analysis for precise lanthanide results as well as particle size and surface area analyses for products requiring specific sizing specifications. Critical customer specifications for individual lanthanides and other elemental constituents are measured, tracked, and reported for in-process and final products ready for shipment. The lab instrumentation detects individual lanthanide elements from major concentrations down to part per million levels in a precise, accurate, and reliable manner.

Our Laboratory Information Management System (LIMS) provides the needed storage capabilities necessary for the thousands of analyses performed monthly. LIMS instantaneous data retrieval feature supports our material tracing ability from the ore through final packaging.

APPLICATIONS BY INDUSTRY

Automotive:

The major use of Lanthanum is in cracking catalysts used
to refine crude oil into gasoline and other fuels.

Cerium is used in pollution control catalysts, which are the active ingredient in catalytic converters in automobiles and other combustible engines.

At the heart of anti-lock brakes (ABS), air bags, and many other systems dependent on electric motors in the modern vehicle, are small powerful permanent magnets based on neodymium.

Dysprosium is an additive for enhancing coercivity in Nd-Fe-B high-strength permanent magnets used in automotive systems.

Samarium cobalt alloys are used in high-temperature-stable permanent magnets that are among the most powerful produced.

As part of an alloy, Praseodymium is used in permanent magnet systems designed to make smaller and lighter motors.

Ceramics:

Praseodymium's color allows production of various pigments used in coloring products such as ceramic tile and glass.

Neodymium compounds help to stabilize electrical properties in ceramic capacitors.

Neodymium oxide has a sky-blue color and is used in the production of various coloring pigments for products such as ceramic tile and artistic glass.

The addition of cerium oxide to zirconia produces a high temperature engineering ceramic having exceptional toughness and good strength. Cerium is also incorporated into Space Shuttle tiles and other shuttle components.

Cerium oxide has a high refractive index and is an opacifying agent in

enamel compositions used as protective coatings on metals.

Defense:

Yttrium and other lanthanides are used as a stabilizer and mold former for exotic light-weight jet engine turbines and other parts.

Yttrium helps stabilize materials used in rocket nose cones.

Yttrium as well as many other lanthanides can be formed into laser crystals specific to spectral characteristics for military communications.

Electronics/Computers:

Computers contain cerium polished disk drives and silicon micro-processors as well as cerium treated glass in the monitor screens.

Neodymium is a key component of permanent magnets used in a large variety of motors and mechanical systems such as cell phones, portable CD players, and computers. The magnets are of the form Nd-Fe-B which maximizes the power/cost ratio.

Neodymium oxide can be added to CRT glass to enhance picture brightness by absorbing yellow light waves. Neodymium has a strong absorption band centered at 580-nm wavelength, which helps clarify the human eye's discrimination between reds and greens.

Cellular phones contain both neodymium magnets and capacitors, which produce powerful electronic generation to boost the power for these communication devices.

Yttrium Iron Garnets (YIG) are used as resonators for use in frequency

meters, magnetic field measurement devices, tunable transistors, and Gunn oscillators.

Yttrium containing garnets are used in cellular communications devices by industries such as defense, satellites, and phones.

Yttrium-Europium phosphors produce the red color in televisions and computer screens.

Dysprosium oxide is an additive in special ceramic compositions for producing high-capacitance, small-size capacitors for electronic applications.

Its unique magnetic behavior allows Gadolinium to be used in alloys that form the heart of magneto-optic recording technology used for handling computer data.

Terbium metal alloys help to provide suitable metallic films for magneto-optic recording of data.

Since Erbium fortuitously lases efficiently at 1.55 microns, it can be used as an amplifier for fiber-optic data transmission.

Samarium offers spectral absorption bands around 950 and 1100 nm that make it useful in filter glasses that surround neodymium laser rods to increase operating efficiency.

Environment:

One of the crucial chemical components in catalytic converters is cerium oxide or other cerium compounds. Other cerium-based pollution control catalysts help to significantly reduce the sulfur oxide emissions from oil refineries.

Cerium is used as a diesel fuel additive for micro-filtration of pollutants and will also promote more complete fuel combustion thus reducing un-combusted smoky particulate and provide for a more energy efficient engine.

Cerium is also used as a recycled oxidant for performing low temperature, energy efficient waste treatment on many pollutants.

