ME589/GEOC589 Advanced Topics

Geology of Critical Minerals

REE

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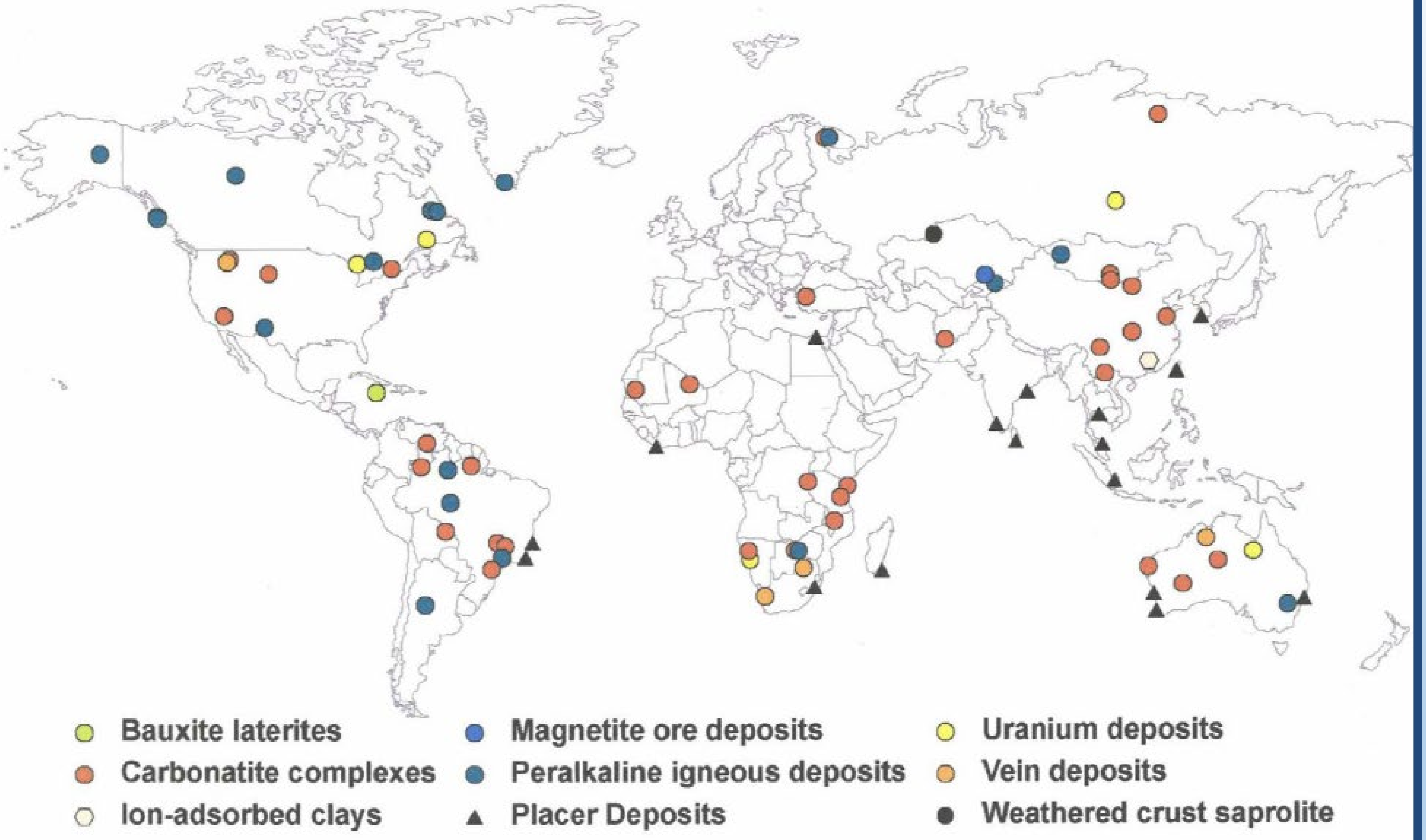
Safety

Paper

TYPES OF REE DEPOSITS

TYPES OF REE DEPOSITS

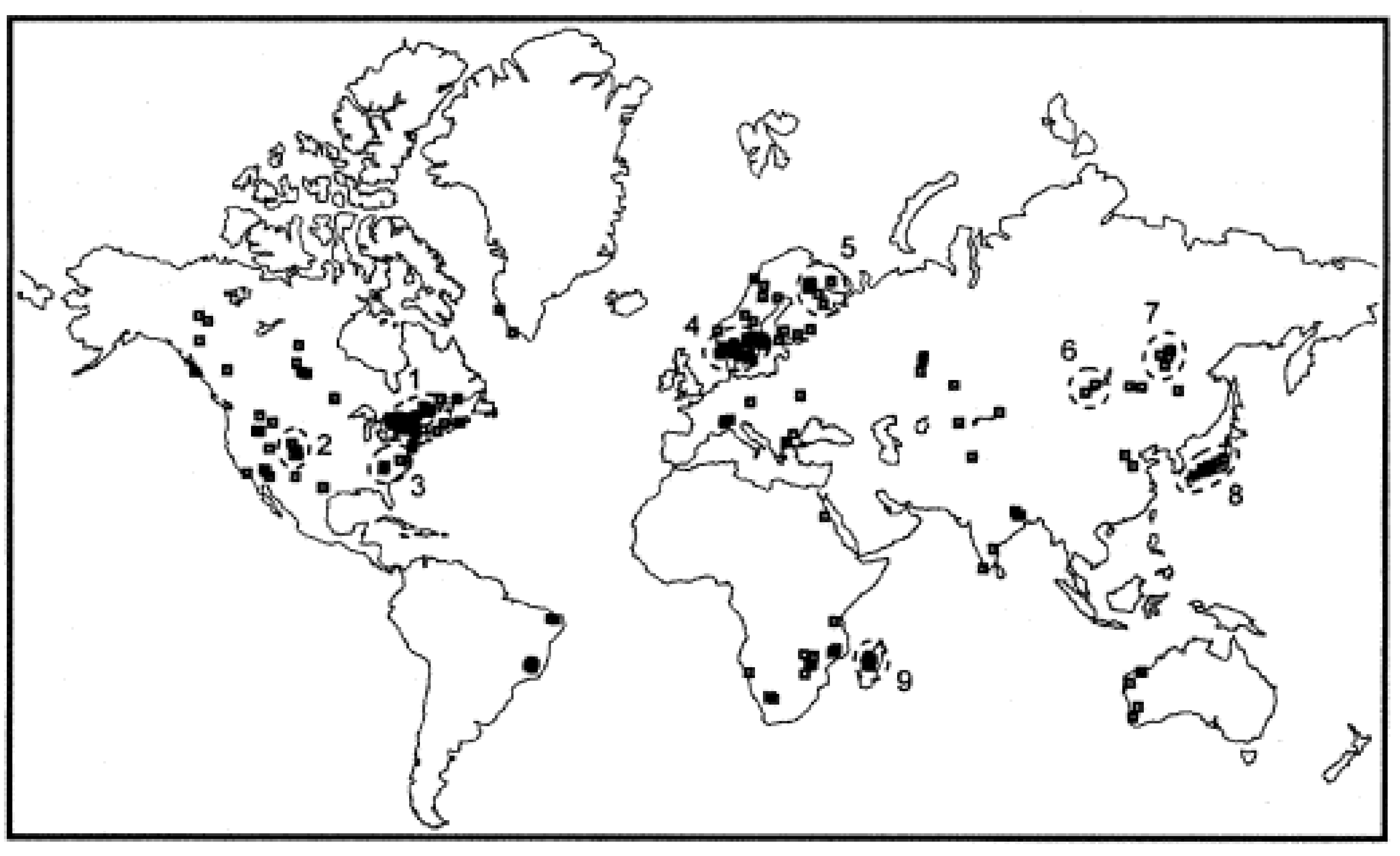
- Alkaline/peralkaline Igneous Rocks
- Carbonatites
- Pegmatites
- Iron oxide Cu-Au (REE)
  - Magnetite ore bodies
- Porphyry Mo
- Metamorphic/ metasomatic
- Paleoplacer/placer/ beach sands
- Colluvial REE
- Residual
  - Stratiform phosphate residual
  - Ion adsorption clays/laterite/bauxite
- REE-Th-U Hydrothermal Veins
- Unconformity uranium deposits
- Quartz-pebble conglomerate deposits
- Collapse breccia pipes
- Sea floor muds
- Other REE-Bearing Deposits



http://www.adimb.com.br/simexmin2012/wp-content/themes/simexmin/palestras/06terras/VII_1_Mariano.pdf

Pegmatites

>551 pegmatites



Pegmatites

- “an essentially igneous rock, commonly of granitic composition, that is distinguished from other igneous rocks by its extremely coarse but variable grain-size, or by an abundance of crystals with skeletal, graphic, or other strongly directional growth-habits.” (London, 2008)
- Products of magmatic differentiation, residual parts of the magma
- Increased volatiles and incompatible elements (large ionic radii)

Pegmatites

- Dikes, sills, veins, irregular masses
- In part due to slow cooling
- Grade into aplites, which formed if the magma losses suddenly the volatiles and only small crystals grow
- mostly due to large volumes of gases (volatiles =H2O, Cl, F)
  - Make it difficult for crystals to form=fewer crystals
  - Makes the normally sticky granitic magma more viscous, which allows for elements to move around
  - Volatiles separate as bubbles surrounded by normal liquid magma and crystals can form from both

Types

- Acidic pegmatites or granitic pegmatites
- Syenitic pegmatites (Na rich with little quartz)
- Basic and ultrabasic (feldspar, olivine, amphibole, biotite)

Table 1: The three petrogenetic families of rare element pegmatites, based on geochemical criteria, and different crustal sources of rare elements (adapted from Cerny, 1993; Cerny and Ercit, 2005). Peralkaline pegmatites are not included in this schema.

Family	*Dominant Pegmatite Subclasses*	*Geochemical Signature*	*Pegmatite Bulk Composition*	*Associated Granites Bulk Composition*	*Source Lithologies*
LCT	REL-Li MI-Li	**L**i,Rb, **C**s,Be,Sn,Ga **T**a > Nb(B,P,F)	peraluminous	mostly late orogenic; S,I or mixed S+I types	undepleted upper-to middle-crust supracrustals and basement gneisses
NYF	REL-REE MI-REE	**N**b > Ta,Ti, **Y**,Sc,REE, Zr,U,Th, **F**	subaluminous-metaluminous (to subalkaline)	mostly anorogenic; A and (I) types	depleted middle to lower crustal granulites, or undepleted juvenile granitoids
Mixed	"Cross-bred" LCT and NYF	mixed	(metaluminous to) moderately peraluminous	(postorogenic to) anorogenic; mixed geochemical signature	Mixed protoliths; or assimilation of supracrustals by A(or I) type granites

Definitions: peraluminous A/CNK>1; subaluminous A/CNK~1; metaluminous A/CNK<1 and A/NK>1; subalkaline A/NK~1, where A = molecular Al_2O_3, CNK = $Ca_2O + Na_2O + K_2O$, and NK = $Na_2O + K_2O$
REL = Rare element pegmatite class, MI = miarolitic pegmatite class

Table 2: Summary of characteristic differences between LCT and NYF petrogenetic pegmatite family endmembers (adapted from Vanstone, 2010).

	LCT (***L***ithium-***C***aesium-***T***antalum)	**NYF** (***N***iobium-***Y***ttrium-***F***luorine)
Relationship to source granites	• Pegmatitic granite phase is required for pegmatite development. • Typically forms part of regional zonation pattern	• No pegmatitic granite phase • Mostly lack of regional zonation patterns
Chemical signature	• Ta > Nb • (Very) low REE contents • Enriched in boron and alkali elements. • Sn content can equal Ta content. • U and Th levels tend to be low.	• Nb > Ta • Enriched in the light and heavy rare earth elements (REE's). • Sn is not commonly enriched. • May be enriched in U and Th.
Mineralogy	• Fluorite is rare (F bound in topaz, lepidolite, amblygonite) • Lithium and phosphate minerals are common. • Tourmaline is common • Generally simple Ta-Nb oxides ± Sn without essential REE • Beryl can be present	• Fluorite is common • Lithium and phosphate minerals are rare • Tourmaline is relatively rare; restricted compositional range • Complex oxides of Nb, Ta and REE's, viz., euxenite, fergusonite, samarskite, aeschynite mineral groups • Beryl can be present.
Western Australian pegmatite examples*	Wodgina district, Pilbara Craton Tabba Tabba field, Pilbara Craton Greenbushes field, Yilgarn Craton Londonderry district, Yilgarn Craton	Cooglegong district, Pilbara Craton Abydos district, Pilbara Craton Mukinbudin district, Yilgarn Craton Fraser Range group, Albany Fraser Orogen

*Principal references for examples: Sweetapple and Collins (2002); Jacobsen et al. (2007)

Figure 1. World map showing the locations of LCT pegmatite deposits or districts, including smaller districts in the United States. The symbols are color-coded by age. Giant deposits are represented by larger symbols.

USGS OF13-1008

Blocky Potassium Feldspar at southeast contact of pegmatite

Lithian muscovite veins cutting blocky potassium feldspar white beryl to right of scale card

http://www.nwopa.net/symposium/nwomms2010/05_PegmatitesRedLake.pdf

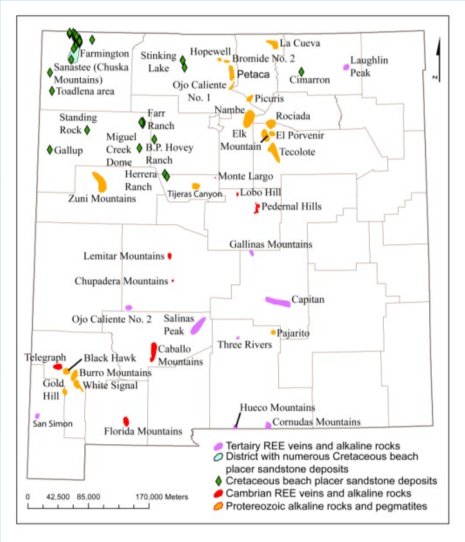
White albite veins in quartz-spodumene zone

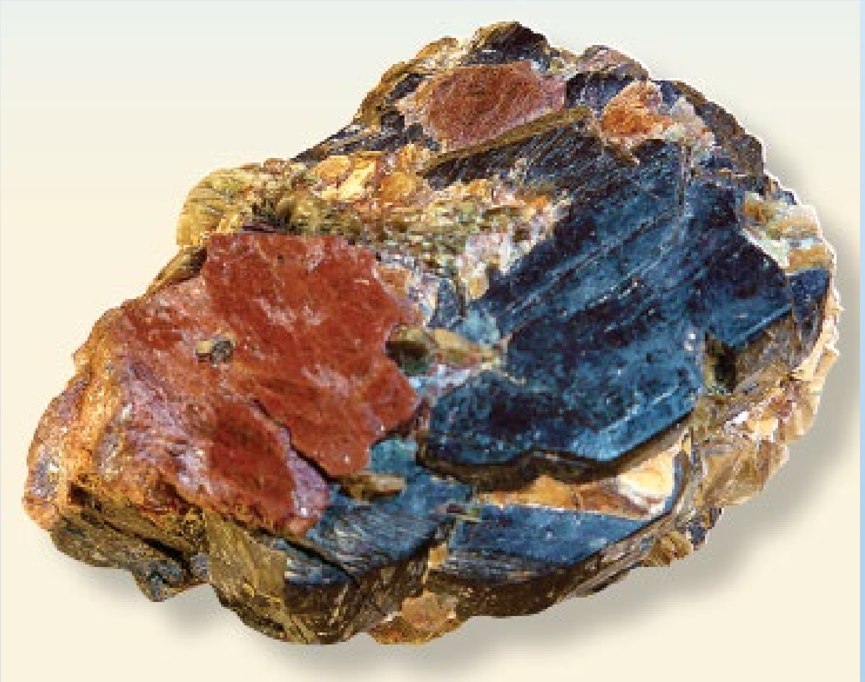
SQUI (spodumene-quartz intergrowth) with blocky blue potassium feldspar

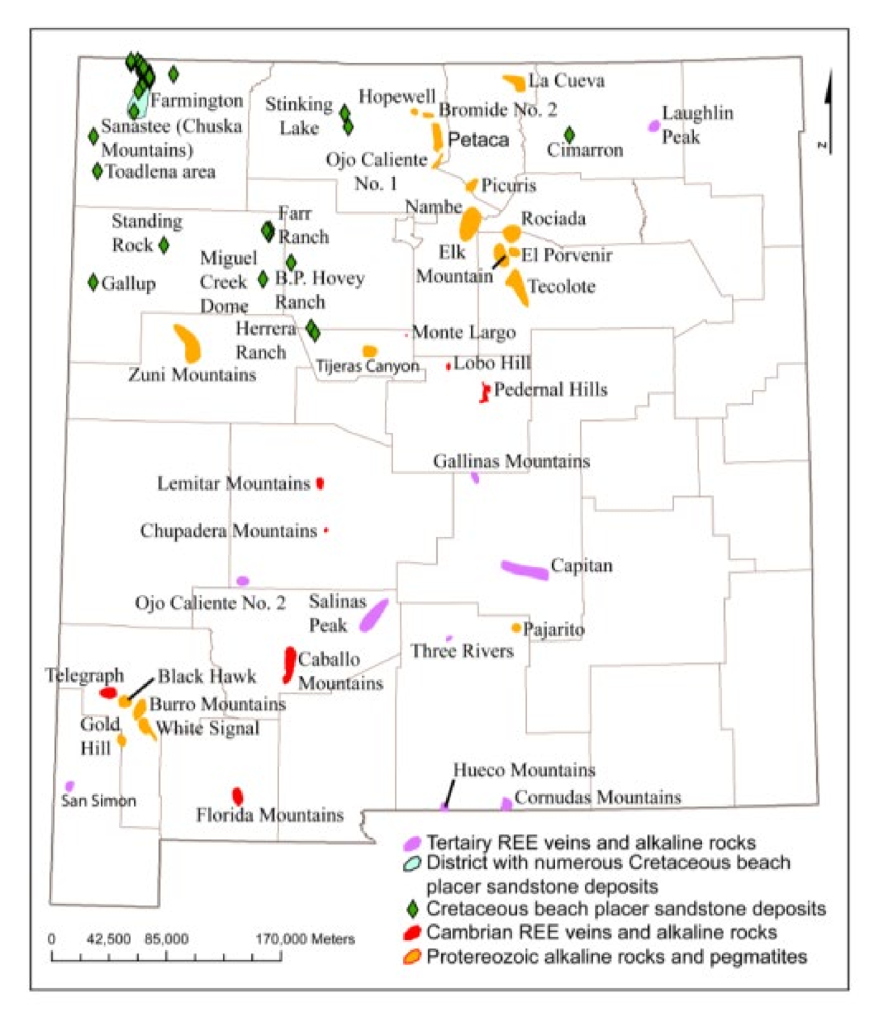
http://www.nwopa.net/symposium/nwomms2010/05_PegmatitesRedLake.pdf

Pegmatites

coarse-grained igneous rocks, lenses, or veins with granitic composition, contains essential quartz and feldspar, and represent the last and most hydrous phase of crystallizing magmas







- Petaca

PEGMATITES

- Burro
- Mountains

La Paz, Arizona

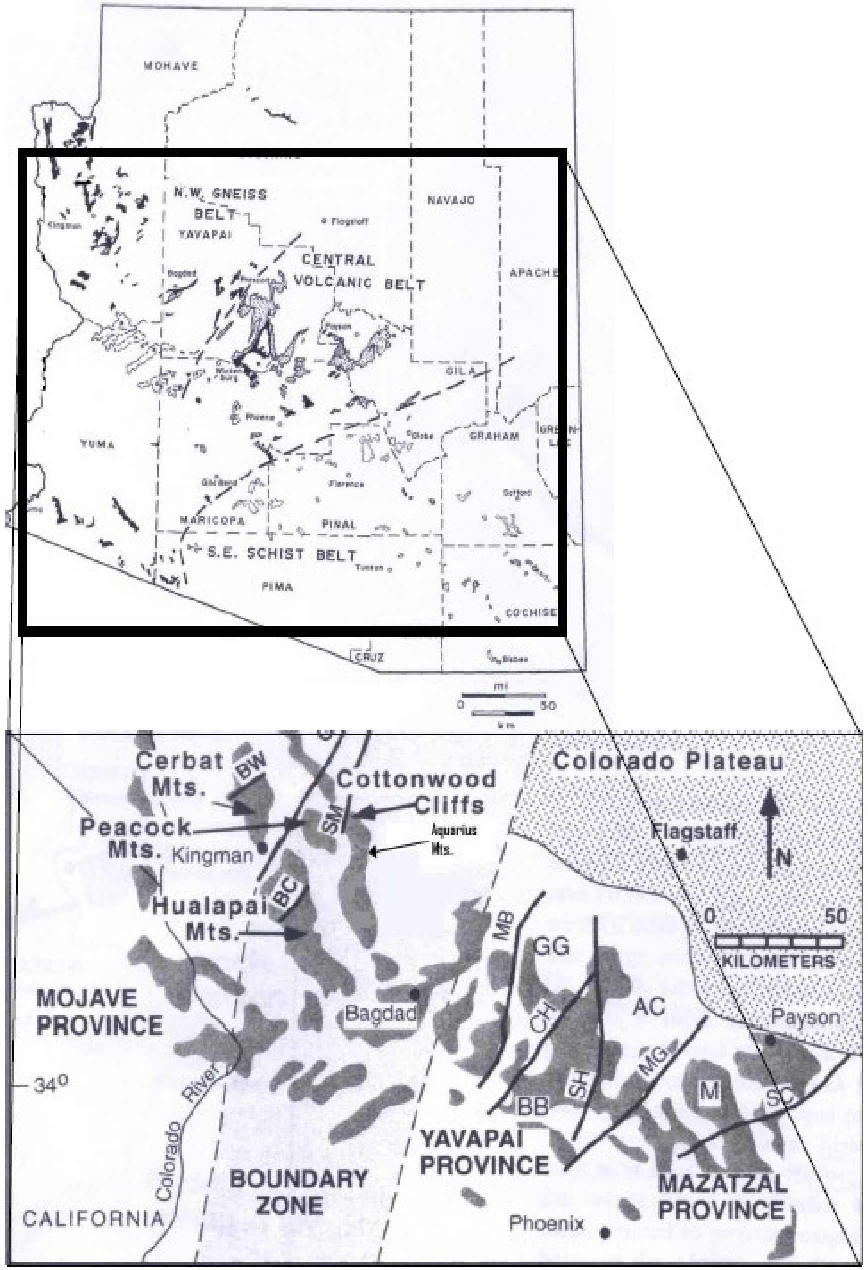


Figure 1a. Arizona state map, modified from Anderson (1989), with study area pulled out, modified from Duebendorfer (2001)

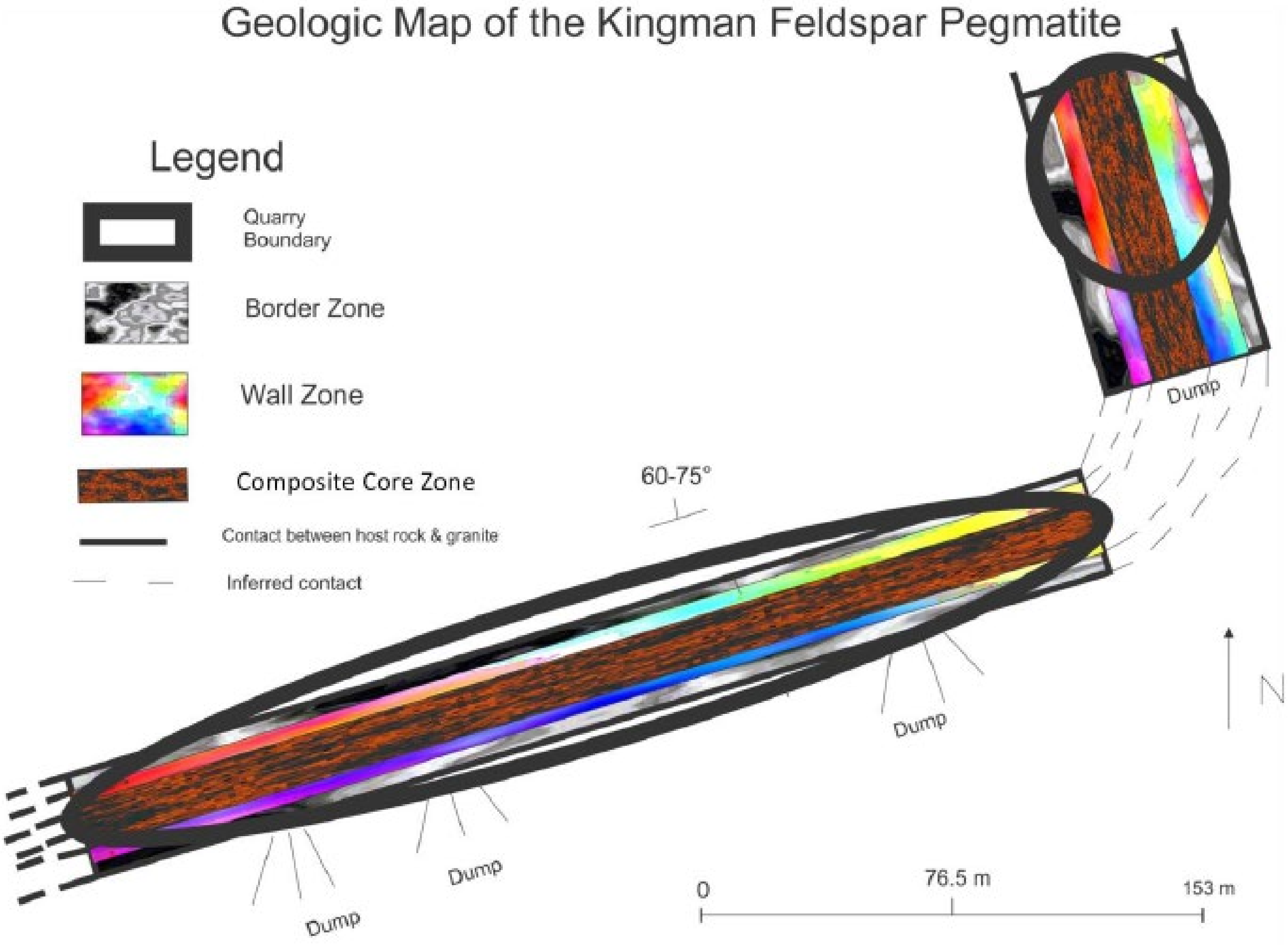


Figure 3. Idealized geologic map of the Kingman Feldspar

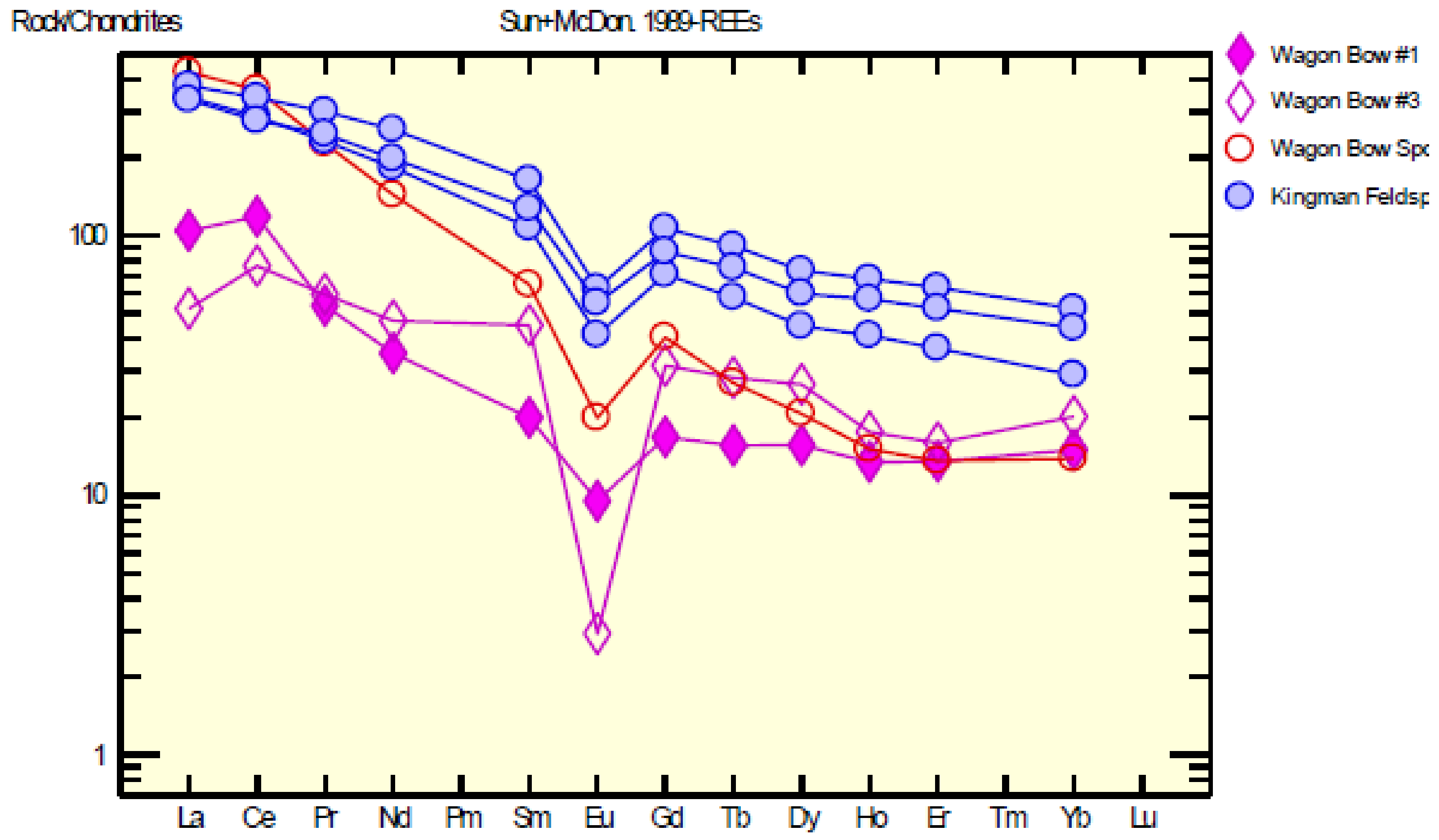


Figure 47. Chondrite diagram showing LREE enrichment trend and negative Eu anomaly, noticeably in the Wagon Bow #3 granite.

http://scholarworks.uno.edu/cgi/viewcontent.cgi?article=2263&context=td

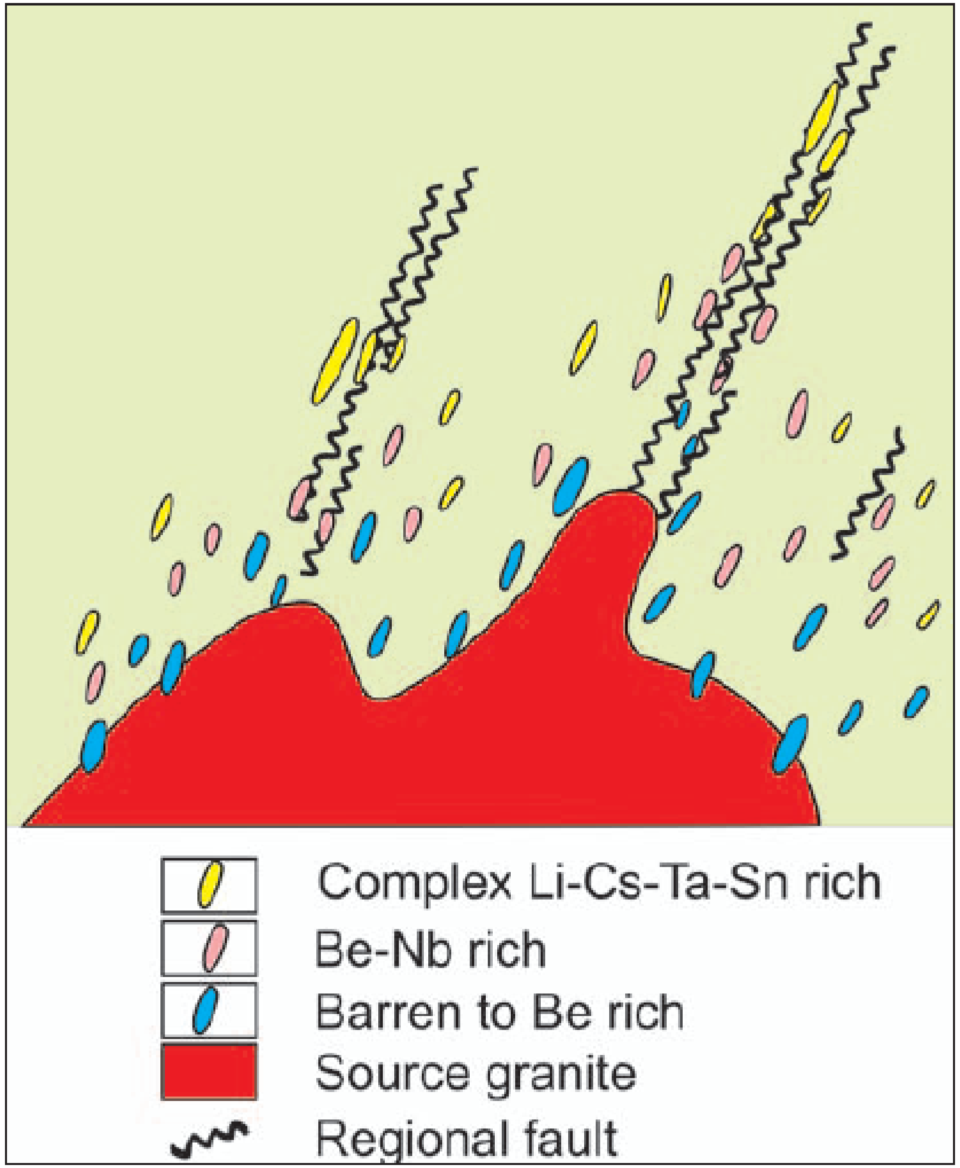


FIGURE 1 Idealized zoned pegmatite field around a source granite. The maximum distance of pegmatites from the source granite is on the order of kilometers or, at most, tens of kilometers. MODIFIED FROM ČERNÝ (1989)

http://web.mit.edu/12.000/www/m2016/pdf/pegmatites_strategic_metals.pdf

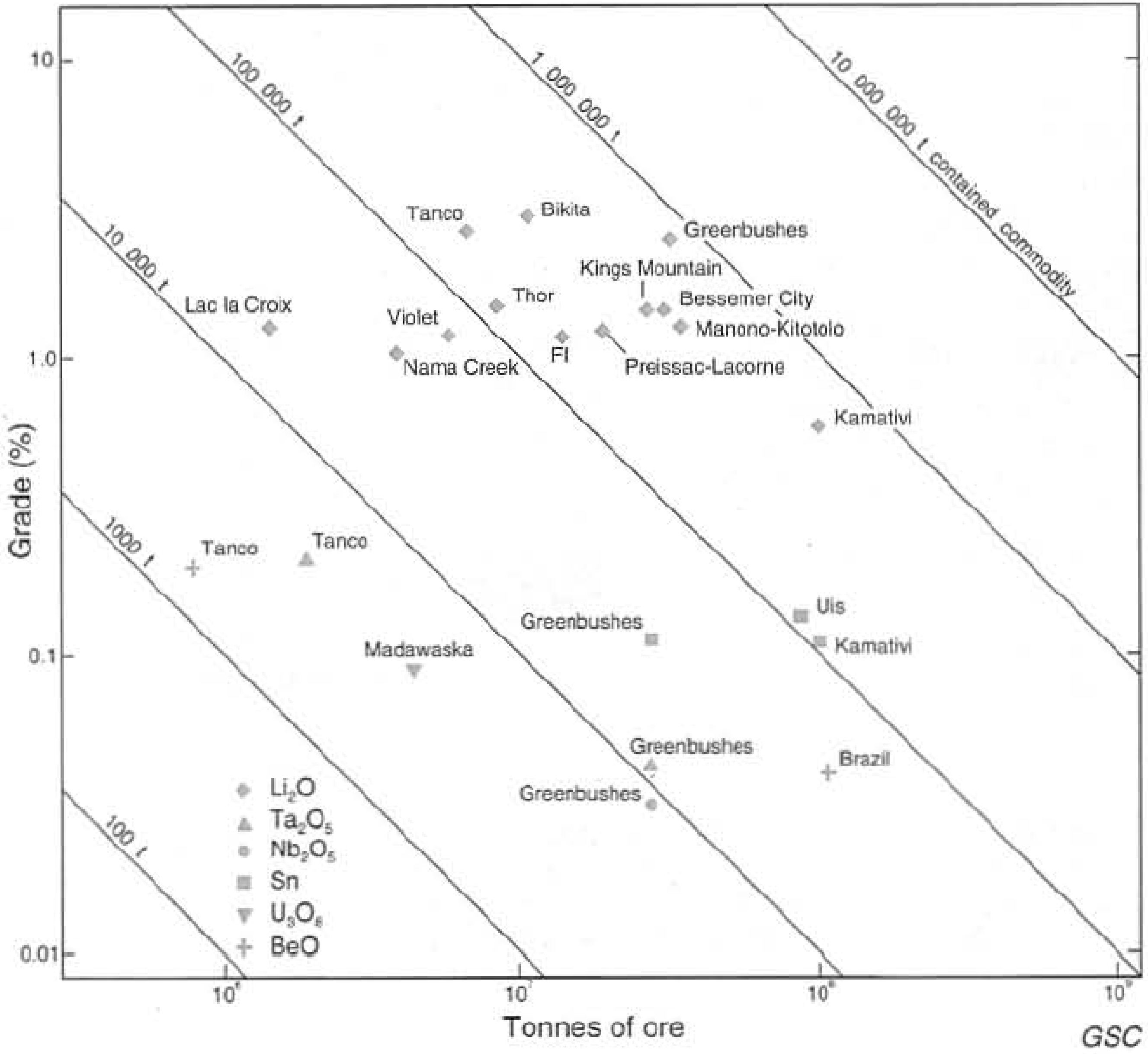


Figure 21-2. Grade versus tonnage diagram for pegmatite deposits (data are from Table 21-2).

Sinclair, 1996

IRON OXIDE-COPPER-GOLD (IOCG) DEPOSITS

IRON OXIDE-COPPER-GOLD (IOCG) DEPOSITS

wide spectrum of S-deficient low-Ti magnetite and/or hematite ore bodies of hydrothermal origin where breccias, veins, disseminations and massive lenses with polymetallic enrichments (Cu, Au, Ag, U, REE, Bi, Co, Nb, P) are genetically associated with, but either proximal or distal to largescale continental, A- to I-type magmatism, alkaline-carbonatite stocks, and crustal-scale fault zones and splays (Corriveau)

IRON OXIDE-COPPER-GOLD (IOCG) DEPOSITS

- Known as
  - Olympic Dam deposit
  - hematite-rich granite breccia
  - Metasomatic skarns
  - Magmatic magnetite-hematite bodies
  - Magnetite ore bodies
- Enriched in Fe, Cu, U, Au, Ag, REE s (mainly La and Ce) and F
- hydraulic fracturing, tectonic faulting, chemical corrosion, and gravity collapse

IRON OXIDE-COPPER-GOLD (IOCG) DEPOSITS

- at the margins of large igneous bodies which intrude into sedimentary strata
- form pipe-like, mantle-like or extensive breccia-vein sheets
- associated with distal zones of particular large-scale igneous events

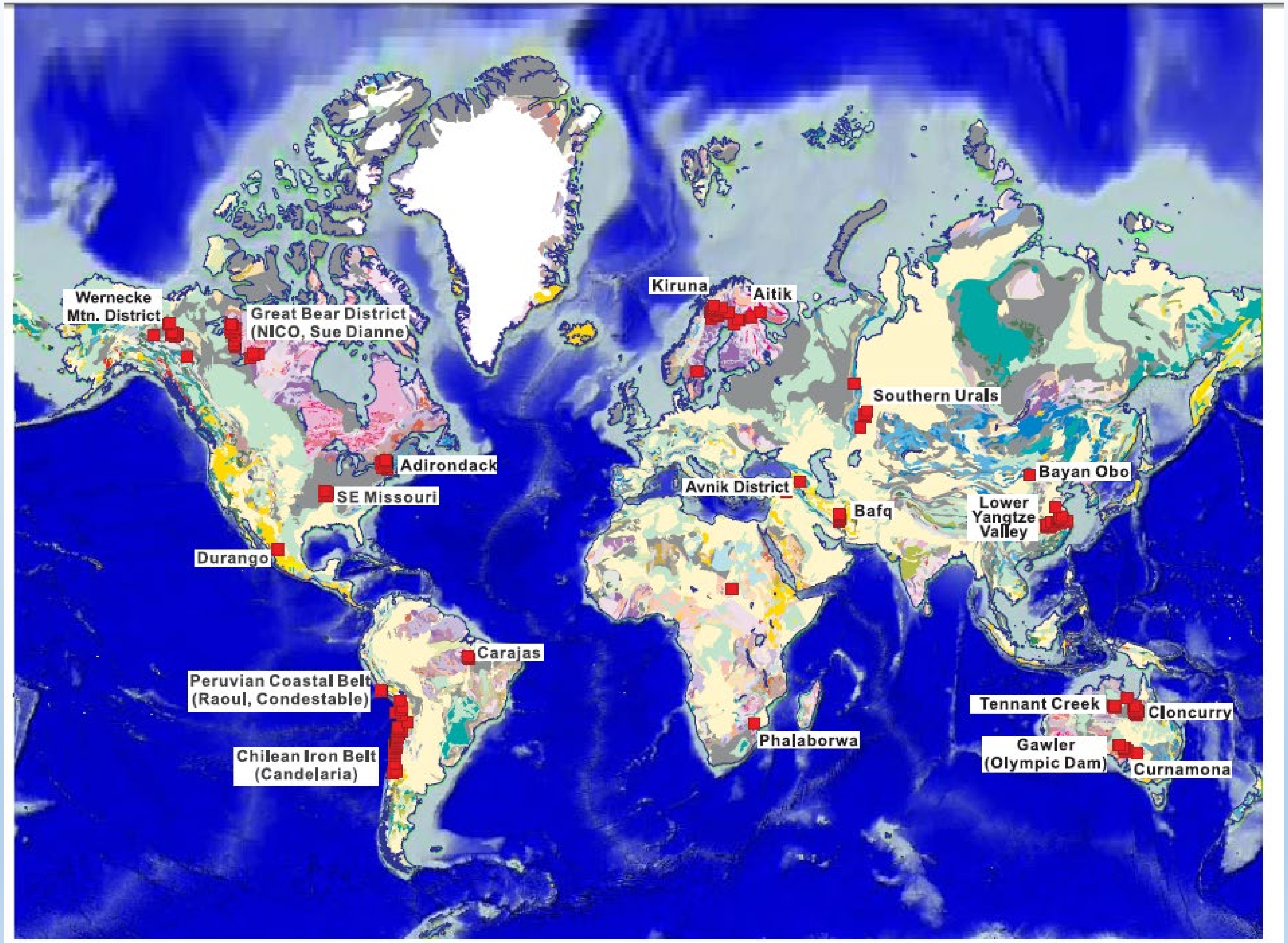


Fig. 1. Distribution of IOCG districts and important deposits worldwide (red dots). Australia: Gawler (Olympic Dam, Acropolis, Moonta, Oak Dam,

http://kenanaonline.com/files/0040/40858/deposit_synthesis.iocg.corriveau.pdf

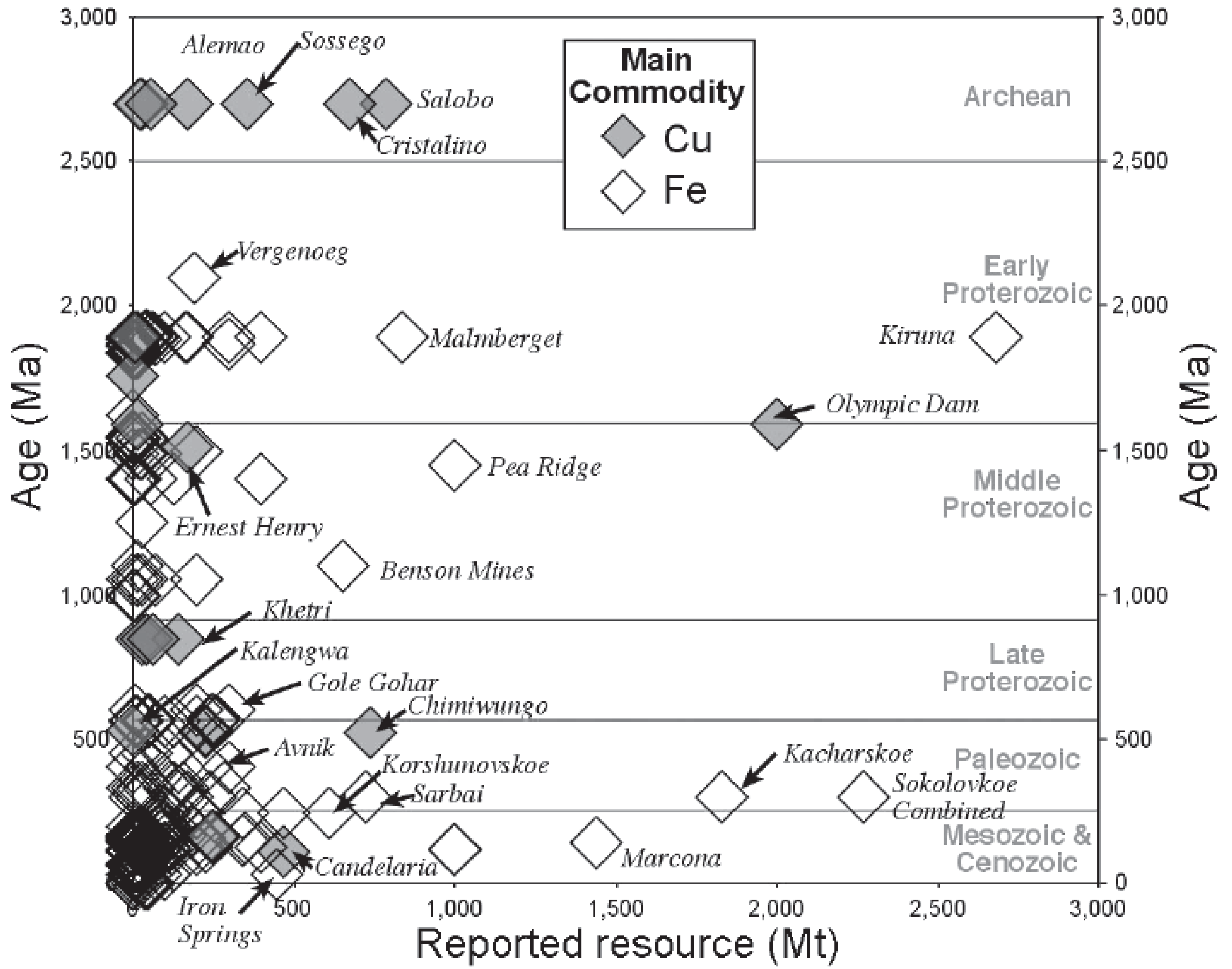


FIG. 2. Age distribution of IOCG deposits and Fe oxide deposits (mainly magnetite-apatite and Fe skarn; cf. Barton and Johnson, 1996), divided on the basis of the main commodity recovered (Cu or Fe). Ages for provinces are summarized in Table A1; deposit data are derived from publicly available data (D.A. Johnson and M.D. Barton, unpub. compilation).

