Geologic and Environmental Characteristics of Rare Earth Element Deposit Types Found in the United States

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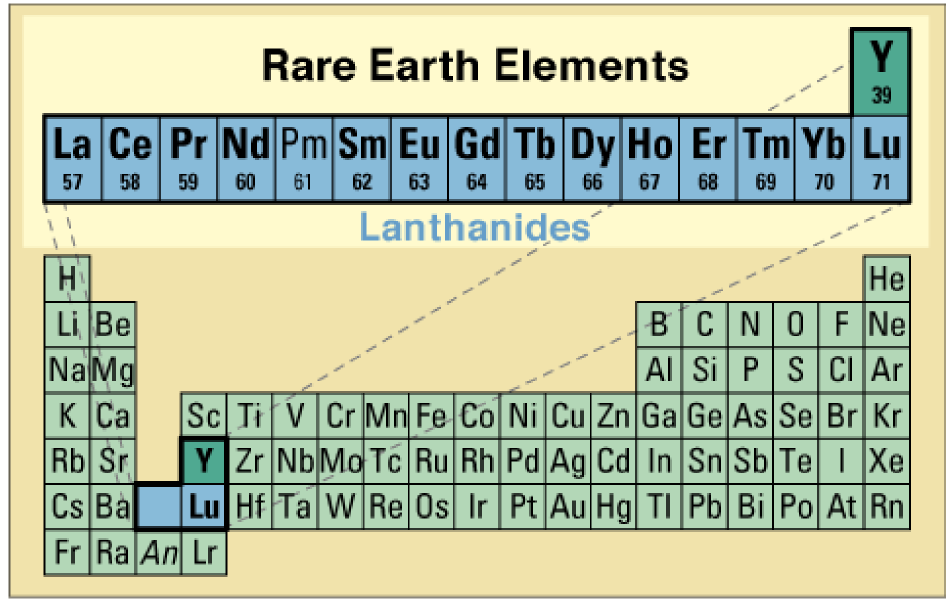
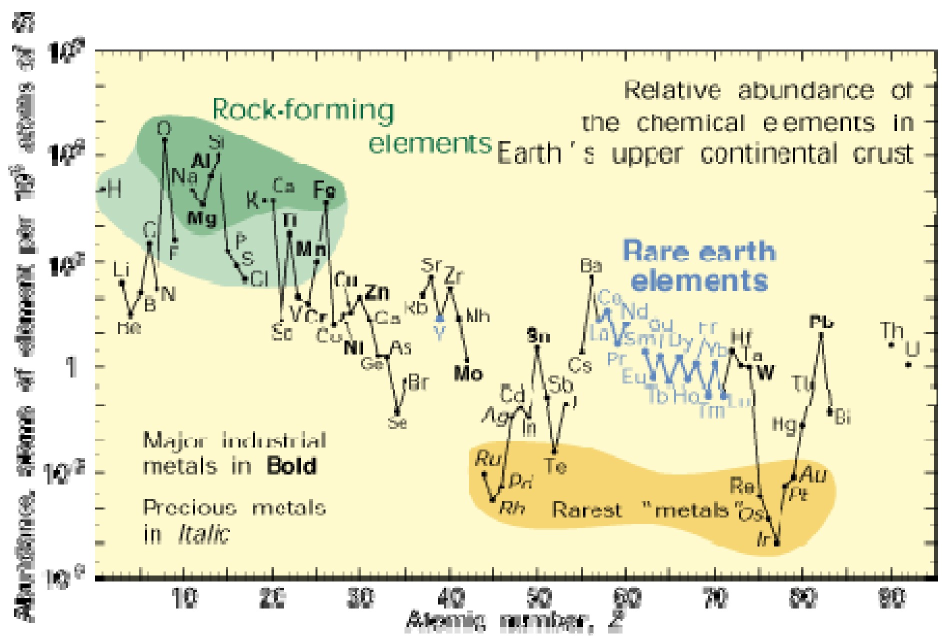
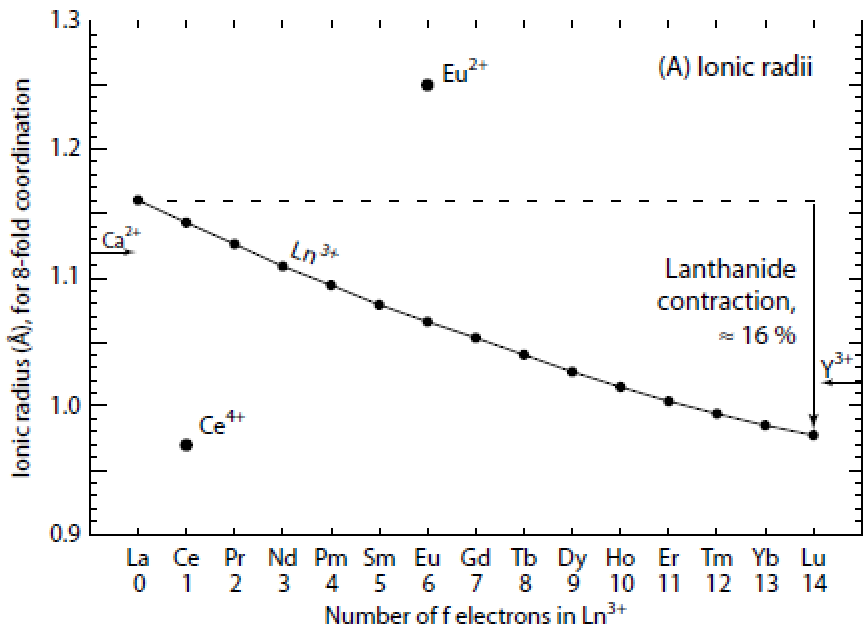
Rare Earth Elements

- Less abundant than common rock-forming elements
- More abundant than precious metals
- More or less abundant than base metals and metalloids.