The most active petroleum cracking catalysts that help create fuel needed to run our vehicles rely on lanthanum-rich material. These catalysts represent the major use of lanthanum and are responsible for eliminating leaded gasoline from our environment. The use of these lanthanide fluidized cracking catalysts also promotes very energy efficient petroleum cracking.

Should electric vehicles become a staple in the future they will most likely use lanthanum-rich, energy efficient battery materials for power generation.

Praseodymium is also used in automobile and other internal combustion engine pollution control catalysts.

Every car contains oxygen sensors composed of yttrium based ceramic materials. The sensors provide for the most efficient use of fuel and eliminates excess pollution from burnt fuels.

Glass:

Bastnasite can be used in television and other glasses to provide ultraviolet shielding and de-coloring.

Cerium oxide slurried in water is the active ingredient in polishing compounds for glass, television faceplates, mirrors, optical glass, silicon microprocessors, and disk drives.

Cerium is also used to de-colorize glass for applications such as containers or tableware. The glass is initially colored by the metal contaminates present in the raw materials used to produce glass. Cerium oxide is strong enough to oxidize these metals to different states thereby eliminating the unwanted color.

TV glass contains cerium to shield us from harmful UV radiation emitted within the tube. The fact that the TV screen has remained clear after prolonged use is also because of cerium.

Modern, anti-glare automobile light glass and mirrors utilize neodymium.

Along with neodymium, praseodymium is used to filter certain wavelengths of light. It can be used in welder's glasses, for example; Praseodymium is used in photographic filters and airport signal lenses.

Erbium's stability means that glass formulations using it will be colored pink. It is the only pink truly stable in glass melts and is used in sunglasses and decorative crystal glassware.

Medical:

Lanthanum phosphors are used in X-ray films and certain lasers to help reduce the dose of radiation to patients up to 75%.
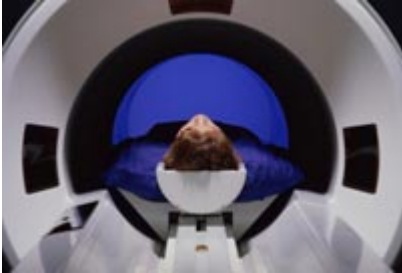
MRI, CAT, and sonogram imaging presentation techniques depend on lanthanum or other lanthanide products.

Highly sensitive luminescence provided by europium attached as a tag to complex biochemicals assist in live tracing of these materials during living tissue research.

The magnetic wave generation on which the non-ionic radiation MRI (magnetic resonance imaging procedure) is based is solely dependent on the Neodymium magnet.

The Neodymium Light laser is the instrument of choice for non-evasive surgical procedures because of the easily seen high intensity blue focal point light.

Lasers based on Erbium have been introduced for medical and dental uses because they are suited to energy delivery without thermal build-up in human tissue.

Magnetic resonance imaging (MRI) systems use materials containing gadolinium to enhance the resulting images.

Optics/Lighting:

Lanthanum provides optical lens designers more flexibility than ever before because lanthanum is the key to modifying glass crystal structure and the refractive index.

Advances in the quality of high-tech digital cameras, video cameras, and many other sensitive optical applications would not be possible without lanthanum or other lanthanides.

Lanthanum or other lanthanides are key to disseminators, capacitors, and light splitters for transmission and conversion of electrical energy to light energy used in fiber optic systems and cellular phones.

Excitation of the Europium atom creates an emission of visible radiation which provides the perfect red phosphors used in color televisions and computer screens around the world. Europium could also be over your head in the shape of energy efficient fluorescent lighting-which cuts energy use by 75% compared to incandescent lighting.

Praseodymium is used in premium quality optical products such as mirrors and lenses.

Certain cerium compounds are used in thin surface coatings applied to optical components to improve performance. The compounds have a refractive index suitable for building up the multiple layers deposited on lenses, sensors, mirrors, etc.

Cerium is used in the core of carbon electrodes for carbon arc lighting. This brilliant light is used in motion picture projection, spotlights, and in the graphic arts industry for photoengraving.

Other Uses:

Yttrium provides strength and hardness when used in silicon nitride grinding media. Yttrium stabilized cubic zirconia produces simulated diamonds.

Cerium improves the physical properties of high-strength, low-alloy steels due to its affinity to scavenge oxygen and sulfur. Cerium is added primarily to provide sulfide shape control.