http://www.unige.ch/sciences/terre/mineral/publications/onlinepub/williams_ironoxidecoppergold_seg05.pdf

Table 1. Size and Grade of Selected IOCG Deposits

Deposit	Tonnes (× 10^6)	Commodity	Grade	Associated Metals	Mineralization Styles
Magmatic End-Member IOCG					
Lightning Creek[1]	–	Cu (%) Au (g/t)	minor minor	–	Qz-Mt ± Py ± chalcopyrite veins
Eloise[2]	3.2	Cu (%) Au (g/t) Ag (g/t)	5.8 1.5 19	Co, Ni, Zn, As, Bi	Veins, stockwork veins, massive sulfide
Hybrid Magmatic–Non-Magmatic IOCG					
Olympic Dam[3]	2320	Cu (%) Au (g/t) Ag (g/t) U_3O_8 (kg/t)	1.3 0.5 2.9 0.4	Co, REE (dominantly La and Ce), Ni, As	Disseminations, veinlets, and fragments within breccia zones, primarily within breccia matrix
Aitik[4]	800	Cu (%) Au (g/t) Ag (g/t)	0.3 0.2 2	Mo	Disseminations and veins
Candelaria[5]	470	Cu (%) Au (g/t) Ag (g/t)	.95 .22 3.1	Zn, Mo, As, LREE	Vein, breccia-hosted, mantos, overprints Mt replacement bodies
Salobo[6]	450	Cu (%) Au (g/t)	1.15 0.5	Ag, U, Co, Mo, F, LREE	Lenses, veins
Ernest Henry[7]	166	Cu (%) Au (g/t)	1.1 0.54	Co, Mo, U, REE, F, Mn, As, Ba	In breccia
Non-Magmatic End-Member IOCG					
Wernecke Breccia[8]	Slab: 20	Cu (%)	0.35	U, Co, Mo	Disseminations, veins, breccia infill
Tennant Creek[9]	West Peko: 3.2 Eldorado: 0.0292	Cu (%) Au (g/t)	4 20.8	Bi	Massive and vein mineralization overprinting ironstone
Redbank[10]	Bluff: 2 Sandy Flat: 1.5	Cu (%) Cu (5)	1.66 2	Pb, Zn, REE	Breccia infill, veins, disseminations

http://www.sfu.ca/~dthorkel/linked/hunt%20et%20al.,%20rev%20iocg_s%202007.pdf

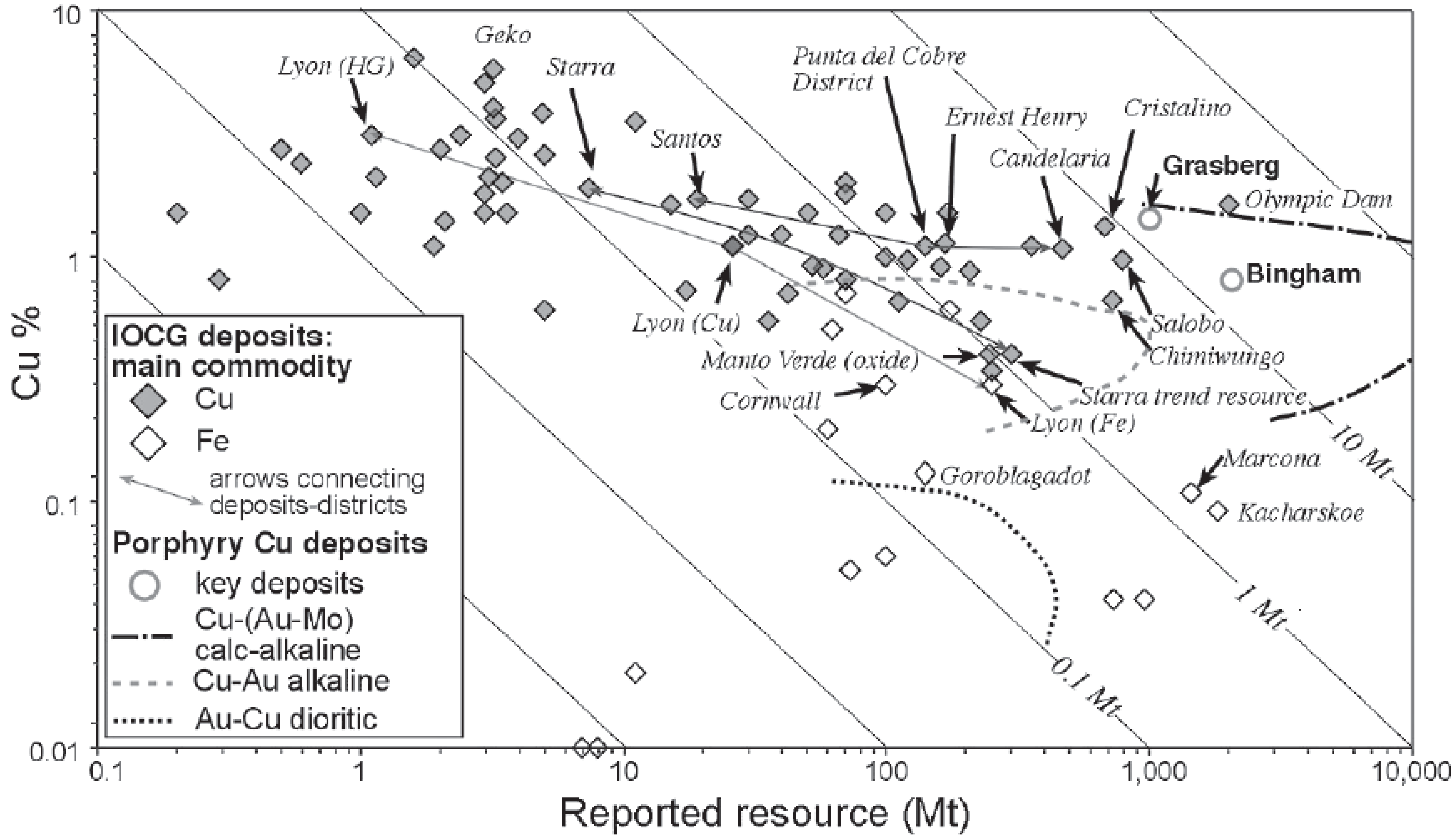


FIG. 3. Grade-tonnage data showing Cu grades for Fe oxide (mainly magnetite-apatite and skarn) and Fe oxide-Cu–rich hydrothermal systems (D.A. Johnson and M.D. Barton, unpub. compilation). Note the arrows connecting various resource categories (deposits and ore types) within the same districts. These data are skewed by the principal commodity produced and by the scarcity of representative Cu data for Fe-producing deposits. Also shown are fields for several types of porphyry Cu-Au–rich systems (modified from Seedorff et al., 2005).

http://www.unige.ch/sciences/terre/mineral/publications/onlinepub/williams_ironoxidecoppergold_seg05.pdf

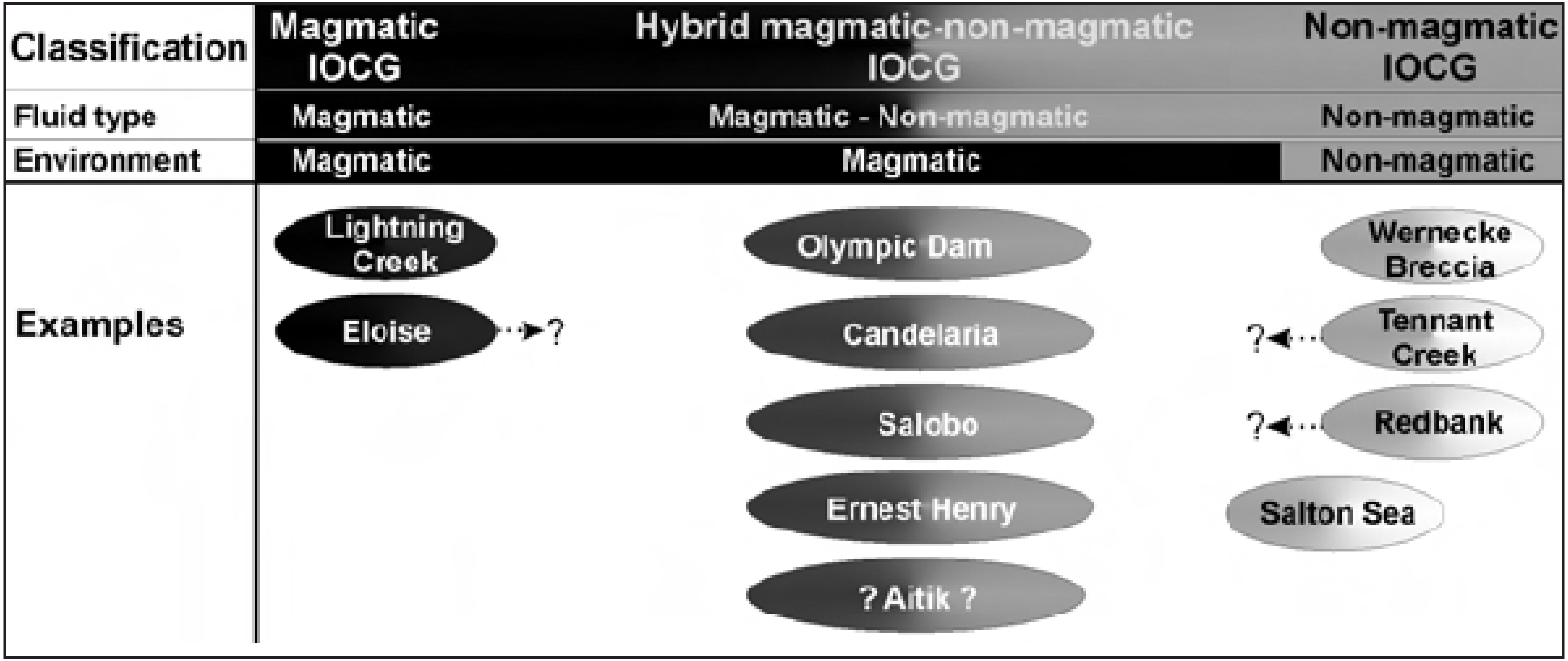


Fig. 7. Suggested classification of IOCG systems into magmatic and non-magmatic end members, with hybrid IOCG systems in between. Also shown are examples for each IOCG category. See text for discussion and references.

http://www.sfu.ca/~dthorkel/linked/hunt%20et%20al.,%20rev%20iocg_s%202007.pdf

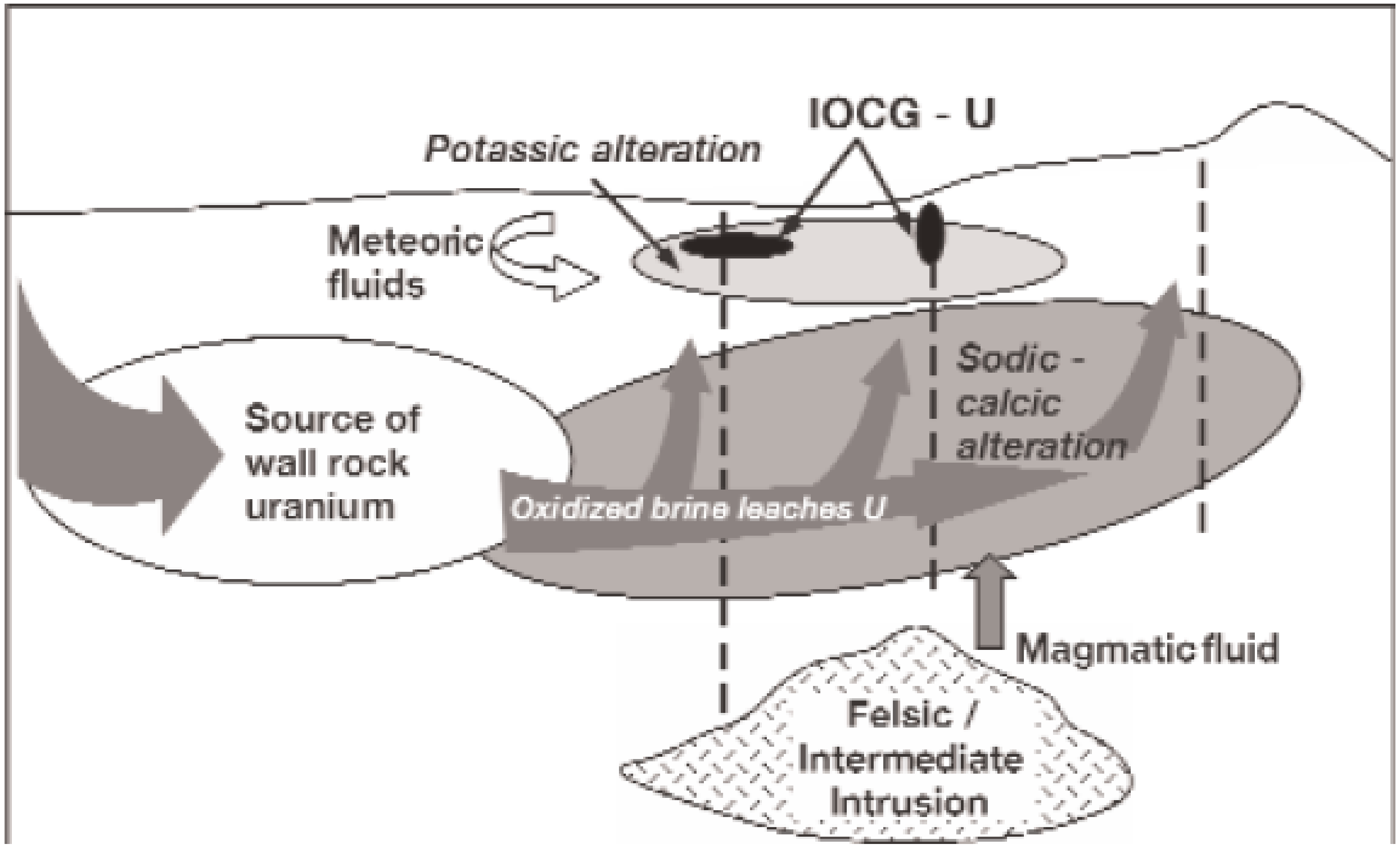


FIG. 2. Schematic model for the formation of uranium-rich IOCG deposits. In this model, uranium-rich IOCG deposits probably require a rich source of wall-rock uranium within the host-rock sequence altered as part of the IOCG system. Additional uranium could also be contributed by magmatic or meteoric fluids.

HITZMAN AND VALENTA, 2005, *ECONOMIC GEOLOGY,* V. 100, PP. 1657–1661

OLYMPIC DAM DEPOSIT IN AUSTRALIA

- Discovered 1975
- production for Cu 1988
- Underground mine, BHP Billiton
- Measured resource of 650 million tons (Mt) of 500 g/t U_3O_8 (425 ppm U), 1.5 percent Cu, and 0.5 g/t Au
- Total resource approximately 3.8 billion tons of 400 g/t U_3O_8 (339 ppm U), 1.1 percent Cu, and 0.5 g/t Au.

Hitzman and Valenta, 2005, *Economic Geology,* v. 100, pp. 1657–1661

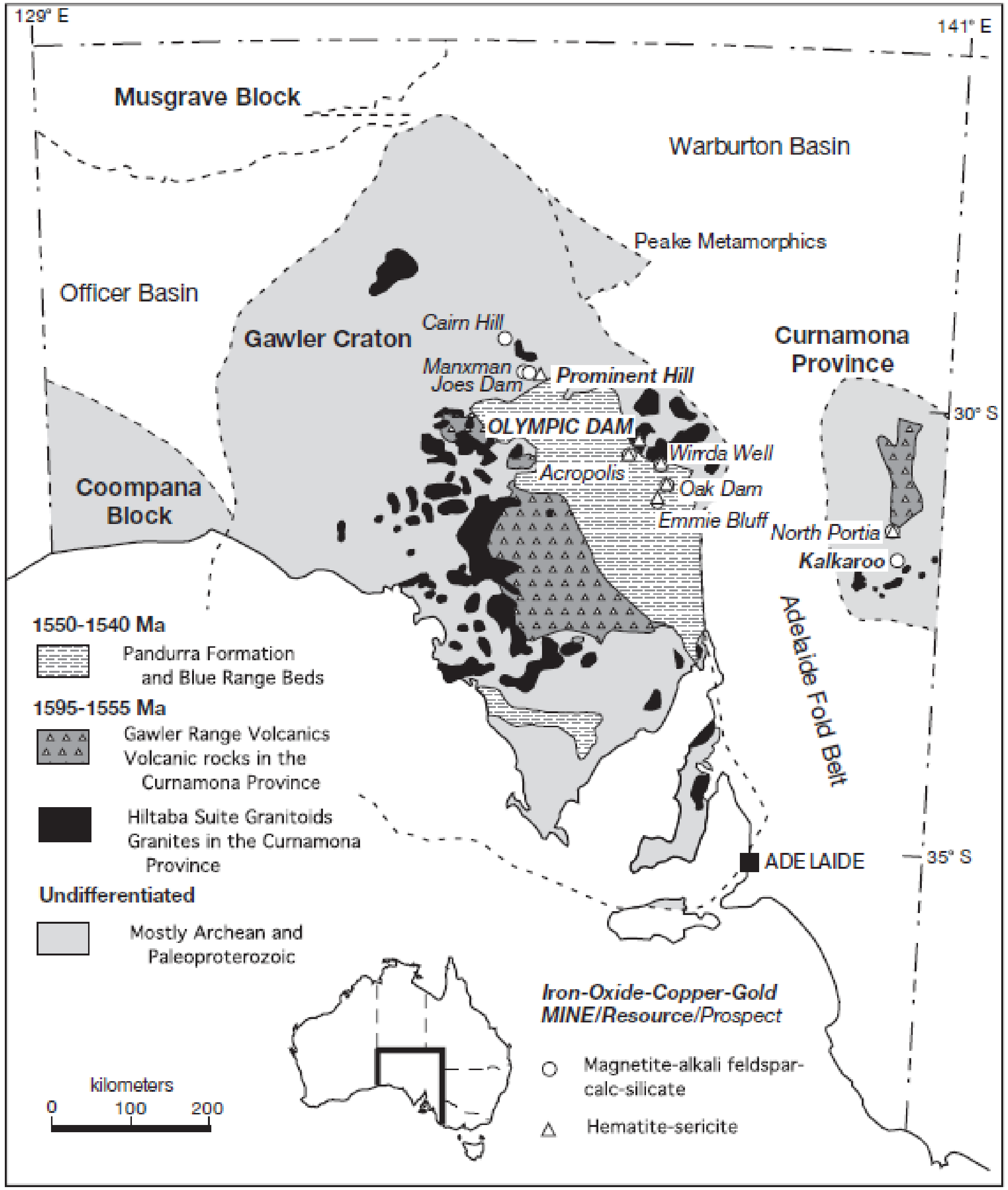
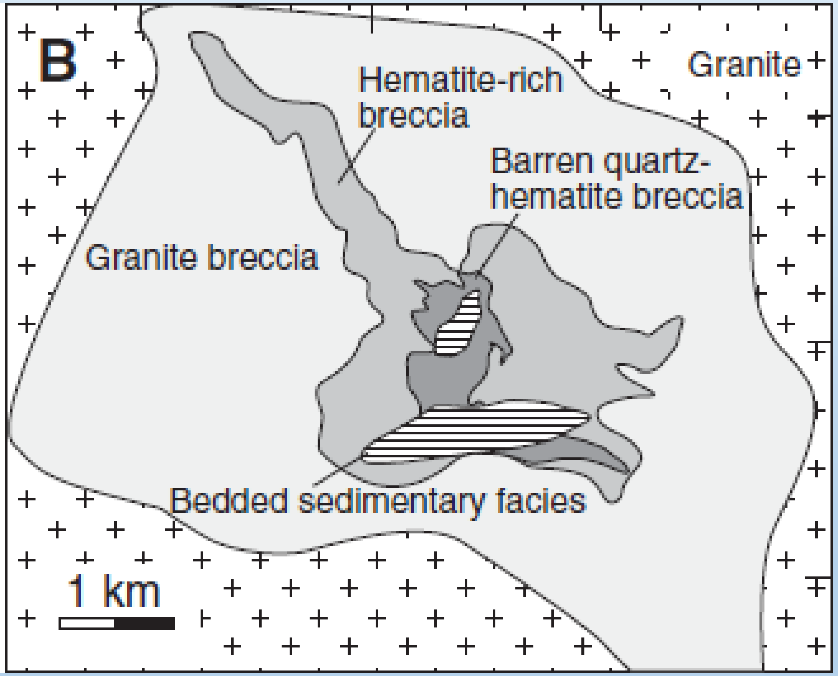


FIG. 10. Simplified geology of South Australia, showing the distribution of IOCG deposits and 1595 to 1555 Ma igneous rocks (adapted from Flint et al., 1993, with additional information from Williams and Skirrow, 2000, and Skirrow et al., 2002). Neoproterozoic and younger cover has been omitted in the cratonic areas. Note that the Gawler Range Volcanics are known to persist extensively under the Pandurra Formation and host several IOCG occurrences south of Olympic Dam, including Acropolis and part of the Emmie Bluff prospect.



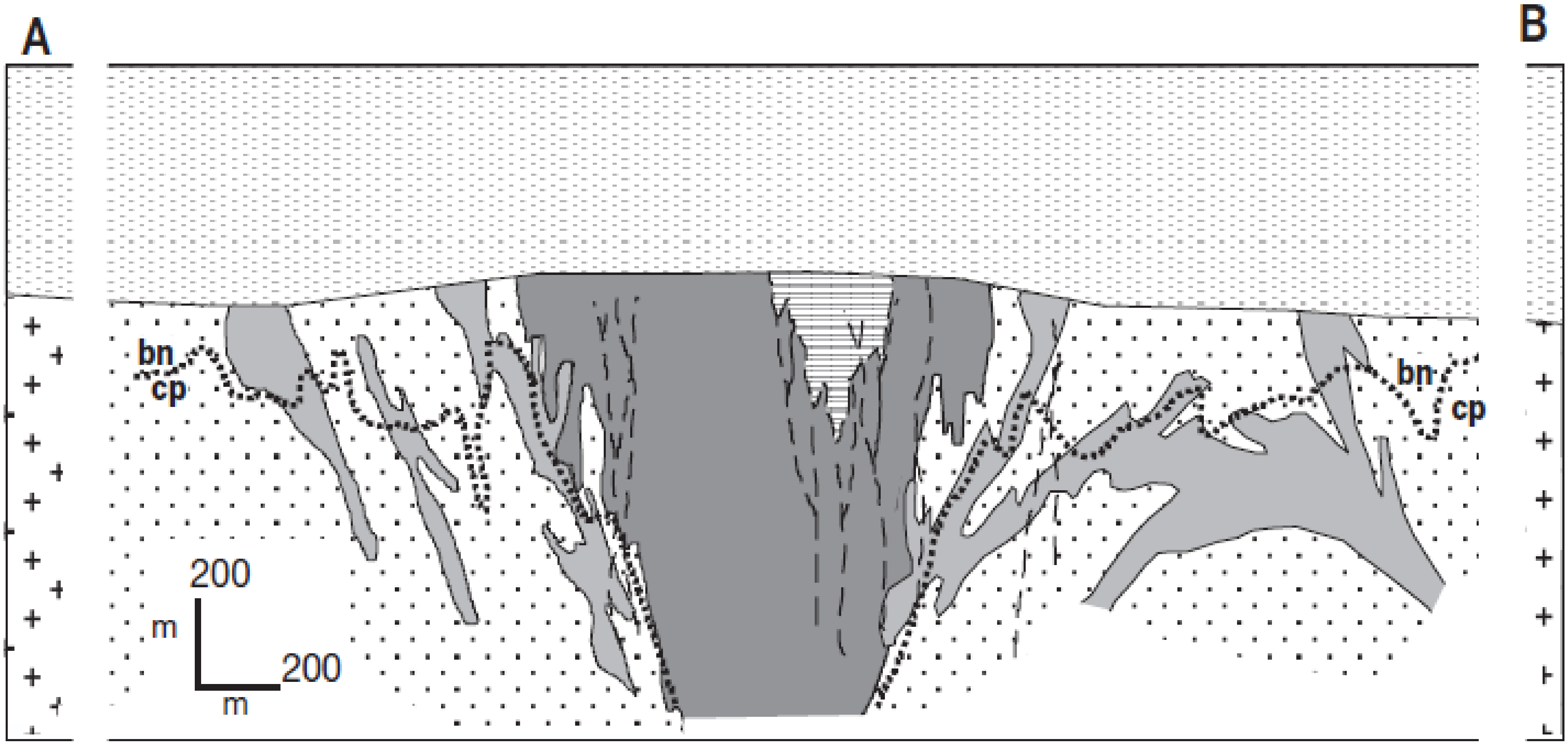


FIG. 11. (a). Geology and ore distribution at around 400 m below land surface at Olympic Dam (adapted and simplified from Reynolds, 2000). (b). Olympic Dam cross section, showing generalized geologic relationships and location of the bornite-chalcopyrite interface (adapted and simplified from Reeve et al., 1990).

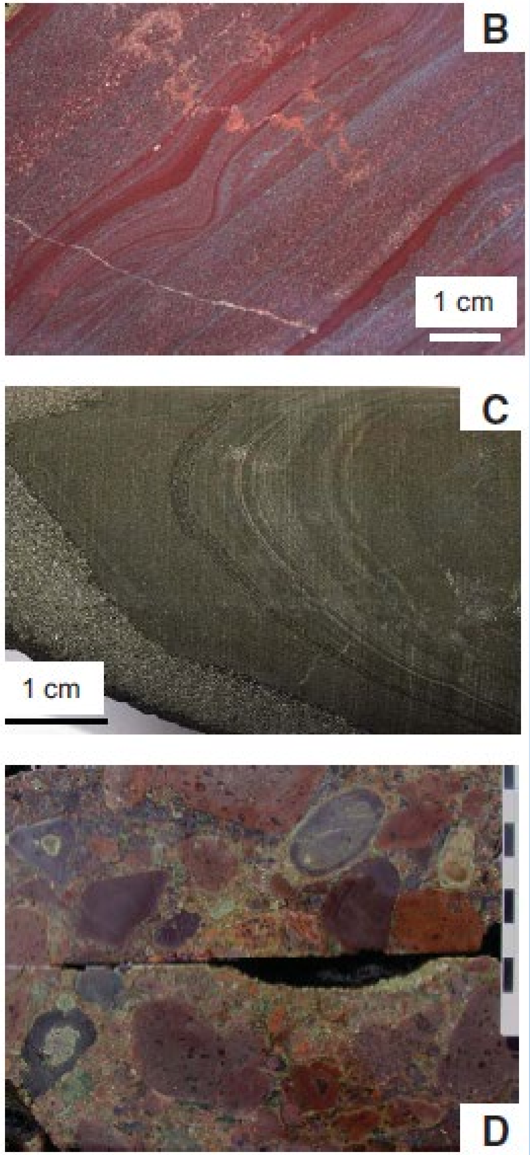


Figure 2. A: Clast of laminated hematite-rich sandstone in hematite-rich breccia, RD3008, 722.2 m. B: Laminated hematite-rich mudstone and sandstone in bedded sedimentary facies, RD3287, 355.3 m. C: Laminated chlorite-rich mudstone and sandstone, RD1989, 422.1 m. D: Polymictic volcanic conglomerate, RD3449, 414 m. Scale bar increments are in centimeters.

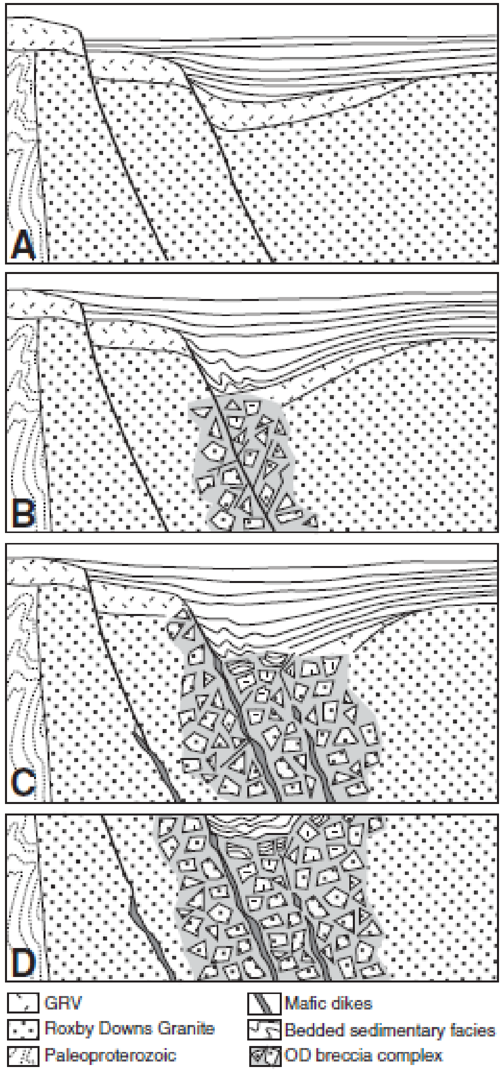


Figure 4. A: Bedded sedimentary facies accumulated in fault-bound basin above Mesoproterozoic granite and lavas. B: Fault-controlled subsurface fragmentation of Roxby Downs Granite, Gawler Range Volcanics (GRV) lavas, and bedded sedimentary facies formed Olympic Dam (OD) breccia complex. C: Mafic dikes intruded granite and breccia complex along faults. D: Erosion unroofed breccia complex, removing almost all traces of bedded sedimentary facies.

- Sedimentary basin
- Brecciation, mineralization
- Intrusion of mafic dikes
- erosion

http://eprints.utas.edu.au/11461/1/Geology_OD1.pdf

Pea Ridge, Missouri

Pea Ridge

- 60 mi SW St. Louis, underground mine
- 1950s—Bethlehem Steel and St. Joseph Lead Co. began developing
- 1964—Meramec Mining Co began production
- 1981—sold to Fluor Corp.
- 1990—sold again
- 2001--bankrupt
- 2001—Upland Wings bought the mine
- 2011—Pea Ridge Resources, Inc. formed and continued development

Mineralogy

- Magnetite
- Hematite
- Monazite
- Xenotime
- Allanite
- Cassiterite
- Pyrite
- Apatite
- Feldspar
- Quartz
- Actinolite

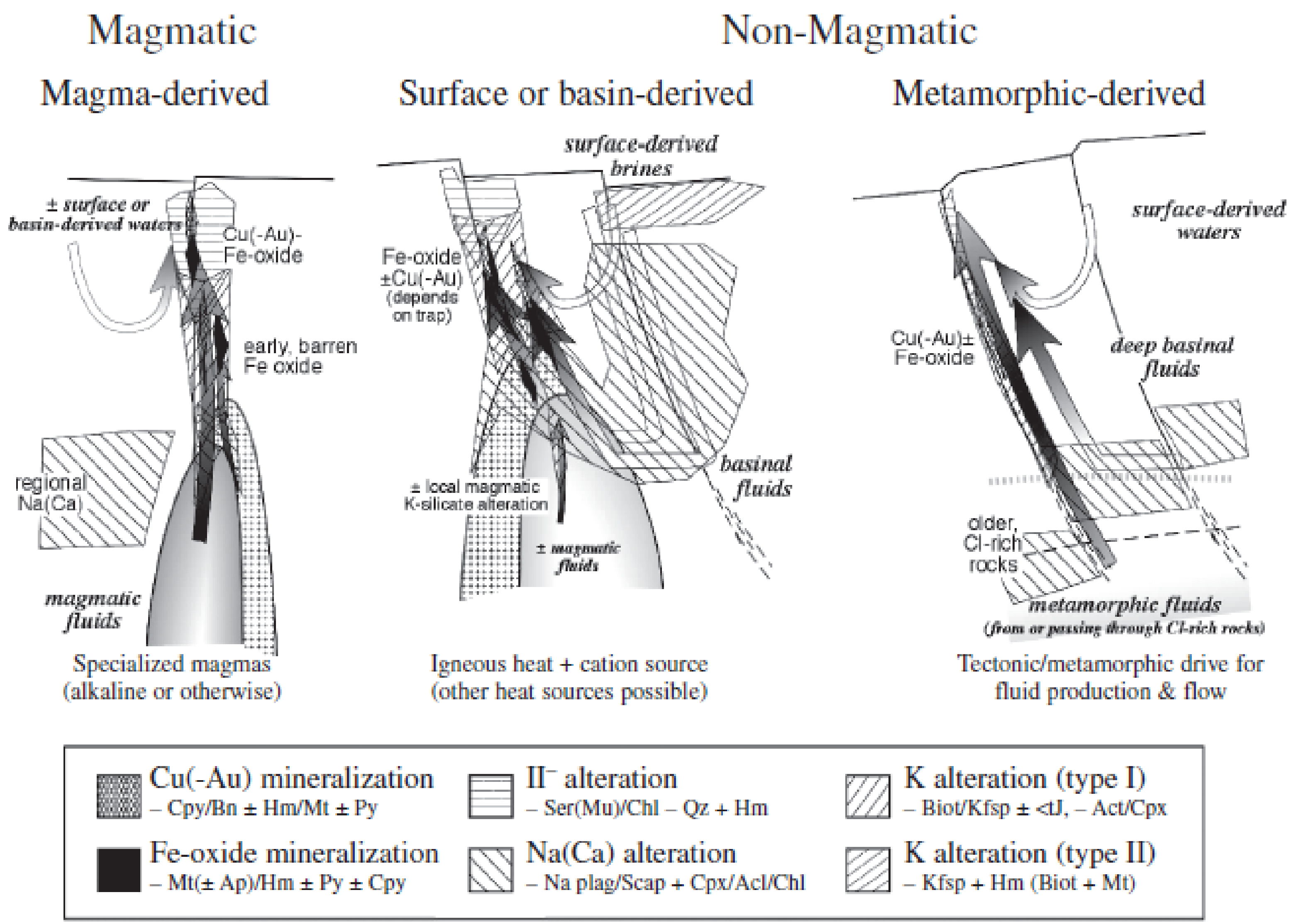


FIG. 18. Schematic illustration of flow paths and hydrothermal features for alternative models for IOCG deposits. See Table 2 for synopsis of characteristics. Shading of arrows indicates predicted quartz precipitation (veining) for a variety of paths in different quartz-saturated rocks that provides a useful first-order indication of flow (from Barton and Johnson, 2004).

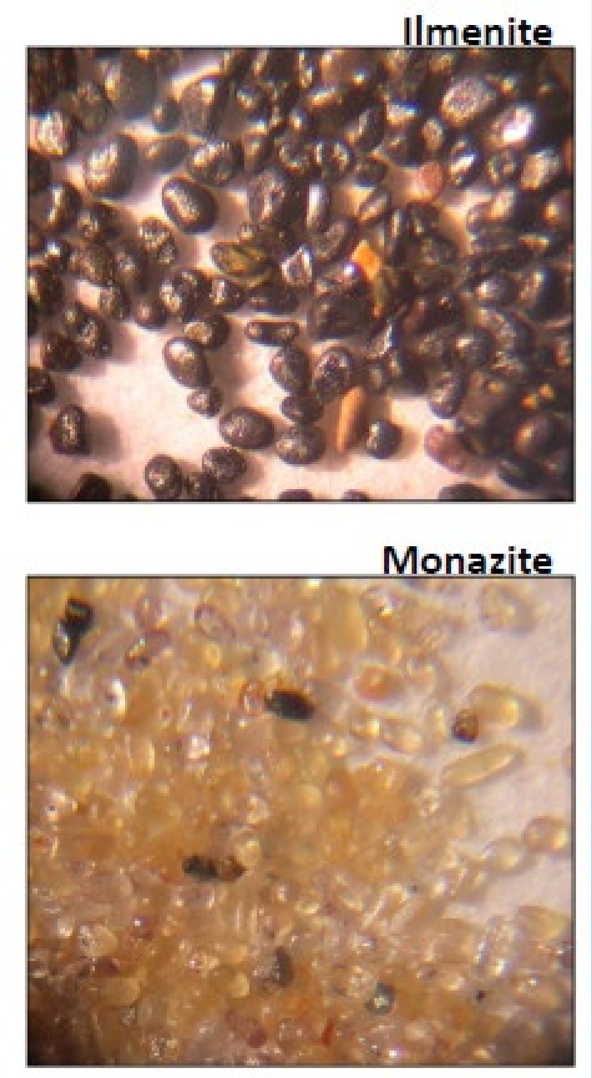
Paleoplacer/placer/ beach sands

Paleoplacer/placer/ beach sands

- Monazite-bearing placers
- Heavy mineral placers
- Beach placers
- fluviatile placers
- eluvial or lag deposits

Heavy minerals sands

- accumulations of heavy, resistant minerals (i.e. high specific gravity) that form on upper regions of beaches or in long-shore bars in a marginal-marine environment
- Currently mined in Virginia and Florida
  - Ilmenite 20-70%
  - Zirocn trace-20%
  - Rutile, leucoxene trace-30%
  - Garnet, starolite, kyanite trace-50%
  - Monazite trace-15%
- Monazite not being produced because of concerns about Th, U



Iluka Concord Mine, Virginia

USGS
science for a changing world

Australia

Heavy Mineral Sand Deposits

Small quantities of monazite-(Ce) are sometimes recovered as a by-product

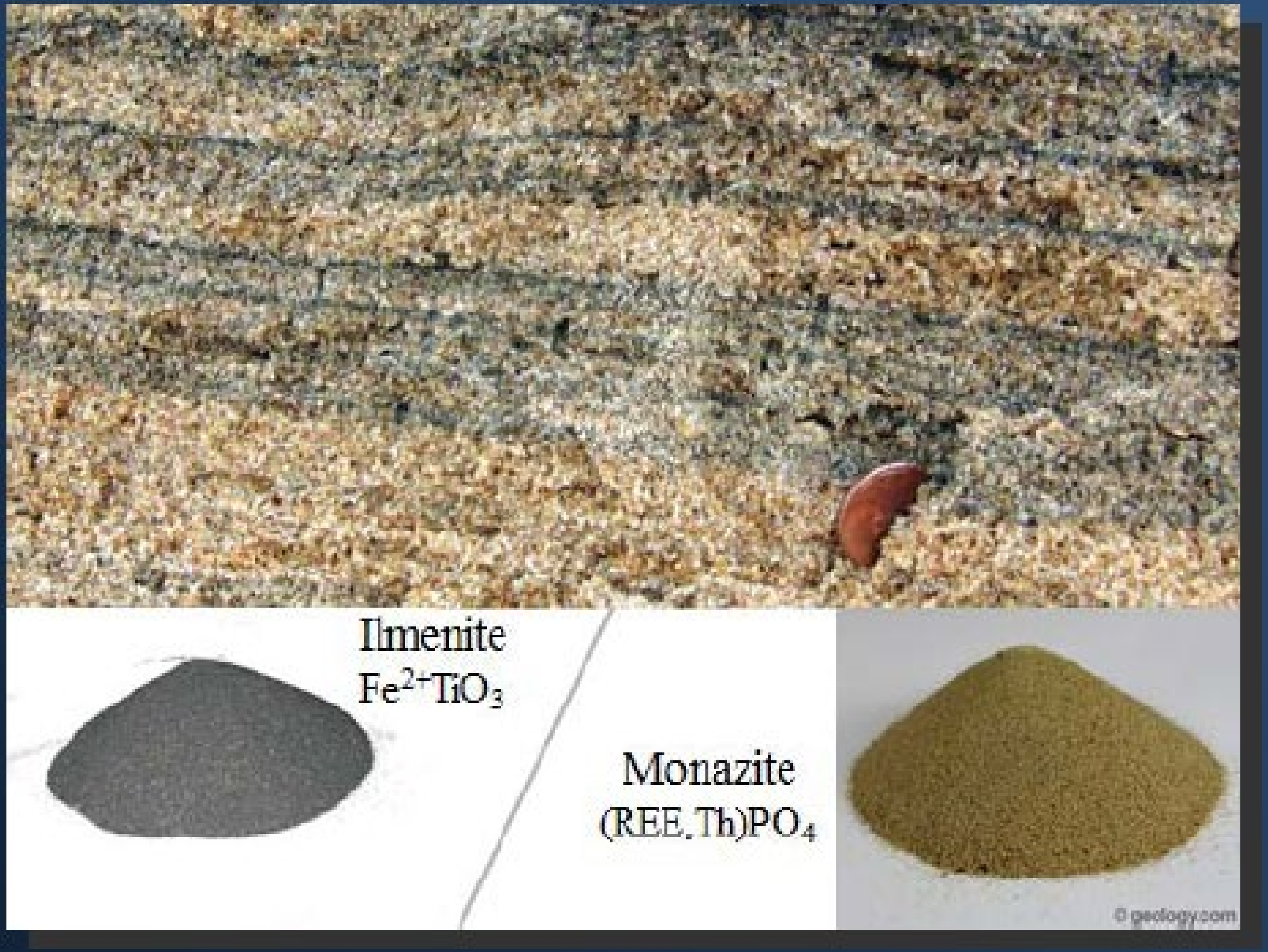
USGS

- Central Idaho stream placers
- North and South Carolina stream placers
- Virginia, Georgia, and Florida beach placers

Monazite-bearing Stream and Beach Placer Deposits

USGS

Monazite-bearing Stream and Beach Placer Deposits



USGS

River placers

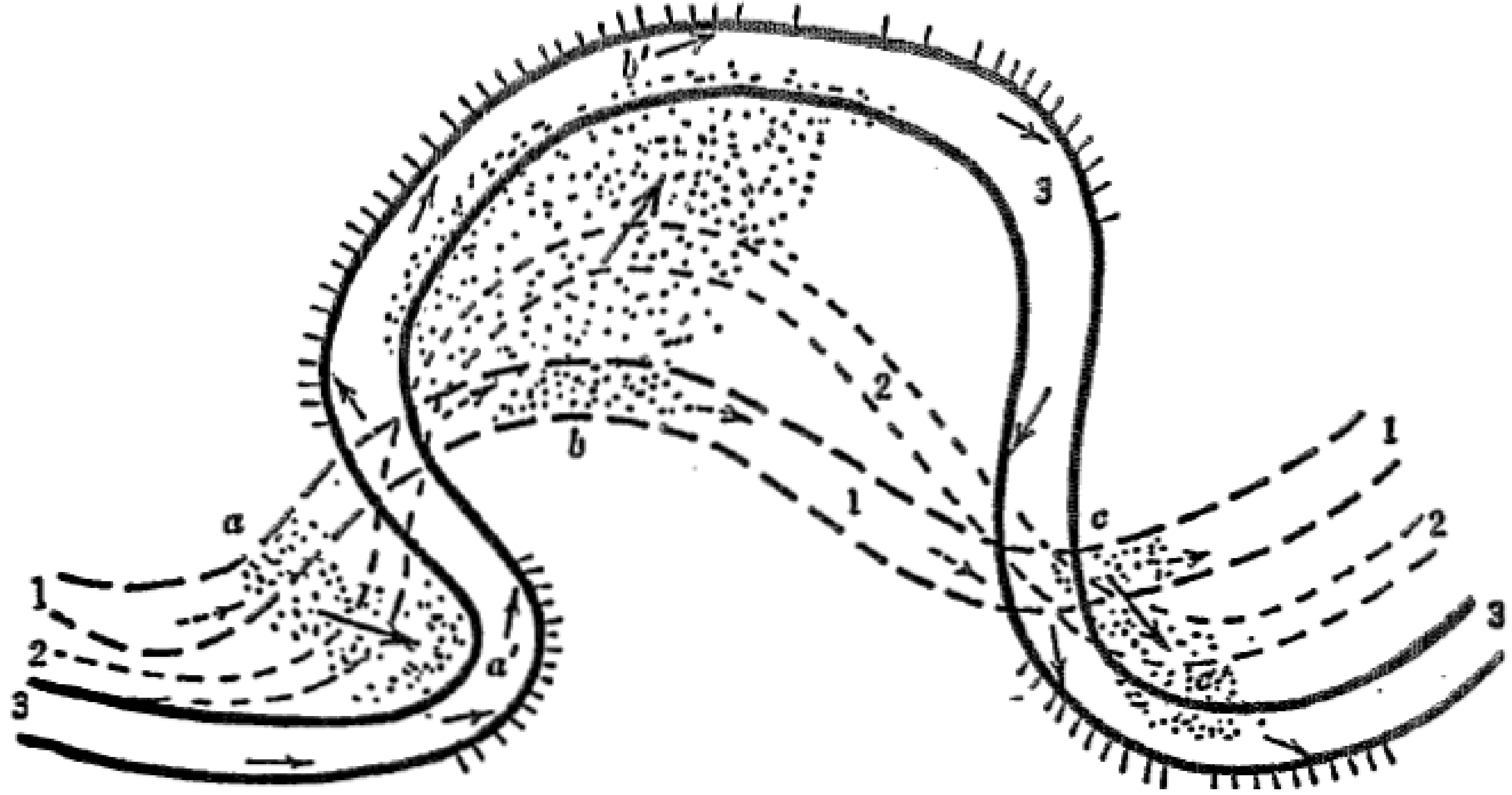
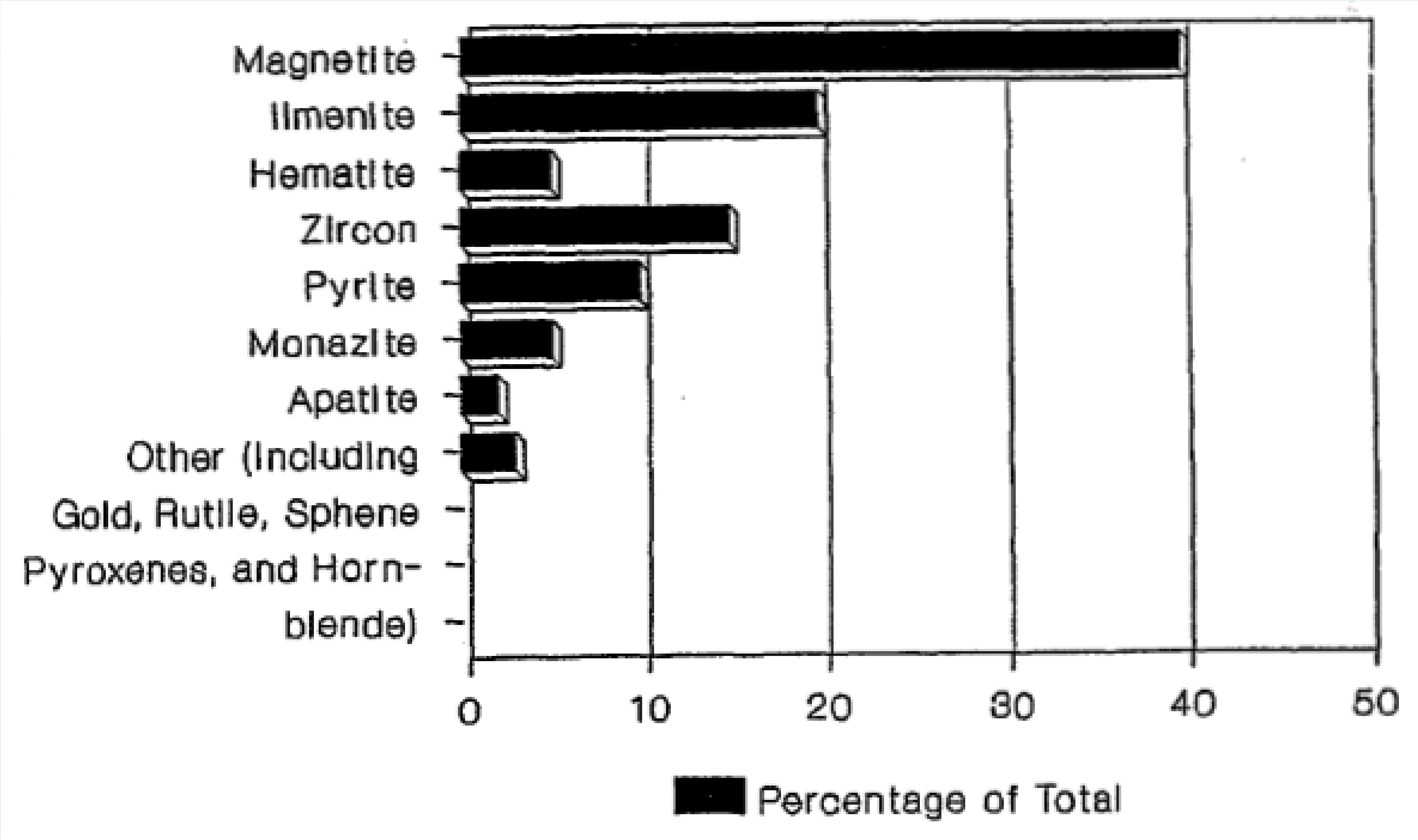


Fig. 4: The meandering of rivers and the location of gold deposition.