Geochemical Controls in Nature

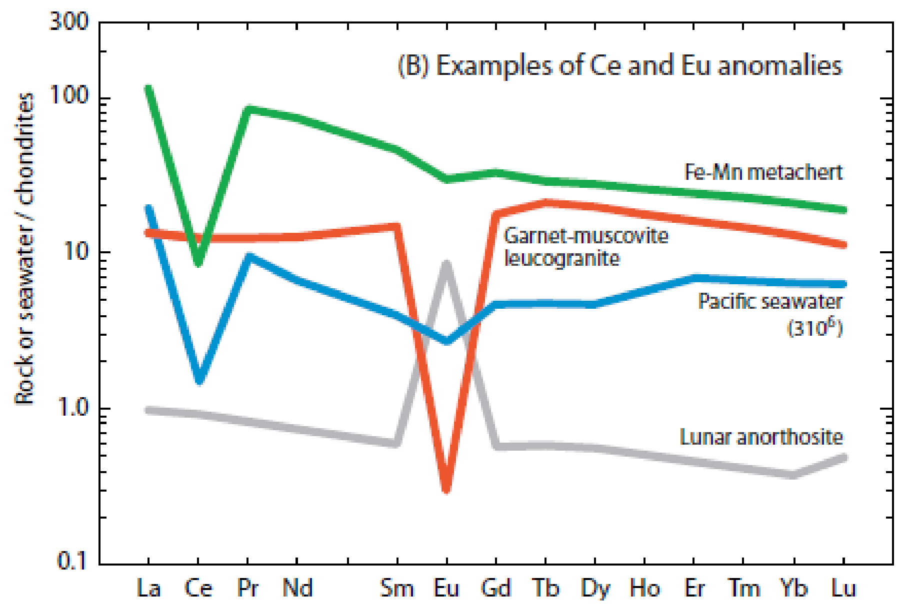


Lanthanide Contraction

- Ionic radius decreases with increasing number

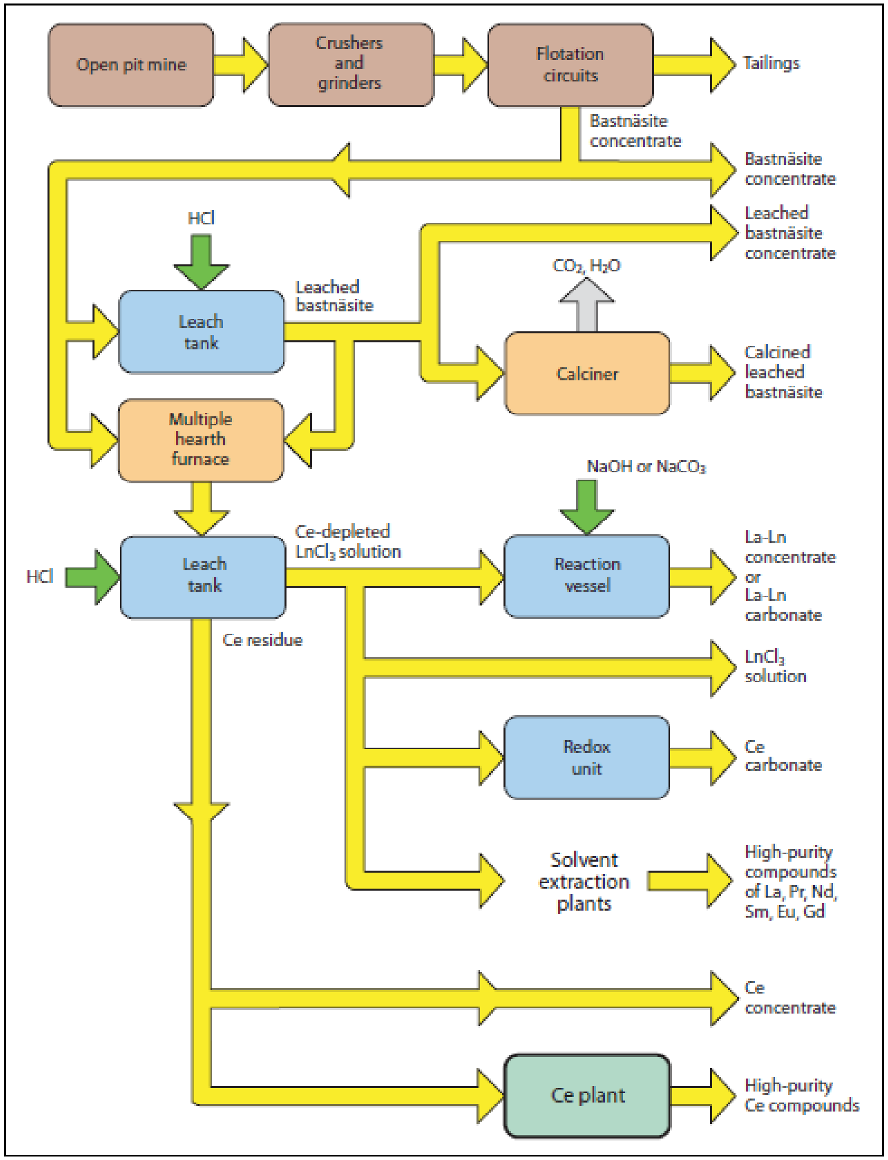
Oxidation State

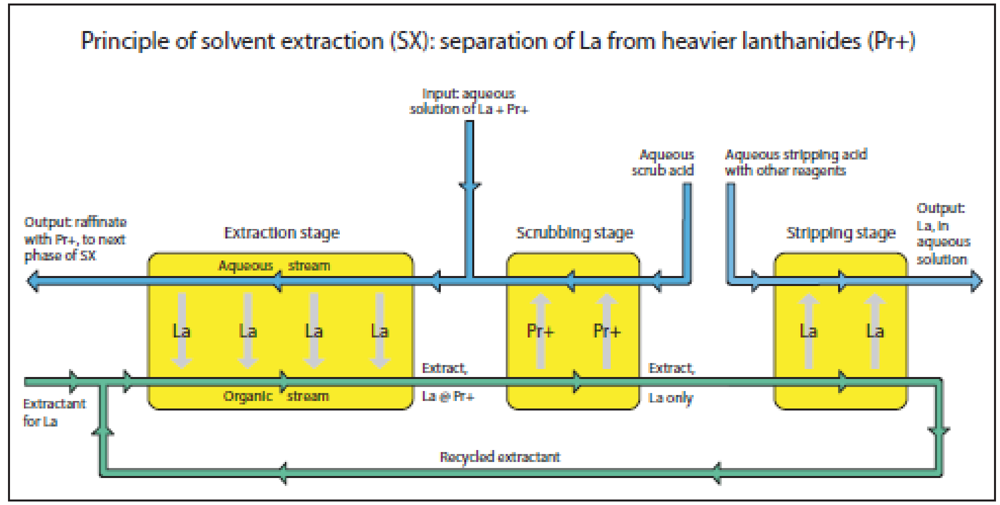
- All REEs occur in 3+ state
- Eu also occurs in 2+ state
  - Substitutes for 2+ cations like Ca^{2+}
- Ce also occurs in 4+ state
  - Even more insoluble



From: Haxel (2005)

Rare Earth Element Ore Processing





Recovery of individual REEs is complicated by:

- Similar geochemical behavior of REEs as a group
- Wide variety of REE host minerals

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From: Haxel (2005)

Primary and Byproduct REE Deposit Types

- Carbonatites
  - **Bayan Obo, China**
  - Mountain Pass, CA
- Alkaline Intrusion-Related Deposits
  - Bokan Mountain, AK
  - Thor Lake (Nechalacho), NWT, Canada
- Magmatic Magnetite-Hematite bodies
  - Pea Ridge Mine, Missouri
  - Olympic Dam, Australia?
  - Kiruna, Sweden?

Potential Byproduct REE Sources

- Monazite-bearing Placer Deposits
  - Central Idaho stream placers
  - North and South Carolina stream placers
  - Virginia, Georgia, and Florida beach deposits

- Phosphorite Deposits
  - Florida, North Carolina
  - Phosphoria Formation, ID, MT