Chromium plating quality is improved with the addition of cerium fluoride to the electroplating bath. The solubility of the cerous fluoride is virtually independent of the temperature of the plating solution thereby stabilizing the active chromium intermediate necessary for quality plating. Cerium is also used in the reduction and co-precipitation removal of waste chromium generated during the plating process.

Mischmetal (lanthanide-iron-silicon) is produced by arc furnace reduction of the lanthanide fluoro-carbonate to a metal form. Mischmetal is used to make alloys for many uses including steel, batteries, and magnets.

Section 5 Searchlight District and the Colorado River Extensional Corridor

Stephen Ludington, US Geological Survey, Menlo Park

The Searchlight district, in Clark County, Nevada, is a distinctive epithermal(?) volcanic-hosted vein deposit that produced about a quarter-million ounces of gold during 1902-1954 and an unknown amount since that time.

The deposits consist of a series of originally-vertical veins from 0-2 km above the roof of the ca. 16.4 Ma-old Searchlight pluton. The veins are hosted in dacite and rhyolite flows that range in age from 18.5 to 16 Ma. At about 16 Ma, the entire area was affected by east-west extension that resulted in all the strata in the Searchlight area tilting to the west at 70 to 90 degrees, thus exposing the pluton, the volcanic section, and the veins of the mining district in cross-section.

The Searchlight pluton is exposed over a 10-km thick section and is stratified, consisting of 6 km of mafic quartz monzonite at the bottom, 2 km of granite in the center, and about 2 km of fine-grained quartz monzonite at the top. Isotopic data suggests the mildly-alkaline magmas to be hybrid with about 40 percent crustal and 60 percent crustal component.

The veins consist essentially of brecciated country rock, with minor amounts of quartz and calcite filling. The material appears to be mostly oxidized, and sulfides are only rarely found (down to the 1100 level in one mine!). Good ore was almost always associated with copper contents of a percent or more, as chrysocolla, cuprite, or rarely, chalcocite. Lead and zinc grades of more than a percent were also not uncommon. The primary alteration minerals are adularia

(reported, not observed) and hematite. Silicification is also present near the veins. Pyrite is almost unknown in the entire district.

We will visit distal exposures of the veins (above the exploited part), a cut in one of the most productive mines, and a quick look at the Searchlight pluton. An optional stop, for those that can stay longer, will look at the structurally similar, but chemically distinct, Spirit Mountain pluton to the south.

FIELD TRIP STOPS OCTOBER 10, 2004

Leave Nipton traveling to the east and enter Nevada. Begin Nevada Route 164.

We will first drive up a long grade in Big Tiger Wash, passing by the old town site of Crescent on the right, and several historic precious-metal mines as we pass through the southern end of the McCullough Range. At the top of the hill, to our left, the Joshua Tree forest is now protected by the Wee Thump Joshua Tree Wilderness. From here, it is a straight run ahead to the Searchlight area.

About 2 miles short of Searchlight, we will leave Nevada Highway 164, turning north (left) past a stock tank, and drive as far as possible (about a half mile) toward the 2 orange-tinged hills.

STOP 1

Upper (distal) part of Searchlight district alteration/mineralization halo.

We will hike a few hundred meters up to the saddle between the two hills in order to examine this altered rhyolite of the volcanics of the Highland Range.

We return to the highway, turning left and proceed to Searchlight, where we turn south (right) on U.S. 93. Proceed past Terrible's Truck Stop (on left), over the crest of the hill, to the first available right turn (about 400 m past Terrible's). This road leads to the Quartette Mine.

STOP 2

Quartette Mine open cut

We walk a short distance to the site of the Quartette mine, which was the largest producer in the Searchlight district. An open cut above the main structure, apparently excavated in the last decade, provides good exposures of the mineralized rock. We will see that alteration is minimal, and gangue and sulfide minerals are rare. The oxide-

dominated mineral assemblage exposed here persisted to the bottom of the mine, at the 1100 level, over 900 feet beneath the surface.