River placers



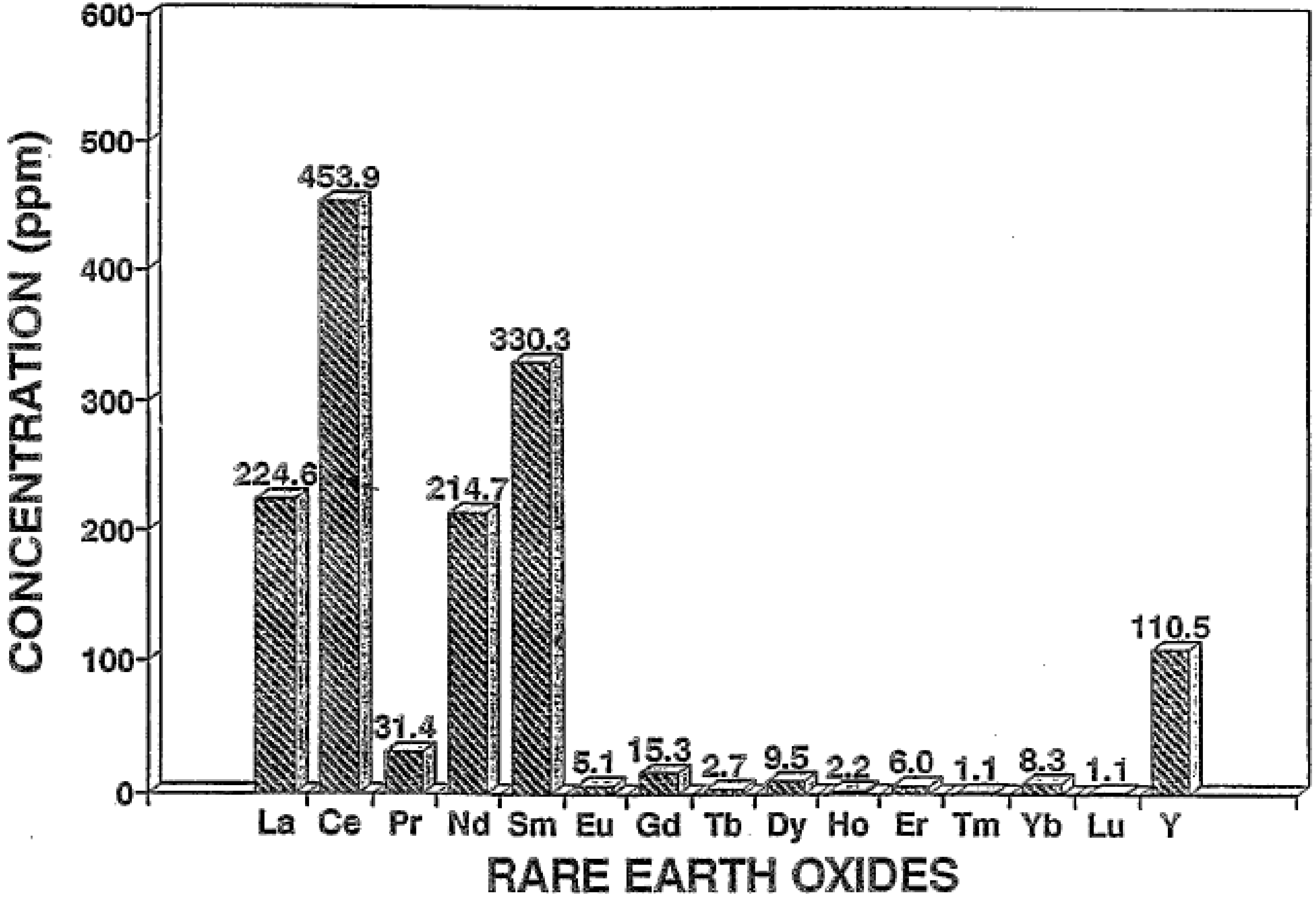
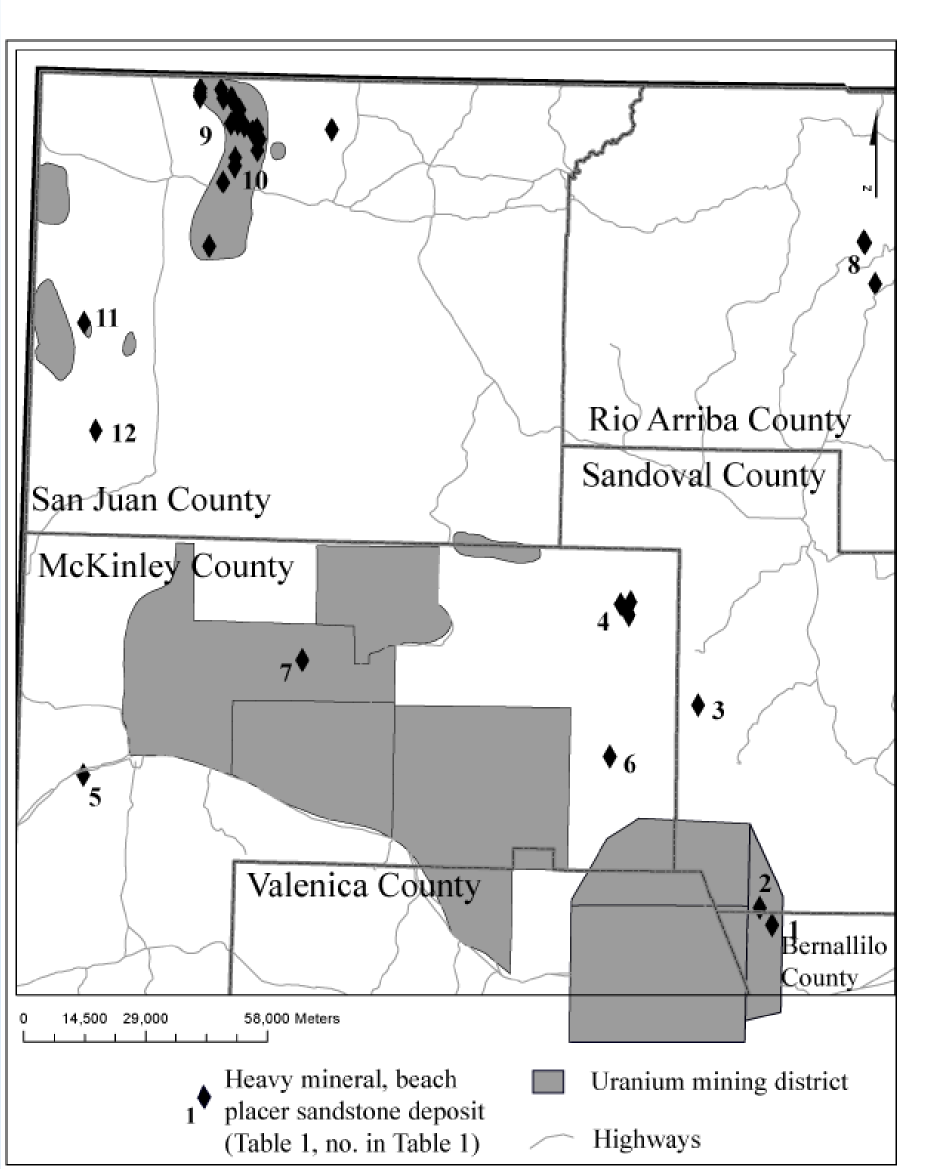
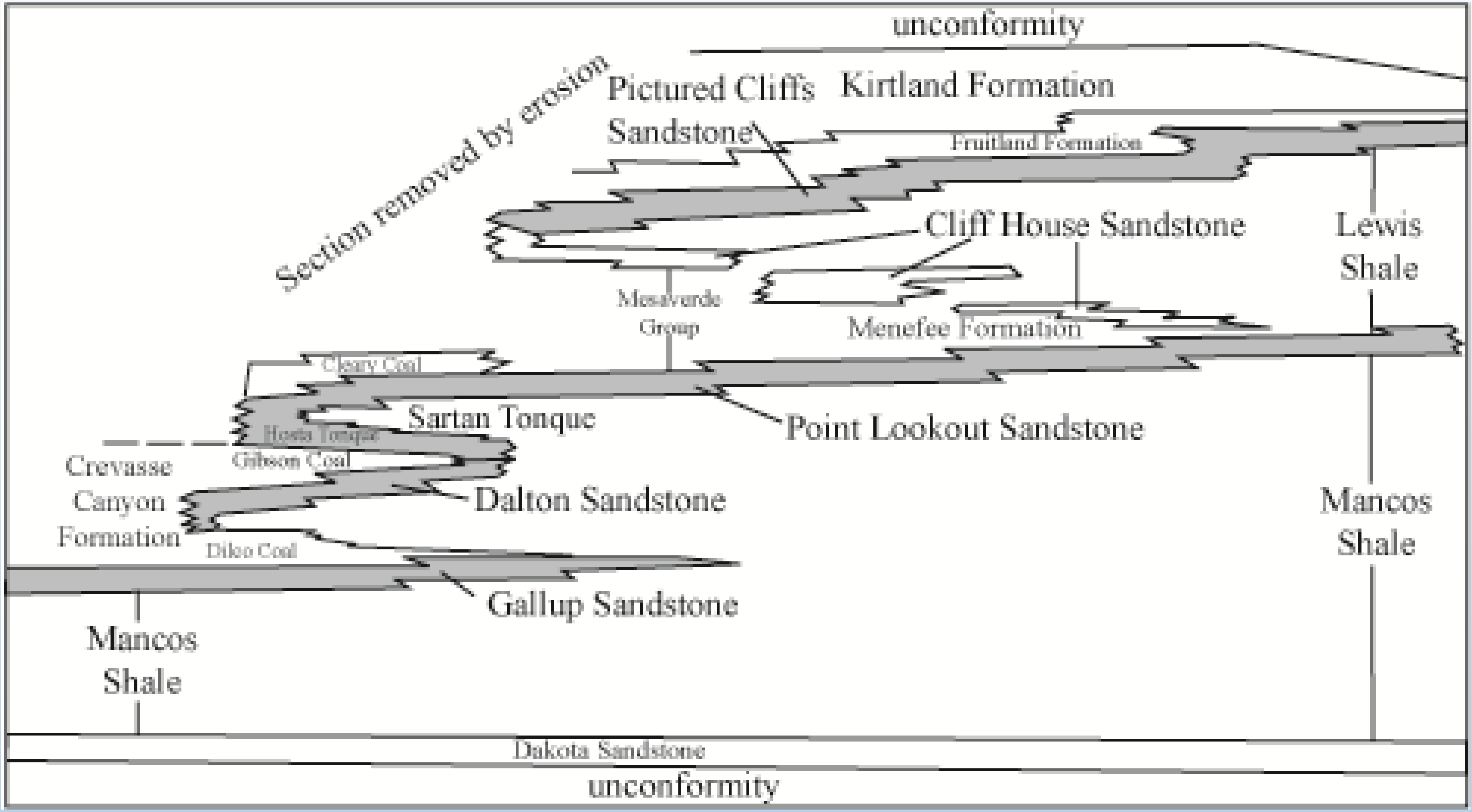


Fig. 7: Rare earth oxides in heavy mineral sand (Typical Urubama).

Paleo Beach Placers

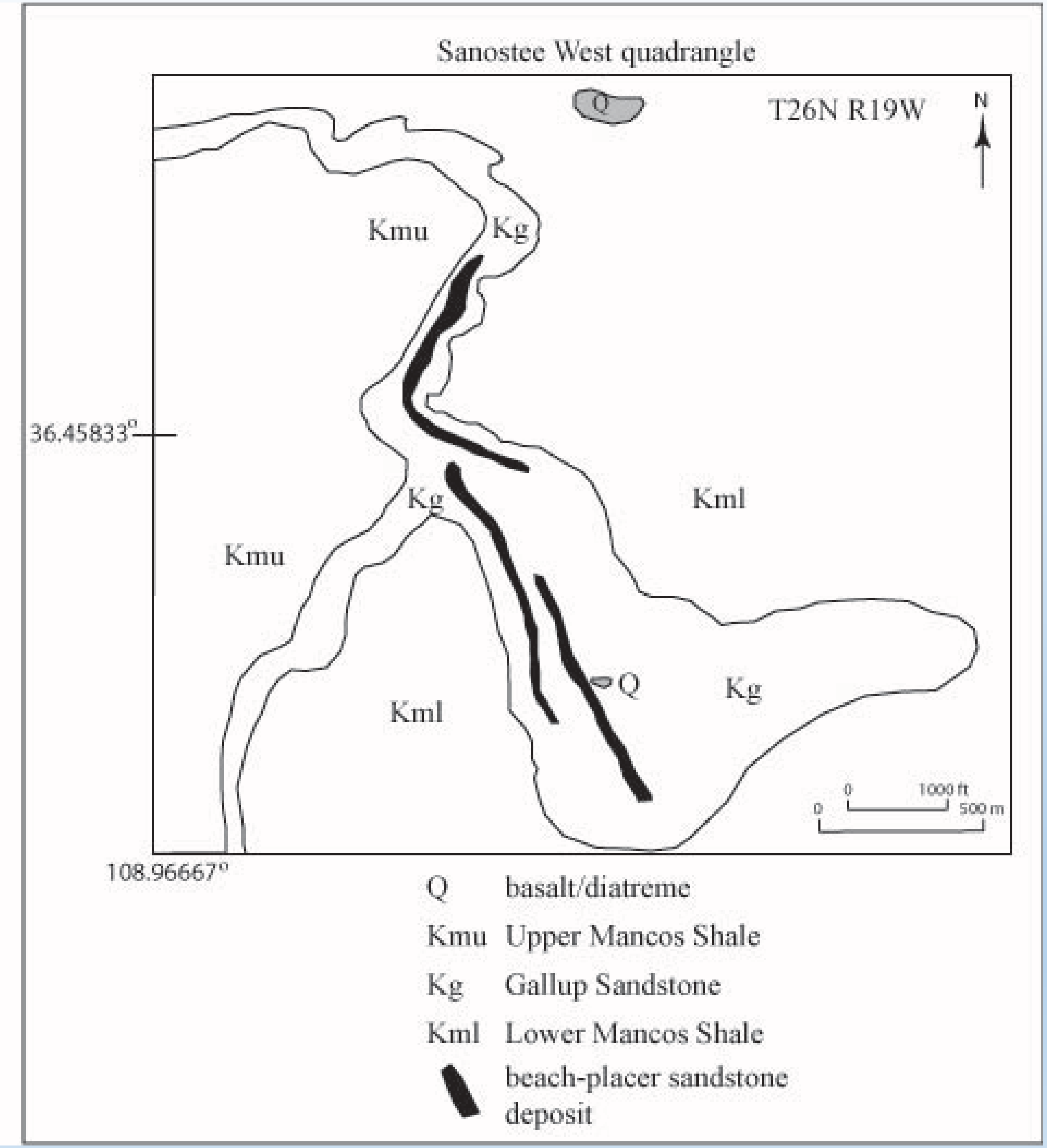




Gray-shaded sandstone units are hosts of known beach-placer sandstone deposits in the San Juan Basin

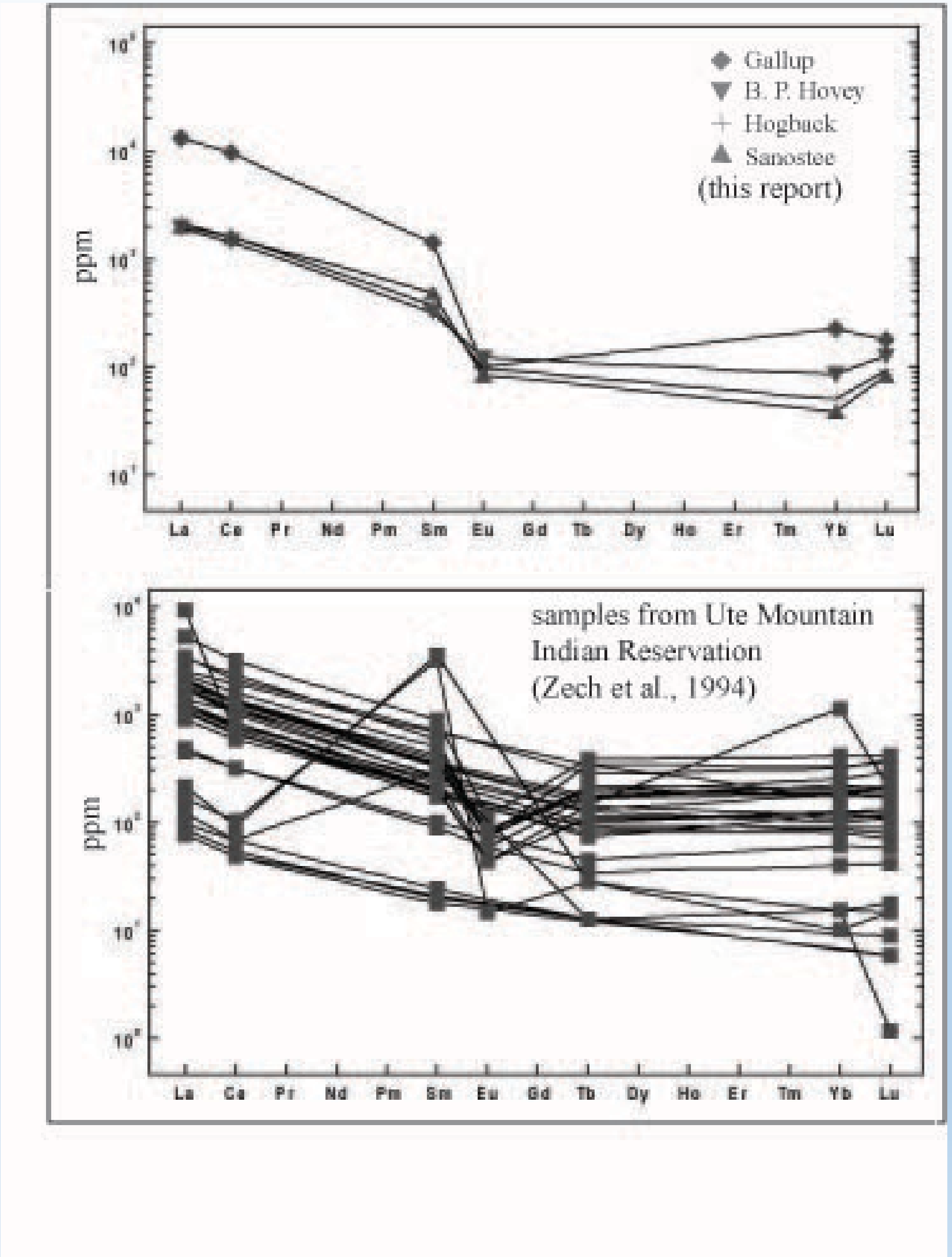
Sanostee deposit, San Juan County

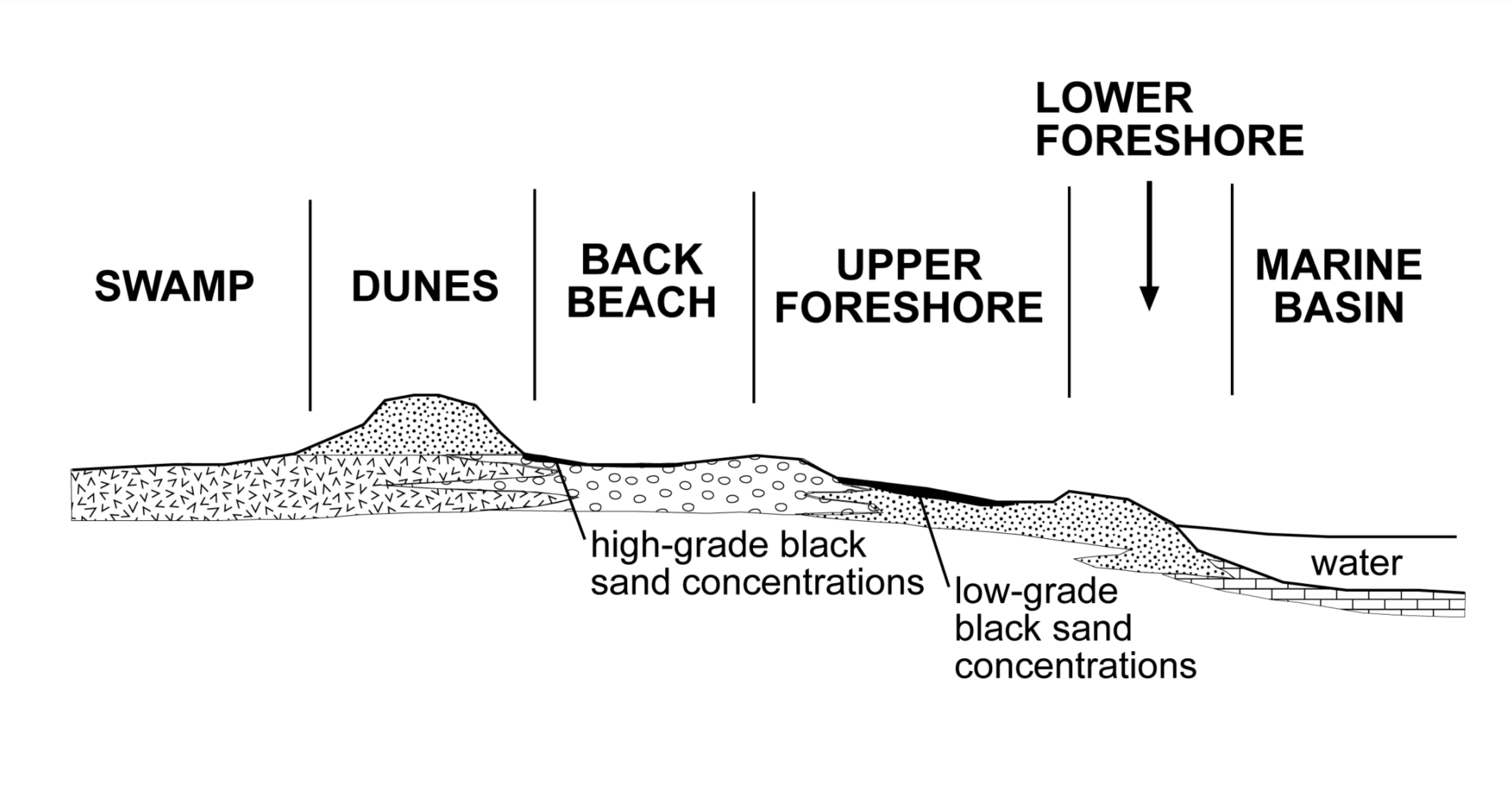
Sanostee



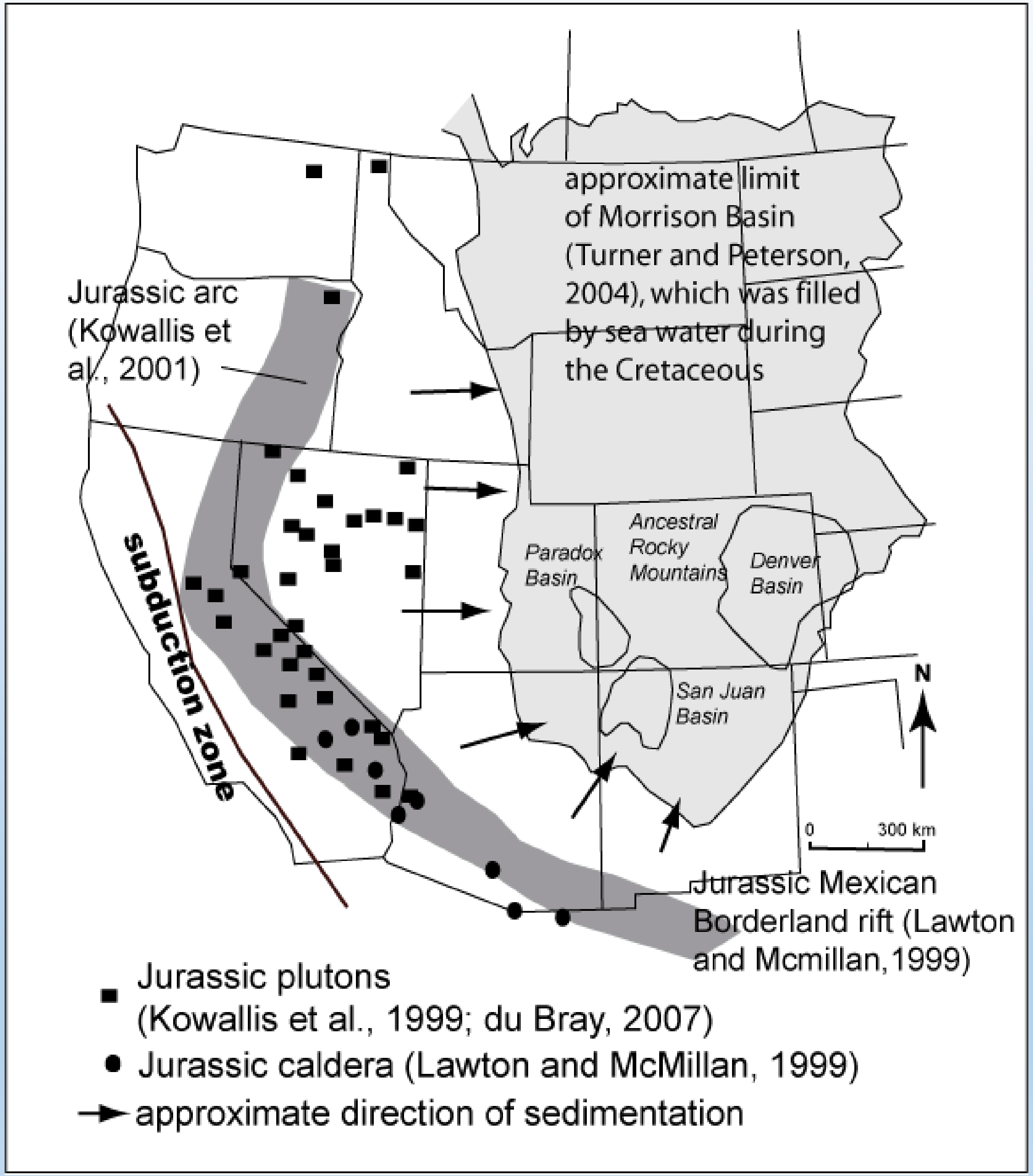
Sanostee West quadrangle
T26N R19W
N
Q
Kmu
Kg
36.45833°
Kml
Kg
Kmu
Q
Kg
Kml
0 1000 ft
0 500 m
108.96667°
Q basalt/diatreme
Kmu Upper Mancos Shale
Kg Gallup Sandstone
Kml Lower Mancos Shale
beach-placer sandstone deposit

REEin Beach placer deposits





Idealized cross-section of formation



Jurassic arc provided a highland consisting of granitic rocks that could have been a source

Porphyry Mo deposits

Porphyry Mo deposits

- Climax-type
- Low F

Climax-type

- Rare
- pluton-related deposits associated with rare-metal granites
- Mo, F, Li, Rb, Cs, Sn, Ta, Nb, REE, Be
- calc-alkaline I-type, peraluminous S-type, or peralkaline
- Closely associated with alkaline-related mineral deposits

Geochemistry

- Rb >250 ppm, Rb >250 ppm, F>2000 ppm
- Ta>2 ppm, Sr<100 ppm, Nb>50 ppm
- enriched in Be, Cs, Li, Sn, Th, W, U, REE

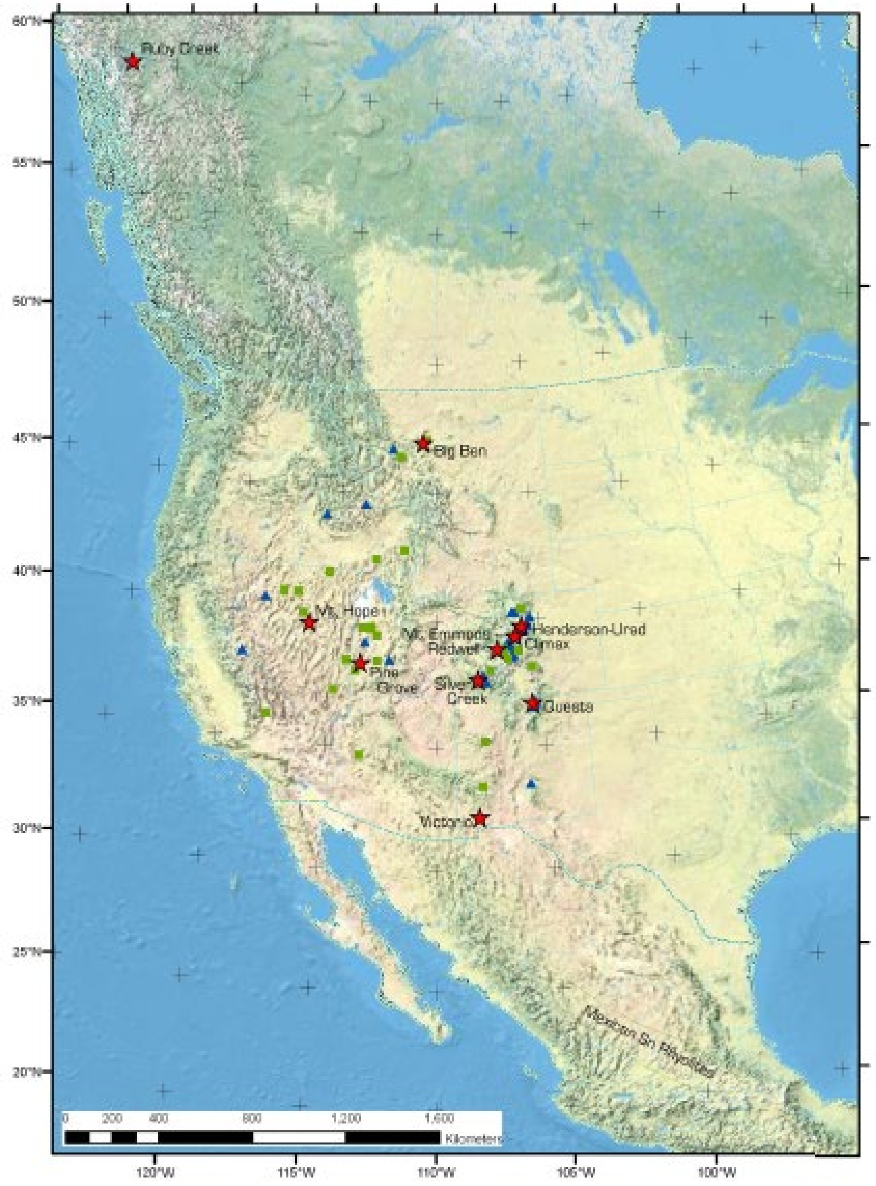
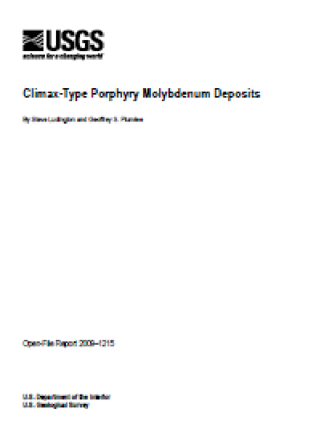


Figure 1. Location of Climax-type porphyry molybdenum deposits, prospects, and igneous centers with Climax-like compositions. Only the deposits (red stars) are labeled. Prospects are shown as blue triangles; igneous centers as green squares.



USGS

Climax-Type Porphyry Molybdenum Deposits

Open-File Report 2009–1215

U.S. Department of the Interior
U.S. Geological Survey

Table 1. Climax-type Porphyry Molybdenum Deposits.

Deposit	Age (Ma)	Longitude	Latitude	Contained Mo (t)*	Primary reference
Climax, Colorado	33–24	-106.171	39.369	1,790,000	Wallace and others, 1968
Henderson, Colorado	30–27	–105.841	39.758	1,070,000	Shannon and others, 2004
Urad, Colorado	29	–105.835	39.760	29,100	Not available
Mt. Emmons, Colorado	17	–107.051	38.884	344,000	Thomas and Galey, 1982
Redwell Basin, Colorado	17	–107.057	38.890	18,400	Sharp, 1978
Silver Creek, Colorado	5	–108.008	37.698	124,000	Cameron and others, 1986
Questa, New Mexico	25	–105.508	36.717	442,000	Ishihara, 1967
Log Cabin, New Mexico	25	–105.570	36.688	53,400	Not available
Victorio, New Mexico	35	–108.103	32.180	112,000	McLemore and others, 2000
Pine Grove, Utah	23	–113.607	38.336	192,000	Keith and others, 1986
Mt. Hope, Nevada	38–26	–116.186	39.795	460,000	Westra and Riedell, 1995
Big Ben, Montana	51	–110.710	46.975	104,000	Johnson, 1964
Ruby Creek, British Columbia	84	–133.403	59.709	208,000	Pinsent and Christopher, 1995

*Molybdenum tonnage from Gregory Spanski, 2009, written commun.

Formation

- very high temperatures, 400° C to >600° C
- Fluid inclusions are hypersaline and contain both halite and sylvite daughter minerals
- Alteration potassic, sericitic, and propylitic, and the potassic zone
- F- and Cl-rich hydrothermal fluid separated from the crystallizing apex of the pluton and moved primarily upward (contained Mo, W, other metals)
- This fluid evolved compositionally as it cooled and moved upward

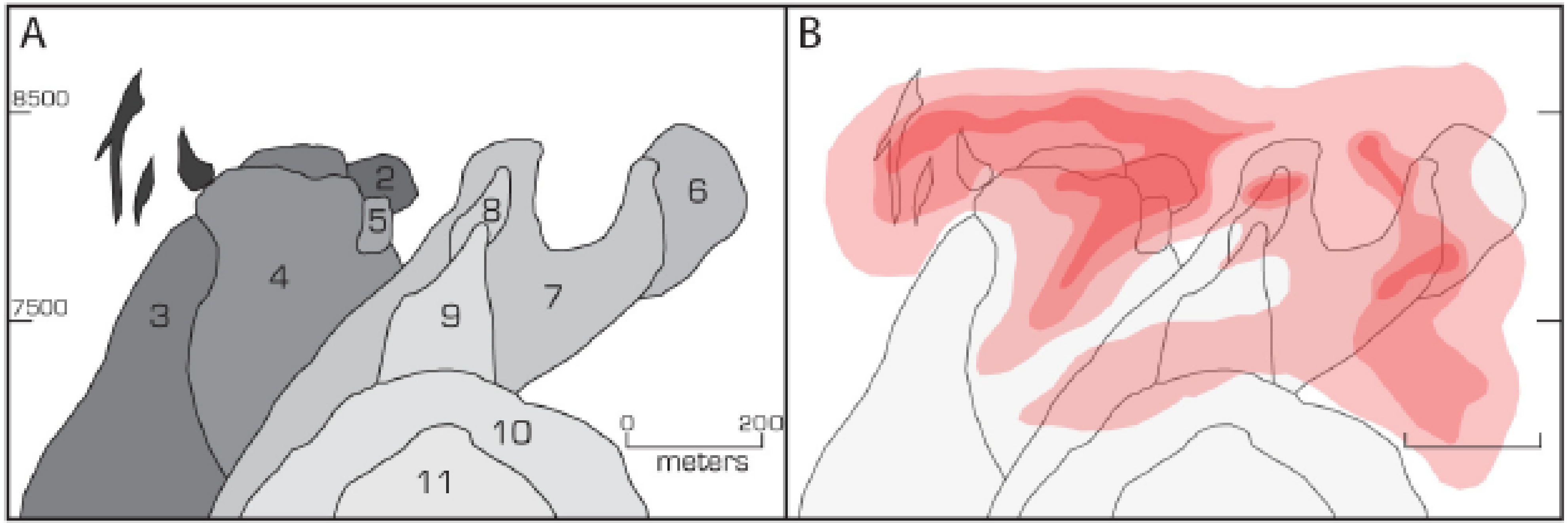
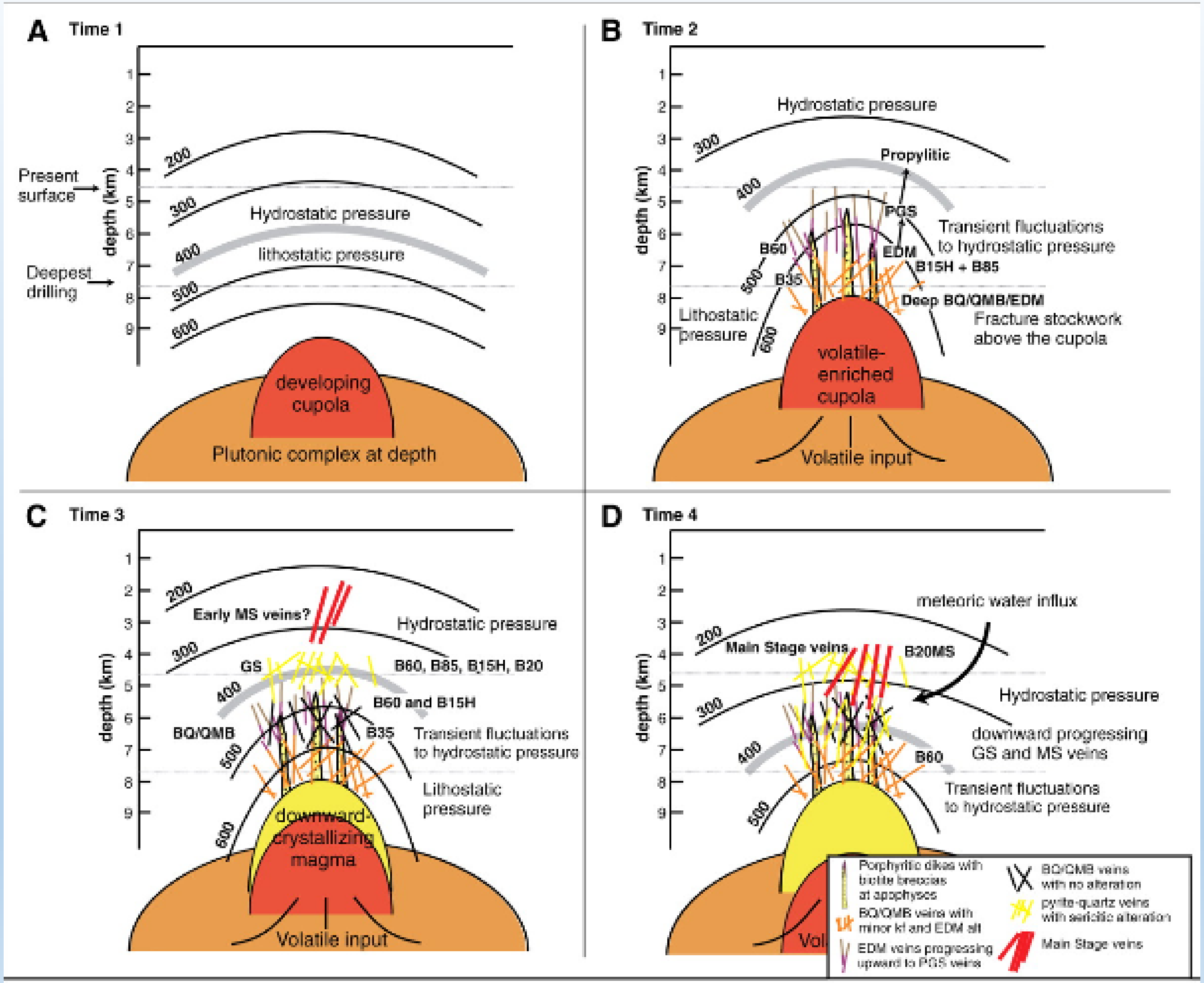


Figure 2. Relationship of multiple intrusions to ore at Henderson. Stocks are shown *A*, Numbered in order of age. Ore tenor is shown. *B*, in successively deeper shades of red, >0.1 percent, >0.3 percent, and >0.5 percent MoS_2. After figure 14 in Carten and others (1988). The earliest stock (the Phantom) does not appear in this cross-section.