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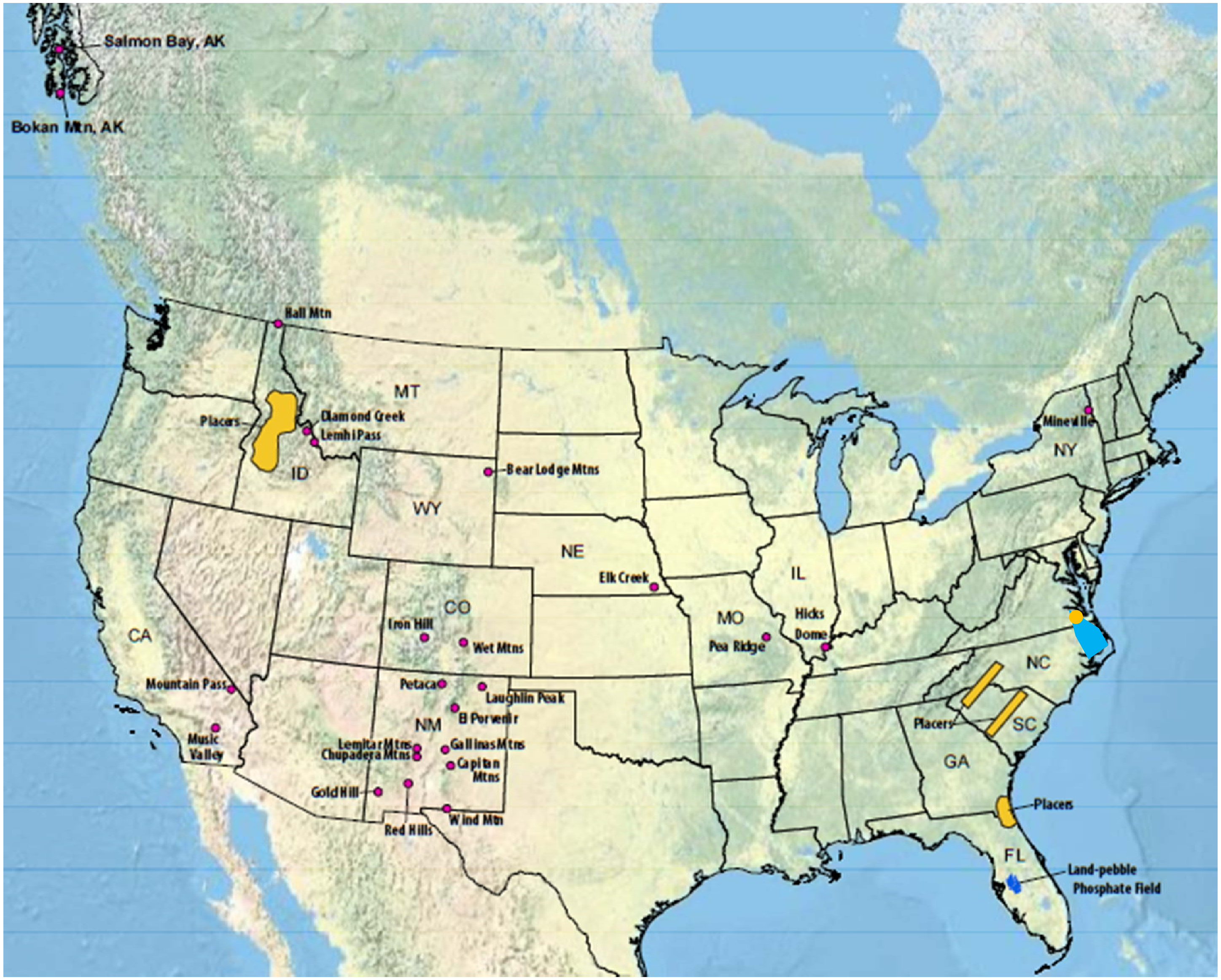
Rare Earth Element Deposits of the United States



Rare Earth Element Minerals & Deposit Types

Group-Mineral	Formula	Carbonatite	Alkaline Intrusion-Related	Placer	Phosphorite
Oxides					
Aeschynite	$(Ln,Ca,Fe)(Ti,Nb)_2(O,OH)_6$		X		
Euxenite	$(Y,Ln,Ca)(Nb,Ta,Ti)_2(O,OH)_6$		X	X	
Fergusonite	$YNbO_4$		X		
Carbonates					
Bastnäsite	$(Ln,Y)CO_3F$	X	X		
Parisite	$Ca(Ln)_2(CO_3)_3F_2$	X	X		
Synchisite	$Ca(Ln,Y)(CO_3)_2F$	X	X		
Tengerite	$Y_2(CO_3)_3 \bullet n(H_2O)$		X		
Phosphates					
Apatite	$(Ca,Ln)_5(PO_4)_3(OH,F,Cl)$	X	X		X
Monazite	$(Ln,Th)PO_4$	X	X	X	
Xenotime	YPO_4		X	X	
Silicates					
Allanite	$(Ln,Y,Ca)_2(Al,Fe^{3+})_2(SiO_4)_3(OH)$		X		
Eudialyte	$Na_4(Ca,Ce)_2(Fe^{2+},Mn^{2+},Y)ZrSi_8O_{22}(OH,Cl)_2$		X		
Thalenite	$Y_2Si_2O_7$		X		
Zircon	$(Zr,Ln)SiO_4$		X	X	

Ln: Lanthanide (a.k.a. REE)

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Carbonatite Deposits

Carbonatite Deposits

- Carbonatite – an igneous rock with greater than 50 % carbonate minerals (calcite, dolomite, ankerite)
- Less than 550 carbonatites known in world.
- Commonly associated with alkaline or peralkaline igneous rocks.
- The REE are “incompatible elements”, such as Th, Nb, and Zr, that do not tend to participate in the earlier mineral-forming events.
- Important sources of Nb, Ta, and REEs.

Bastnäsite
(REE)CO_3F

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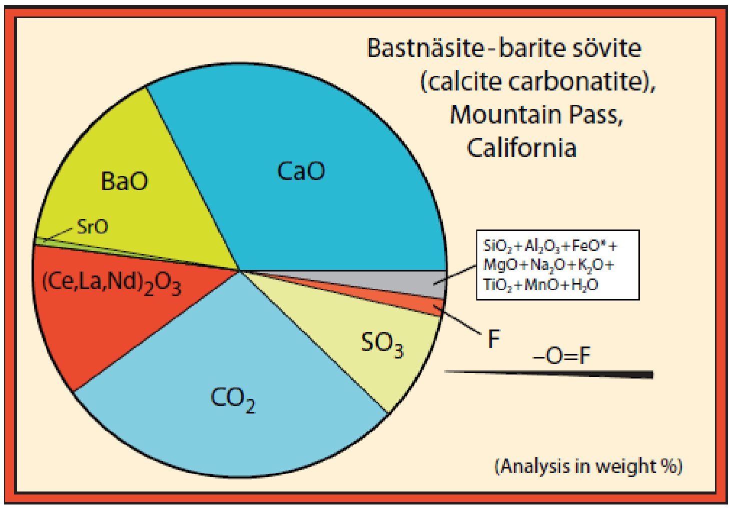
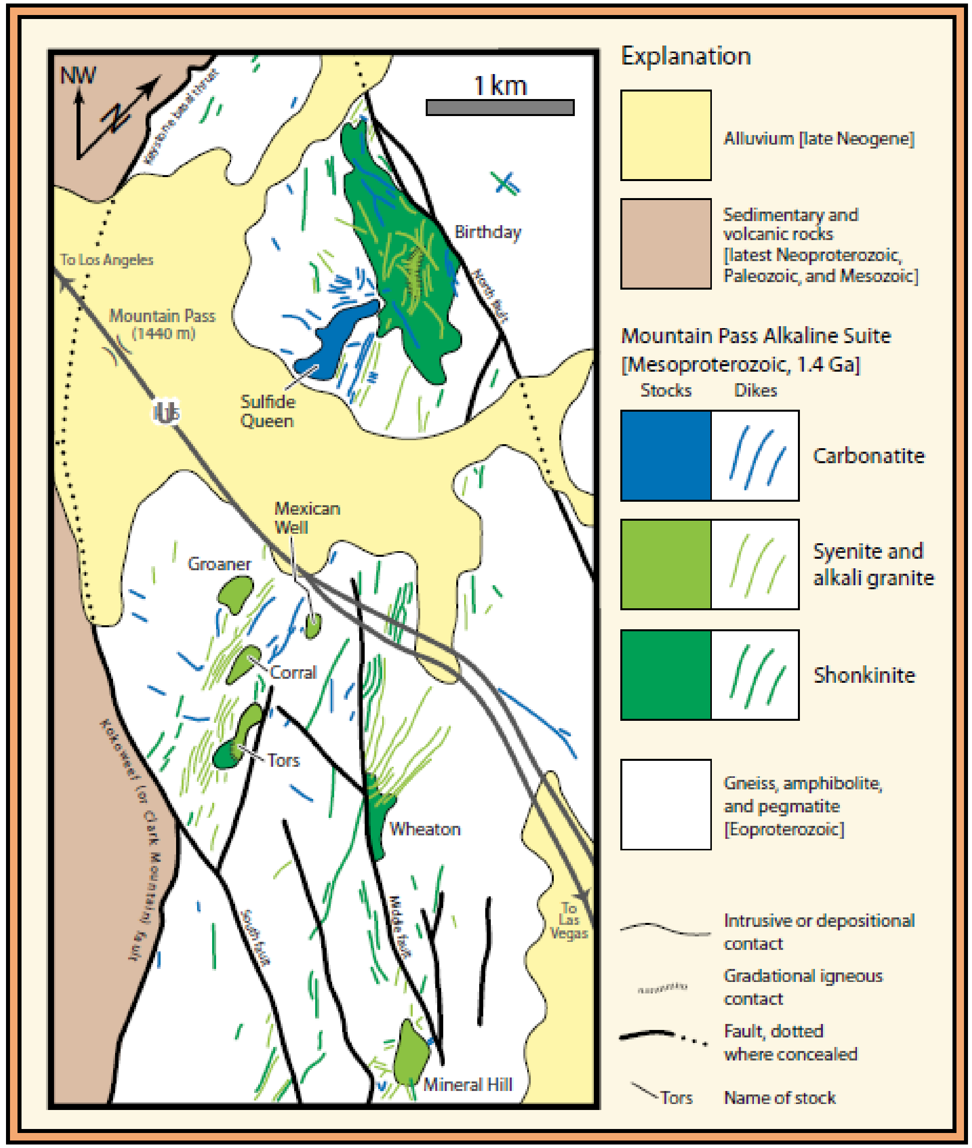
Mountain Pass, California