Return to the highway, and turn north (left). Be careful of traffic! Return *back* through Searchlight to a turnoff (right) about 2.5 miles beyond the intersection with Highway 164 and the Cottonwood Cove road. We will follow this road (labeled 'Oregon Trail') about one mile (right turn at 3/4 mi) to Stop 3.
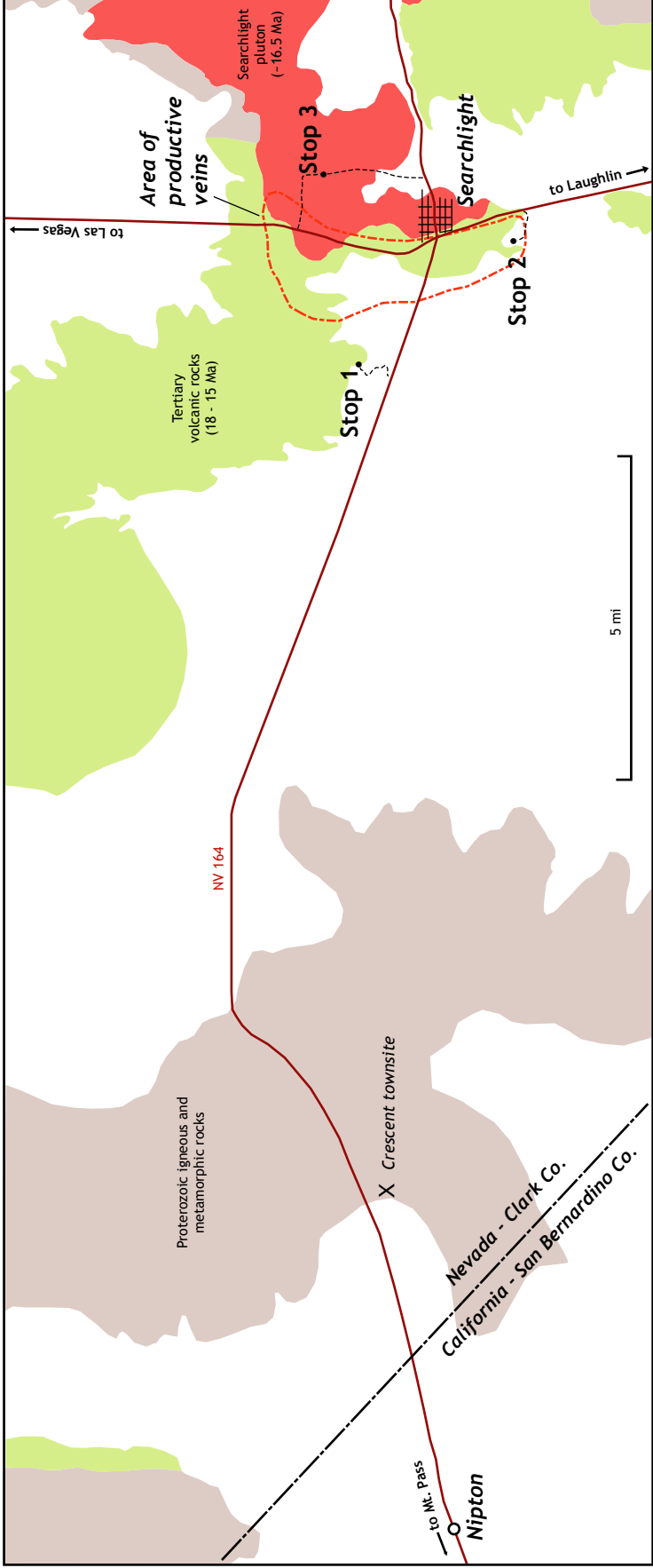
STOP 3

Upper fine-grained porphyritic phase of the Searchlight pluton

Here we can see the typical texture and mineralogy of the upper phase of the Searchlight pluton.

END of formal part of trip. For those who have more time, we can make several stops between here and Laughlin to examine a different granite, the intriguing Spirit Mountain pluton.
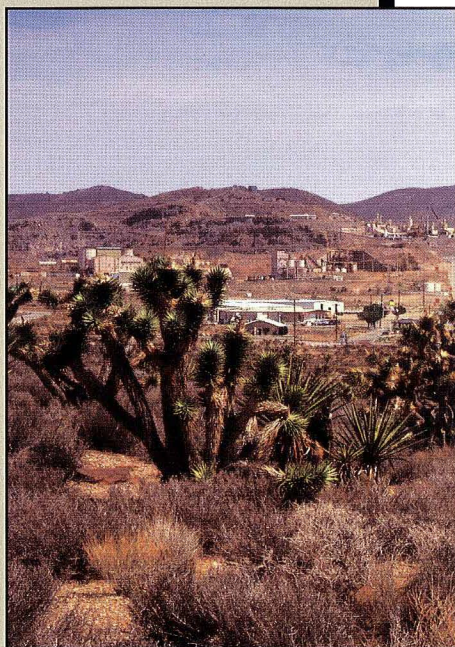
Sketch map of route from Nipton to Searchlight, showing generalized bedrock, area of productive veins in the Searchlight district, and field trip stops.