A Time 1
Present surface
Deepest drilling
depth (km)
200
300
Hydrostatic pressure
400
lithostatic pressure
500
600
developing cupola
Plutonic complex at depth
B Time 2
Hydrostatic pressure
Propylitic
PGS
Transient fluctuations to hydrostatic pressure
B60
EDM
B15H + B85
B35
Deep BQ/QMB/EDM
Lithostatic pressure
Fracture stockwork above the cupola
volatile-enriched cupola
Volatile input
C Time 3
Early MS veins?
Hydrostatic pressure
GS
B60, B85, B15H, B20
B60 and B15H
BQ/QMB
B35
Transient fluctuations to hydrostatic pressure
Lithostatic pressure
downward-crystallizing magma
Volatile input
D Time 4
meteoric water influx
Main Stage veins
B20MS
Hydrostatic pressure
downward progressing GS and MS veins
B60
Transient fluctuations to hydrostatic pressure
Porphyritic dikes with biotite breccias at apophyses
BQ/QMB veins with minor kf and EDM alt
EDM veins progressing upward to PGS veins
BQ/QMB veins with no alteration
pyrite-quartz veins with sericitic alteration
Main Stage veins

Colluvial REE

Colluvial Xenotime and Monazite

Xenotime

Monazite

Serra Verde, Goiás, Brazil

Colluvial REE Deposits

One of the interesting sources for independent REE and Y mineralization can be in large volume colluvial deposits derived from weathered granite or metamorphic rocks. In some occurrences heavy mineral accumulations can represent several percent of the colluvium.

Heavy minerals may include liberated coarse-grained xenotime and monazite that are readily amenable to well established physical processing techniques without resorting to grinding.

An example of this scenario under current exploration by Mining Ventures of Brazil is the Serra Verde occurrence of Northern Goiás, Brazil.

Colluvial REE

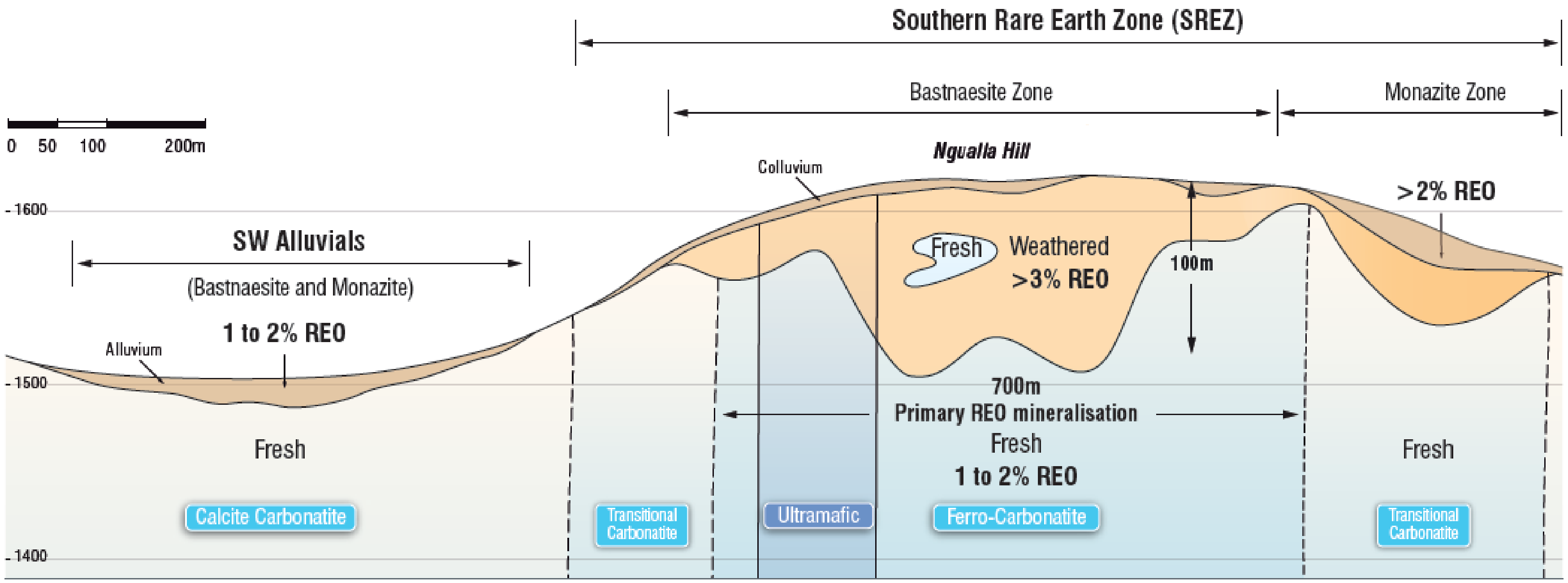


Figure 1: Cross section of Ngualla Hill showing bastneasite zone.

http://content.stockpr.com/peakresources/media/cb0ead90dcba68198a149dafcba9ccfd.pdf

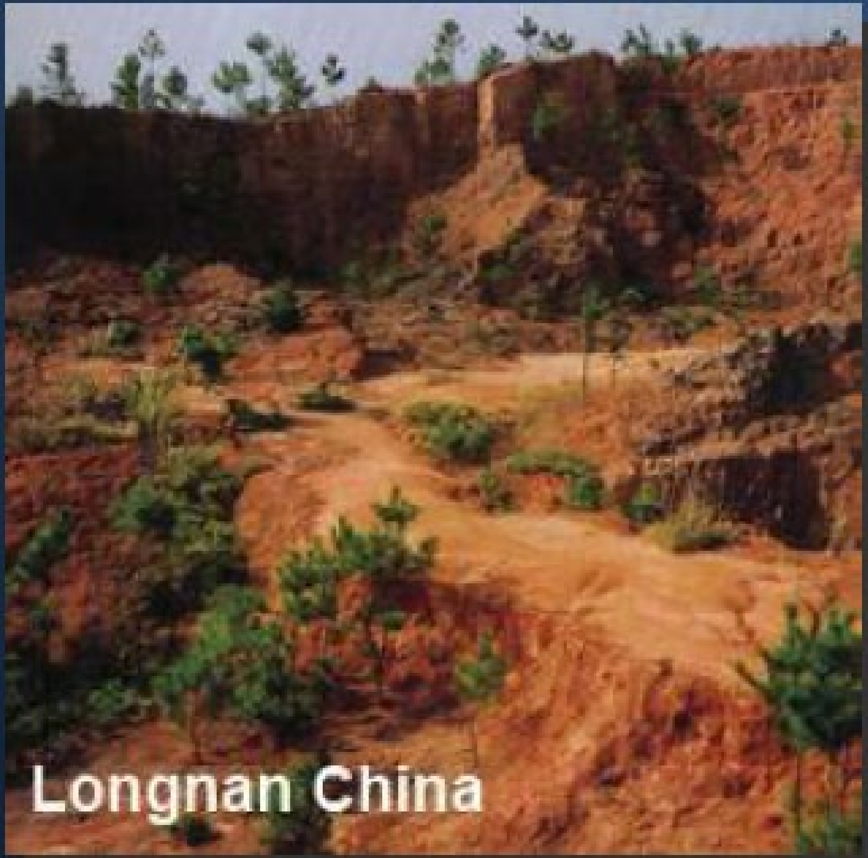
Residual/LATERITE

- Stratiform phosphate residual
- Ion adsorption clays/laterite/bauxite
- Supergene

Residual/LATERITE

- Jianghua, China with 0.012 Mt @ 0.035% total rare earth oxides or TREO)
- Mt. Weld, Australia (23.94 Mt @ 7.9% rare earth oxides or REO)
- Araxa, Brazil (6.34 Mt @ 5% TREO)
- Tantalus, Madagascar (1.5 Mt @ 0.8% REO)
- Ngulla, Tanzania (40 Mt @ 4.07% REO)

Ionic Clay Deposits, SE China



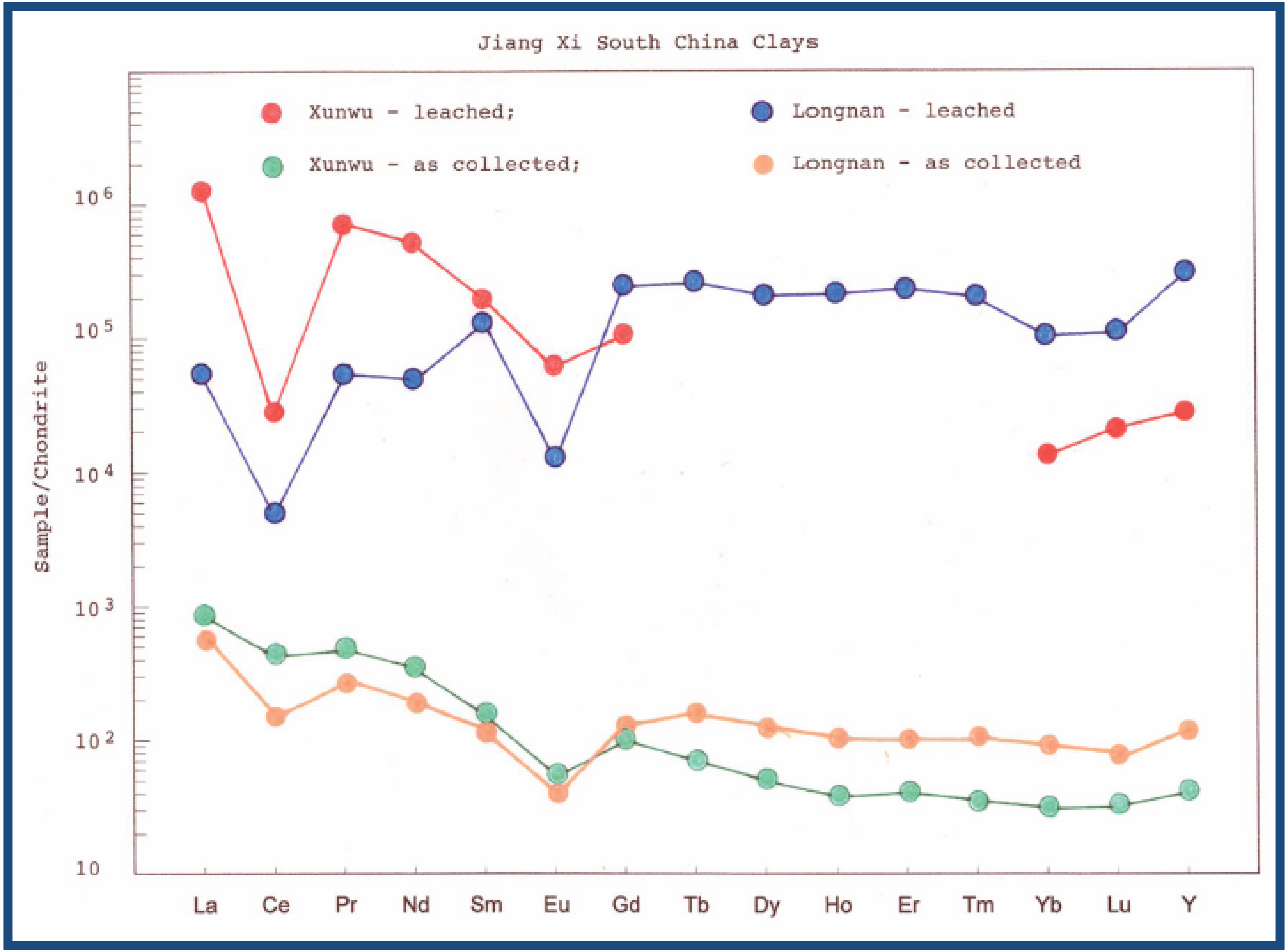
T. Tagaki, Geological Survey of Japan

About 0.5 percent TREO in a readily leached form in laterite formed on “tin” granites in southern China. Many of these deposits are enriched in HREE.

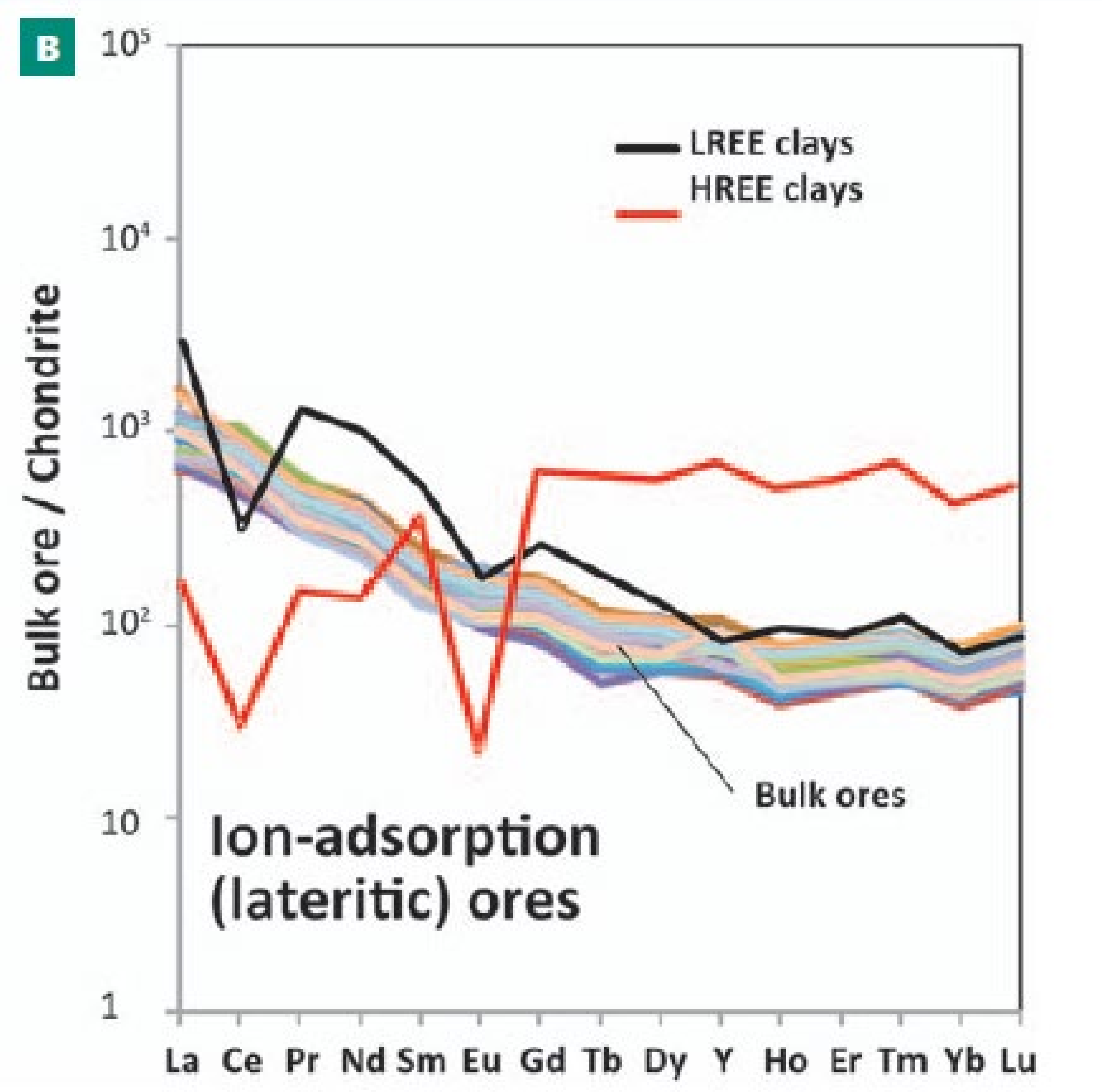
A significant source of REE, especially HREE, but resources are rapidly being depleted. Mining of these deposits in South China by undercapitalized small operators is environmentally problematic.

USGS


Ion-Adsorbed Clays
Xunwu Longnan District, Jiangxi Province, China



Jiang Xi South China Clays
Xunwu - leached;
Longnan - leached
Xunwu - as collected;
Longnan - as collected
Sample/Chondrite
10^6
10^5
10^4
10^3
10^2
10
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Y



Kynicky et al., 2012

Mount Weld, Australia

- 35 km south Laverton, western Australia
- Open pit with a strip ratio of 4.6:1
- Mined June 2008
  - 773,300 tonnes ore at 15.4% REO
  - 2 mill cubic meters of overburden removed
- Ore is stockpiled according to mineralogy and grade

http://www.lynascorp.com/Pages/rare-earths-project.aspx

Mount Weld, Australia With no Topographic Expression

March 10, 1980

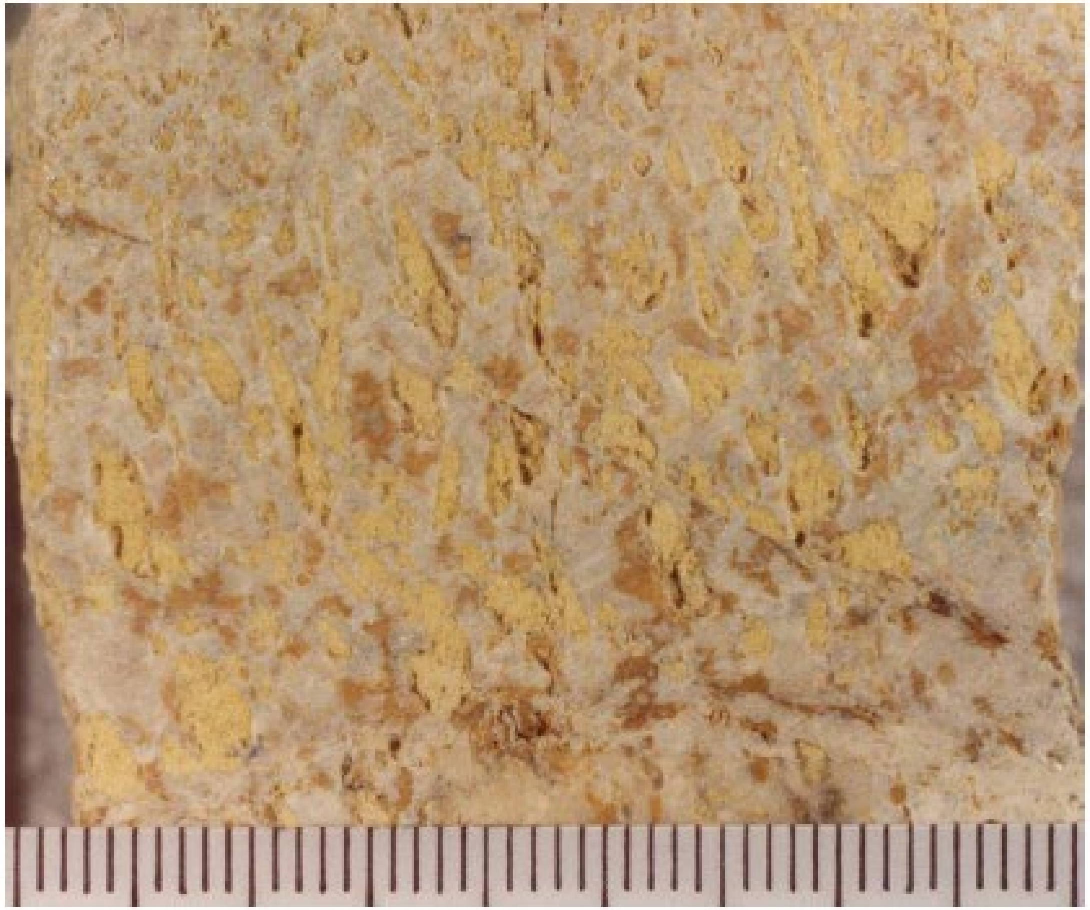
Category	Tonnes (Mt)	Grade (% REO)	Tonnes REO
Measured	1.2	15.6	186,000
Indicated	5.0	11.7	583,000
Inferred	1.5	9.8	148,000
Total	7.7	11.9	917,000

June, 2008

- Initial mining completed by Lynas Corporation in June 2008
- 773,000 metric tons of ore mined at an average grade of 15.4% REO
- Monazite, REE-bearing crandallite-group, cerianite, rhabdophane, churchite
- Mt Weld Resource Estimate – Central Lanthanide Deposit

Supergene Monazite
light greenish yellow in ferric iron-rich laterite
Araxá, Brazil
(34-A-3)
(coll. A.N.M. January, 1968)

Supergene Monazite
replacing massive apatite mineralization
Araxá, Brazil Furo O-IXMO, 191.25 meters
(12-A-1)



Pseudomorphs of Monazite after Apatite prisms in Carbonatite – Araxá, MG, Brazil

These pseudomorphs are the result of descending water that is enriched in REE from the dissolved primary minerals in the upper level weathered carbonatite. This section of drill core illustrates the leaching of Ca from the apatite and its replacement by REE as a result of the high affinity (partition coefficient) of REE for phosphate.

Reserves, Mount Weld

Rare Earths Oxides	CLD	Duncan Deposit
Lanthanum Oxide	23.88%	24.87%
Cerium Oxide	47.55%	39.38%
Praseodymium Oxide	5.16%	4.75%
Neodymium Oxide	18.13%	17.89%
Samarium Oxide	2.44%	2.83%
Europium Oxide	0.53%	0.77%
Gadolinium Oxide	1.09%	1.99%
Terbium Oxide	0.09%	0.26%
Dysprosium Oxide	0.25%	1.27%
Holmium Oxide	0.03%	0.19%
Erbium Oxide	0.06%	0.41%
Thulium Oxide	0.01%	0.04%
Ytterbium Oxide	0.03%	0.18%
Lutetium Oxide	0.00%	0.02%
Yttrium Oxide	0.76%	5.17%
Total	**100.00%**	**100.00%**

http://www.lynascorp.com/Pages/rare-earths-project.aspx

Phosphorite deposits

Rare Earth Element Minerals & Deposit Types

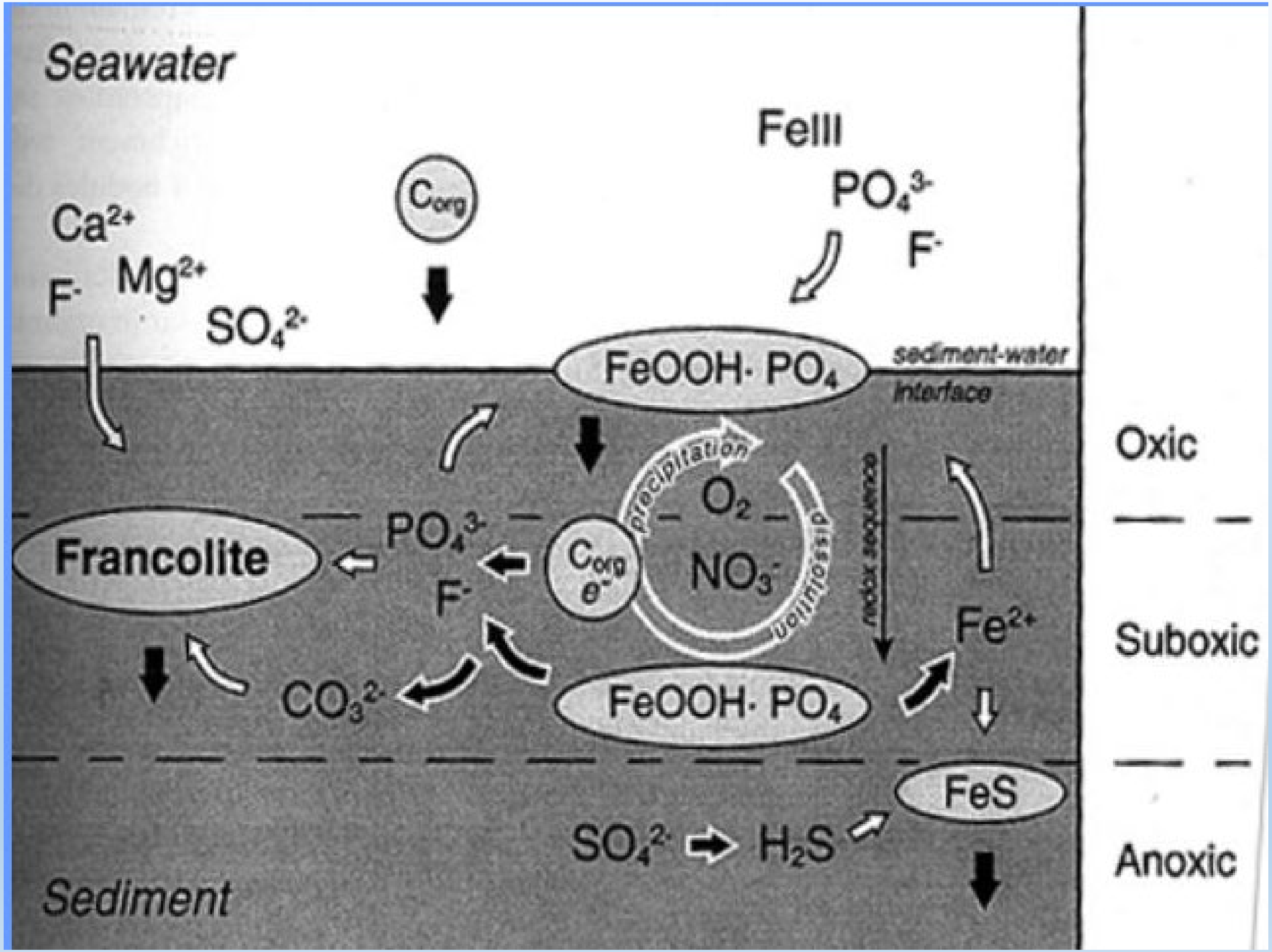
Group-Mineral	Formula	Carbonatite	Alkaline Intrusion-Related	Placer	Phosphorite
Oxides					
Aeschynite	$(Ln,Ca,Fe)(Ti,Nb)_2(O,OH)_6$		X		
Euxenite	$(Y,Ln,Ca)(Nb,Ta,Ti)_2(O,OH)_6$		X	X	
Fergusonite	$YNbO_4$		X		
Carbonates					
Bastnäsite	$(Ln,Y)CO_3F$	X	X		
Parisite	$Ca(Ln)_2(CO_3)_3F_2$	X	X		
Synchisite	$Ca(Ln,Y)(CO_3)_2F$	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	

USGS science for a changing world

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

Phosphorite deposits

- Florida, North Carolina
- Phosphoria Formation, Idaho, Montana
- High P_2O_5, 1-40%
- Sedimentary deposits (limestones, muds)
- Apatite, fluorapatite


Seawater
FeIII
PO_4^{3-}
F^-
C_{org}
Ca^{2+}
F^- Mg^{2+}
SO_4^{2-}
$FeOOH \cdot PO_4$
sediment-water interface
Oxic
precipitation
O_2
dissolution
redox sequence
Francolite
PO_4^{3-}
F^-
C_{org} e^-
NO_3^-
Fe^{2+}
Suboxic
CO_3^{2-}
$FeOOH \cdot PO_4$
FeS
SO_4^{2-} → H_2S
Anoxic
Sediment

Ancient Phosphorites	**Modern/Quat. Phosphorites**
• Grainstone phosphorites	Phosphorite nodules
• **Stromatolites (stratiform and columnar Microbial mats)**	Stromatolites are unknown
• A few meters to 100 m thick Phosphorite beds	Scattered on the sea floor
• Both upwelling and non-upwelling regions	Mostly confined to the western margins - **upwelling regions**
• Extensive reworking & **Benthic microbial activity**	**Inorganic processes**

No Modern/Quat. analogs for ancient phosphorites - (Bentor, 1980; Cook, 1994) ??

http://www.ias.ac.in/meetings/annmeet/69am_talks/vprao/img10.html

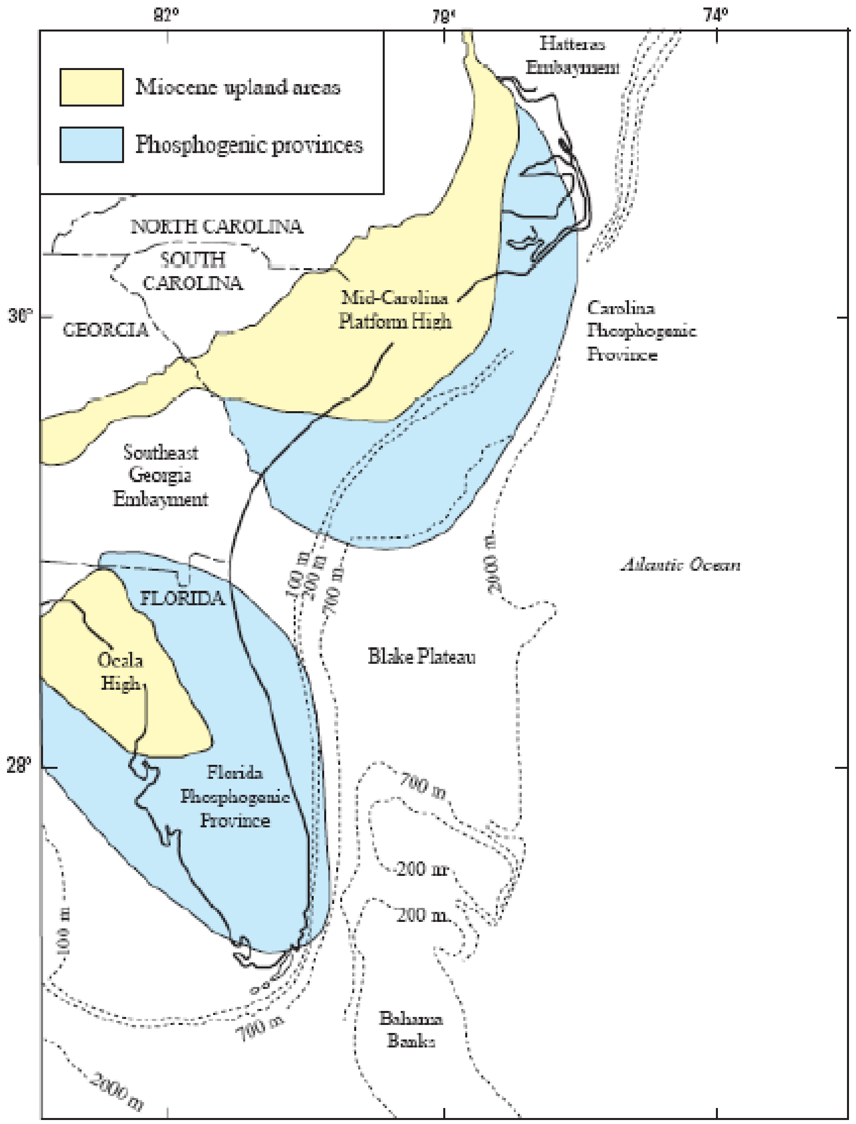
Stromatolites

Stromatolites are organo-sedimentary deposits produced by sediment trapping, binding and/or precipitation as a result of the growth and metabolc activity of microorganisms, principally Cyanobacteria

(Walter, 1976)

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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Modern environments in Marine seas

- continental shelves and slopes
  - Peru, Chile, Namibia, South Africa, Baja California
- submarine plateaus, ridges, and banks, such as Blake Plateau off the southeastern US Chatham Rise off New Zealand
- islands, atolls, and within atoll lagoons (guano; Nauru Island)
- mid-plate seamounts

Unconformity-associated uranium deposits

REE in Uraninites (UO_2)*

Location	Rössing Mine, Namibia	Faraday Mine, Ontario, Canada	Fission Mine, Ontario, Canada	Eldorado Mine, N.W.T., Canada	Collins Bay, Saskatchewan, Canada	Pine Creek Geosyncline, Australia
Geologic Environment	Alaskitic-Granite	Granite Pegmatite	Metamorphic Vein Dike	Hydrothermal Vein Deposit	Unconformity Type Deposit	Unconformity Type Deposit
REE	2.52%	2.89%	1.89%	0.71%	0.13%	0.17%
LREE/HREE	0.41	1.10	1.03	1.15	0.08	0.19

*Fryer, B.J. and Taylor, R.P., 1987, Rare-Earth Element Distributions in Uraninites, Implications of Ore Genesis, Chemical Geology, 63, 101-106.
These analyses do not include Y

REE in Uraninite

	Rossing	Faraday Mine	Fission Mine	Eldorado Mine	Collins Bay	Pine Creek
	Mine, Namibia	Ontario, Canada	Ontario, Canada	N.W.T., Canada	Saskatchewan. Canada	Geosyncline, Australia
Deposit type	Alaskitic-granite	Granite-pegmatite	Metasomatic vein dyke	Hydrothermal vein deposit	Uncontbrmity-type deposit	Unconformity-type deposit
La (ppm)	1,281	602	652	368	3.9	30
Ce	5,687	8,413	5,692	1,437	50	92
Pr	695	1,317	824	272	14	n.a.
Nd	3,390	7,080	4,374	1,211	83	200
Sm	1,657	2,503	1,454	705	62	214
Eu	n.d.	605	185	298	20	61
Gd	1,849	2,247	1,316	935	202	277
Tb	523	458	301	193	76	83
Dy	4,205	2,869	2,072	958	507	490
Er	2,822	1,766	1,180	389	168	144
Yb	3,060	991	830	347	90	127
TREE (ppm)	**25,163**	**28,856**	**18,872**	**7,115**	**1,276**	**1,741**

Fryer & Taylor (1987)

TYPES OF UNCONFORMITY-ASSOCIATED URANIUM DEPOSITS

- Clay-bound Proterozoic unconformity
- Strata-bound Proterozoic unconformity
- Strata-bound Proterozoic unconformity
- Phanerozoic unconformity-related

Unconformity-associated uranium deposits

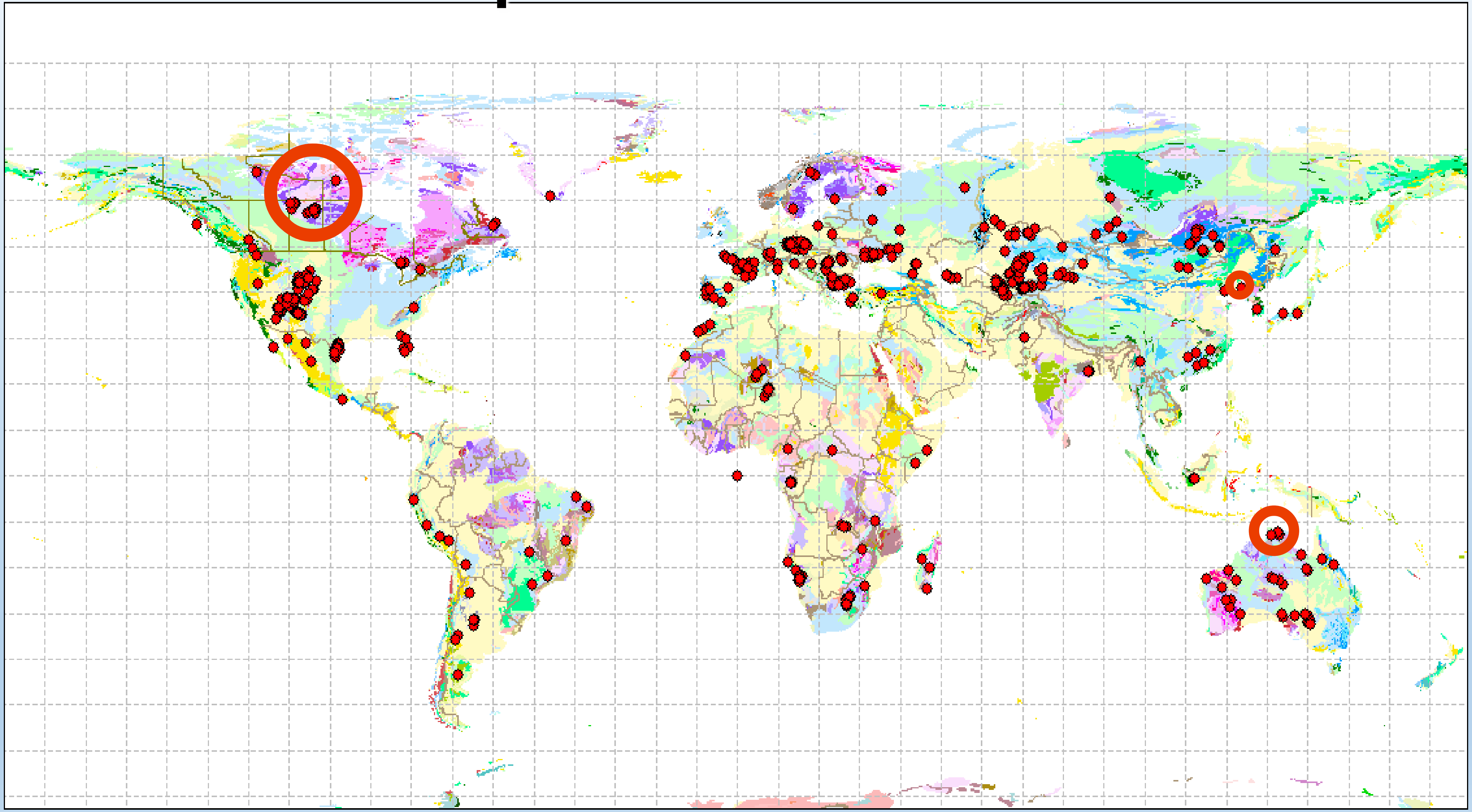
- Massive pods, veins and/or disseminated uraninite associated with unconformities between Proterozoic siliciclastic red beds and metamorphic basement that includes graphitic metapelite and radiogenic granite.

Unconformity-associated uranium deposits

- Pitchblende fills extensional features in reactivated fault zones and replaces matrix in sandstone

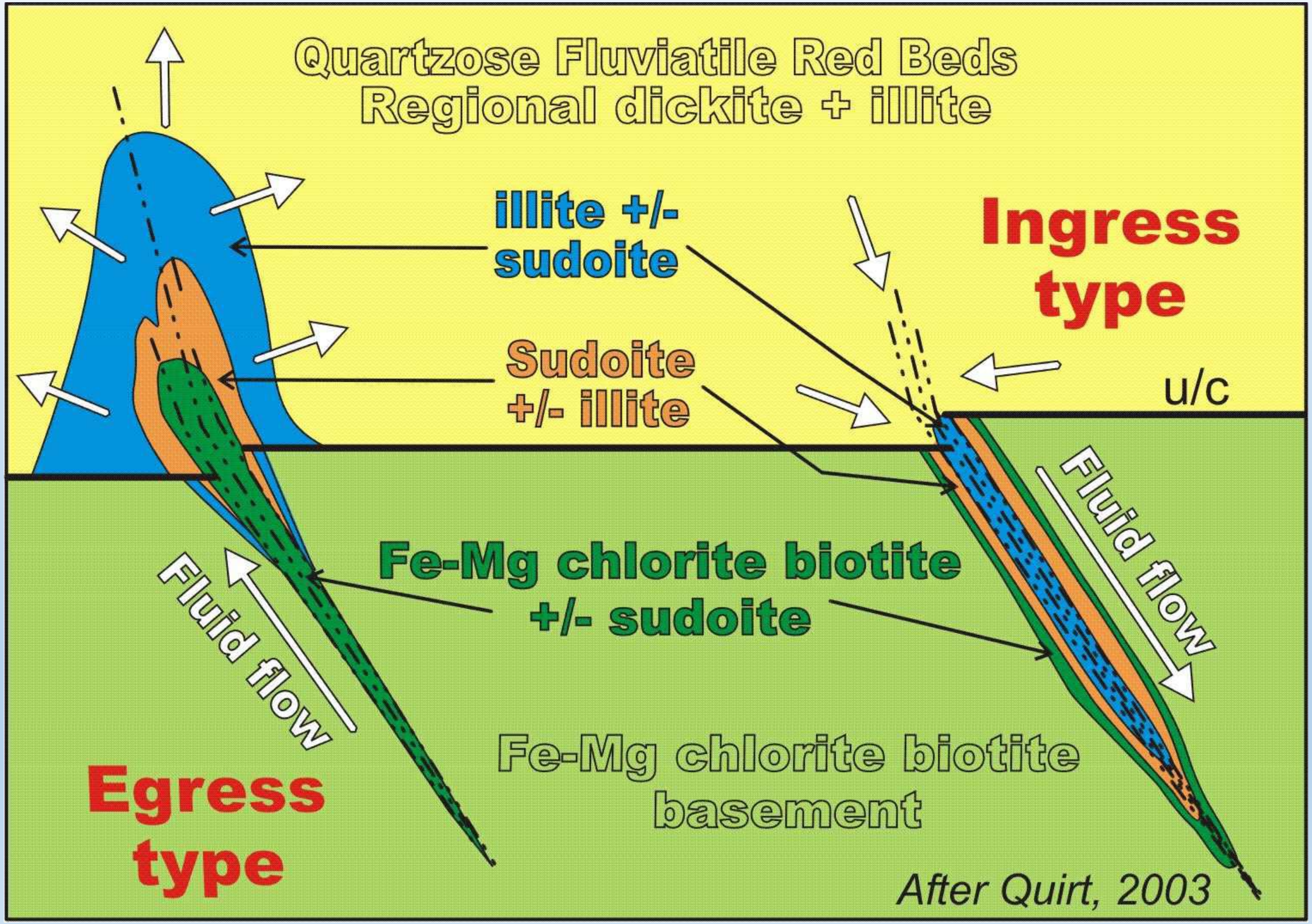
- One mining district in Canada
  – the Athabasca Basin
  - >30 deposits /prospects
  - most in eastern ¼ of basin
  - produces 1/3 of world's U

Unconformity-associated uranium deposits

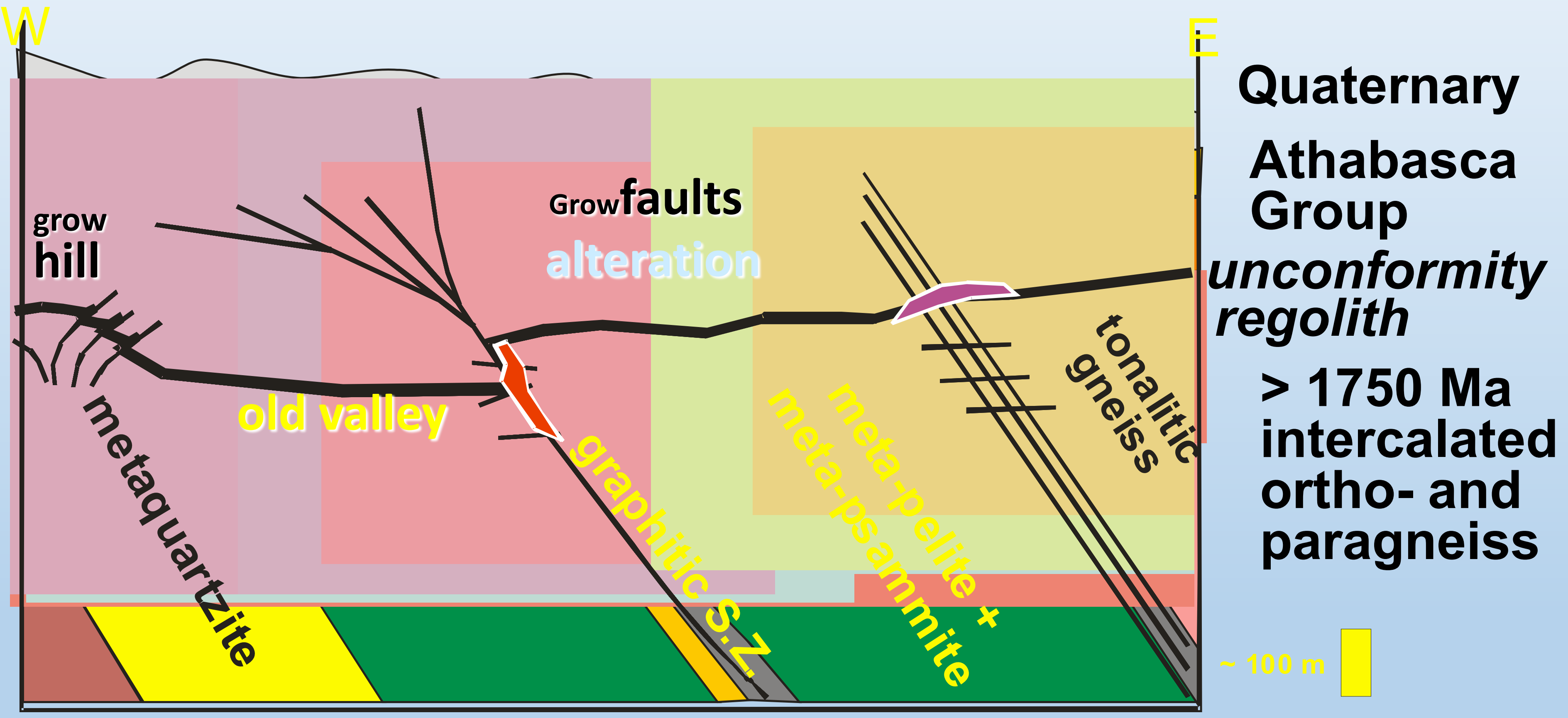


590 Economic / potential U deposits all types >500 Tonnes U @ >0.03% U (IAEA)

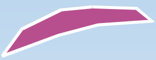
One deposit type, two end-member fluid flows



Summary—Unconformity-associated uranium deposits



Mono-metallic
- -basement hosted
- -uranium
- -Lower total REE



Poly-metallic
- -"sandstone" hosted
- -U, Ni, Co, Cu, As
- -high total REE

MAJOR UNCONFORMITY TYPE DEPOSITS IN THE WORLD

- Athabasca Basin, Saskatchewan, Canada
- Pine Creek Geosyncline, Northern Territory, Australia

QUARTZ-PEBBLE CONGLOMERATE DEPOSITS

QUARTZ-PEBBLE CONGLOMERATE DEPOSITS

- Upper Archean to Lower Proterozoic age
- consist of detrital ore minerals of uranium and other metals
- pyrite
- Interbedded within siliciclastic sequences containing layers of quartzite and argillite
- mineralized conglomerates.
  - Blind River, uranium and rare earth elements base of the stratigraphic sequence above the unconformity.
  - In the Witwatersrand, uranium in multiple beds dispersed through a thick stratigraphic sequence and is recovered as a by-product of gold production.