- Located in Mojave Desert
- Discovered in 1949 by uranium prospector.
- 1.4 Ga carbonatite complex
- Stopped mining in 2002
- Reopened 2010





From: Haxel (2005)

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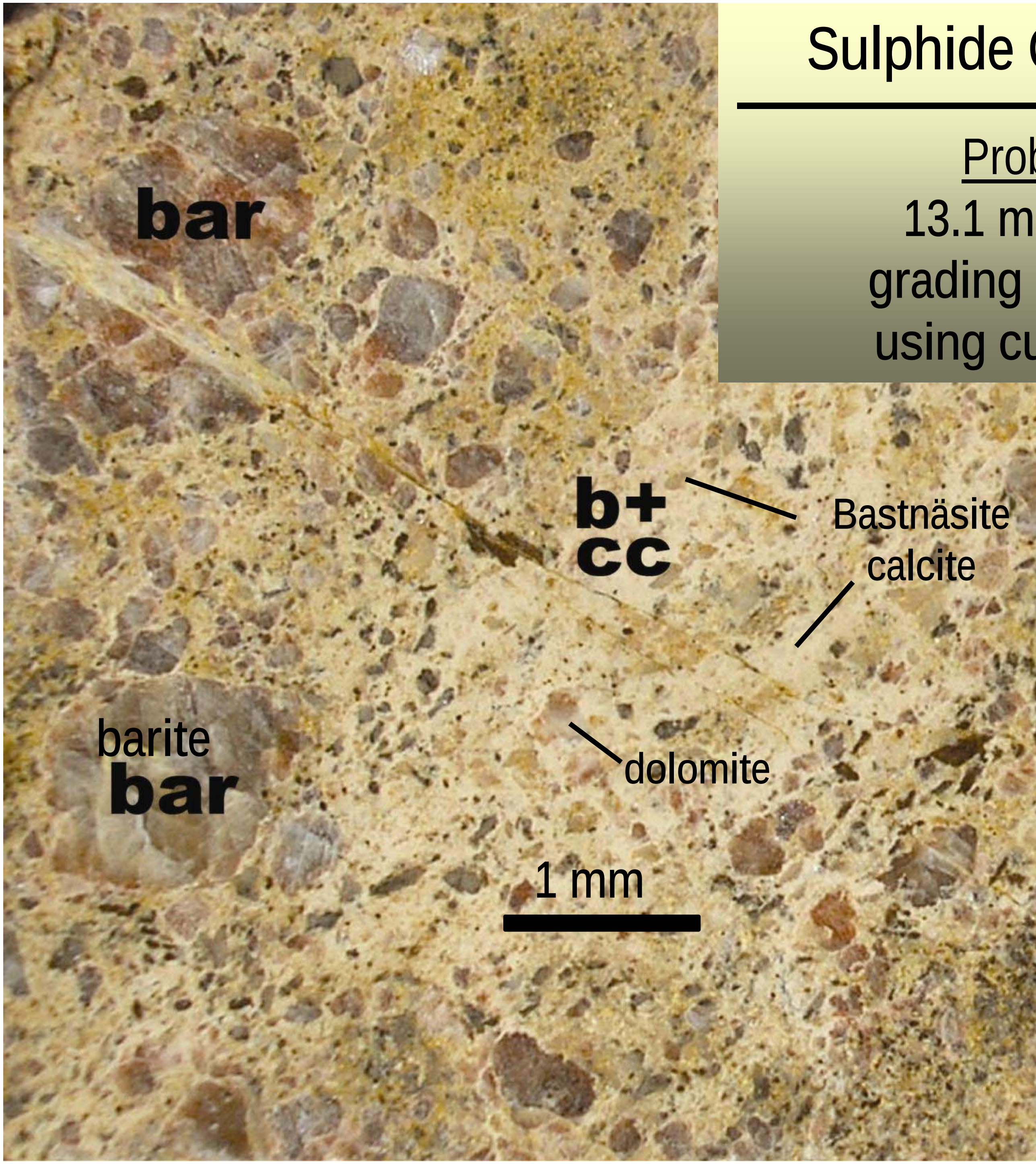
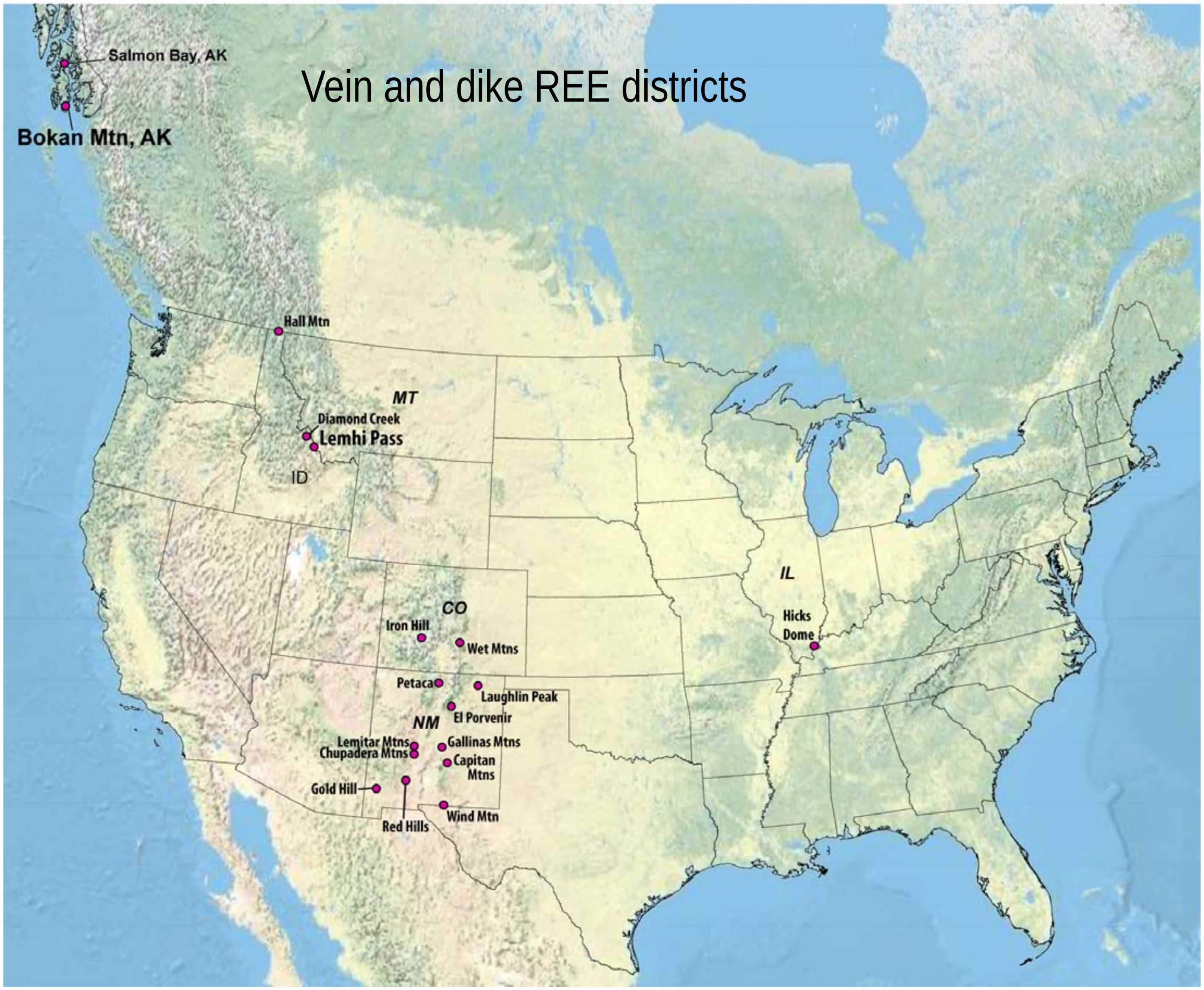
Sulphide Queen carbonatite