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The
Lanthanides
& Molycorp

MOLYCORP, INC.

The Lanthanides & Molycorp

What are they?
*What do they do?*
What does Molycorp do?

Molycorp produces Lanthanides at its Mountain Pass mine, one of the world's premier sources for these materials and the only commercial deposit in the United States.

- We give color to your television.
- Your vehicle runs with our aid.
- We are essential for your computer.
- The air is cleaner because of us.
- We make possible innovative medical diagnostics.
- We speed your phone calls.
- And?

The Lanthanides play hidden, but absolutely essential, roles in many modern technologies.

Without them, life would be duller, slower, more expensive and less healthy.
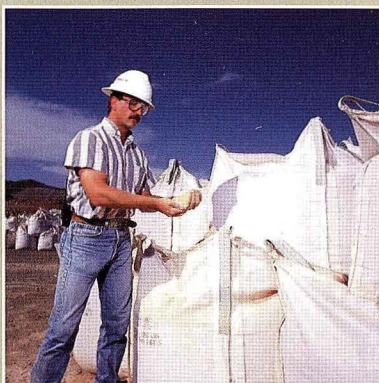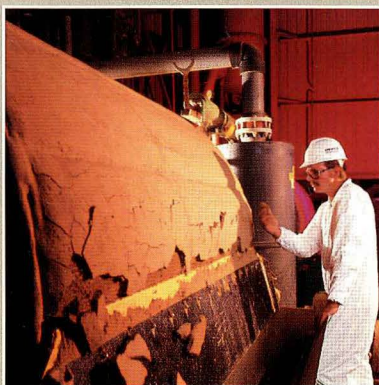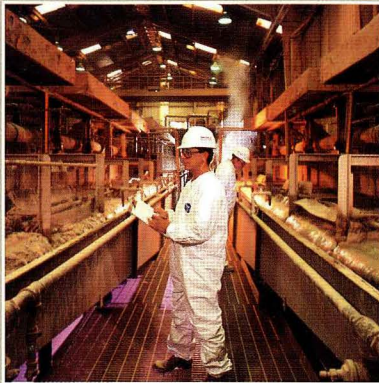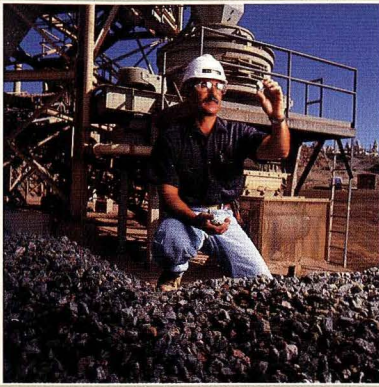
Lanthanides

Among the inorganic elements, several — with similar properties — are grouped together and collectively called the "Lanthanides" or "Rare Earths." The chemist's Periodic Table places these in a special position.

These 15 elements have unusual names, many difficult to pronounce — try "Praseodymium" or "Neodymium" — but they are not truly that rare as they can be found scattered throughout the earth's crust. It is just that they seldom occur in concentrations sufficient to make economic recovery practical — and until 40 or so years ago they did have limited availability.

Mountain Pass

Our Mountain Pass, California, mine is one of those few locations on the earth where a fortuitous combination of geology and chemistry has brought the Lanthanides together in a goodly concentration.

The development of our mine has — in those 40 years — provided several of those elements in quantities that made possible many advances in the technologies upon which modern life depends.