QUARTZ-PEBBLE CONGLOMERATE DEPOSITS

- Blind River — Elliot Lake, Ontario, Canada
- Witwatersrand, South Africa

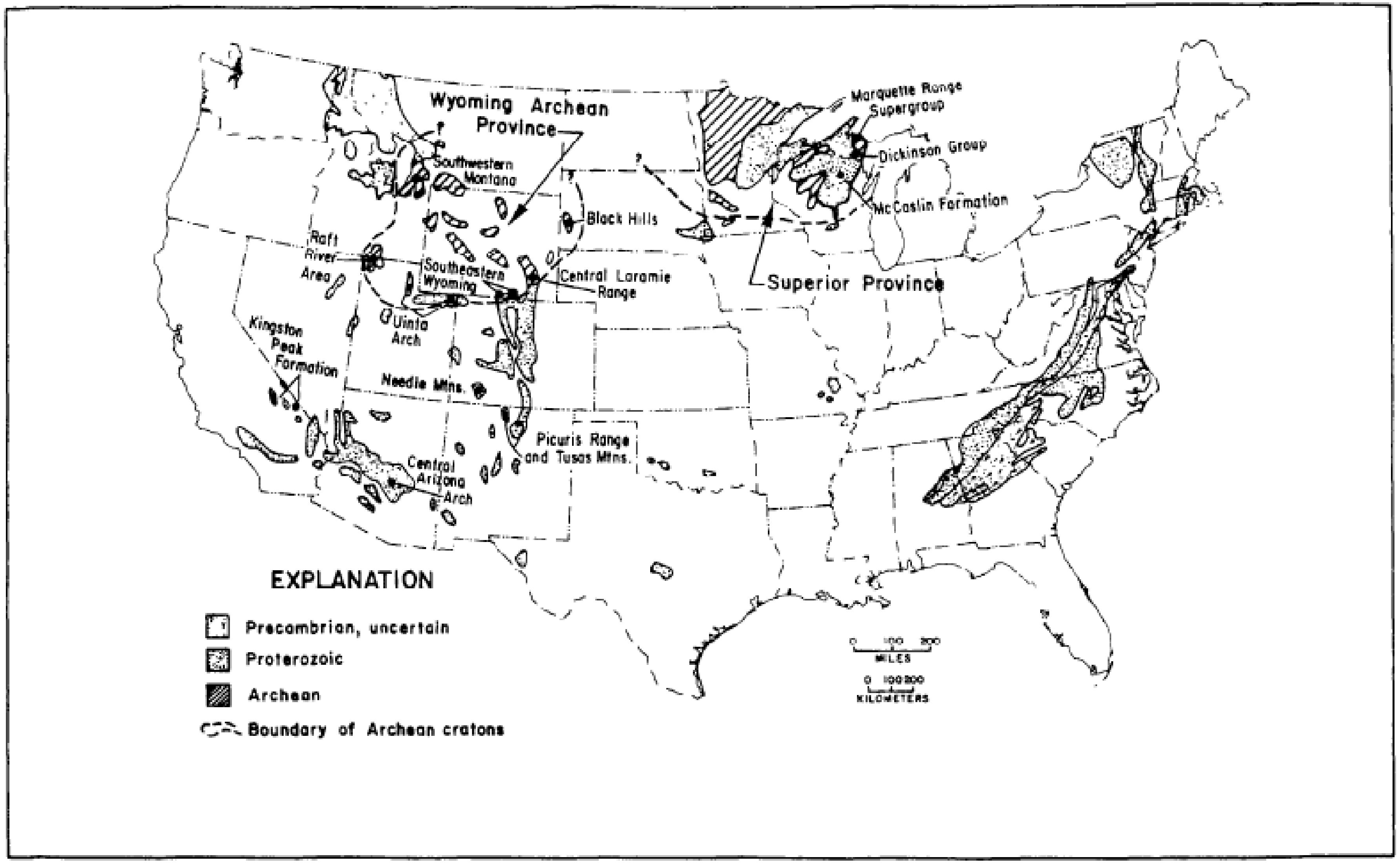


Figure 1. Generalized map of Archean and Proterozoic rocks in the conterminous United States showing specific areas with conglomeratic facies.

Sea floor

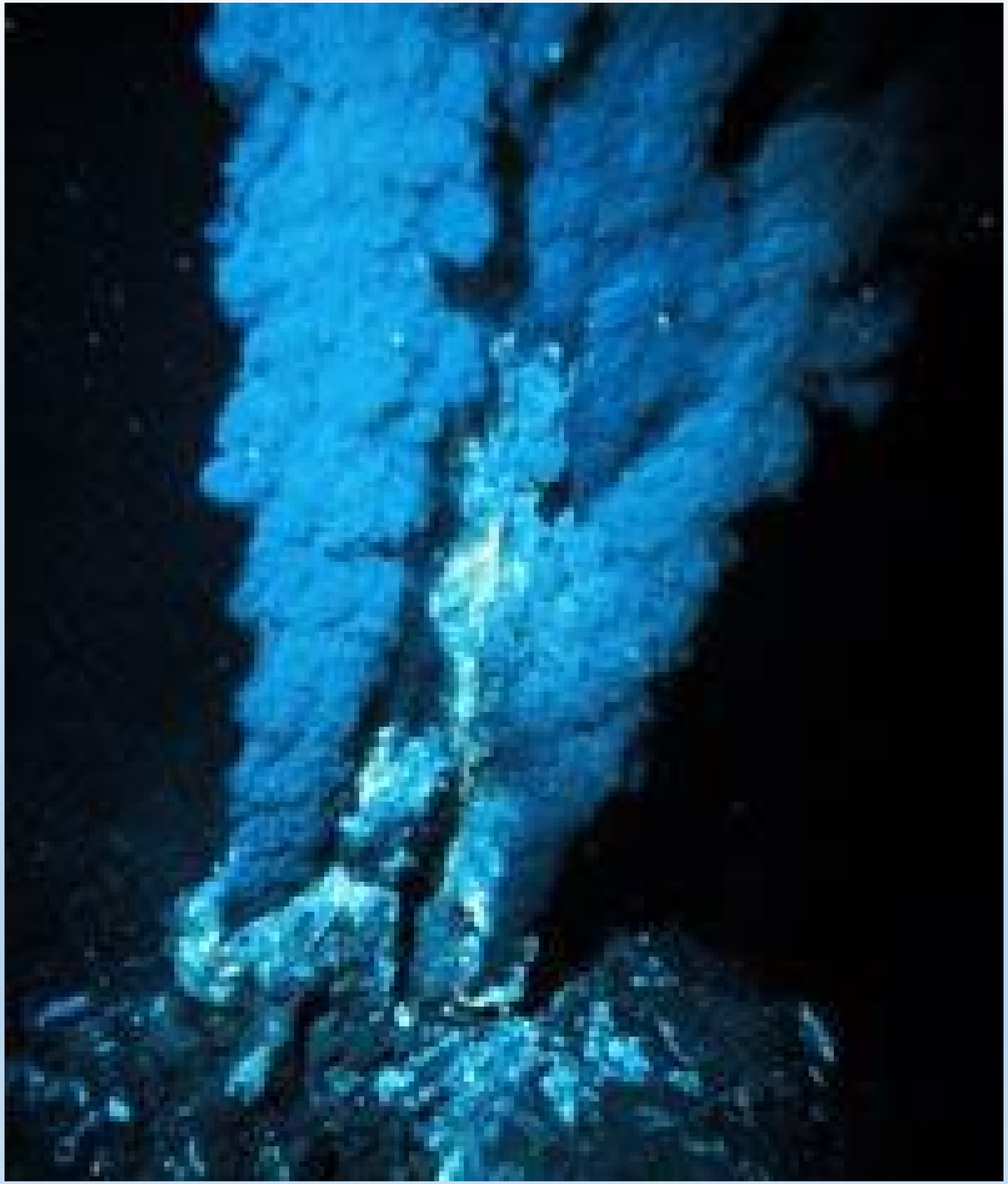
- Muds
- Manganese nodules
- Ferromanganese crusts (sea mounts)

Figure 3. Ferromanganese crust coating phosphorite from a Pacfiic seamount.

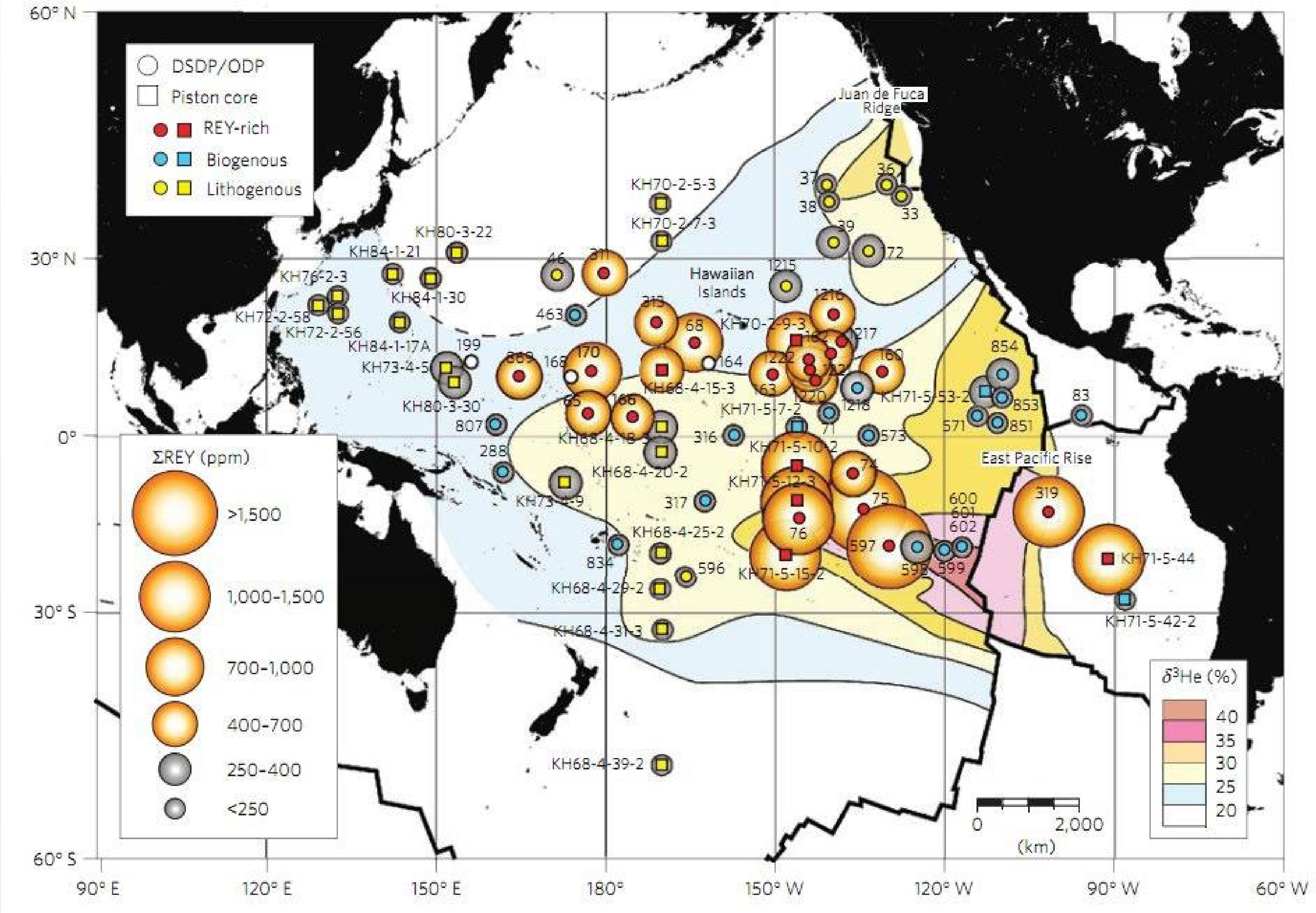
Figure 1. A cluster of manganese nodules 20 cm in diameter and weighing 25 kg. Photograph courtesy of the German Federal Institute for Geosciences and Natural Resources (BGR).

http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6107119

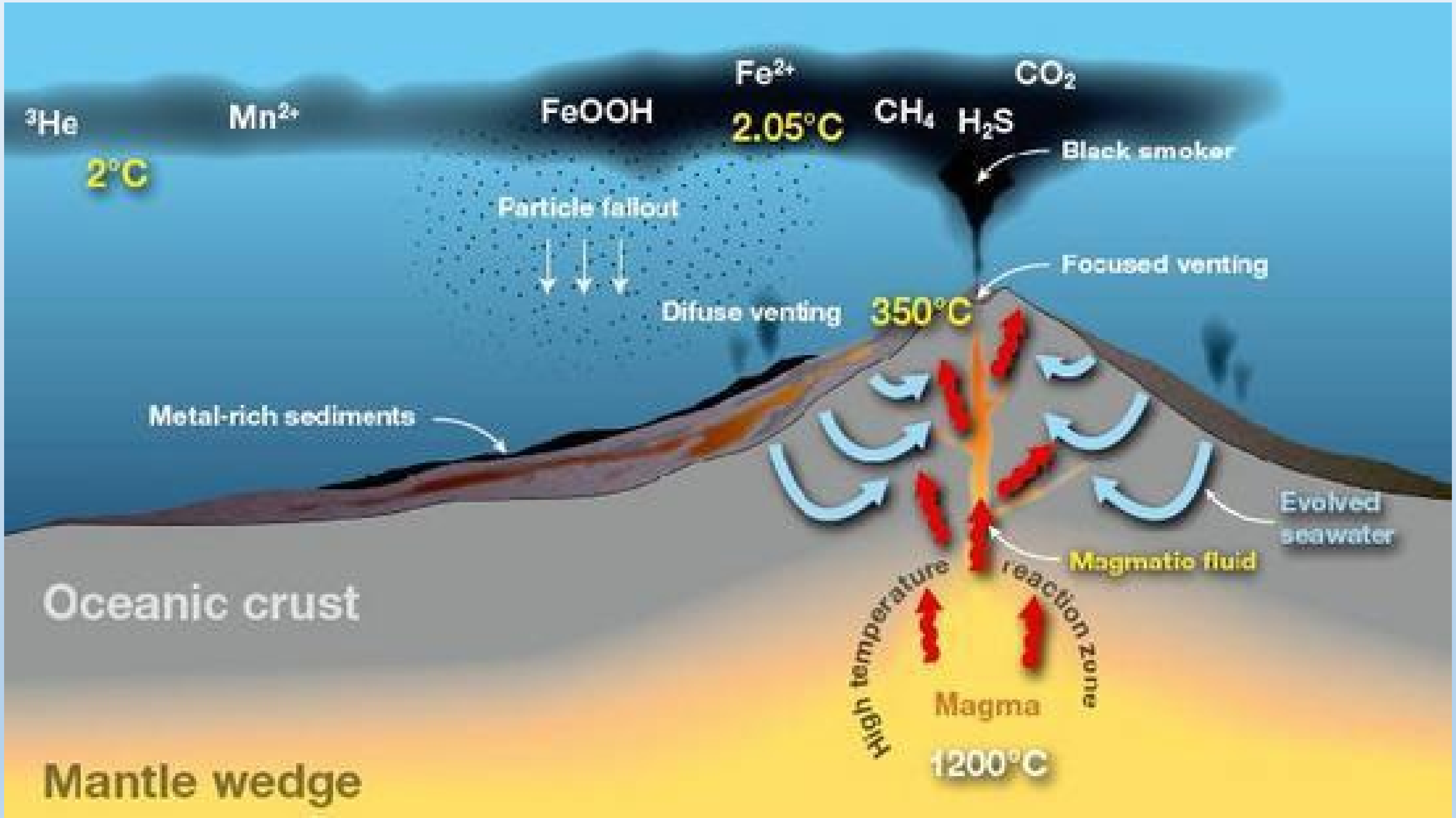
Sea floor muds



Sea floor muds



Sea floor muds



Alkaline/peralkaline Igneous Rocks

>791 Alkaline/peralkaline igneous rock complexes in the world

Definition alkaline rocks

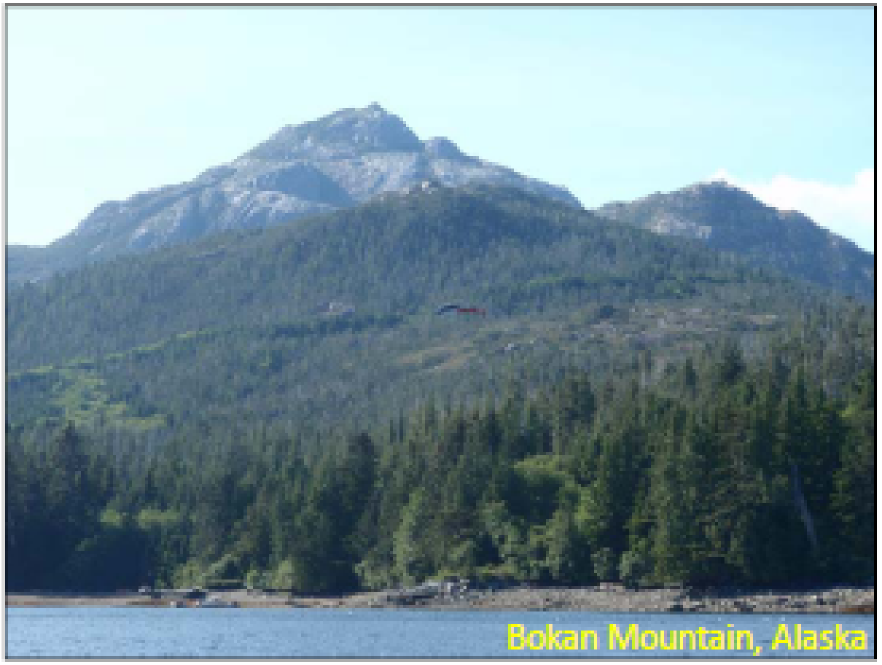
- Deficient in SiO_2 relative to Na_2O, K_2O, and CaO
- Peralkaline=$Na_2O+K_2O>Al_2O_3$ (excess Al)
- Peraluminous=$Al_2O_3>Na_2O+K_2O$

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.



Bokan Mountain, Alaska

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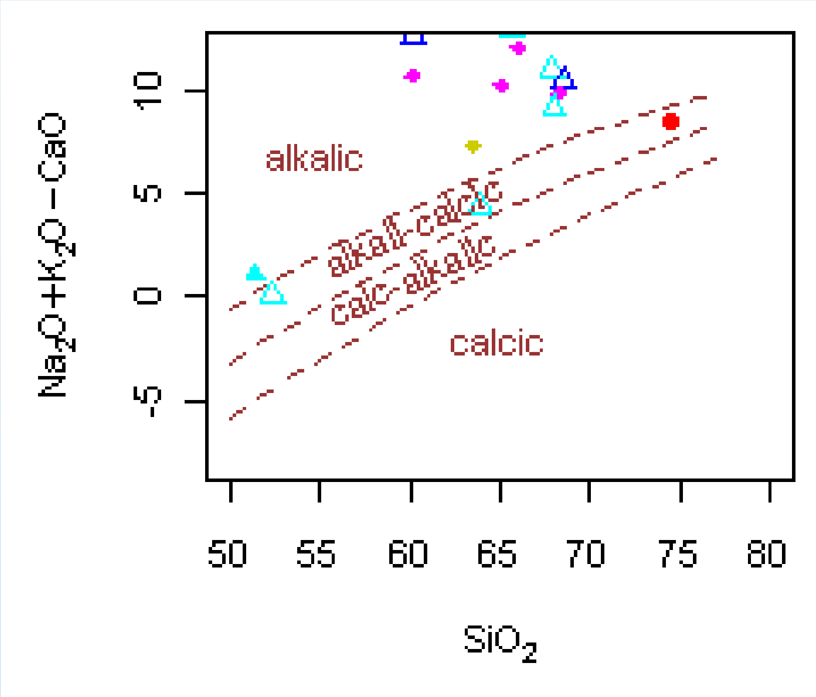
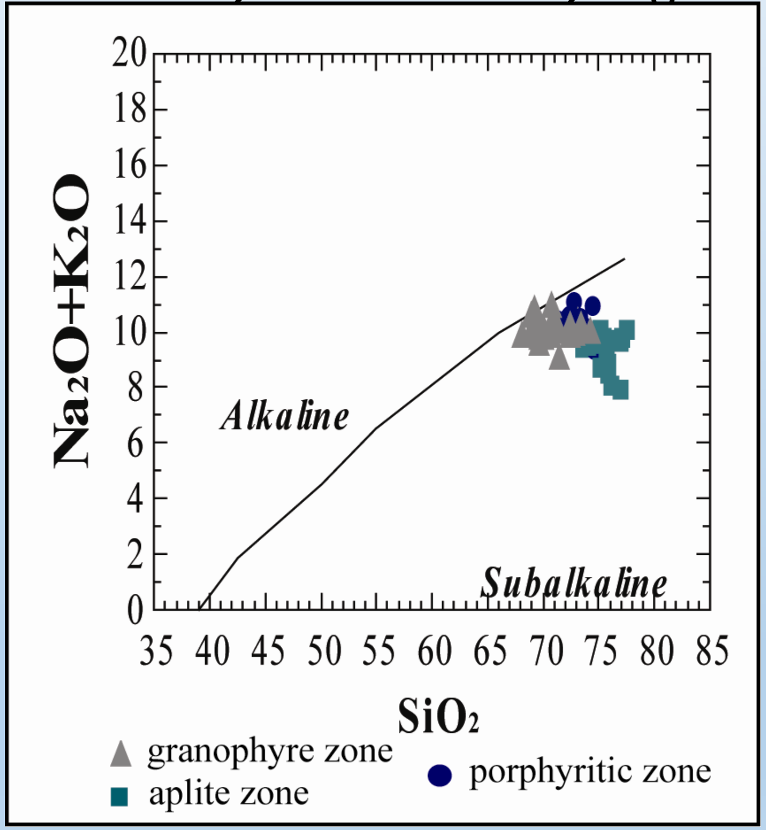
Alkaline Igneous Rocks

- Igneous rocks with $Na_2O+K_2O>0.3718(SiO_2)-14.5$
- Igneous rocks with mol Na_2O+mol K_2O>mol Al_2O_3



Gallinas Mountains



Capitan pluton

Alkaline/peralkaline Igneous Rocks—characteristics

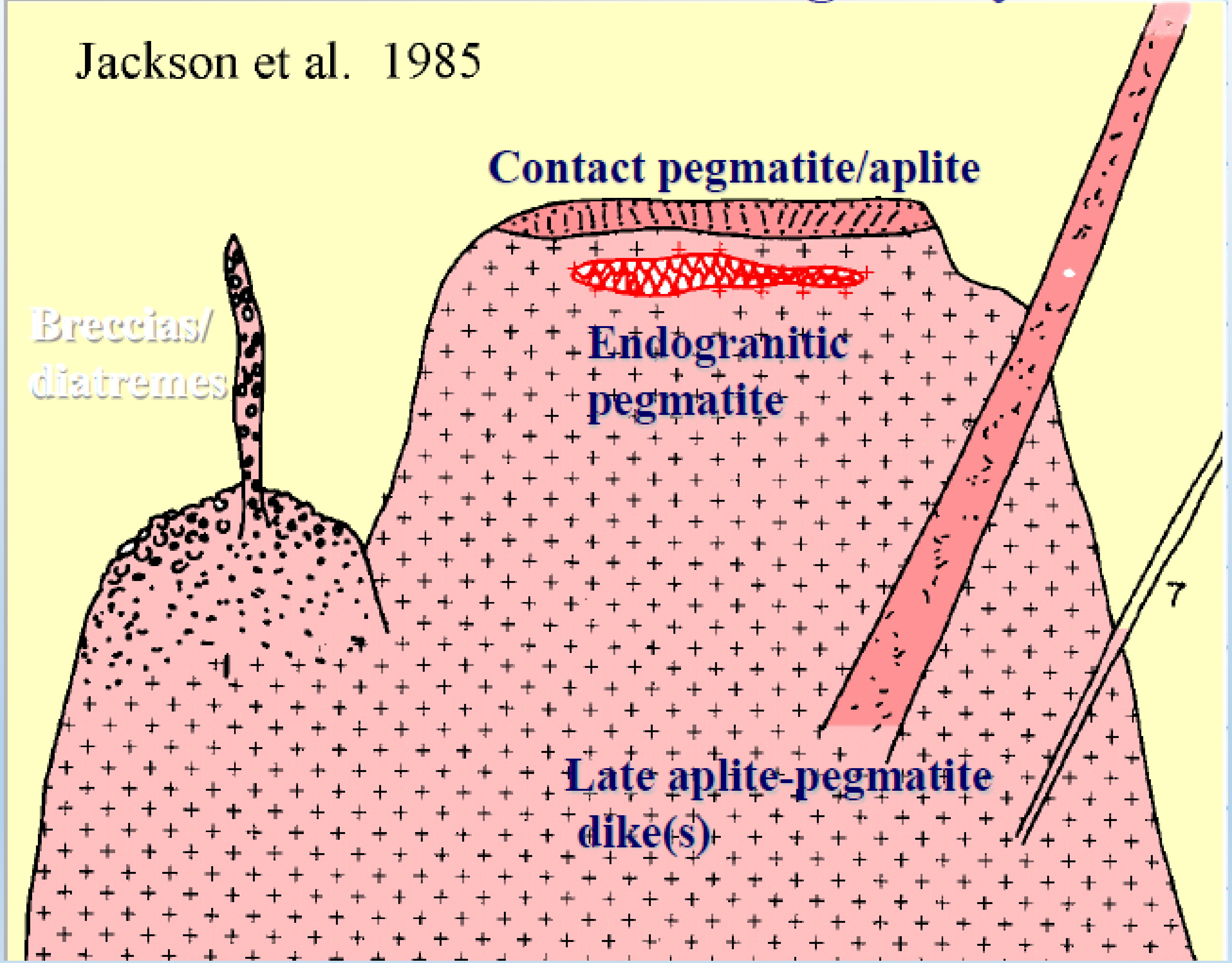
- Cooling of magmas derived by partial melting of rocks
- Enriched in Zr, Nb, Sr, Ba, Li, REE, U, Th
- None are currently being mined for REE
- Examples Bokan Mountain, southeastern Alaska; Thor Lake, Strange Lake and Kipawa Lake in Canada; Kola Peninsula, Russia; and Ilímaussaq, Greenland
- Contain a variety of ore minerals that are usually either REE-bearing carbonates, phosphates, or fluorates
- Complex replacements of minerals
- Associated with metasomatic alteration called fenitization
  - Alkali-rich fluids from the crystallizing magma, converts the host rock minerals to an assemblage of alkali-bearing minerals (either K- or Na-rich)

According to Richardson and Birkett (1996) other comparable rare metal deposits associated with peralkaline rocks include:

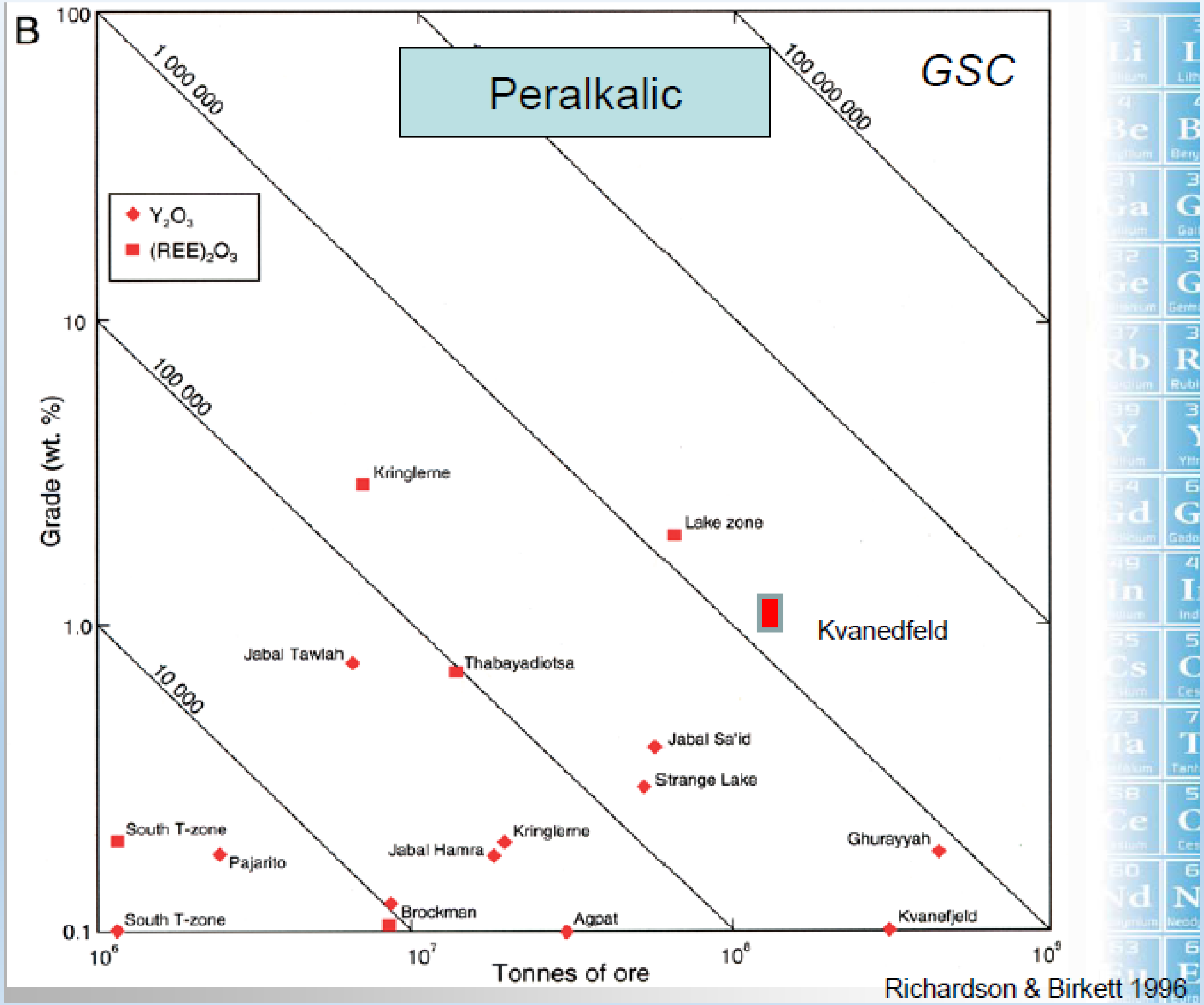
- Strange Lake, Canada (zircon, yttrium, beryllium, niobium, REE)
- Mann, Canada (beryllium, niobium)
- Illimausaq, Greenland (zircon, yttrium, REE, niobium, uranium, beryllium)
- Motzfeldt, Greenland (niobium, tantalum, zircon)
- Lovozero, Russia (niobium, zircon, tantalum, REE)
- Brockman, Australia (zircon, yttrium, niobium, tantalum)

Model for Peralkalic Magma Systems

Jackson et al. 1985

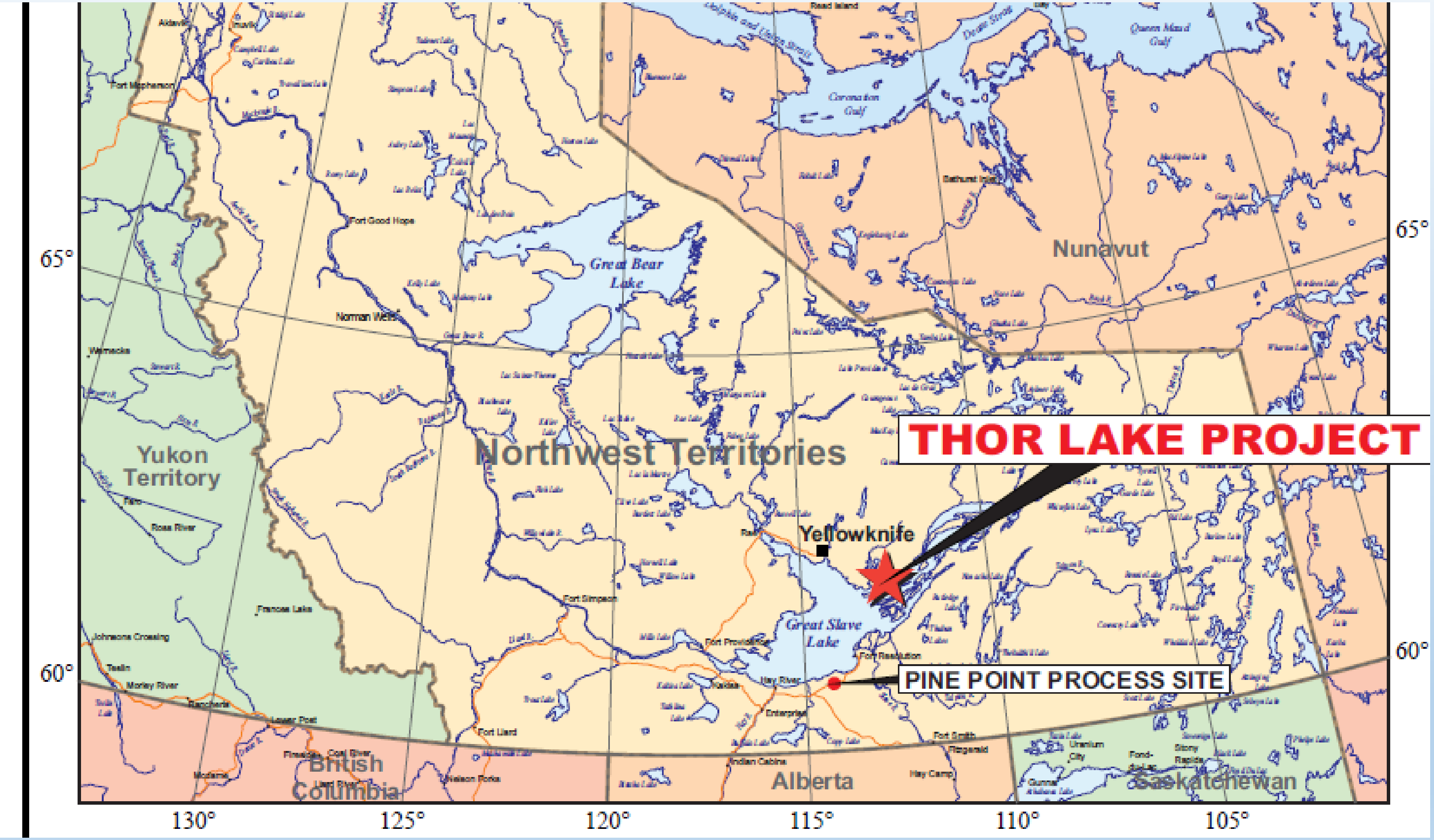


Grade-tonnage



Richardson & Birkett 1996

Thor Lake (Nechalacho Rare Earth Element Project), Northwest Territories, Canada


THOR LAKE PROJECT
PINE POINT PROCESS SITE
Yellowknife
Northwest Territories
Yukon Territory
Nunavut
British Columbia
Alberta
Saskatchewan
Great Bear Lake
Great Slave Lake
65°
60°
130°
125°
120°
115°
110°
105°

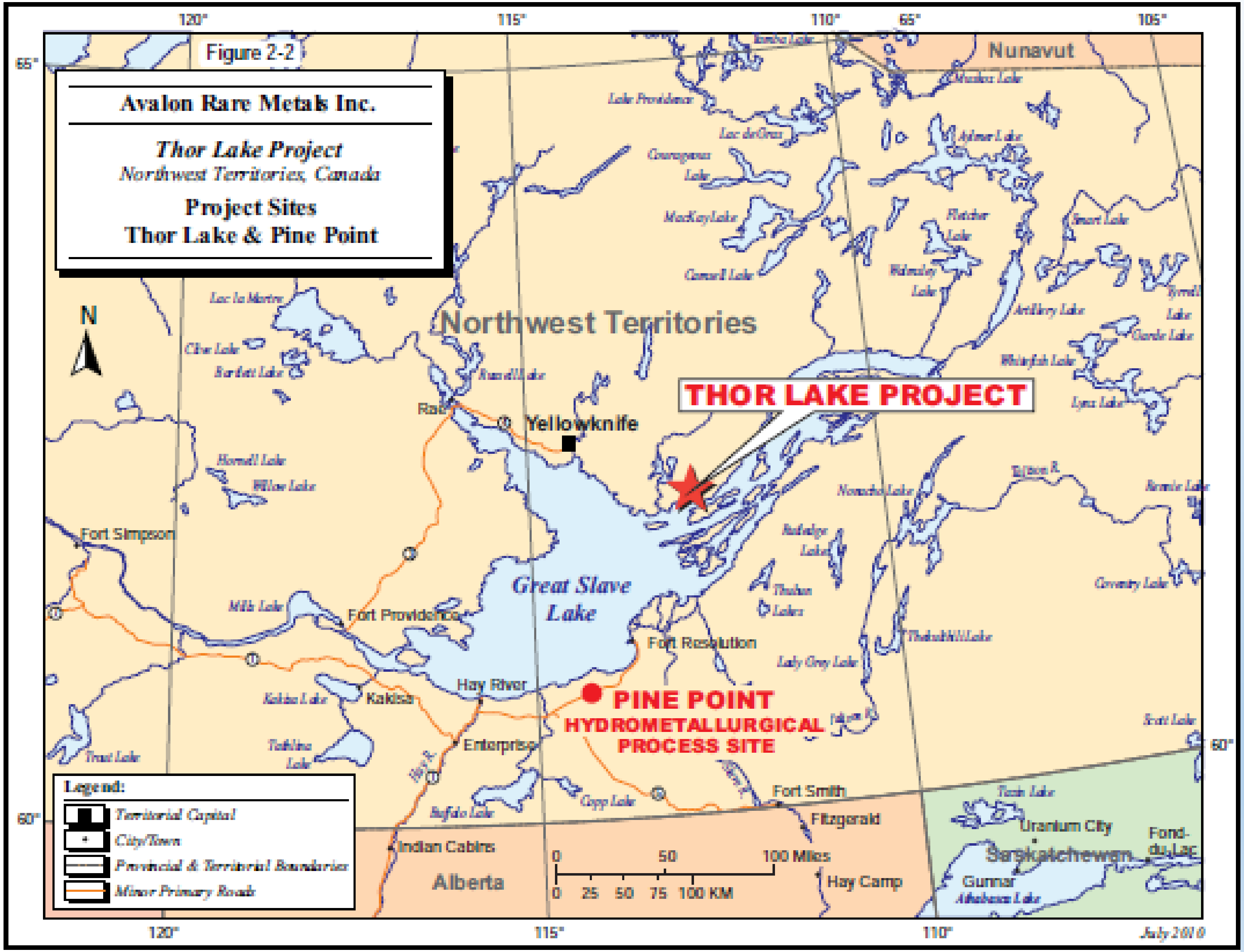


Figure 2-2
Avalon Rare Metals Inc.
Thor Lake Project
Northwest Territories, Canada
Project Sites
Thor Lake & Pine Point
THOR LAKE PROJECT
PINE POINT
HYDROMETALLURGICAL
PROCESS SITE
Northwest Territories
Nunavut
Alberta
Saskatchewan
Great Slave Lake
Yellowknife
Rae
Fort Simpson
Fort Providence
Fort Resolution
Hay River
Kakisa
Enterprise
Fort Smith
Fitzgerald
Indian Cabins
Hay Camp
Uranium City
Gunnar
Fond-du-Lac
N
Legend:
Territorial Capital
City/Town
Provincial & Territorial Boundaries
Minor Primary Roads
0 50 100 Miles
0 25 50 75 100 KM
120°
115°
110°
105°
65°
60°
July 2010

Thor Lake

- Discovered in 1976
- Highland Resources Ltd. 1976-2004 >$12 mill
- Placer Development Ltd (now Placer Dome Inc.) 1980-1981
- Highland 1983
- Hecla Mining Co of Canada 1986
- 2001 Navigator Exploration Corp 2001
- Avalon 2005 purchased

Thor Lake

- Peralkaline Blackford Lake intrusion, ~2.14 Ga
- Syenites, granites, and gabbros, with pegmatites and a core of nepheline-sodalite syenite
- 5 distinct zones (tabular zones)
  - Nechalacho
  - North T
  - South T
  - S
  - R
- Nepheline-sodalite syenite at Nechalacho
- complex interplay of magmatic and hydrothermal processes

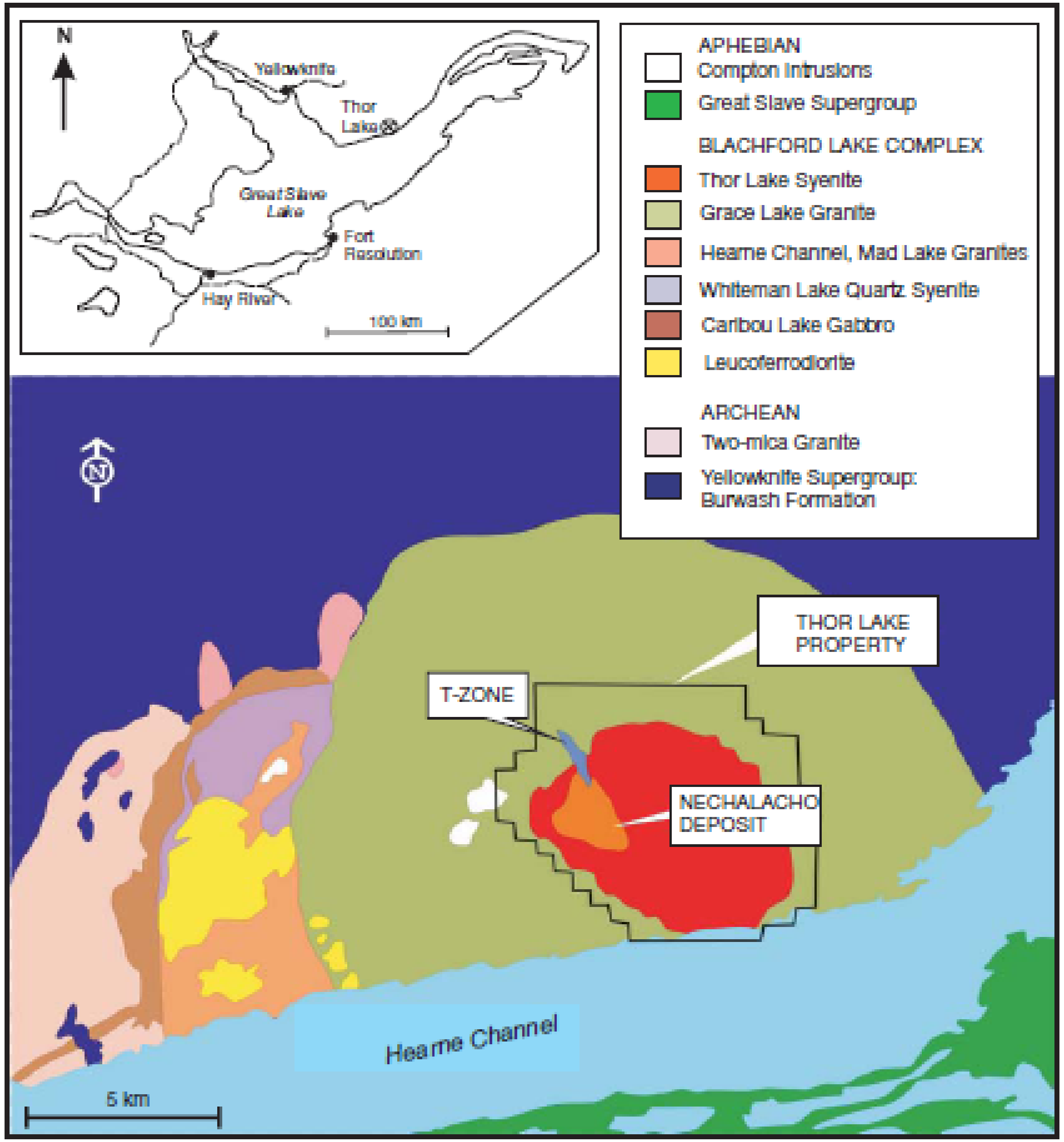
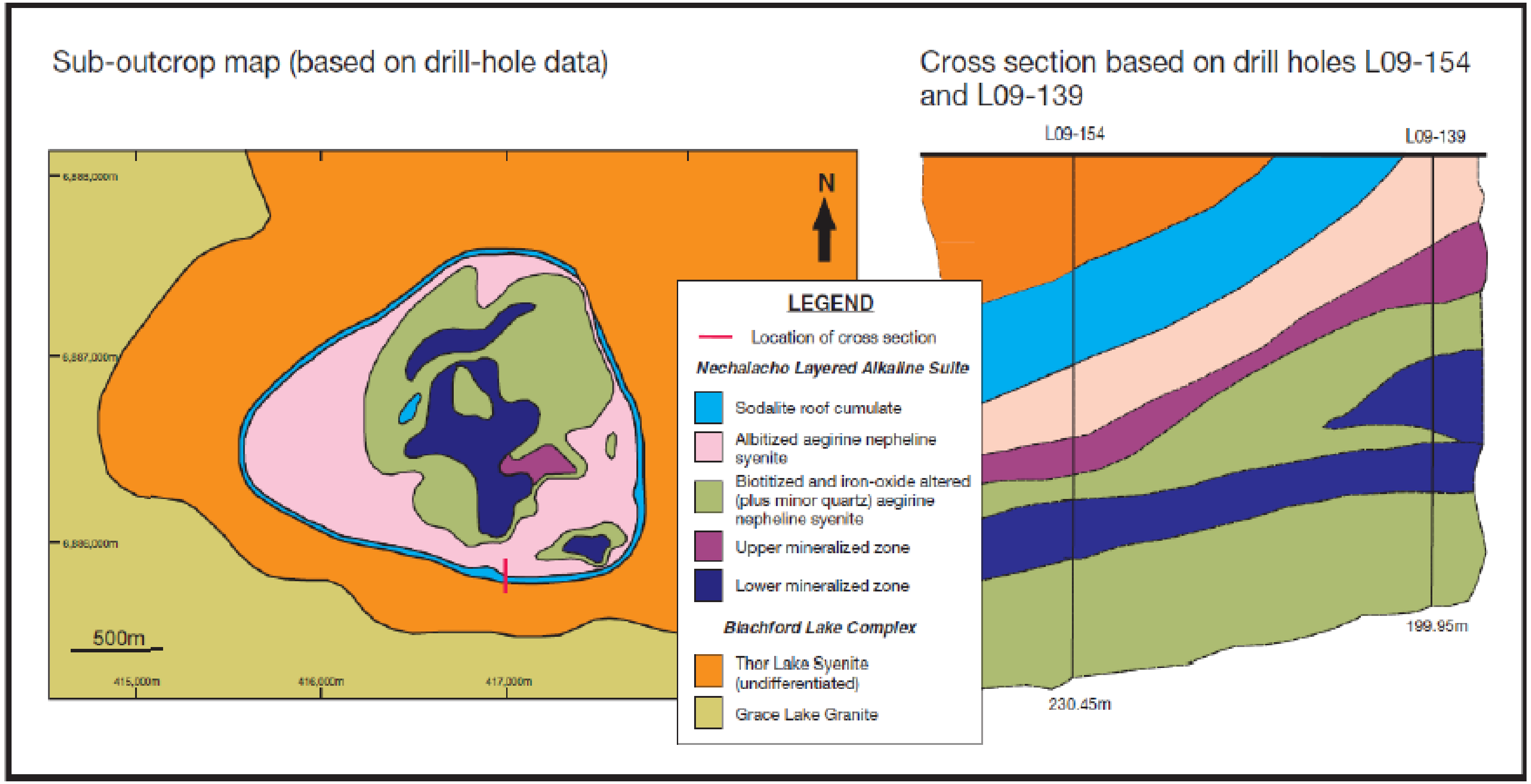


FIG. 1. Geologic map of the Blachford Lake Intrusive Complex, showing the location of the Nechalacho deposit and T zone within the Thor Lake rare metal deposit (modified after Davidson, 1982).