Probable reserves
13.1 million tons of ore
grading 8.2 % REE oxides,
using cut-off grade of 5 %



Bastnäsite
(REE)CO_3F

Alkaline Intrusion-Related Deposits

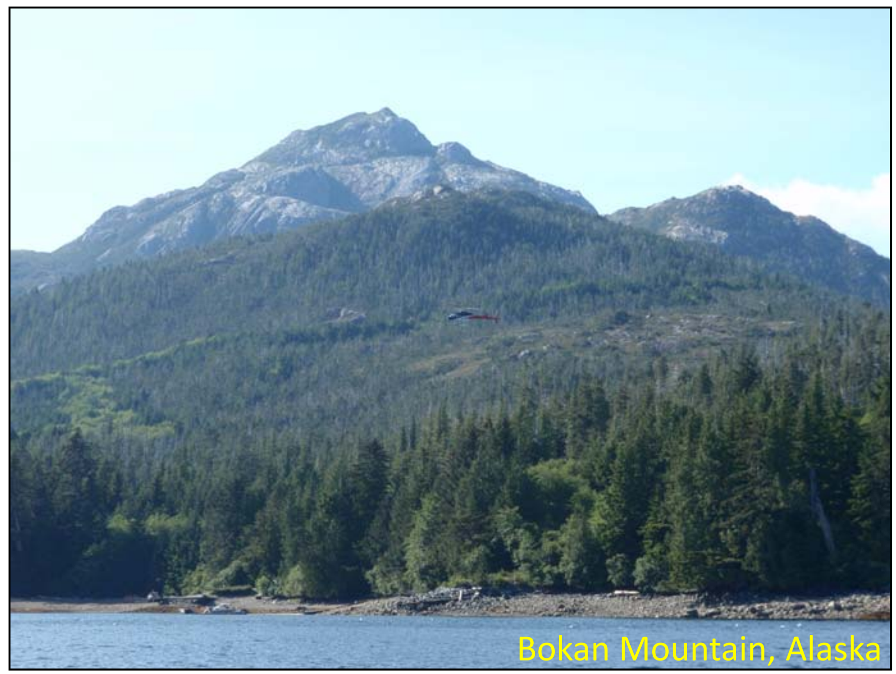


Alkaline Intrusion-Related Deposits

- Associated with alkaline or peralkaline igneous complexes

  Peralkaline: $Na_2O + K_2O > Al_2O_3$

- Structural control on the veins, dikes & breccias
- In zoned alkaline intrusive complexes, REE veins, dikes, and breccia bodies are late phases.
- The REE are "incompatible elements", such as Th, Nb, and Zr, that do not tend to participate in the earlier mineral-forming events.



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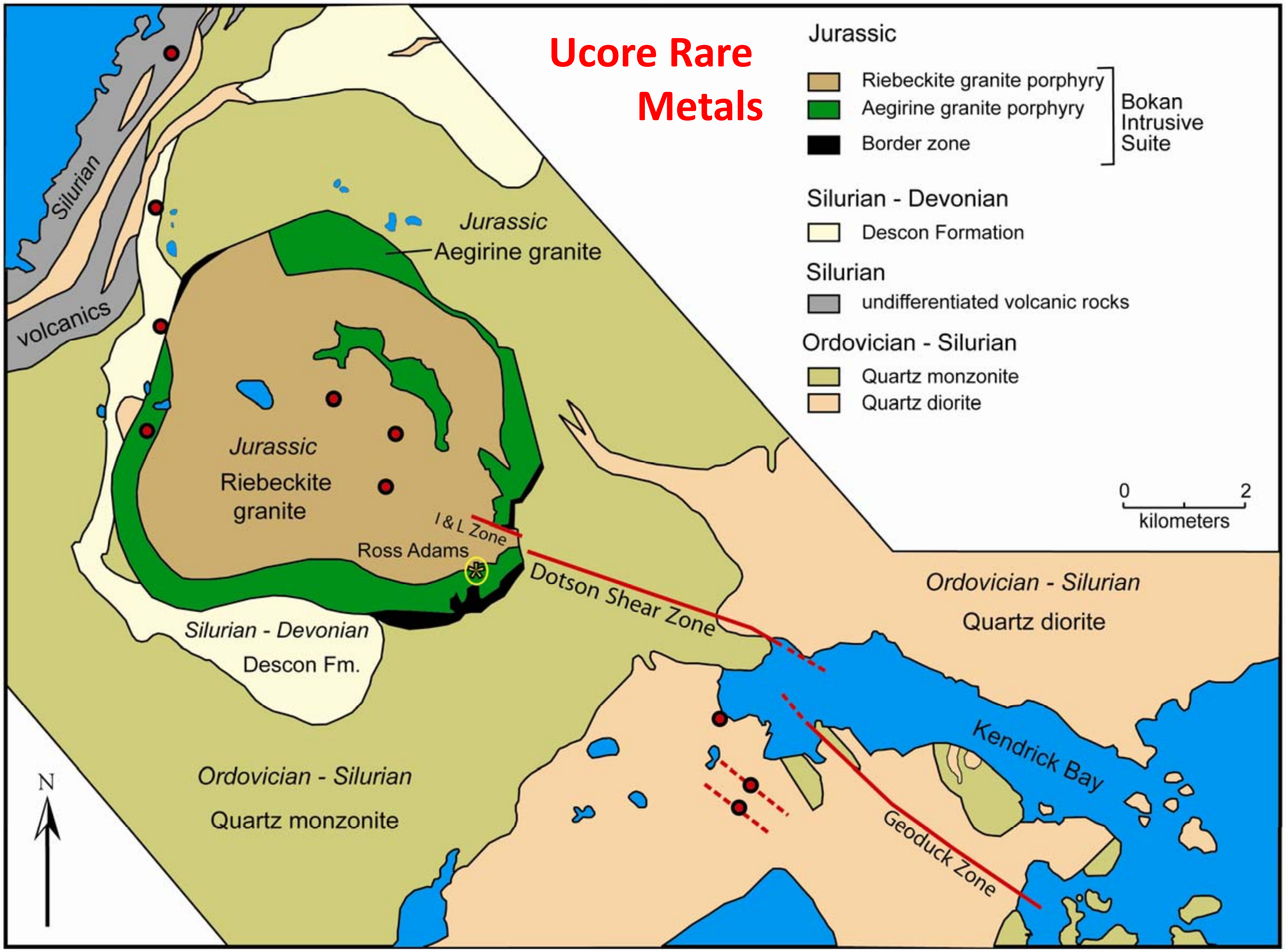
Bokan Mountain, Alaska