Future technologies, many still unknown to us, will continue no doubt to be aided by the materials produced at our site.
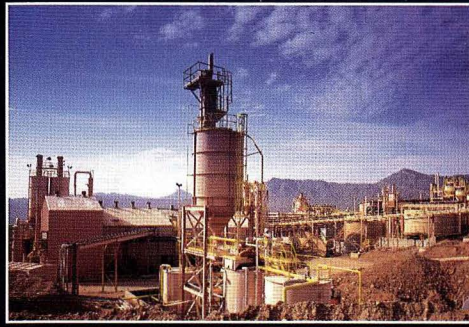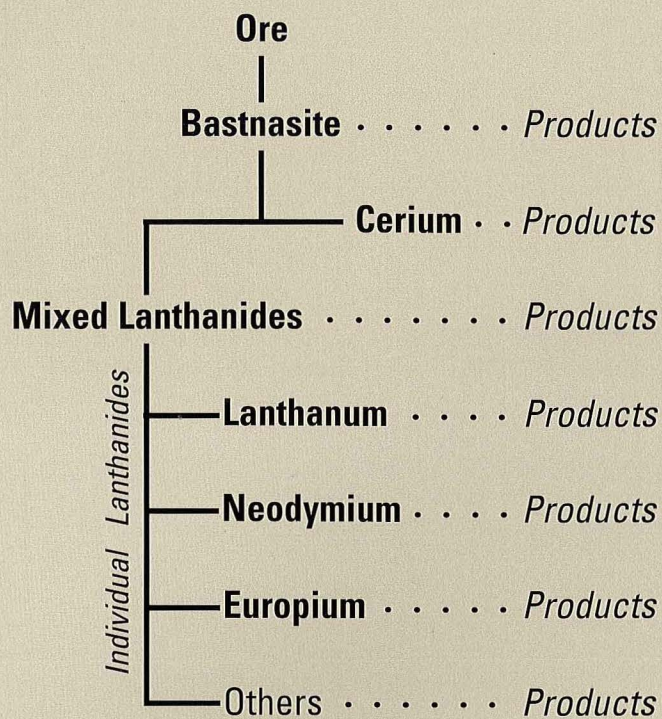
Benefits

• A blend of three phosphors – all based on Lanthanides – with red, blue and green emissions, has significantly improved fluorescent lighting technology over the past decade.

• The introduction of zeolite cracking catalysts revolutionized the petroleum refining industry. For the highest gasoline yields, the zeolite contains Rare Earths.

• Cerium oxide is the essential oxygen storage component in the three way catalytic converter that reduces automobile emissions.

• Energy transfer mediated by Praseodymium in optical fibers will make possible tomorrow's information networks.

• Gadolinium complexes, as injectable pharmaceuticals, enhance the differentiation between normal and abnormal tissue in MRI (magnetic resonance imaging).

• The vital red for color TV and CRT's is created by a phosphor containing Europium.

• "Neo" permanent magnets, relying on iron-Neodymium-boron alloys, are at the heart of highly efficent motors and much related technology.

• And many more.

```
Ore
 |
Bastnasite · · · · · · Products
 |
 |——— Cerium · · Products
 |
Mixed Lanthanides · · · · · · · Products
 |
 |——— Lanthanum · · · · Products
 |
 |——— Neodymium · · · · Products
 |
 |——— Europium · · · · · Products
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 |——— Others · · · · · · Products
```

Individual Lanthanides

Production Flow

At the Mountain Pass plant, Molycorp mines ore containing the mineral Bastnasite and then concentrates, separates and prepares a wide range of Lanthanide compounds. Bastnasite contains predominantly the light Lanthanides, that is the elements at the start of the Lanthanide group - in particular Cerium, Lanthanum and Neodymium.
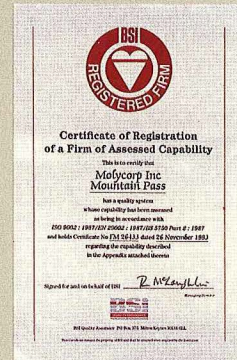
Today's Technologies