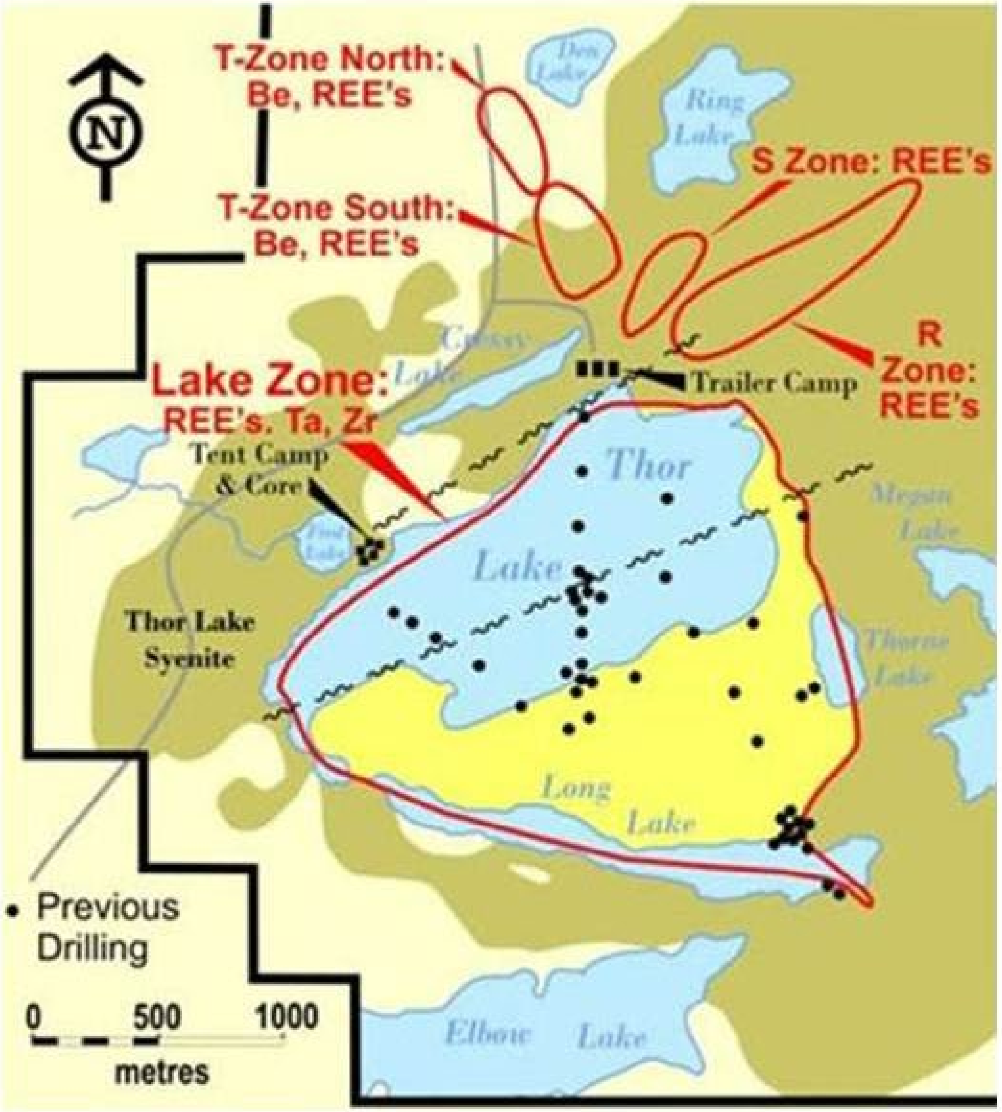
Sheard et al., 2012

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.

Rare Metal Zones at Thor Lake

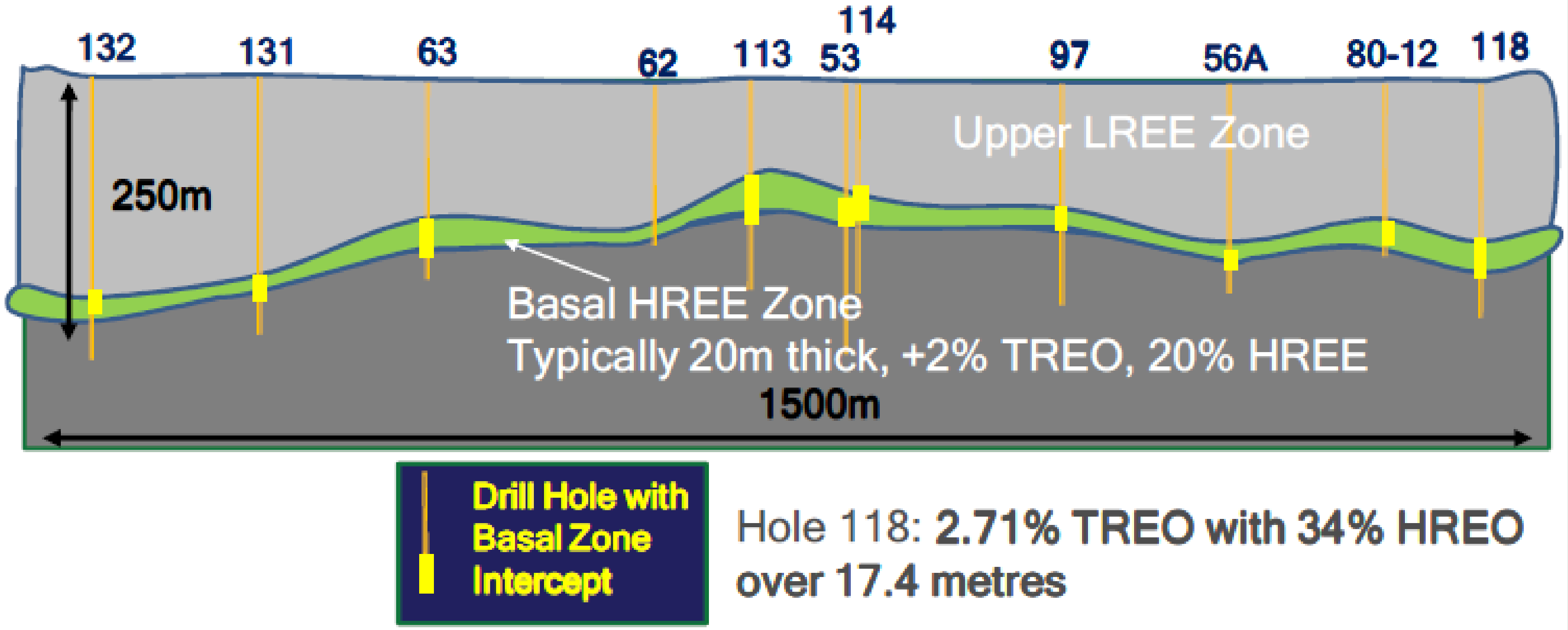


Thor Lake—geology

- tabular hydrothermal alteration zone
- averages 100-150 m thick
- replacement of the primary mineral assemblage by chlorite, magnetite, biotite, zircon, monazite, allanite, bastnaesite and fergusonite
- distinct horizontal layering with HREE content generally increasing towards the base of the deposit

Nechalacho (Thor Lake) REE Deposit

E-W Composite Section
(looking north, no vertical exaggeration)



Hole 118: **2.71% TREO with 34% HREO over 17.4 metres**

TABLE 8-3 MINERALS OF PRINCIPAL ECONOMIC INTEREST IN THE T-ZONE

Avalon Rare Metals Inc. – Thor Lake Project

Element	T-Zone
Y + HREE	xenotime
LREE	bastnaesite, synchisite, parisite
Be	phenacite
Nb, Ta	columbite
Zr	zircon
Ga	albite (var. cleavelandite)

TABLE 9-1 AVERAGE PERCENT OF ORE MINERALS

Avalon Rare Metals Inc. – Thor Lake Project

	All Rock	Upper Zone	Basal Zone	Concentrate
Zircon	65.3%	62.8%	66.2%	63.0%
Fergusonite	3.7%	2.6%	4.3%	5.4%
Bastnaesite	3.8%	4.0%	3.4%	0.7%
Synchysite	4.1%	4.4%	3.8%	1.5%
Monazite	6.4%	9.4%	5.2%	5.5%
Allanite	12.3%	12.0%	13.3%	19.6%
Other REE	0.1%	0.1%	0.0%	0.1%
Columbite	4.3%	4.5%	3.8%	4.1%
Total	**100%**	**100%**	**100%**	**100%**

Nechalacho fergusonite and zircon (brown) compared to Illimaussaq eudialyte (pink).

http://www.goldgeologist.com/mercenary_musings/musing-091103-Avalon-Rare-Metals-Inc-A-Real-Rare-Earth-Story.pdf

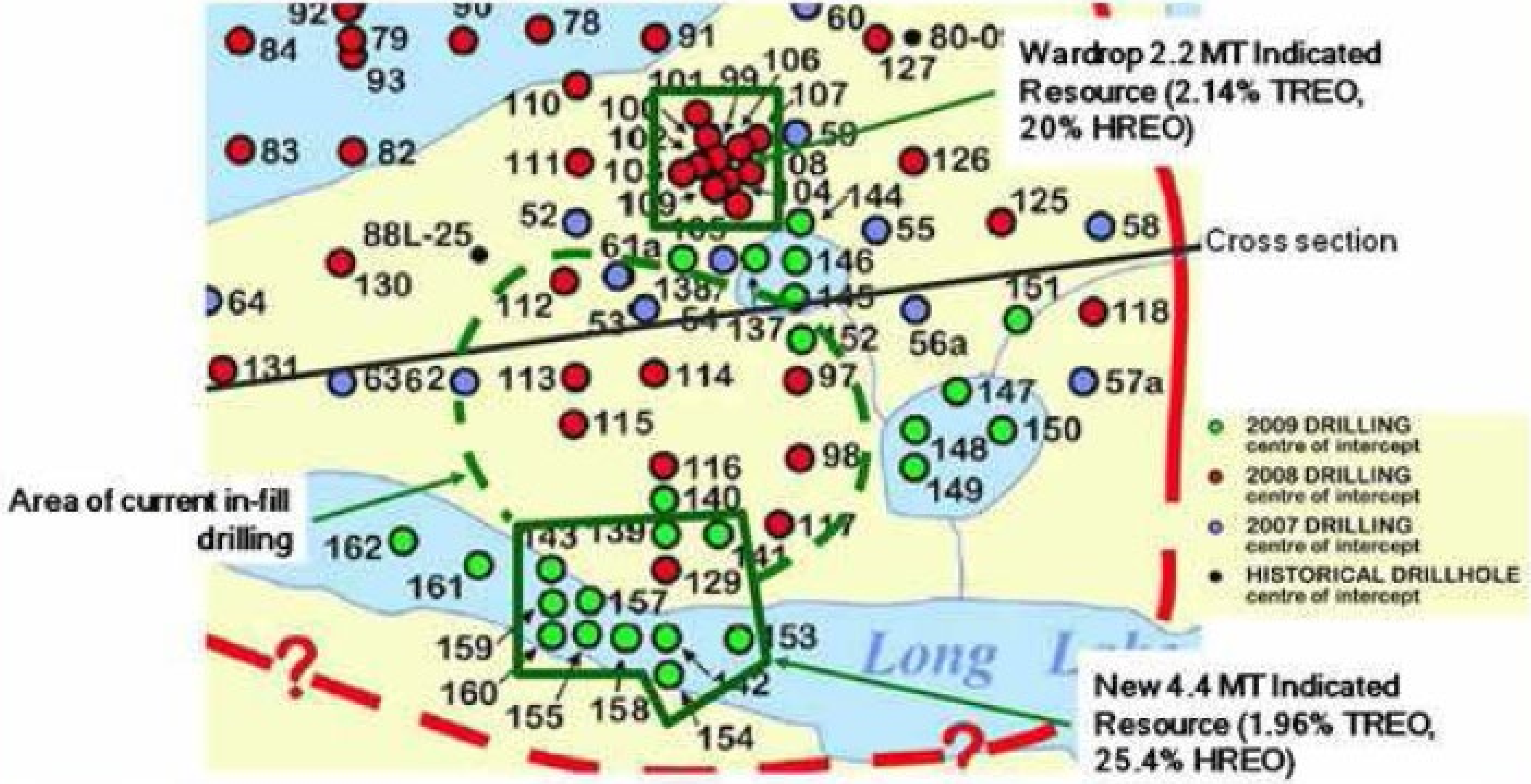
Thor Lake—mineralogy

- HREE in fergusonite ((Y,HREE)NbO_4) and zircon ($ZrSiO_4$)
- LREE in bastnaesite, synchysite, allanite and monazite
- Nb and Ta in columbite as well as zircon and fergusonite

Thor Lake

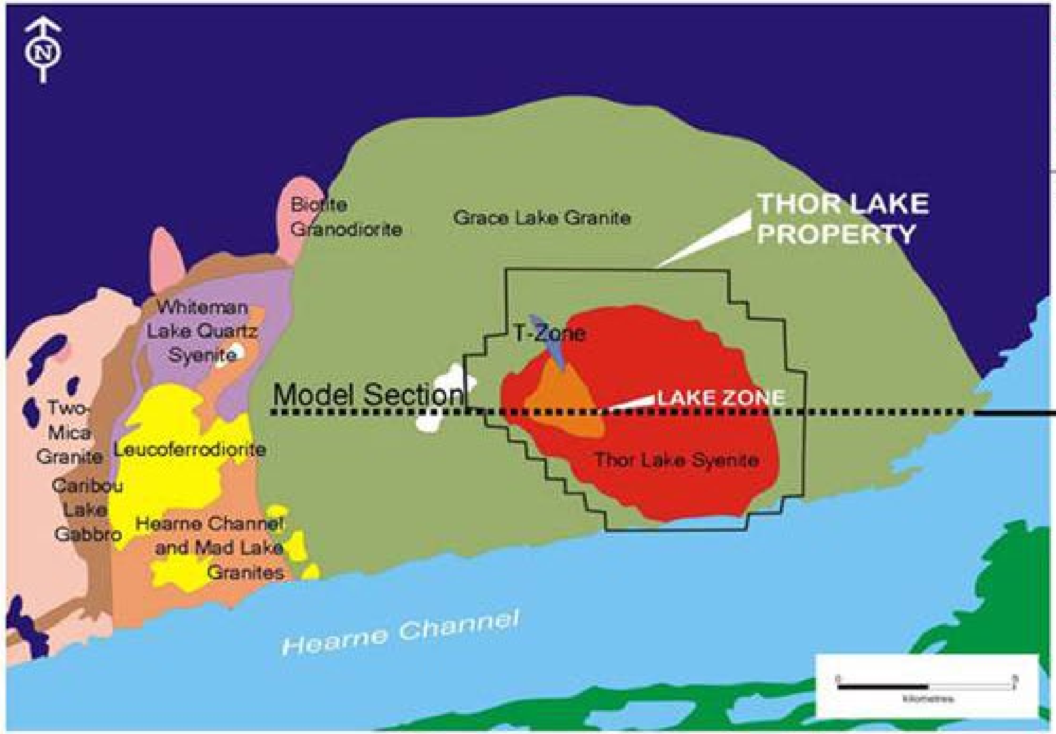
- “Basal Zone” contains between 1.5 and 2.5% total rare earth oxides 20 m thick
- Model=REE and rare metals being originally precipitated as cumulate minerals as part of the magmatic process
- Subsequent hydrothermal activity altered these to the presently seen assemblage of REE minerals
- 23 ppm U and 114 ppm Th

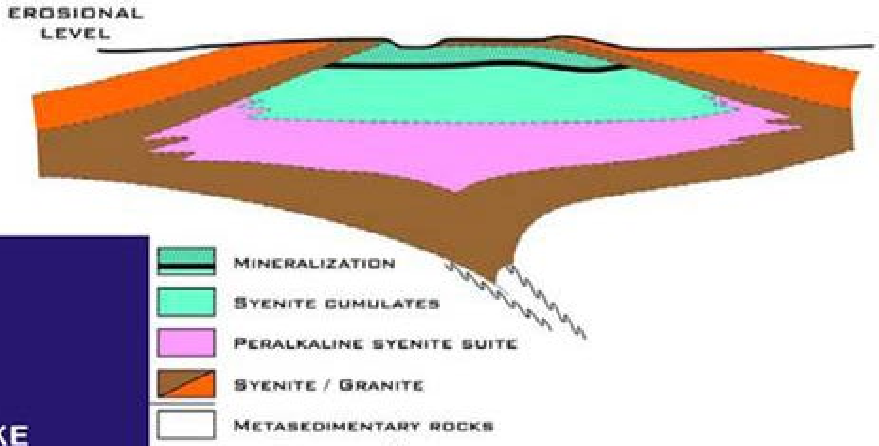
South Part of Lake Zone: Indicated REE Resources



Nechalacho Geological Model Evolving

Blachford Lake Peralkaline Intrusive Complex, NWT





Interpreted Geometry in Cross Section

A unique example of a layered Peralkaline intrusive complex, with the upper, rare metal-rich part of the system readily accessible for mining.

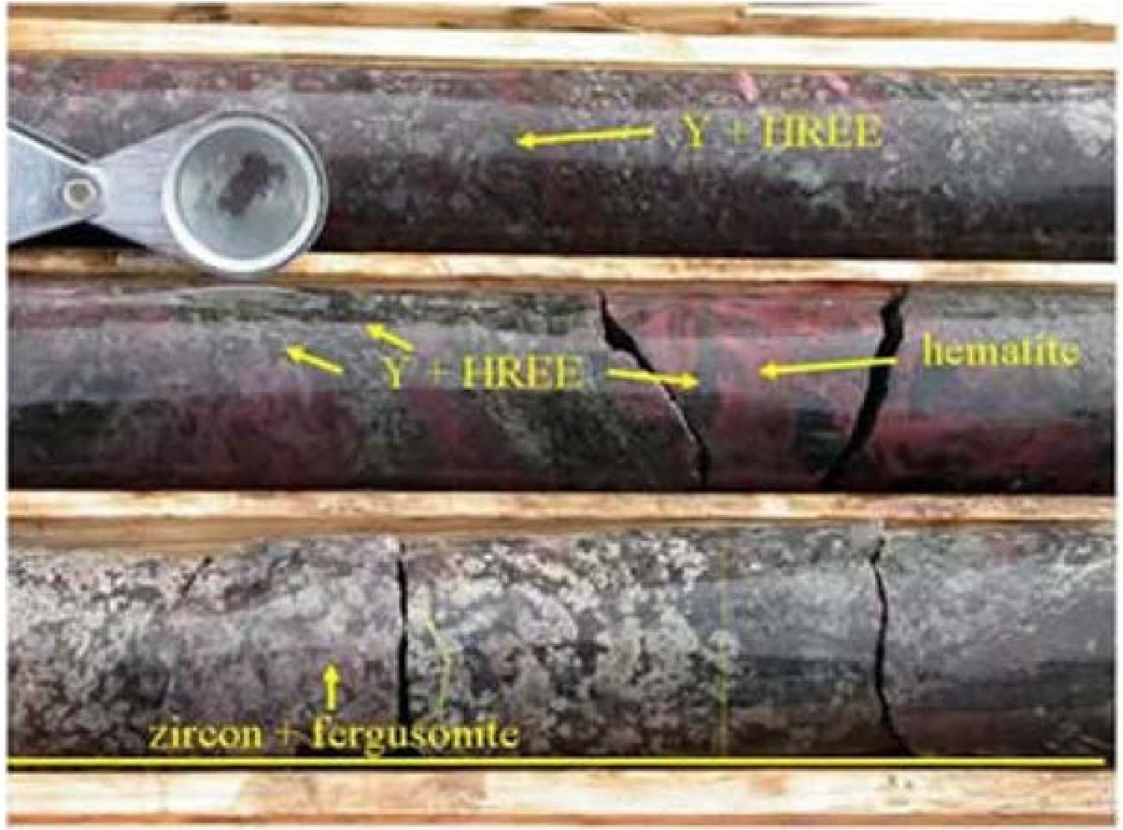
Lake Zone Y + HREE Mineralization

AVALON RARE METALS INC.

TSX:AVL OTCQX:AVARF

DDH L07-54

(Lake Zone - ~145 M – mineralized mafic replacement unit)



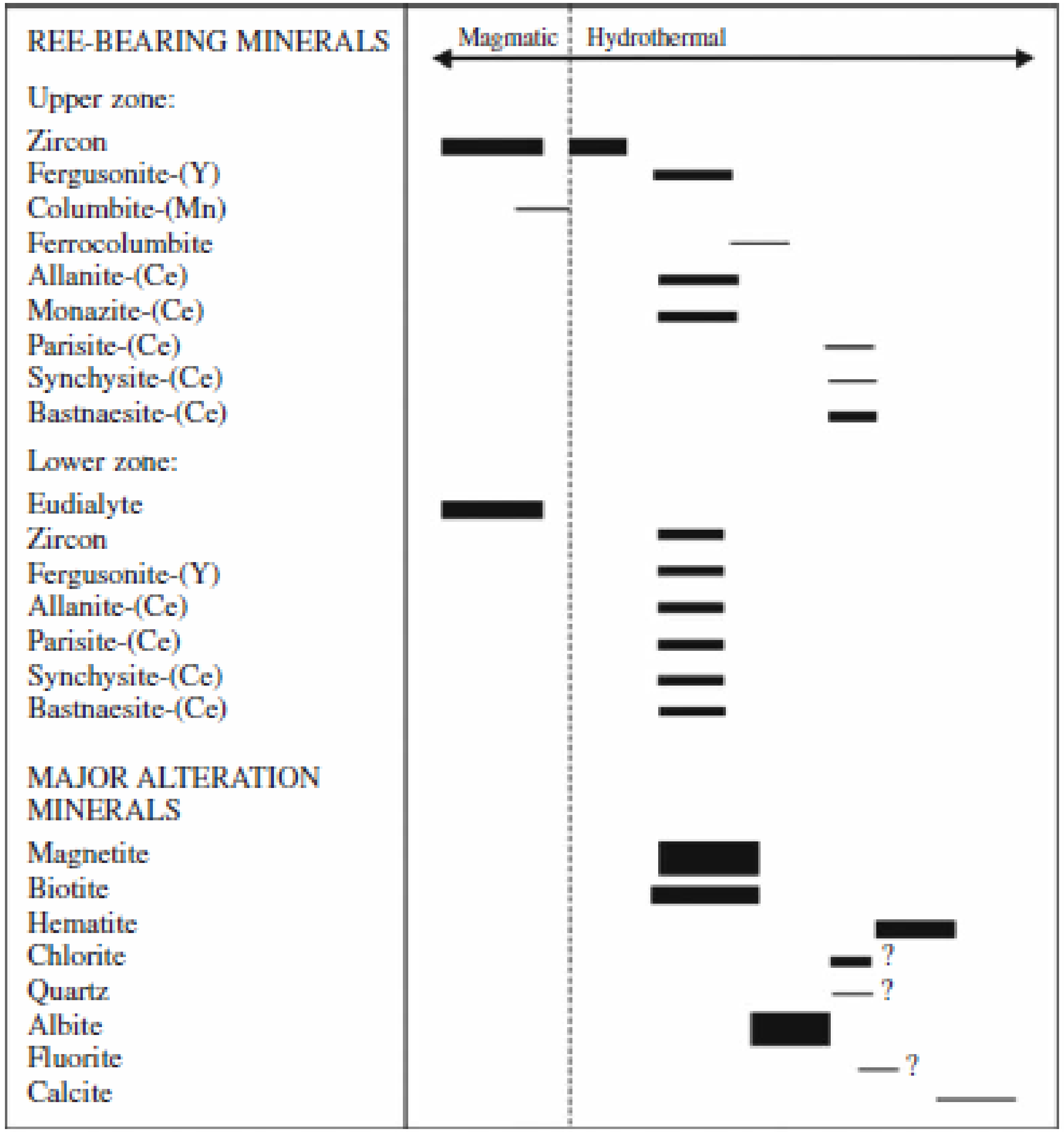


FIG. 9. Paragenetic sequence for the major REE-bearing and alteration minerals in the Nechalacho deposit. Line widths indicate relative abundances of phases. Uncertainty in the precise placement of a mineral within the paragenesis due to a lack of textural evidence is indicated by '?'.

TABLE 1-6 MINERAL RESOURCES

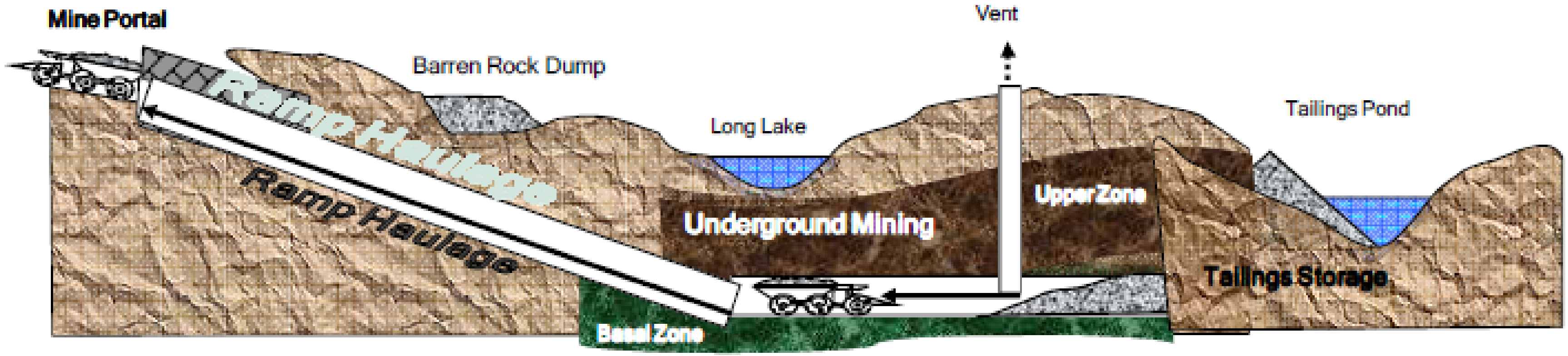
Avalon Rare Metals Inc. – Thor Lake Project

	Tonnes (millions)	% TREO	% HREO	ppm ZrO_2	ppm Nb_2O_5	ppm Ga_2O_3	ppm Ta_2O_5
Indicated							
Upper Zone	6.89	1.45	0.17	18,560	2,856	175	194
Basal Zone	14.48	1.82	0.40	33,843	4,370	144	430
Total Indicated	**21.36**	**1.70**	**0.32**	**28,917**	**3,882**	**154**	**354**
Inferred							
Upper Zone	99.06	1.29	0.12	24,371	3,640	172	210
Basal Zone	76.87	1.60	0.33	31,378	4,428	134	413
Total Inferred	**175.93**	**1.43**	**0.21**	**27,433**	**3,985**	**155**	**298**

Notes:

1. CIM definitions were followed for Mineral Resources.
2. Mineral Resources are estimated using price forecasts for 2014 for rare earth oxides (US$21.94/kg

Nechalacho REE Deposit Conceptual Mine Plan



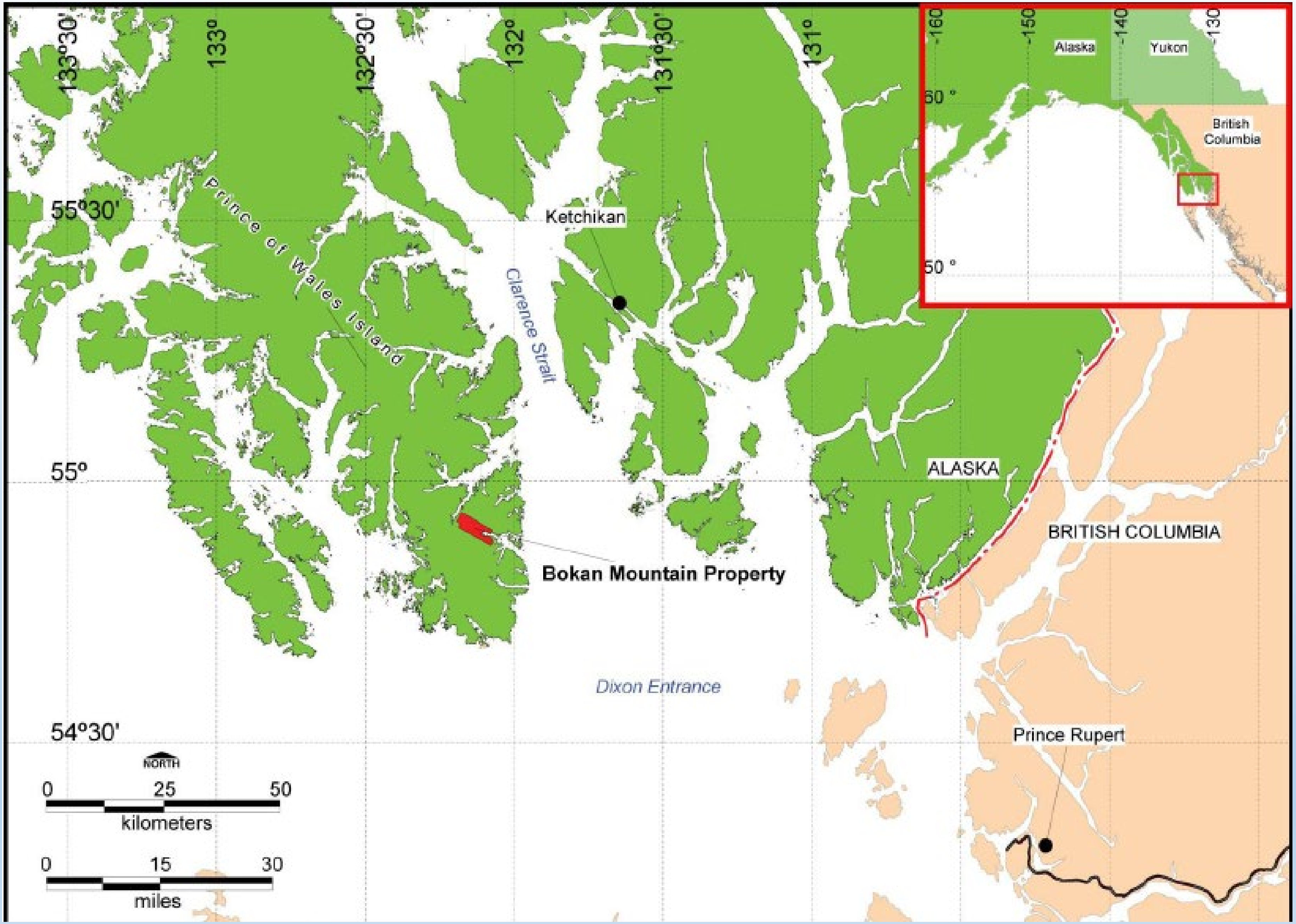
Initial mine production rate: 1,000-2,000 t/day of ore through the mill.
To produce approx. 5,000-10,000 tpy TREO in chemical concentrates… equivalent to just 2-5% of est. 2014 market (5-10% of HREO demand).

Current forecast on operating costs: $200/tonne (mining & processing)

Metallurgical Testwork Progress

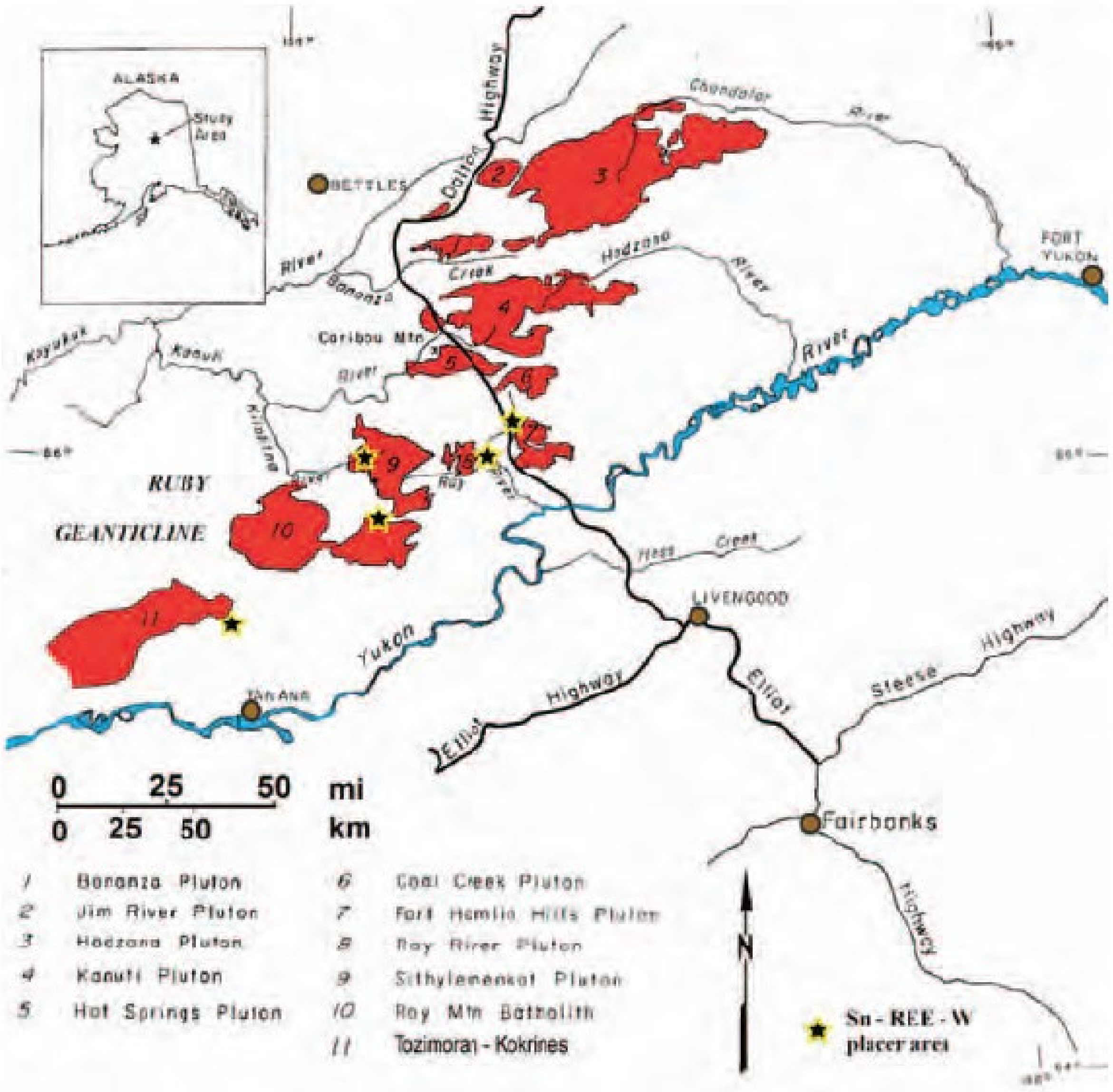
- Flotation
  1. Benchscale - basically complete, optimization continuing
  2. Main Pilot Plant (40 tonne) - completed (SGS). 6 tonnes concentrate produced
  3. Follow up mini-pilot plant work at XPS in progress
- Hydrometallurgy (Sulphuric Acid Bake Process)
  1. Pilot plant trial and process optimization in progress (SGS)
  2. Produces mixed rare earth concentrate with zircon residue
  3. Zircon residues contain REE & require caustic or alkali cracking. Presently being marketed as an REE-enriched zirconium product
- Separation & Refining (HCl Solvent Extraction)
  1. Prefeasibility completed in April 2012 by SNC-Lavalin
  2. Feasibility Study underway for proposed plant site in Geismar, Louisiana, USA
  3. Pilot plant testwork set to begin. Identifying potential partners

Bokan Mountain, Alaska



133°30'
133°
132°30'
132°
131°30'
131°
55°30'
55°
54°30'
Prince of Wales Island
Ketchikan
Clarence Strait
ALASKA
BRITISH COLUMBIA
Bokan Mountain Property
Dixon Entrance
Prince Rupert
NORTH
0
25
50
kilometers
0
15
30
miles
-160
-150
-140
-130
Alaska
Yukon
British Columbia
60 °
50 °

Peraluminous plutons of the Ruby batholith associated with widespread alluvial Sn-REE-W occurrences. Figure modified from Barker and Foley (1986).



Mining Engineering, 2012, http://ucore.com/MiningEngineering%20Jan2012.pdf

HISTORY

Ross Adams Mine

- Disc. Don Ross & Kelly Adams 1955 (uranium)
- 1.3 million lbs. U_3O_8 produced 1957-1971
- Remaining resources, historic, (non NI 43-101 compliant) est'd 365,000 st at 0.17% U_3O_8
- 1950s-60s USGS geological mapping projects, presence of REE-Nb noted in Bokan area

http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=12&ved=0CDgQFjABOAo&url=http%3A%2F%2Fwww.legis.state.ak.us%2Fbasis%2Fget_documents.asp%3Fsession%3D26%26docid%3D7452&ei=sWM2UY7PMuLRyAGjh4Ao&usg=AFQjCNHfwV6sj77hCvqlL07GZx_hg_KjTA&sig2=vaFBys12VGB2VfhEoUo3-A

http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=12&ved=0CDgQFjABOAo&url=http%3A%2F%2Fwww.legis.state.ak.us%2Fbasis%2Fget_documents.asp%3Fsession%3D26%26docid%3D7452&ei=sWM2UY7PMuLRyAGjh4Ao&usg=AFQjCNHfwV6sj77hCvqlL07GZx_hg_KjTA&sig2=vaFBys12VGB2VfhEoUo3-A

2007-present

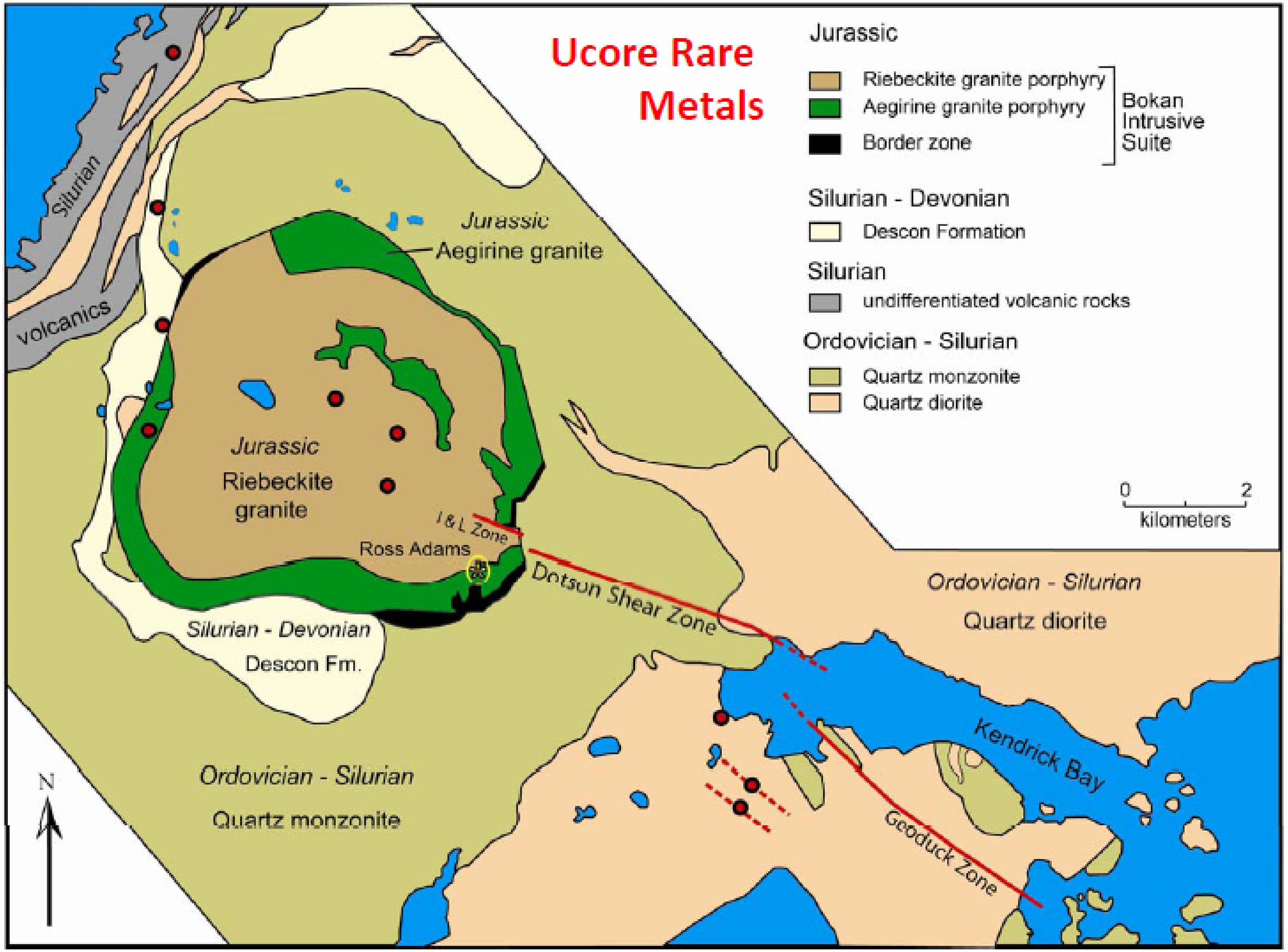
Rare Earth One, LLC (wholly owned Alaska subsidiary)

Ucore Uranium Inc.