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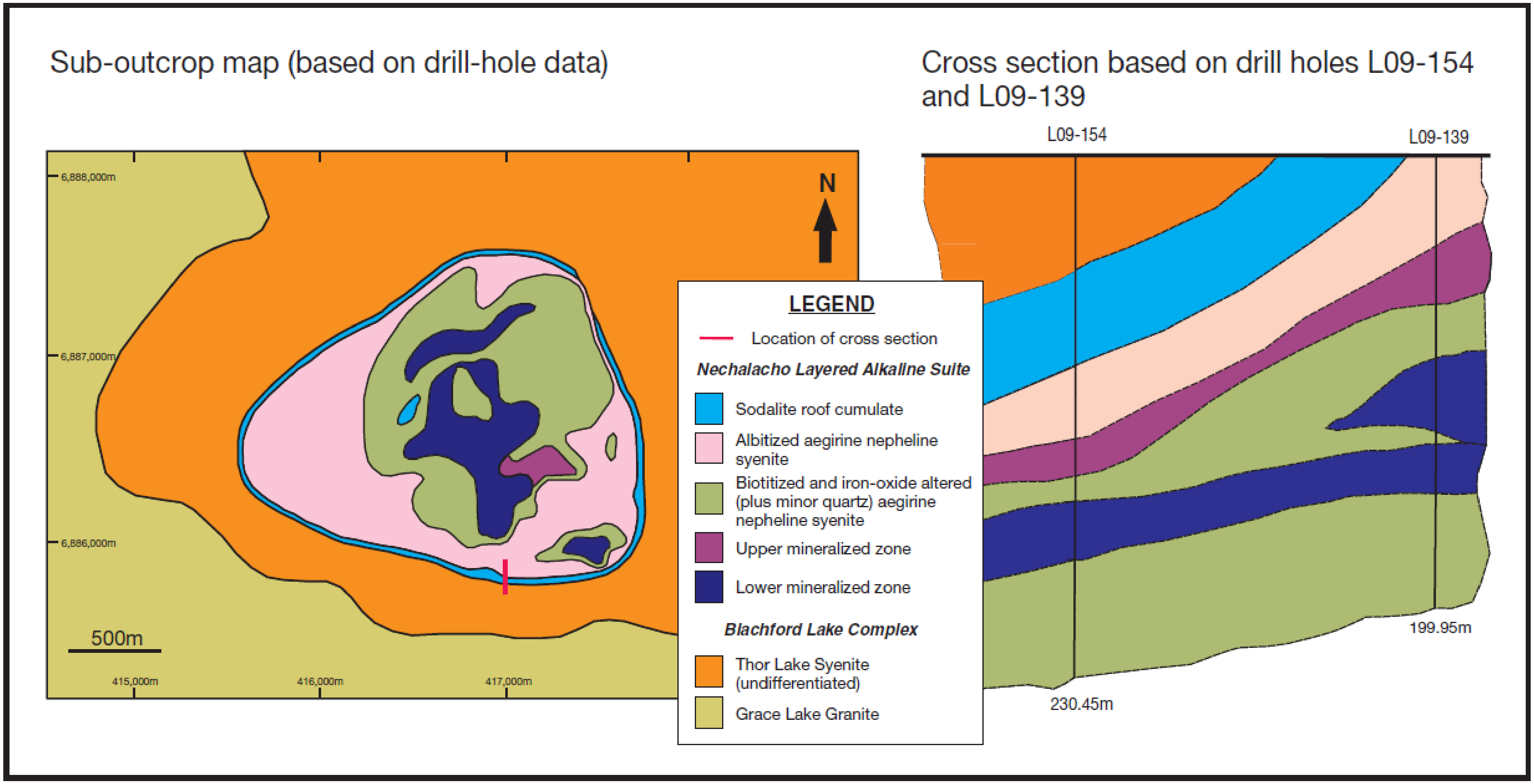
Thor Lake, NWT, Canada



From: Sheard, E.R., Williams-Jones, A.E., Heiligmann, M., Pederson, C., and Trueman, D.L., 2012, Economic Geology, v. 107, p. 81-104.

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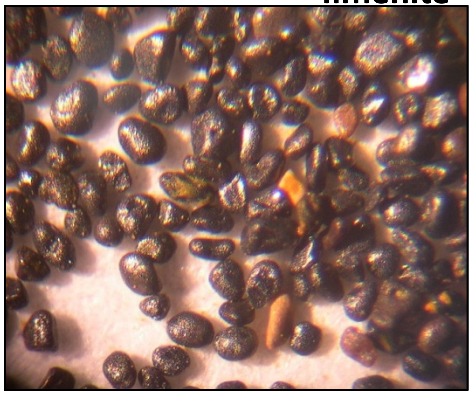
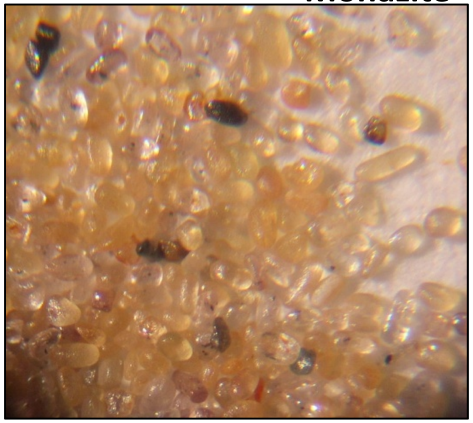
Heavy Minerals Sands (Placers)

- Heavy mineral sands are currently produced in Virginia and Florida.
- Grades average ~2% heavy minerals
  - Ilmenite 20 – 70 %
  - Zircon trace – 20%
  - Rutile, leucoxene trace – 30 %
  - Garnet, staurolite, kyanite trace – 50 %
  - Monazite trace – 15 %

Ilmenite



Monazite



- Monazite ((Ln,Th)PO_4) concentrates are currently not produced because of concerns about thorium.
- Monazite production risks: uranium & thorium

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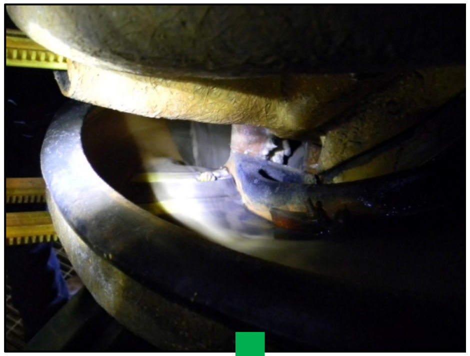
Iluka Concord Mine, Virginia