- Gasoline production catalysts
- Emission control devices
- TV and computer monitor color phosphors
- Computer hard-disk drive motor magnets
- Energy efficient fluorescent lighting
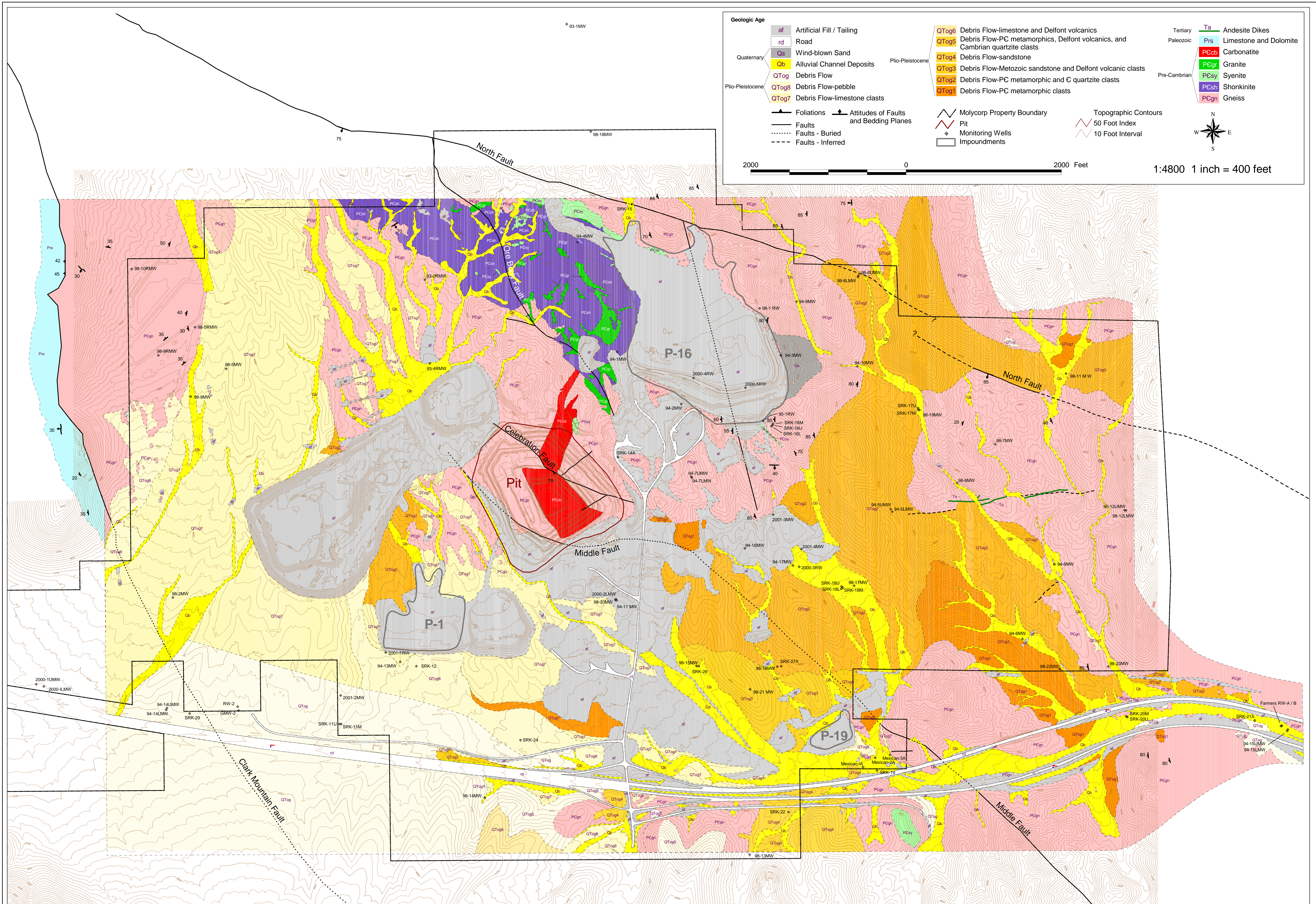
Tomorrow's Technologies

- Hydride batteries for electric vehicles
- Magnets for motors for those vehicles
- Power generation by zero-emission fuel cells
- Selective biochemical sensors for medicine
- Hair-thin fibre-optic cables for worldwide communications

CALIFORNIA
MINING ASSOCIATION

MOLYCORP INC.
MOUNTAIN PASS MINE

has been awarded this certificate
in recognition of outstanding service

SAFETY AWARD FOR LARGE OPERATION

Carolyn V. Clark
President

Denise M. Jones
Executive Director

BSI
REGISTERED FIRM

Certificate of Registration
of a Firm of Assessed Capability

This is to certify that
Molycorp Inc
Mountain Pass

For further information about Molycorp, about the
Lanthanides and their applications,
please contact us at:

Molycorp, Inc.

Customer Service
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Mountain Pass, California 92366
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(760) 856-2201
www.molycorp.com

Figure 3.6-2. Geologic setting for Mountain Pass Mine site.