Over 17,500 feet of drilling thru Nov. 2009, on Bokan area prospects

rare earth ONE

Bokan Mountain, Alaska



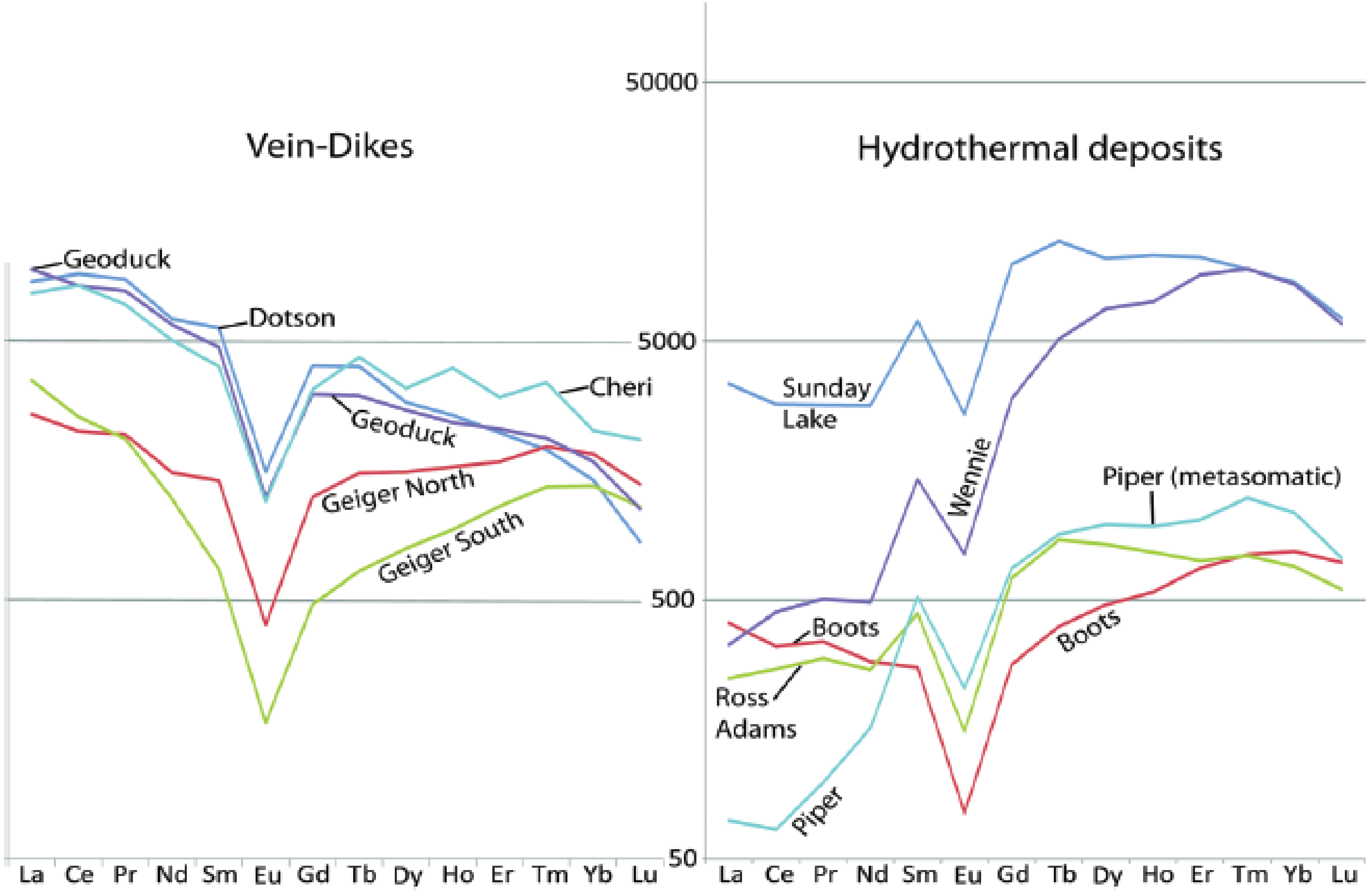
USGS
science for a changing world

Inferred resource estimates by varying cutoff grade for the Dotson dike system, Bokan Mountain, Alaska.

% TREO Cut-off	Tonnes	% TREO	HREO/TREO	Contained TREO (lbs)
0.8	1,021,000	1.054	36.80%	23,718,000
0.7	1,549,000	0.951	37.70%	32,467,000
0.6	2,489,000	0.834	39.60%	45,751,000
0.5	3,669,000	0.746	38.60%	60,325,000
0.4	5,276,000	0.654	40.00%	76,049,000
0.3	6,126,000	0.613	40.80%	82,765,000
0.2	6,702,000	0.58	41.30%	85,673,000

- All intercepts with a true width of less than 1.5 m were diluted to a potential minimum mining width of 1.5 m.
- Additional details at www.ucore.com.

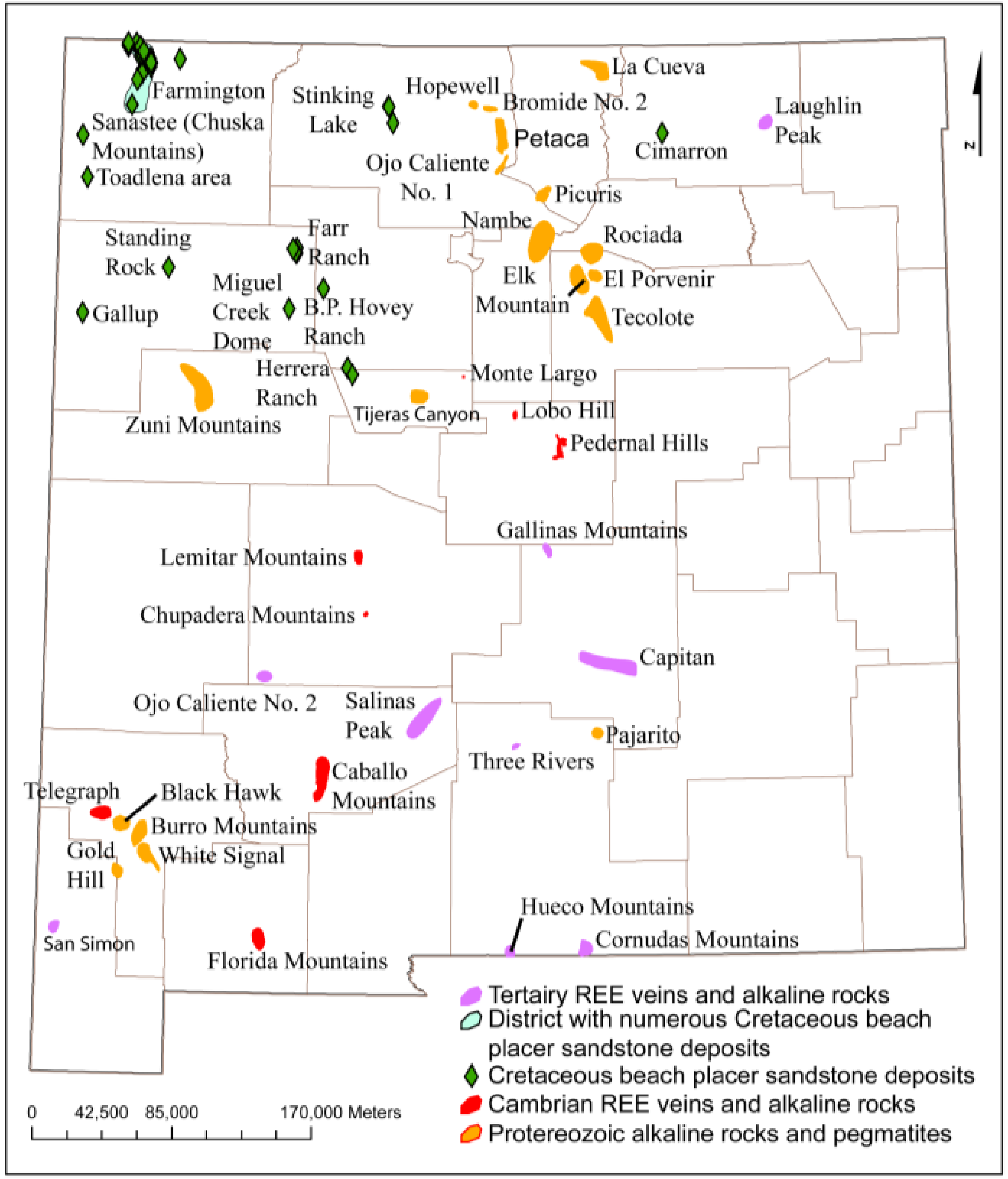
Normalized REE plots comparing vein-dikes (typically with 40% HREE) to more evolved hydrothermal REE prospects at Bokan Mountain (>80% HREE).

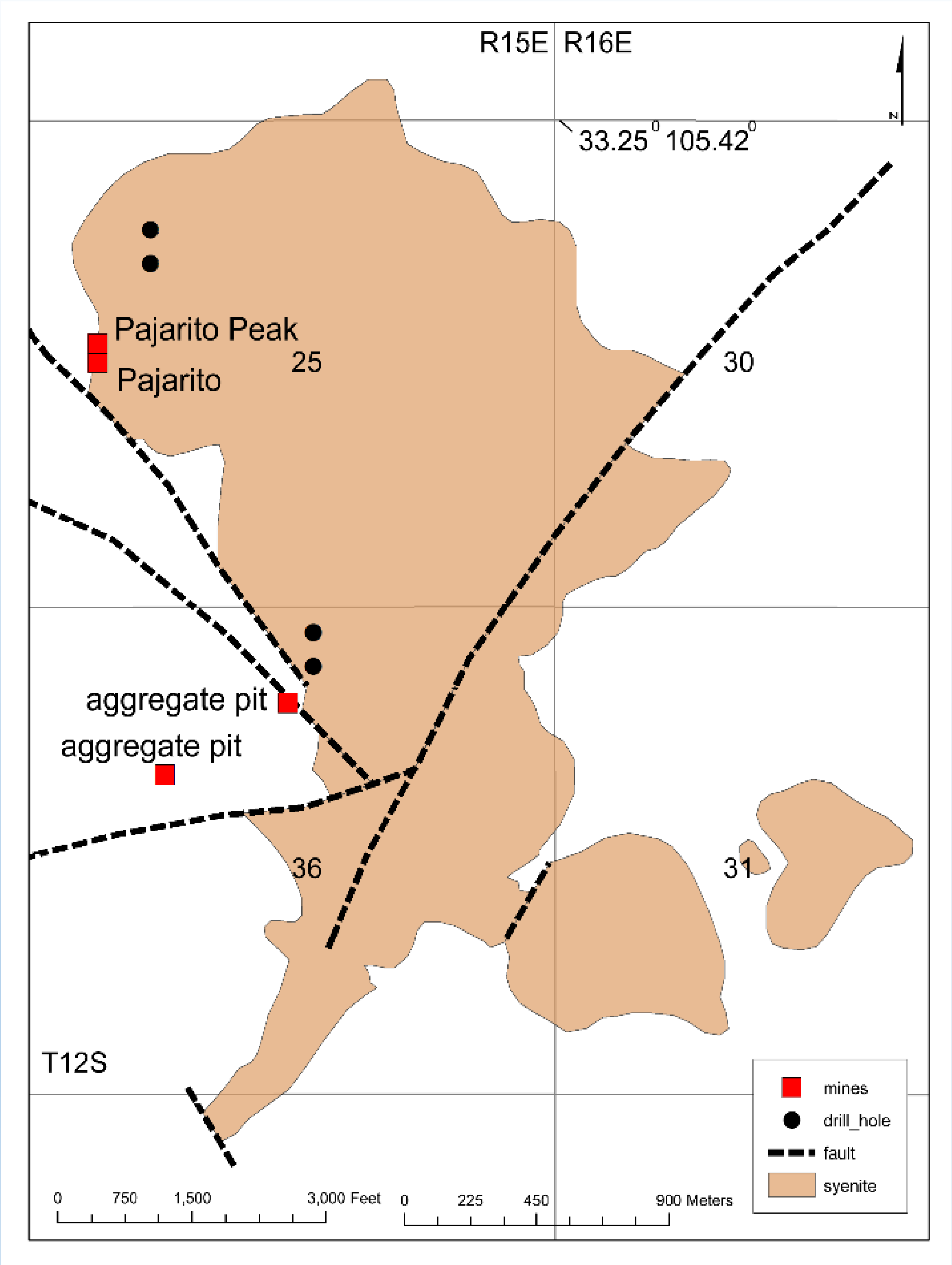


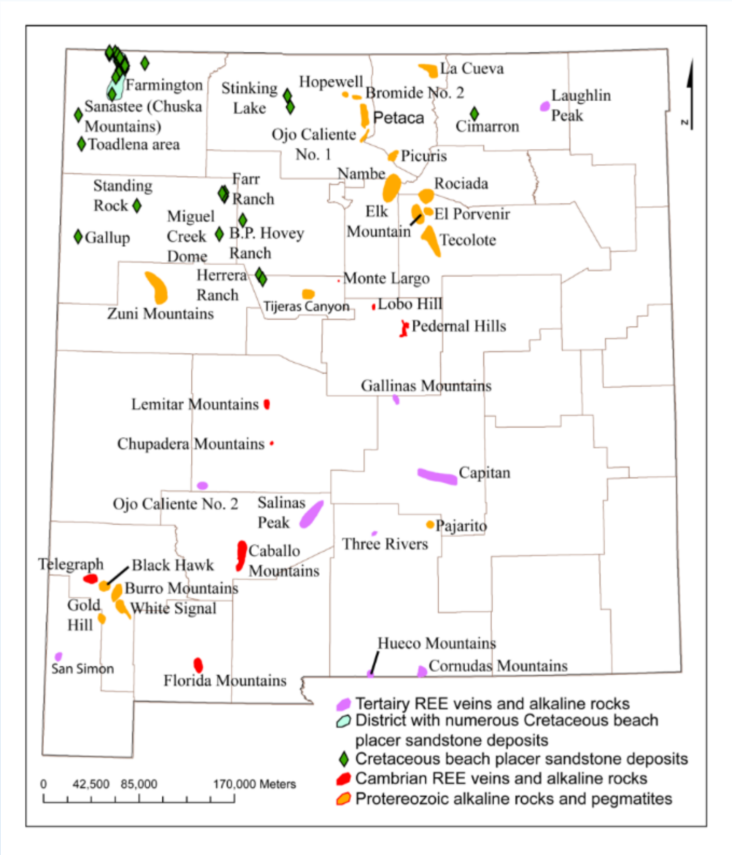
DEVELOPMENT ISSUES- *Bokan Project*

- Federal land- Tongass Nat'l Forest Management Plan completed, area zoned for mineral development
- State of Alaska Prince of Wales Area Plan completed, Kendrick Bay area classified for mineral and forestry access/development
- No overland access/transport requirements: Immediate access to property by ocean transport
- Native Land claims issues resolved
- Labor and services locally available

Pajarito Mountain, Mescalero Apache Indian Reservation near Ruidoso







Proterozoic Pajarito Mountain

Proterozoic Pajarito Mountain

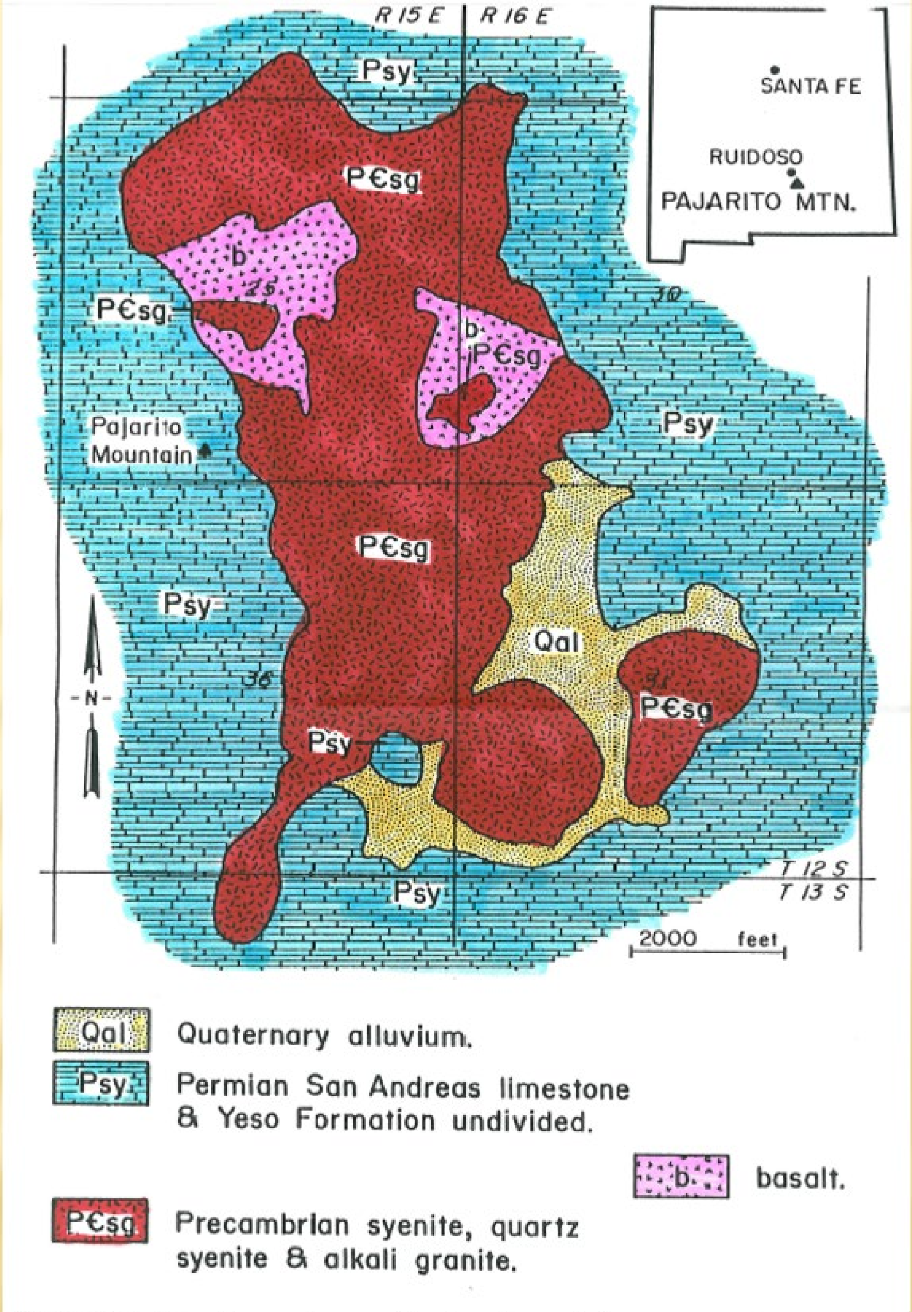
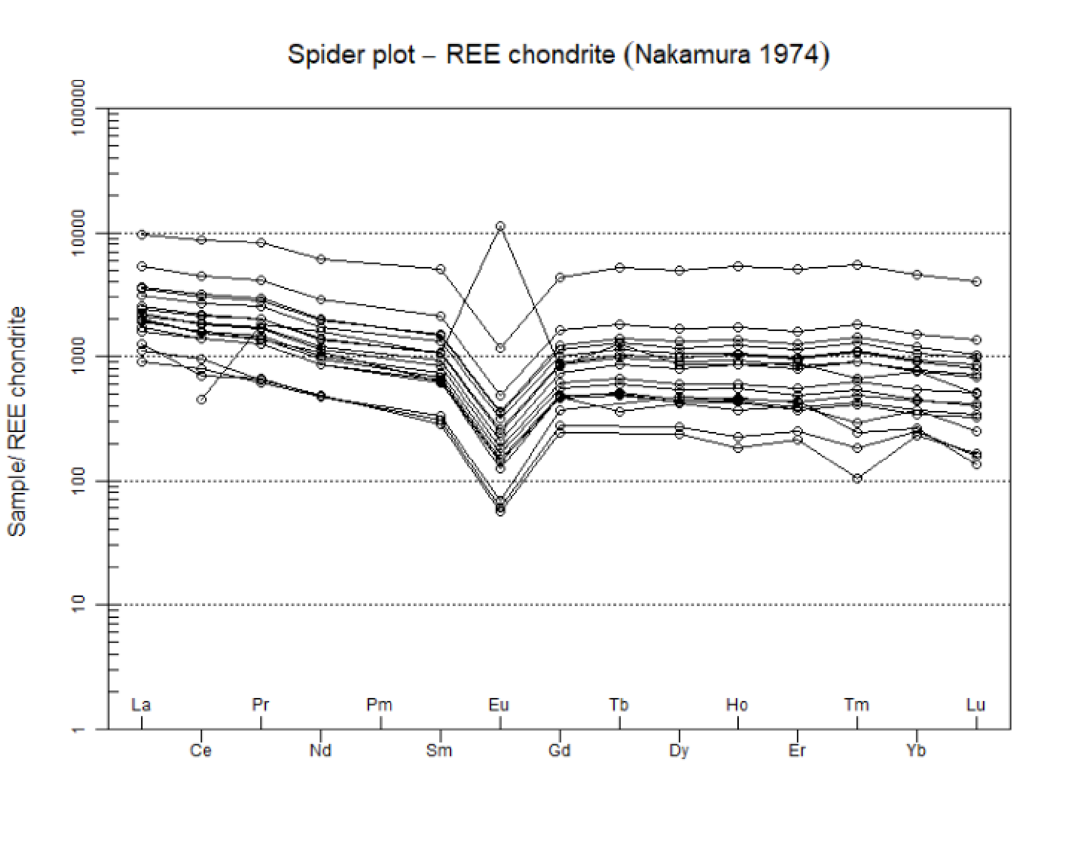


FIGURE 1—Location and generalized geology of the yttrium–zirconium deposit at Pajarito Mountain. SHERER (1990)



Mineralogy Proterozoic Pajarito Mountain (Berger, 2018)

Eudialyte $Na_4(Ca,Ce)_2(Fe^{++},Mn,Y)ZrSi_8O_{22}(OH,Cl)_2$

Fluorite CaF_2

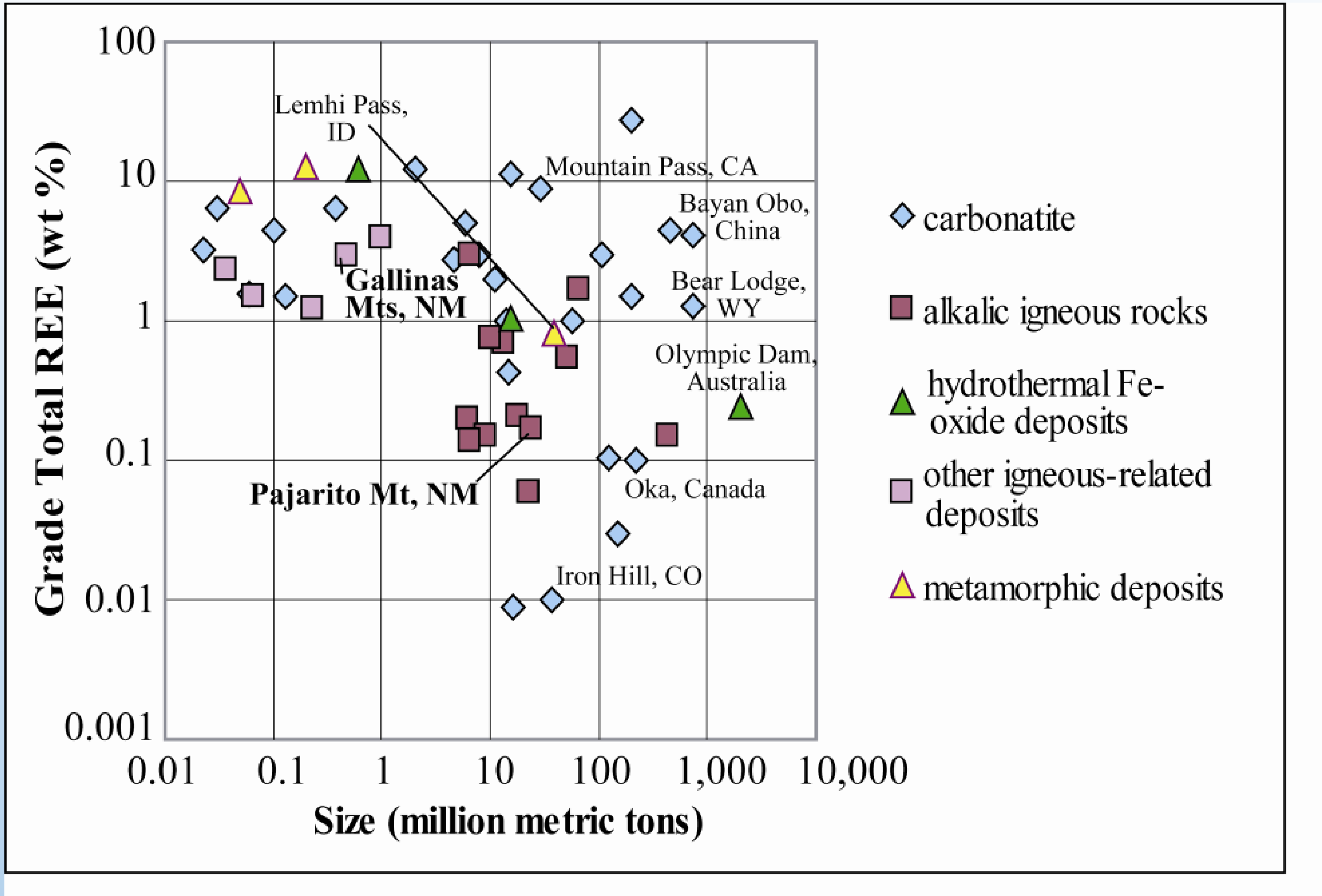
Apatite $Ca_5(PO_4)_3(OH,F,Cl)$ (with U, Th)

Zircon $ZrSiO_4$ (with U, REE)

2 REE-bearing silicates

Proterozoic Pajarito Mountain

- In 1990, Molycorp, Inc. reported historic resources of 2.7 million short tons grading 0.18% Y_2O_3 and 1.2% ZrO_2 as disseminated eudialyte
- Historic REE resources—537,000 short tons of 2.95% total REE (Jackson and Christiansen, 1993)



Grade and size (tonnage) of selected REE deposits, using data from Oris and Grauch (2002) and resources data from Jackson and Christiansen (1993). Deposits in bold are located in New Mexico.

Carbonatites

>330 Carbonatites

Carbonatites

- An igneous intrusive or extrusive rock containing more than 50% carbonate (calcite, dolomite, ankerite) (Bell, 1989)
- Rich in carbonate minerals that form central plugs within alkaline intrusive complexes, or dykes, sills and veins (Barker, 1989)

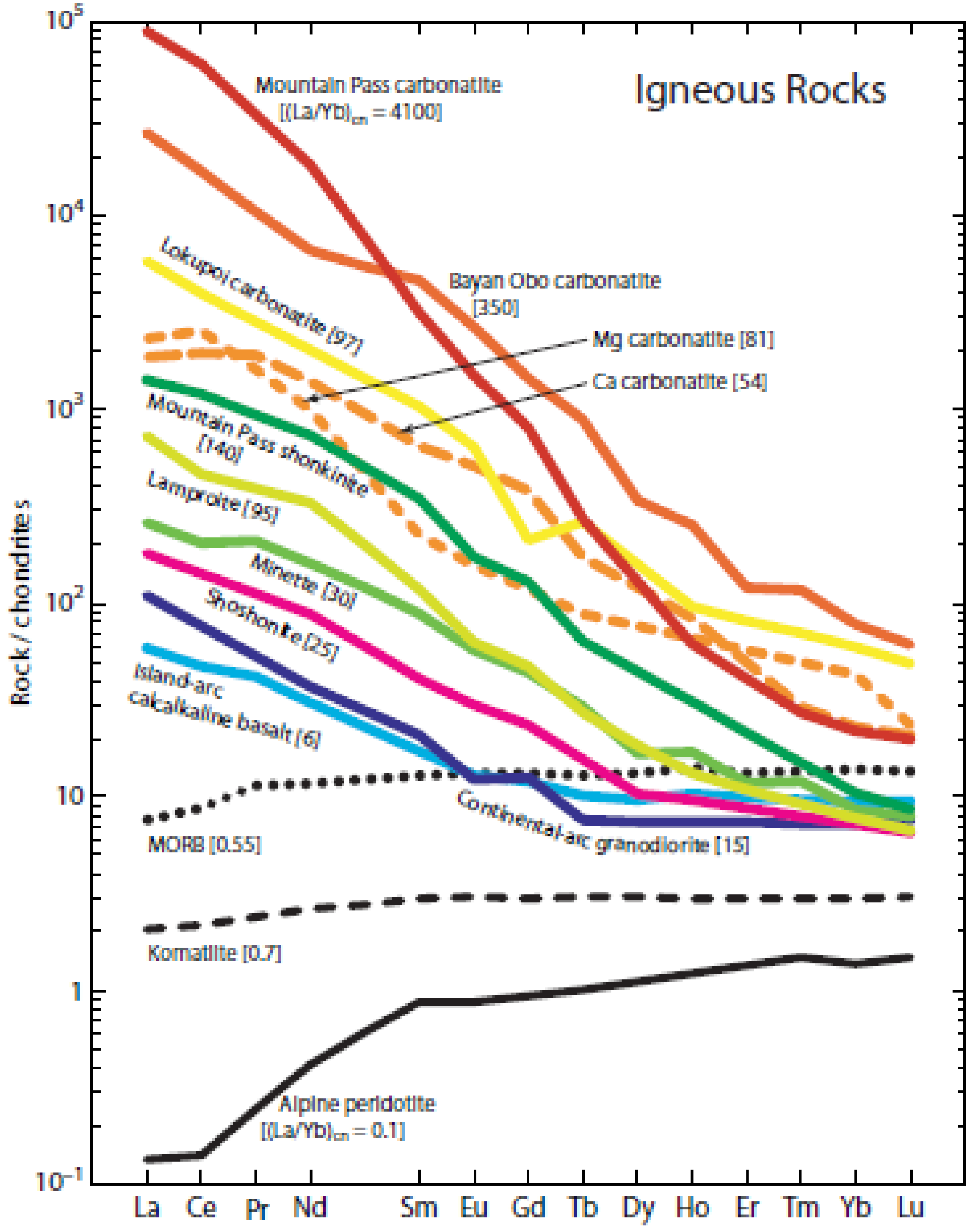


Figure 3. Chondrite-normalized (Table 1; Nakamura, 1974) REE spectra for average (labeled in italic) or representative compositions (labeled in upright type) of several common suites of ultramafic to intermediate, tholeiitic and calcalkaline

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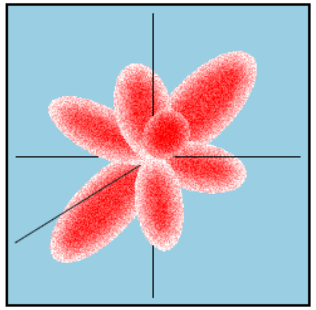
science for a changing world

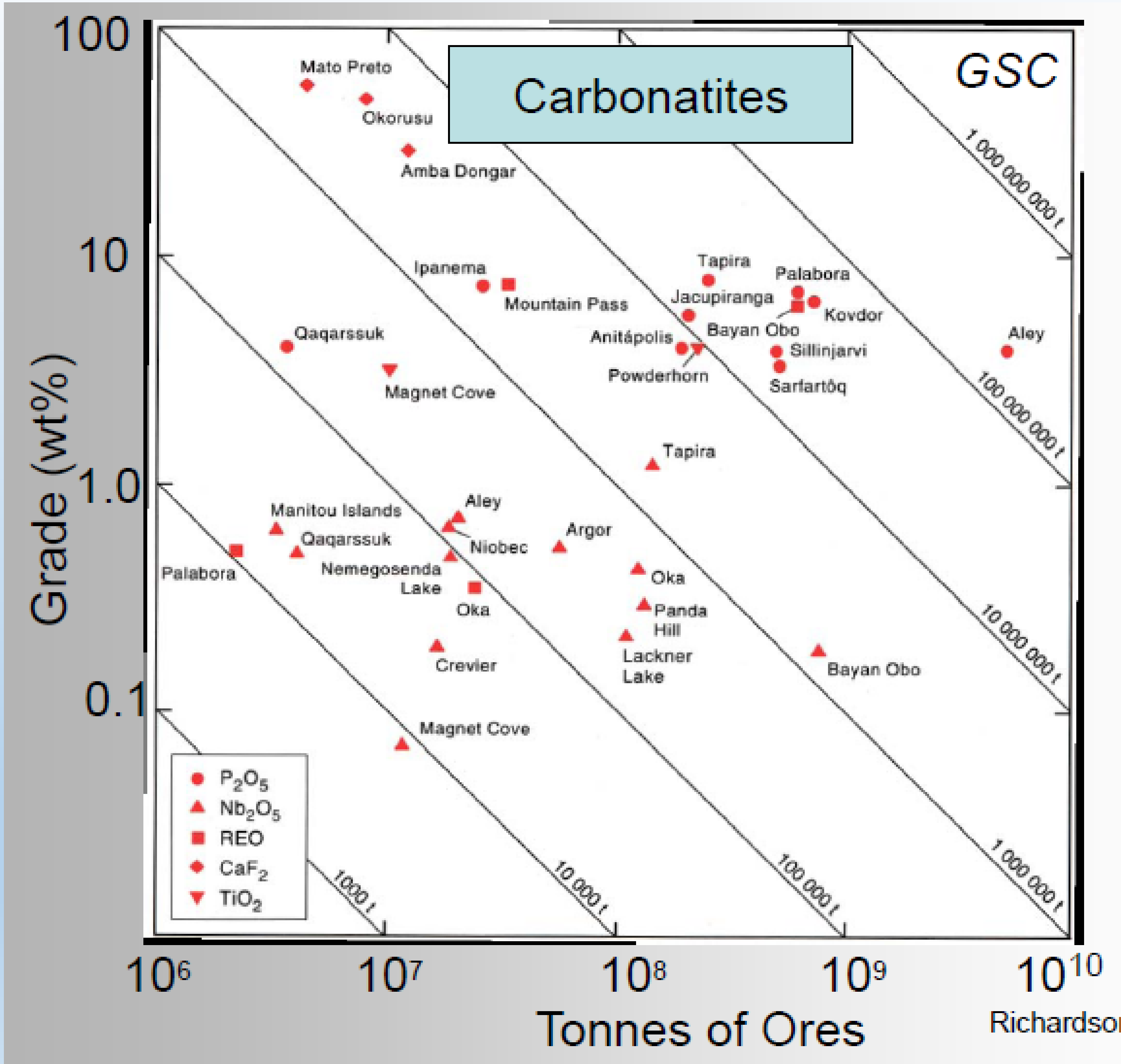
Ultrapotassic Mafic Dikes and Rare Earth Element- and Barium-Rich Carbonatite at Mountain Pass, Mojave Desert, Southern California: Summary and Field Trip Localities

by Gordon B. Haxel



Schematic representation of the probability density function for one of the f orbitals. Progressive filling of the 4f orbitals characterizes the fifteen lanthanide (rare earth) elements, lanthanum through lutetium.

Open-File Report 2005-1219
2005



Richardson & Birkett 1996

Bayan Obo, China

Bayan Obo, China

- Largest carbonatite in the world
- Discovered in 1927, mined for Fe ore
  - 1500 Mt 35% Fe
- REE discovered in 1936
  - 100) million tonnes at 6% REE2O3
- Nb discovered in 1950s
- Dolphins harmed by mine tailings in the Yellow River
- Could be a IOCG?????

Mineralogy

- Bastnasite
- Monazite
- Aeschynite
- Orthite
- apatite
- Parisite

- Huanghoite
- Fergusonite
- Fersmite
- Xenotime
- Daqingshanite
- Cordylite
- Chevkinite
- britolite

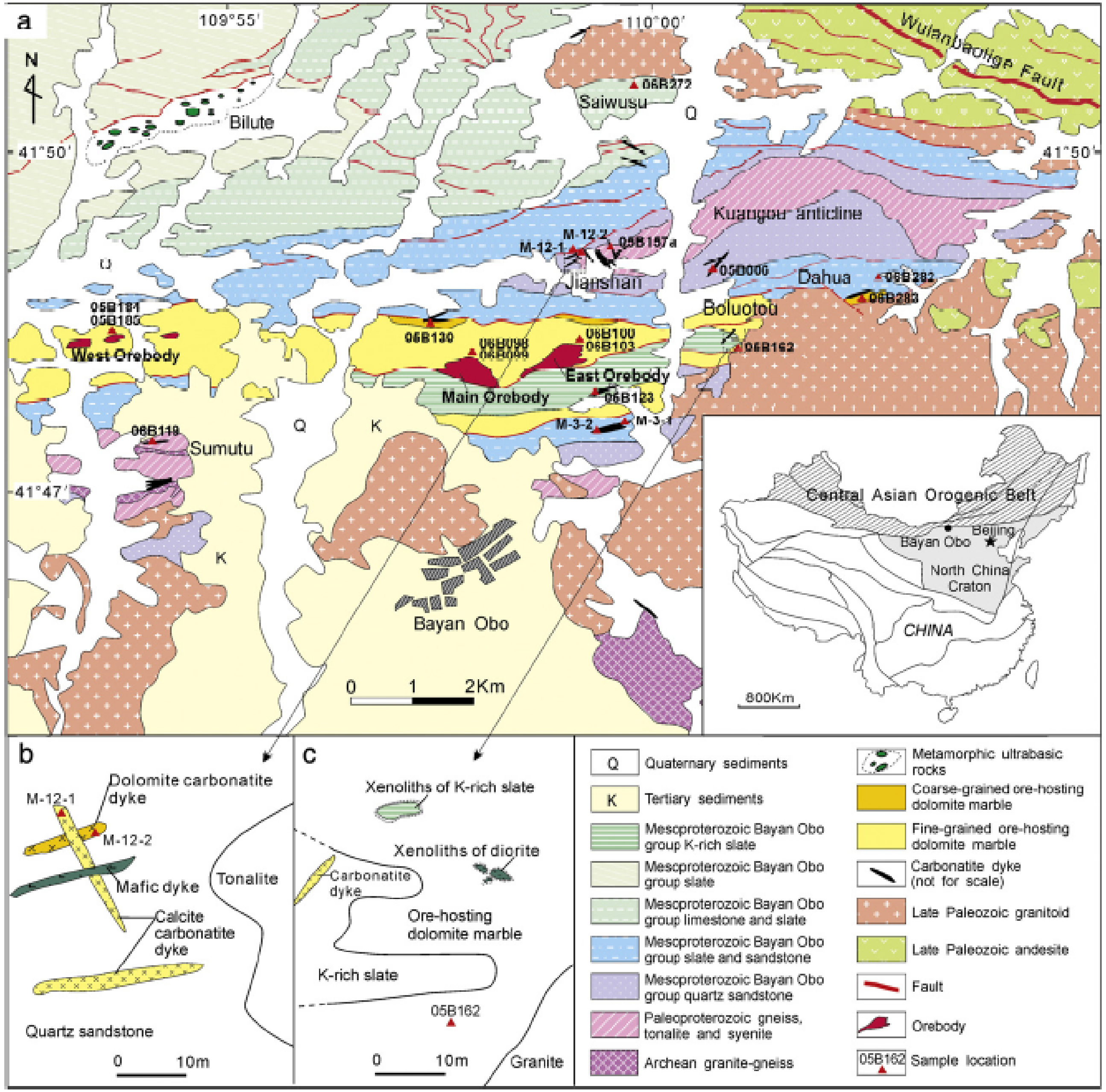


Fig. 1. Geological map of the Bayan Obo REE deposit (a). Intrusive contact between dolomite and calcite carbonatite dykes (b). Xenoliths of K-rich slate and diorite in fine-grained ore-hosting dolomite marble with extensive fenitization and flow structure around them (c).

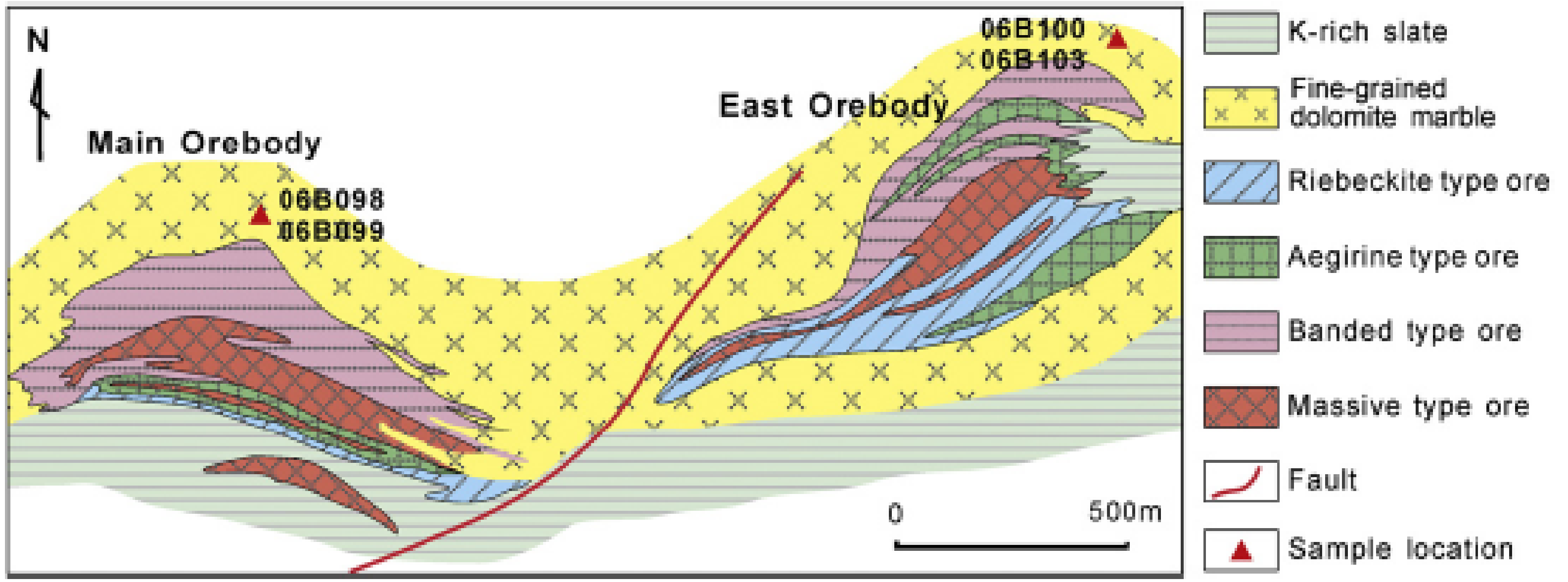


Fig. 2. Structural map of the Main and East Orebody. (Modified after Institute of Geology and Guiyang Geochemistry Chinese Academy of Sciences, 1974).

http://www.igg.cas.cn/rssdy/201108/W020110824363804401800.pdf

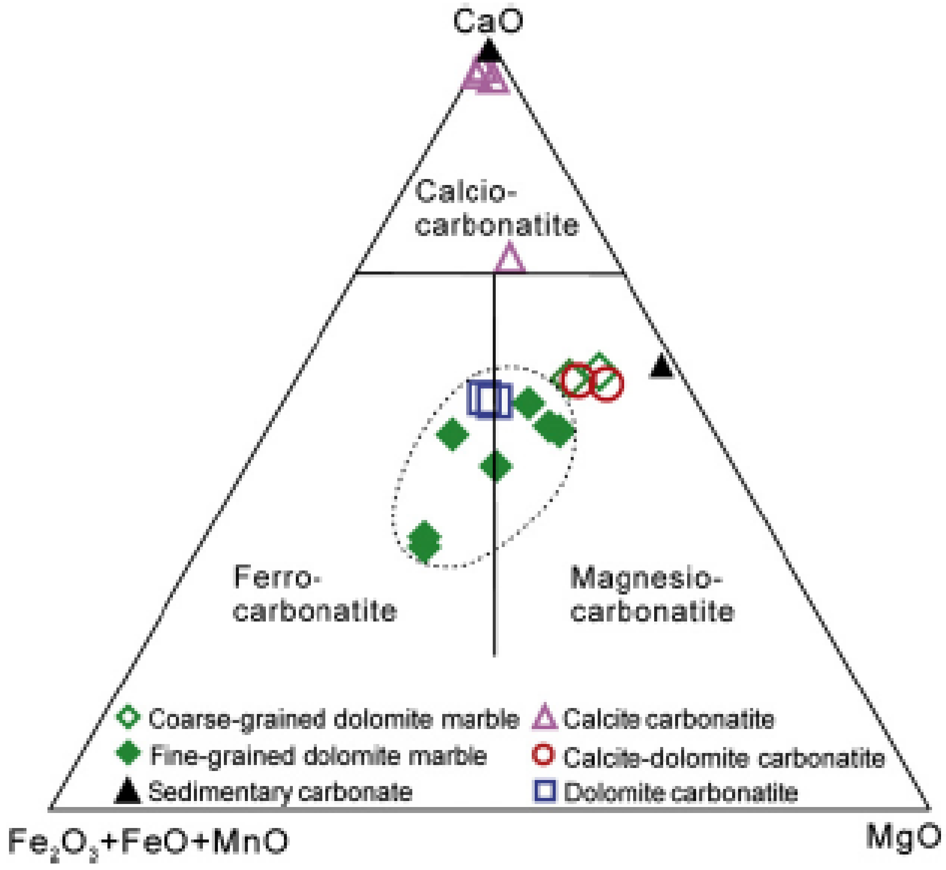


Fig. 3. CaO-MgO-(FeO + Fe_2O_3 + MnO) classification diagram (Woolley and Kempe, 1989) for the carbonatite dykes, ore-hosting dolomite marble and sedimentary carbonate rocks from Bayan Obo district.