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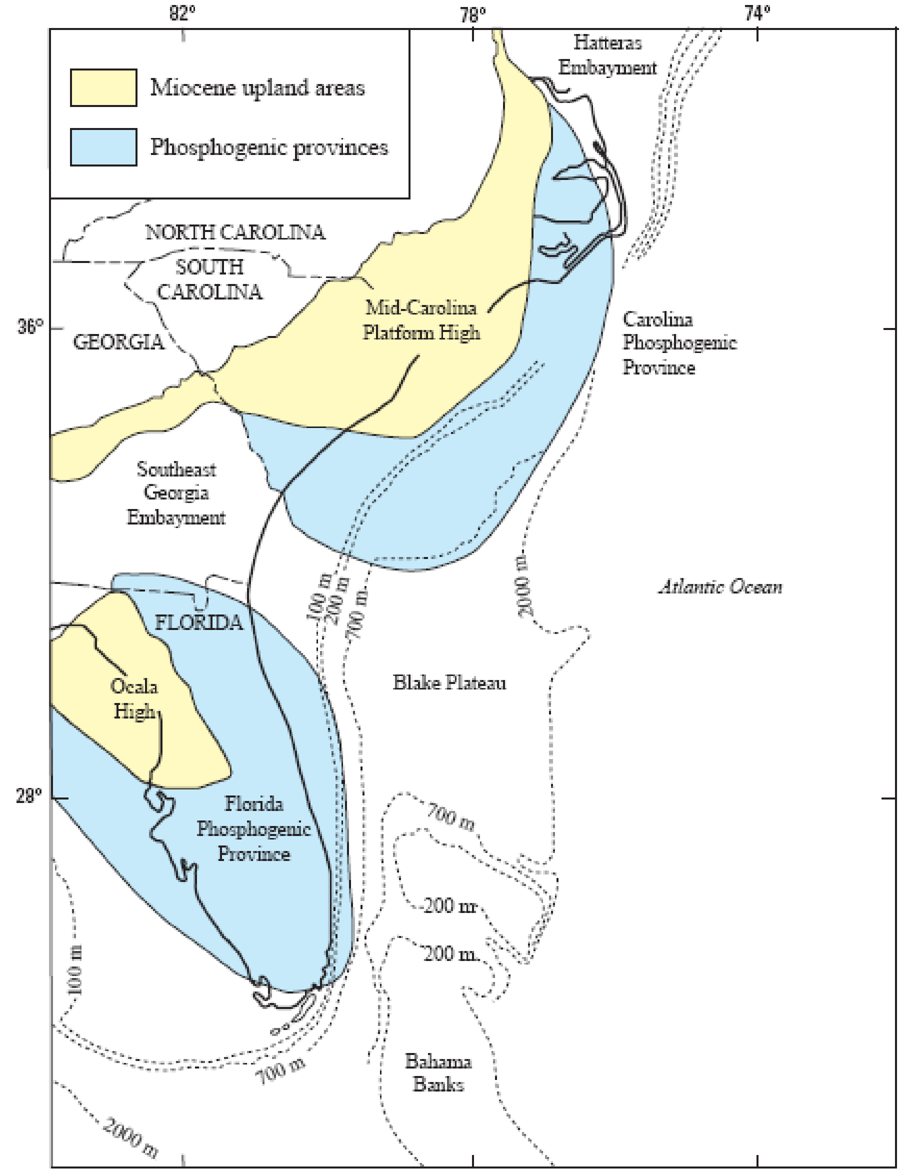
Phosphate Deposits

- Phosphate is mined in Florida (~65 %), North Carolina, Idaho and Utah
- Current potential and past production in Montana and Wyoming
- REE concentrations approach 0.5 %.
- REEs currently are not recovered.
- REEs are part of the waste stream for phosphoric acid production.
- Risks: uranium (radon), selenium



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Environmental Characteristics of REE Deposits

- Limited Data (Case Studies)
- Few Active, Inactive, or Abandoned Mines
  - Bayan Obo
  - Mountain Pass
  - Thor Lake (advanced exploration)
- Phosphate Fertilizer Industry
  - The Netherlands (water, sediment & soil guidelines)
  - China
- Microbial bioassay studies confirm the Free-Ion Model for lutetium (Weltie et al., 2004)
  - REE toxicity to aquatic organisms may be a more complex function of water chemistry (e.g., Wood, 1990)
- Geologic Characteristics

Rare Earth Element Minerals & Chemistry

Group-Mineral	Formula	REO Wt%	ThO_2 Wt%	UO_2 Wt%
Oxides				
Aeschynite	$(Ln,Ca,Fe)(Ti,Nb)_2(O,OH)_6$			
Euxenite	$(Y,Ln,Ca)(Nb,Ta,Ti)_2(O,OH)_6$			
Fergusonite	$YNbO_4$			
Carbonates				
Bastnäsite	$(Ln,Y)CO_3F$	70 - 74	0 - 0.3	0.09
Parisite	$Ca(Ln)_2(CO_3)_3F_2$	59	0 – 0.5	0 – 0.3
Synchisite	$Ca(Ln,Y)(CO_3)_2F$	49 – 52	1.6	
Tengerite	$Y_2(CO_3)_3 \bullet n(H_2O)$			
Phosphates				
Apatite	$(Ca,Ln)_5(PO_4)_3(OH,F,Cl)$	0 -20		
Monazite	$(Ln,Th)PO_4$	35 - 71	0 - 20	0 - 16
Xenotime	YPO_4	52 – 67	0 - 3	0 -5
Silicates				
Allanite	$(Ln,Y,Ca)_2(Al,Fe^{3+})_2(SiO_4)_3(OH)$	3 – 51	0 -3	
Eudialyte	$Na_4(Ca,Ce)_2(Fe^{2+},Mn^{2+},Y)ZrSi_8O_{22}(OH,Cl)_2$	1 - 10		
Thalenite	$Y_2Si_2O_7$			
Zircon	$(Zr,Ln)SiO_4$	0 – 0.7	0.1 – 0.8	

Ln: Lanthanide (a.k.a. REE)

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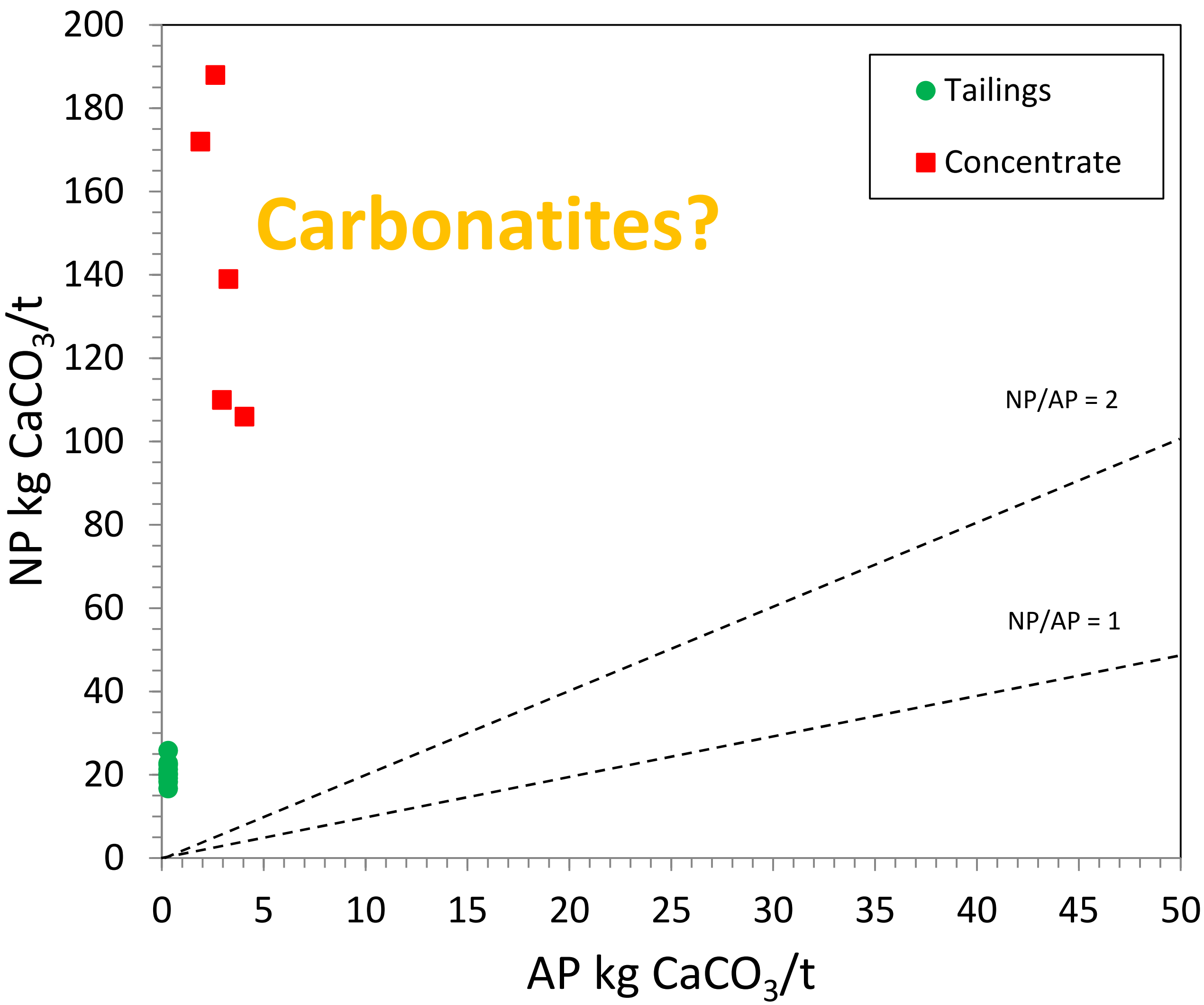
Acid-Generating Potential - Thor Lake, NWT, Canada



- Despite lack of data, carbonatite-hosted REE deposits would be expected to be strongly net alkaline.

Thor Lake data: http://www.reviewboard.ca/registry/project.php?project_id=87

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Rare Earth Elements: Surface Water Guidelines

		Yellow River, Baotou, China Bayan Obo Industrial Complex			Valzinco, VA		Thor Lake, NWT, Canada
	MPC* µg/L	Main Channel	Site F	Site G	VLZN-10	VLZN-3	Tailings HCT
pH		7.6 - 8.2		3.7 - 6.9	1.1	3.3	7.5
Y µg/L	6.4				370	2.0	0.183
La µg/L	10.1	0.103	140	988	340	4.6	
Ce µg/L	22.1	0.22	152	1149	870	9.5	
Pr µg/L	9.1	0.0304	16.08	294	150	1.2	
Nd µg/L	1.8	0.095	52.01	1193	650	4.7	
Sm µg/L	8.2	0.023	6.91	62.35	180	0.9	
Gd µg/L	7.1	0.028	7.22	67.33	140	0.7	
Dy µg/L	9.3	0.082	3.8	9.08	93	0.4	

*From: Maximum Permissible Concerntration; Sneller et al. (2000)

Thor Lake data: http://www.reviewboard.ca/registry/project.php?project_id=87

Thor Lake Tailings & Concentrate: Leachate (HCT)

	Chronic Surface Water	Acute Surface Water	Drinking Water	Tailings
SO_4 mg/L			250	2.9
Y µg/L	0.28	6.4		0.18
Al µg/L	750	87	200	20
As µg/L	340	150	10	0.5
Cd µg/L	0.3	2	5	0.2
Co µg/L	3.1	195		0.1
Cr µg/L	570	74	100	1.7
Cu µg/L	13	11	1,300	1.4
Fe µg/L		1,000	300	5.8
Mo µg/L	239	10,100		12.1
Ni µg/L	470	52		1.2
Pb µg/L	65	2.5	15	0.15
Sb µg/L	104	985		52
Se µg/L		5	50	<1
Sn µg/L	73.7	2680		2.2
U µg/L	1.87	33.5	30	3.9
V µg/L	19.1	284		0.04
Zn µg/L	120	120	5,000	3
Zr µg/L	54.9	982		0.71

Thor Lake data: http://www.reviewboard.ca/registry/project.php?project_id=87

Thor Lake Tailings & Concentrate: Sediment & Soil

	Unit	Sediment		Soil		Thor Lake
		TEC/NC*	PEC/MPC*	Residential	Industrial	Tailings
Al	mg/kg			77,000	990,000	62,000
As	mg/kg	9.79	33	23	160	4.4
Cd	mg/kg	0.99	4.98	70	810	6
Cr	mg/kg	43.4	111	280	1,400	640
Cu	mg/kg	31.6	149	3,100	41,000	18
Mo	mg/kg			390	5,100	73
Ni	mg/kg	22.7	48.6	1,600	20,000	330
Pb	mg/kg	35.8	128	400	800	9.9
Se	mg/kg			390	5,100	3.2
U	mg/kg			230	3,100	9.9
Zn	mg/kg	121	459	23,000	310,000	68
Ce	mg/kg	256.2	18,800			1,900
Dy	mg/kg	26.2	2,200			170
Gd	mg/kg	23.2	1,800			210
La	mg/kg	83.6	4,700			850
Nd	mg/kg	43.2	7,500			970
Pr	mg/kg	66.1	5,800			250
Sm	mg/kg	30.9	2,500			210

*Neglible Concentration, Maximum Permissible Concentration; Sneller et al. (2000)

Thor Lake data: http://www.reviewboard.ca/registry/project.php?project_id=87

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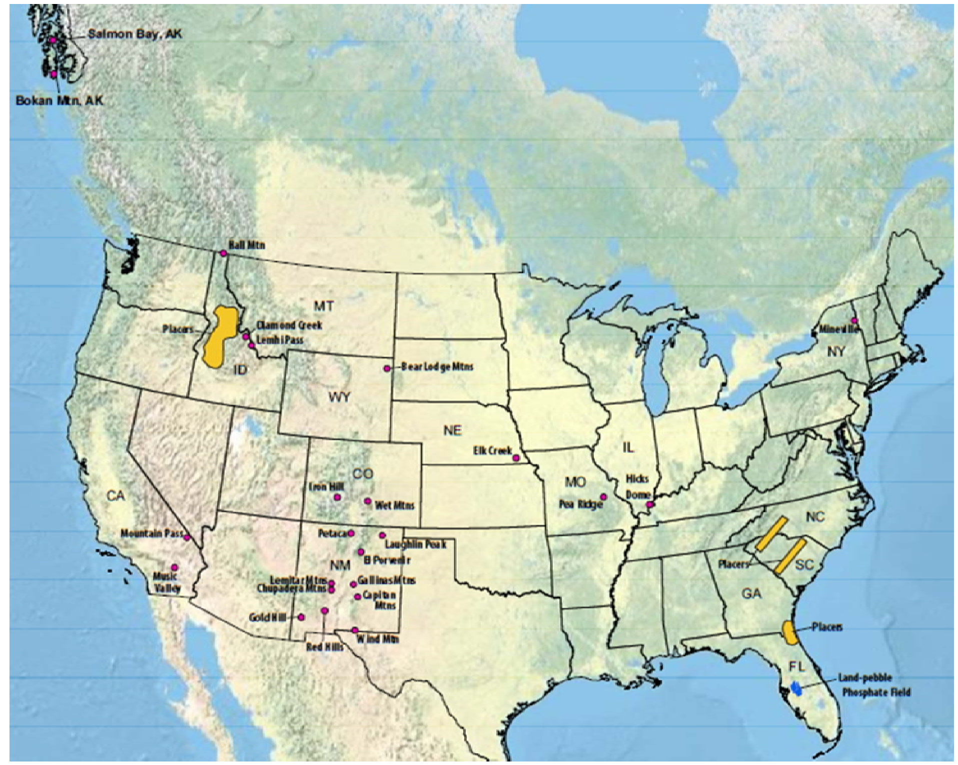
Geologic Summary

- Primary and byproduct deposits
  - Carbonatites
  - (Per)alkaline intrusive complexes
- Potential byproduct sources (?)
  - Phosphate deposits
  - Heavy minerals (placer) deposits
- Economic Risks
  - Estimated 1 in 10,000 showings become mines
  - Estimated 1 in 2,000 or 3,000 prospects become mines
  - Ore processing is very deposit specific because of variety of REE minerals



- In other words, the United States has potential, but do not expect a flood of new REE mines in the near future.

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Environmental Summary

- Knowledge is extremely limited
  - Few mines (active, inactive, abandoned)
- Environmental risks vary among deposit types, but some risks are common to most types
- Acid-Generating Potential is Low
  - Scarce sulfide minerals
  - Carbonatites have abundant carbonate minerals

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Environmental Summary (continued)

- Uranium
  - Radium: windblown dust; waterborne potential low because of low acid-generating potential
  - Radon
  - Potential for recovery
- Thorium
  - Current liability; domestic market limited
  - Future development and construction of thorium-based nuclear reactors in China, India, or France may represent future market.
- Other trace elements
  - REEs? Cd? Ni?

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More work is needed!
Questions?

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