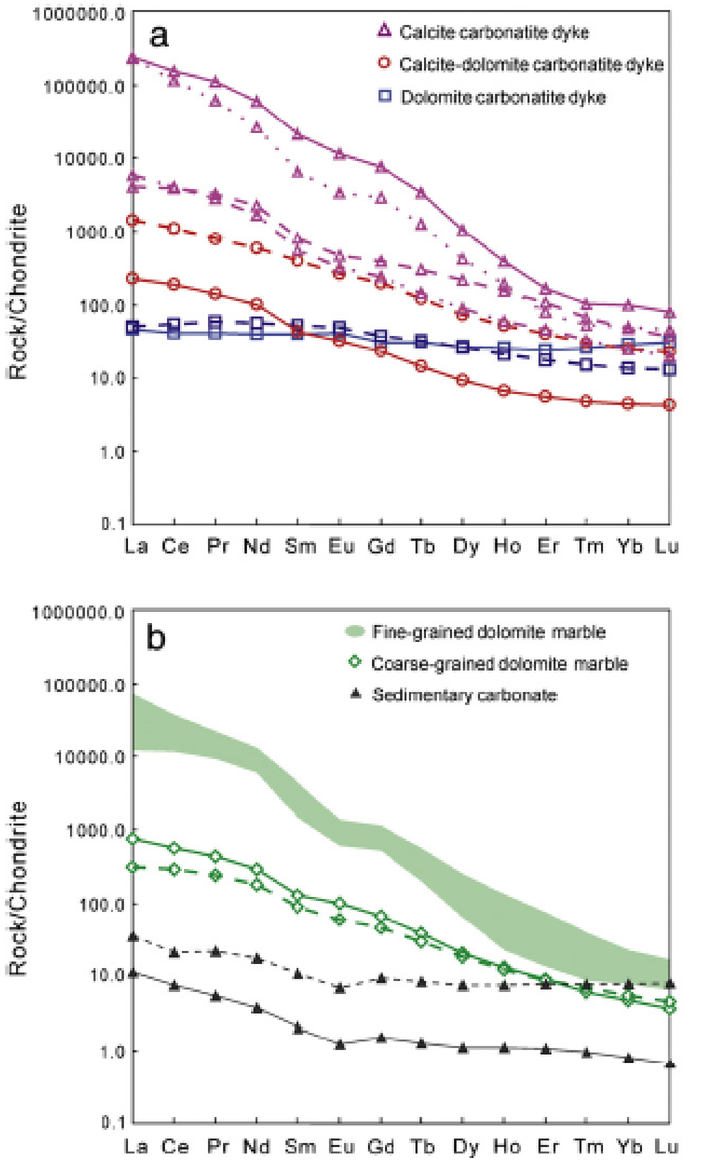


Fig. 6. Chondrite-normalized REE abundance diagram for carbonatite dykes, ore-hosting dolomite marble and sedimentary carbonate rocks from Bayan Obo district. Chondrite values are from Taylor and McLennan (1985).

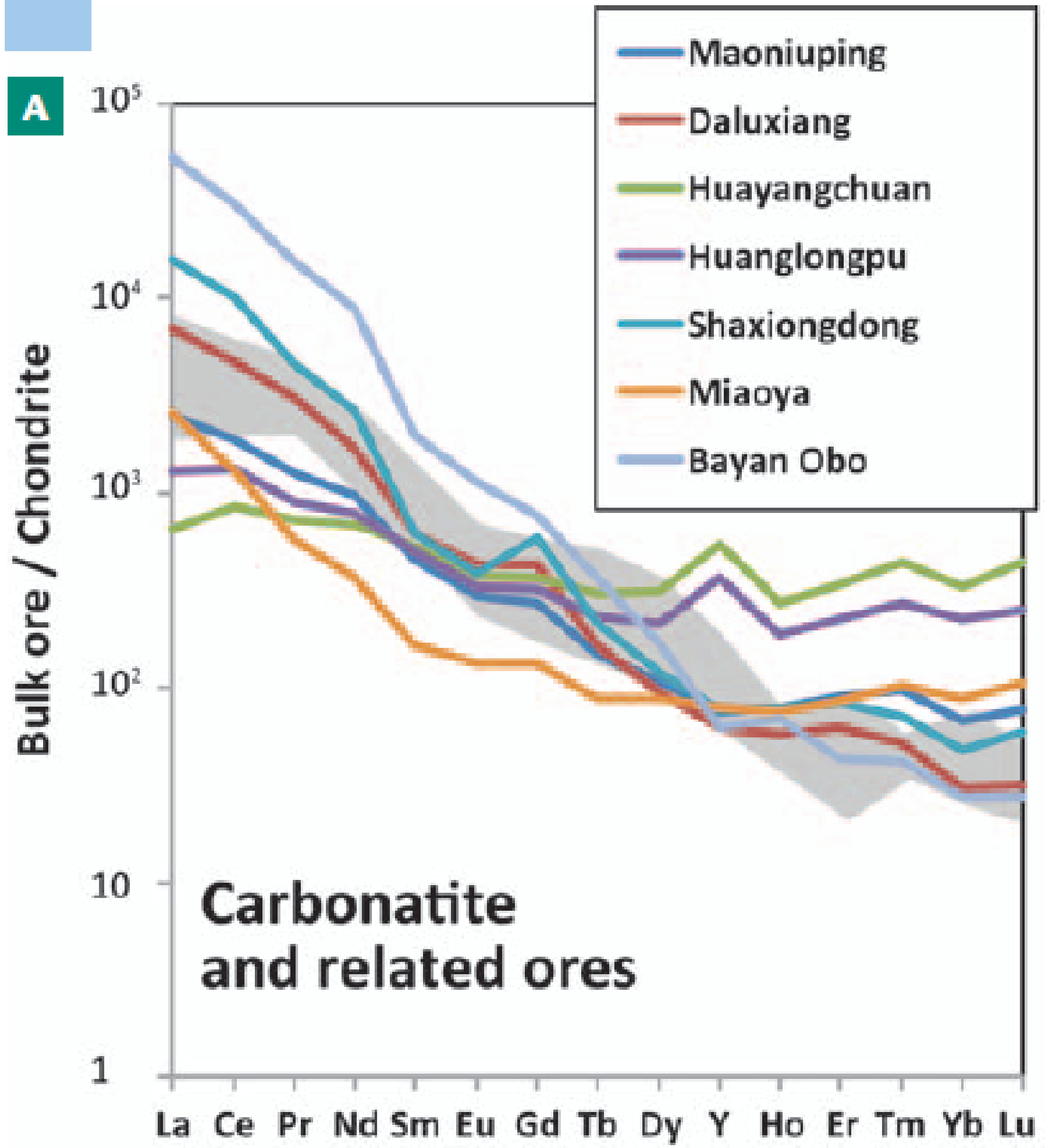
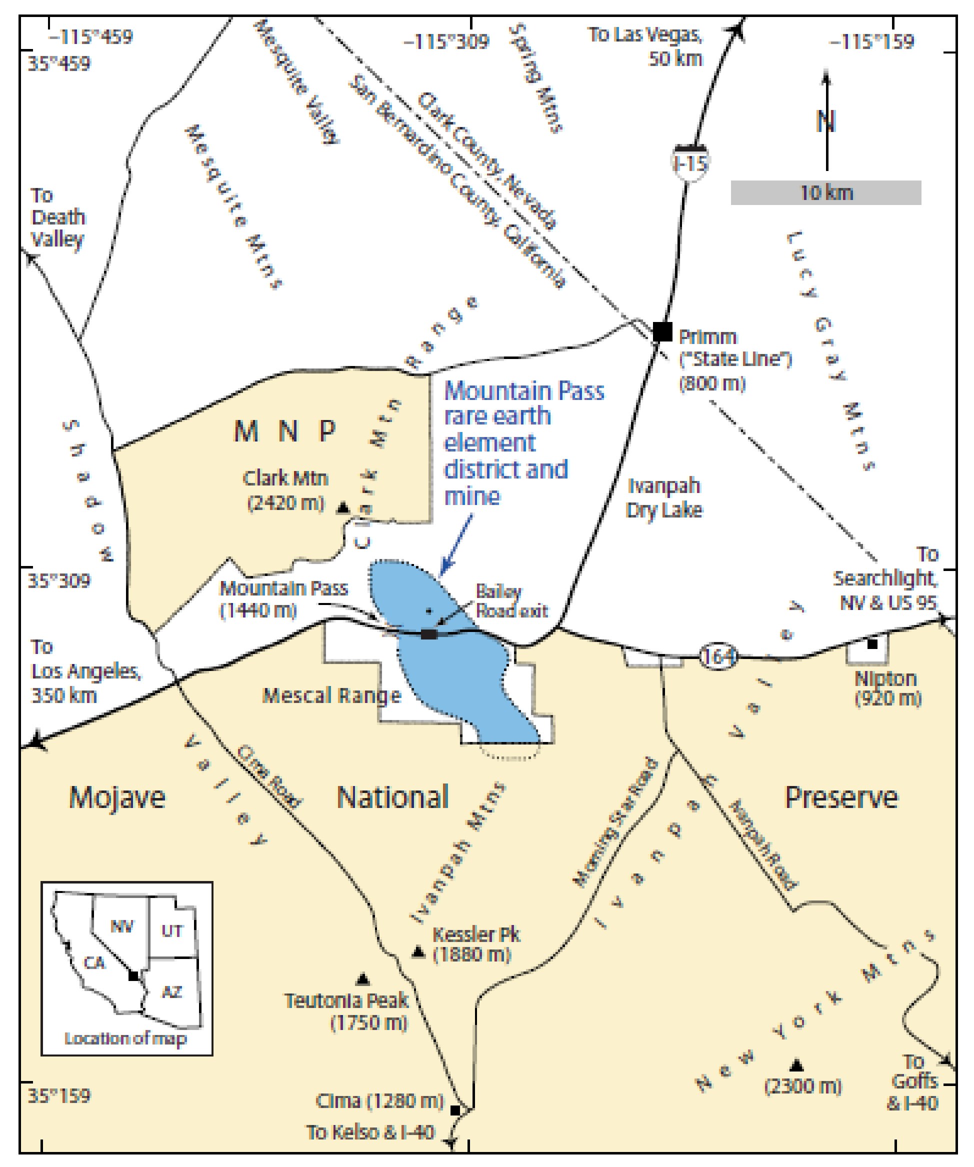


FIGURE 2 Representative chondrite-normalized plots showing the distribution of REEs in the deposits discussed in the text. Yttrium is plotted as a pseudo-lanthanide between Dy

Kynicky et al. 2012

Molycorp Mountain Pass

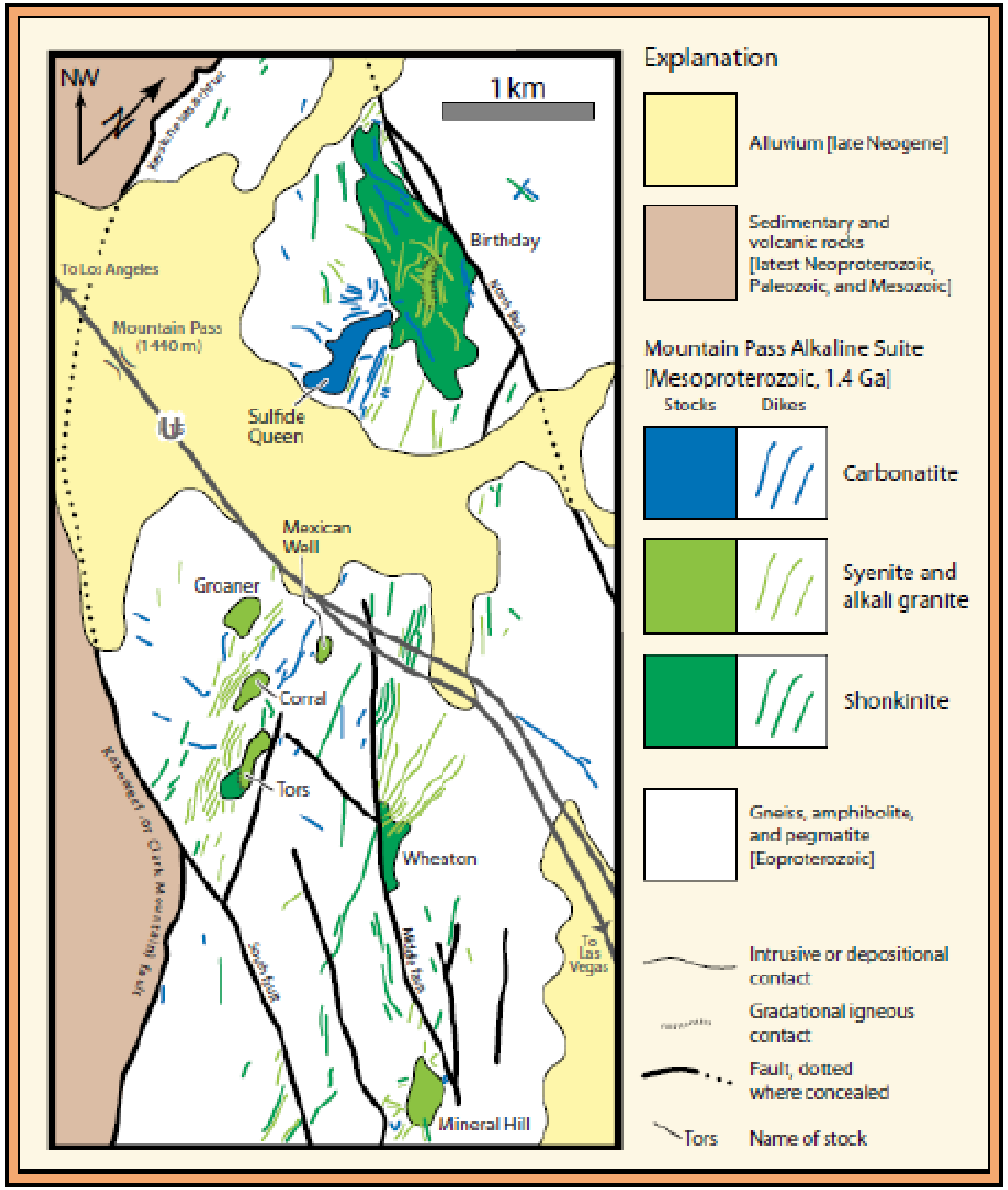


Molycorp Mountain Pass

- Mojave Desert
- Discovered in 1949 during exploration for U
- 1.4 Ga

Birthday vein


0 10 20 30 40 50 60 70 80 mm
Mineralium Deposita
SGA
Society for Geology
Applied to Mineral Deposits
0 1 2 Inch 3

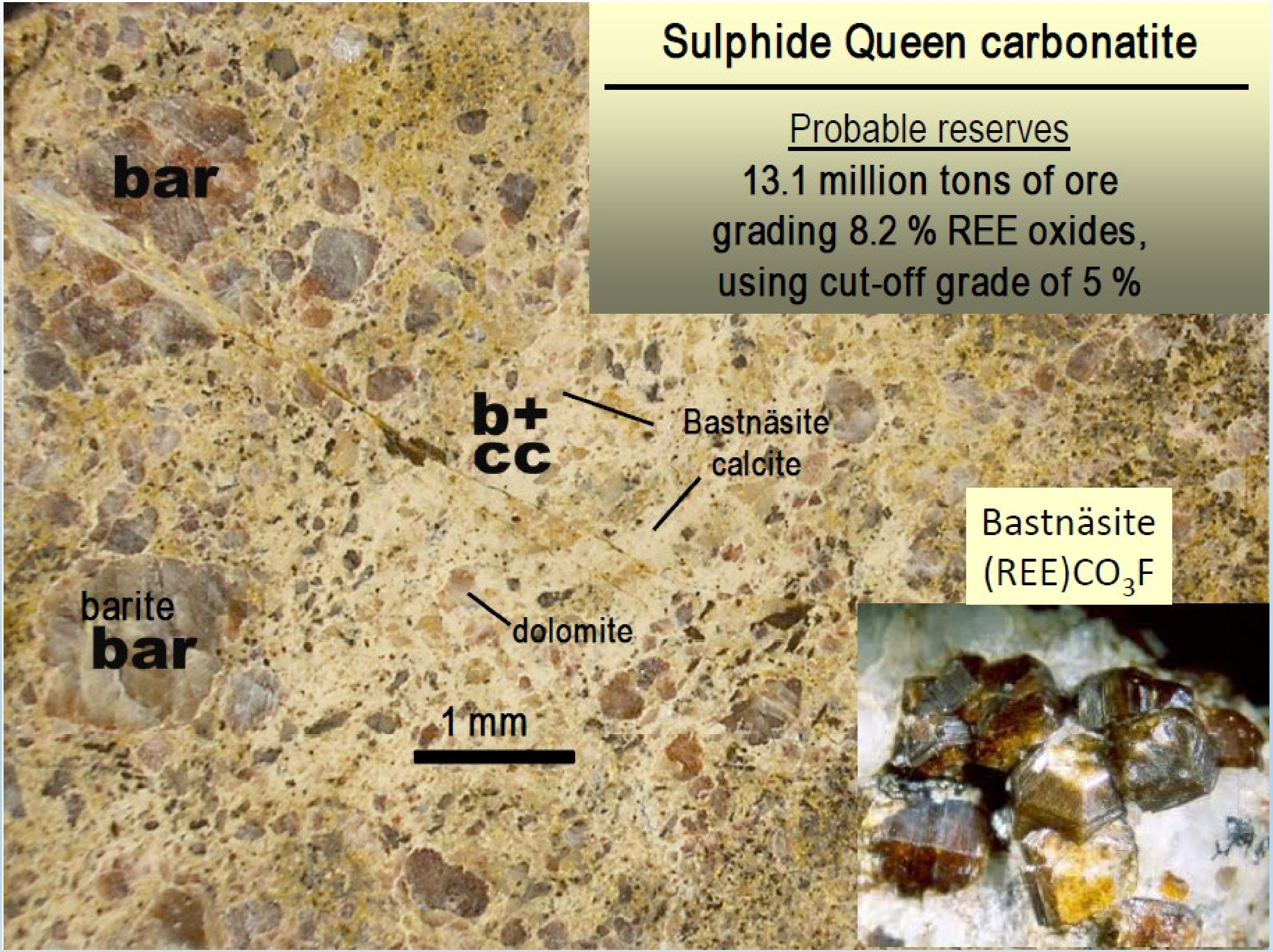


From: Haxel (2005)

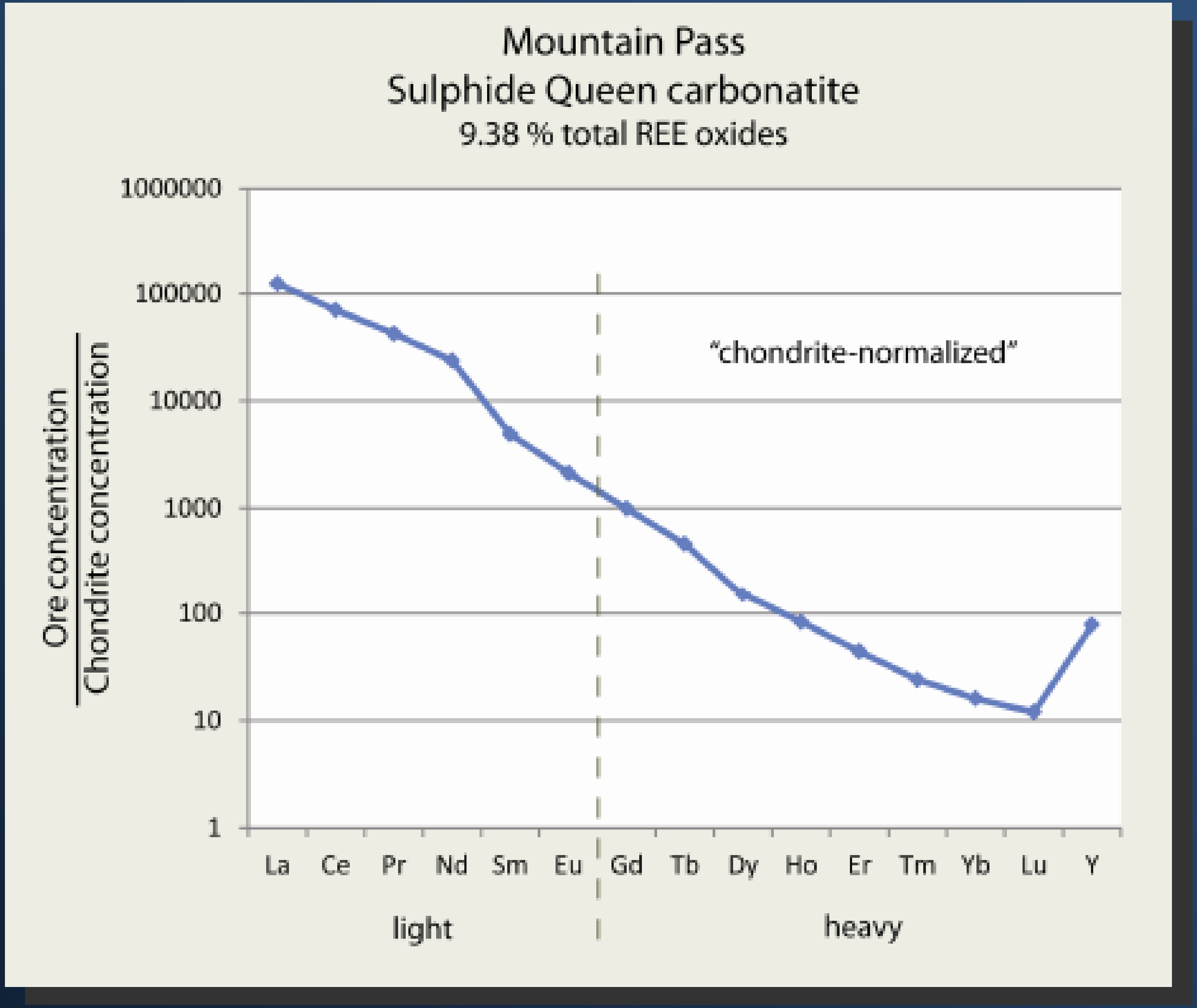
Sulphide Queen carbonatite

Probable reserves

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



Mountain Pass Sulphide Queen Carbonitite



USGS

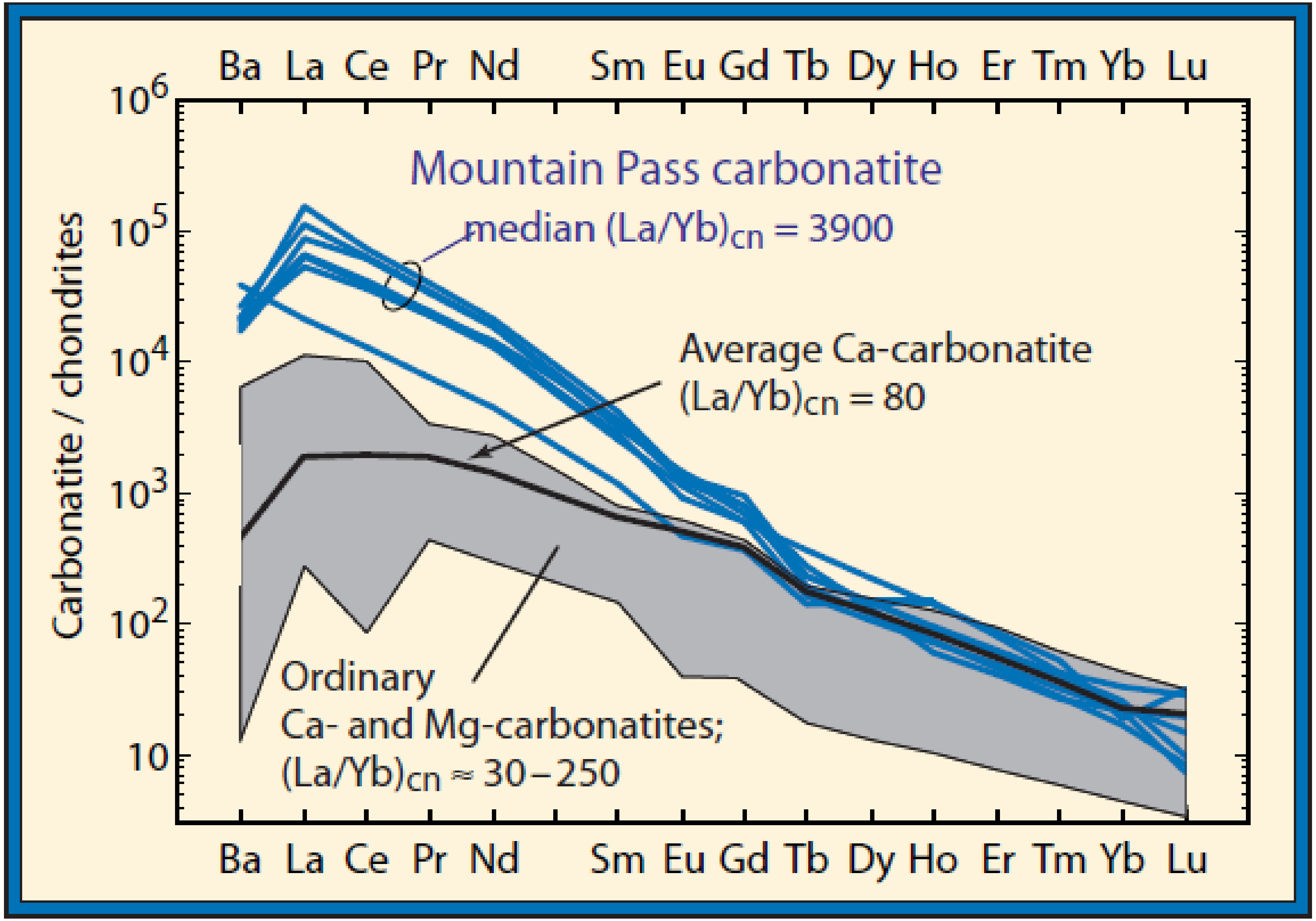


Figure 15. Extended REE spectra (lanthanides plus Ba) of Mountain Pass carbonatite (including one analysis from Johnson and Sisneros, 1982), compared with ordinary carbonatites (Woolley and Kempe, 1989); chondrite normalized (Table 1; Nakamura, 1974). See also Figures 3, 13, and 14.

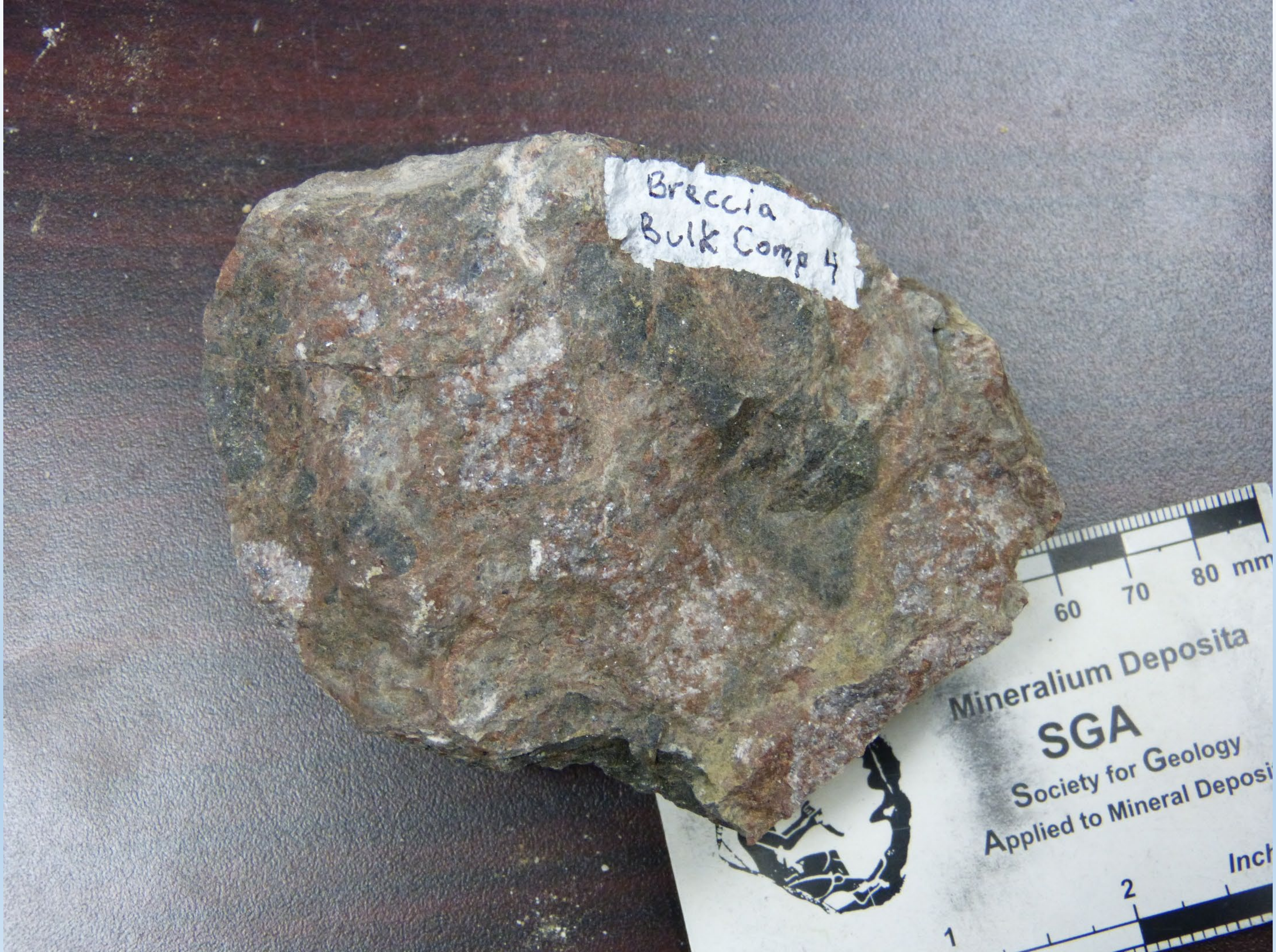
Mountain Pass, Ca timeline

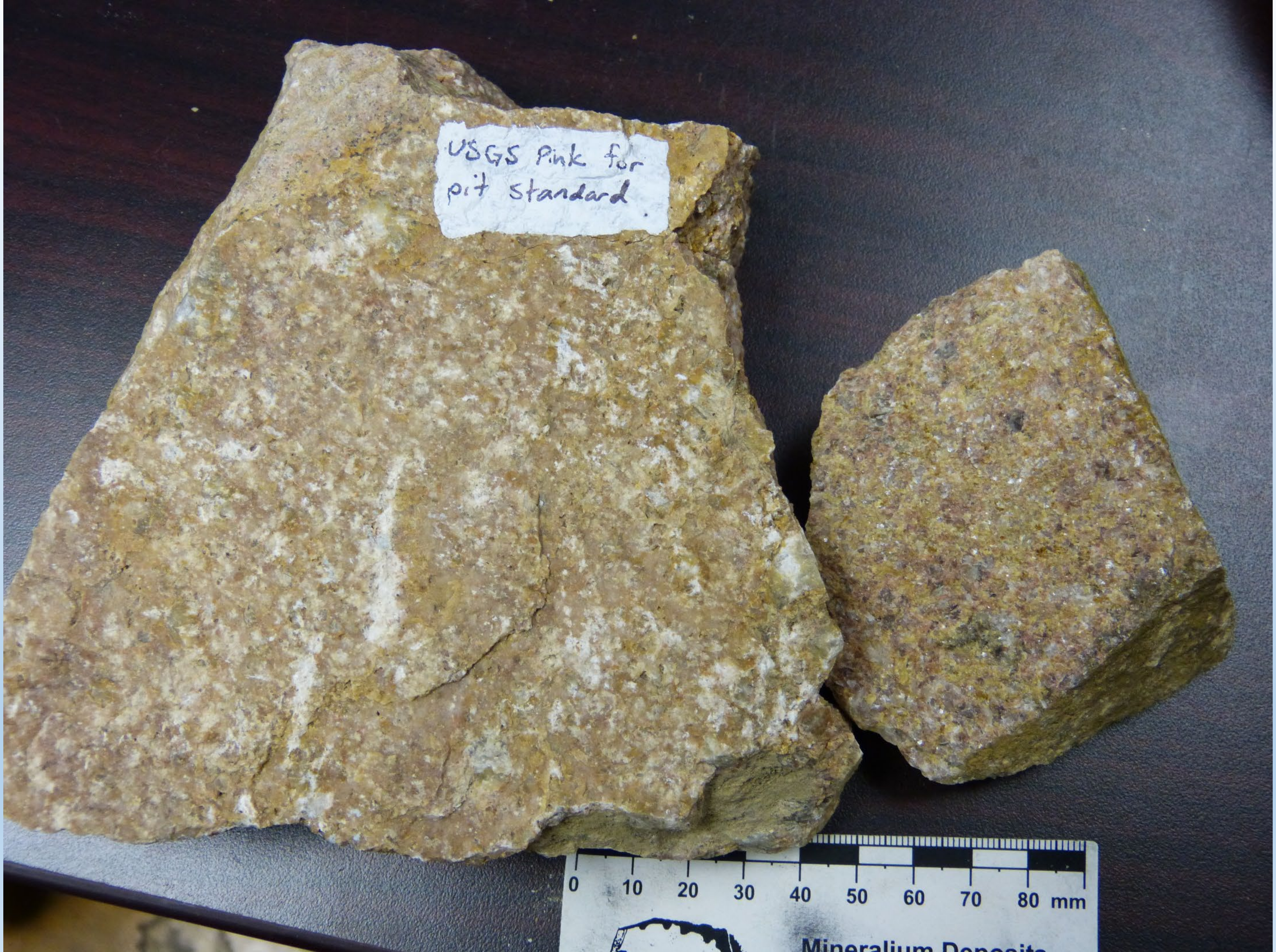
- 1949 Discovered as an U anomaly
- 1952 Mountain Pass mine opens (Molybdenum Corporation of America)
- 1974 Molybdenum Corporation of America change to Molycorp
- 1977 Became Union Oil Co.
- 2002 Pipe break, mine closes
- 2005 Became Chevron Corp.
- 2008 Chevron sells to Molycorp Minerals LLC
- 2012 Mining resumed
- 2015 Molycorp Minerals LLC declares bankruptcy
- 2016 Neo Performance Materials acquires mine
- 2017 JHL Capital Group LLC, QVT Financial LP, and Shenghe Resources Holding Co., a Chinese minority shareholder, acquires mine, retaining name MP Materials
- 2018 MP Materials resumes mining
- 2022 MP gets $35 mill grant from DOD for processing
  - Plans to process REE end of this year

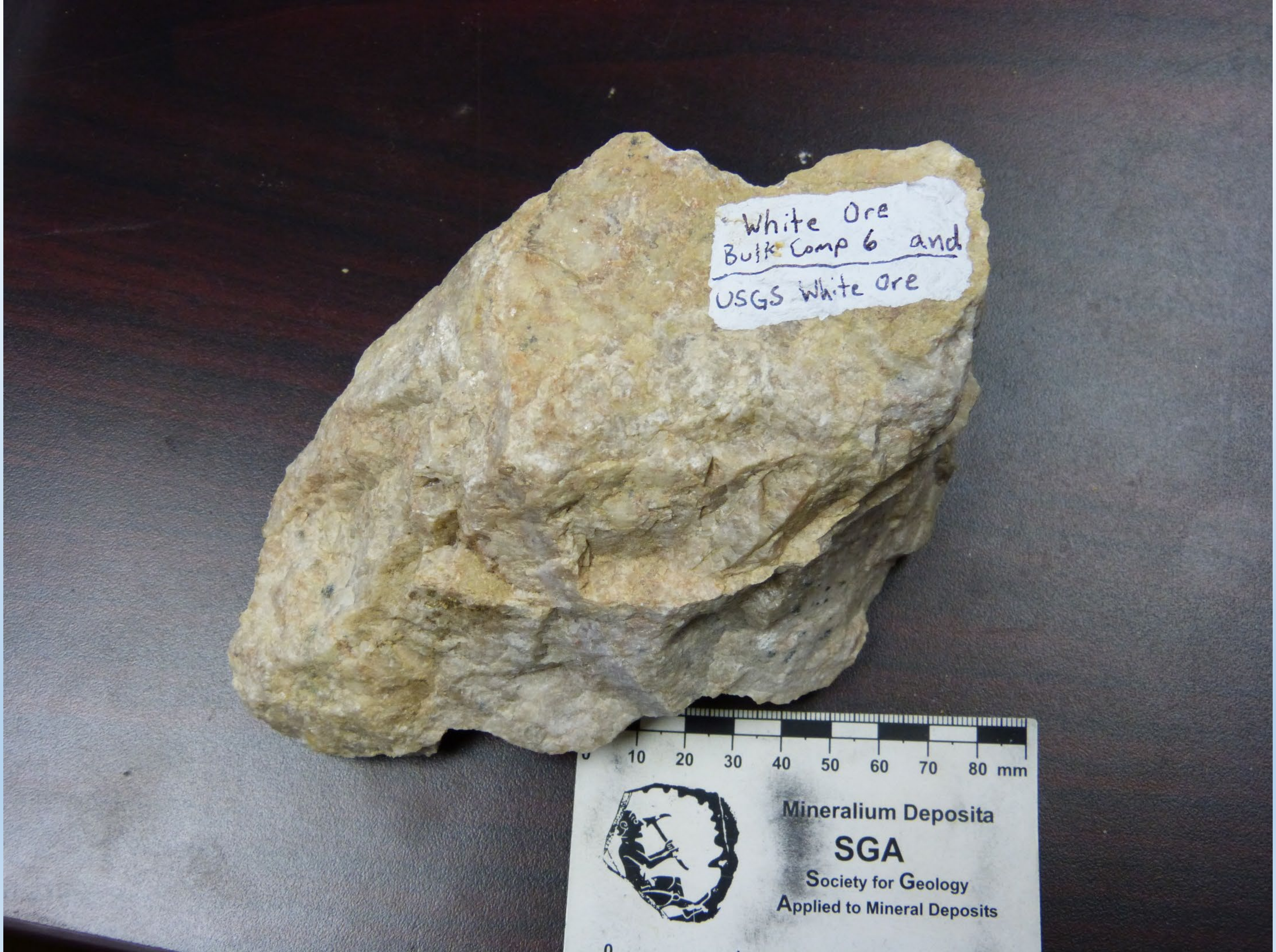
Black Ore
Bulk Conc 2
0
10
20
30
40
50
60
70
80 mm
Mineralium Deposita
SGA

20 30 40 50 60 70
SGA
Society for

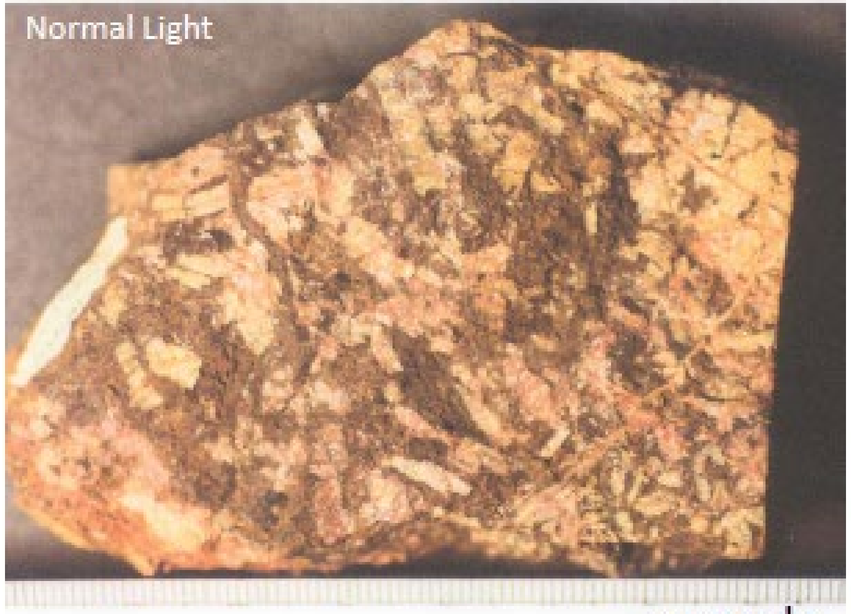

USGS Brown
for pit standard
20 30 40 50 60 70 80 mm
Mineralium Deposita
SGA
Society for Geology


Breccia
Bulk Comp 4
60
70
80 mm
Mineralium Deposita
SGA
Society for Geology
Applied to Mineral Deposi
Inch
1
2

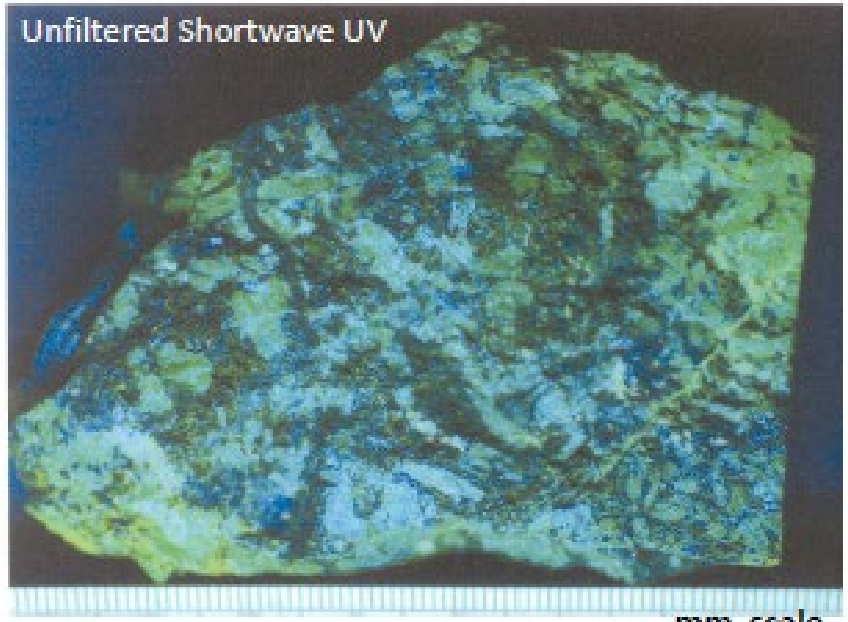

USGS Pink for pit standard.
0 10 20 30 40 50 60 70 80 mm


White Ore
Bulk Comp 6 and
USGS White Ore
10 20 30 40 50 60 70 80 mm
Mineralium Deposita
SGA
Society for Geology
Applied to Mineral Deposits

Bastnäsite, Mountain Pass, CA

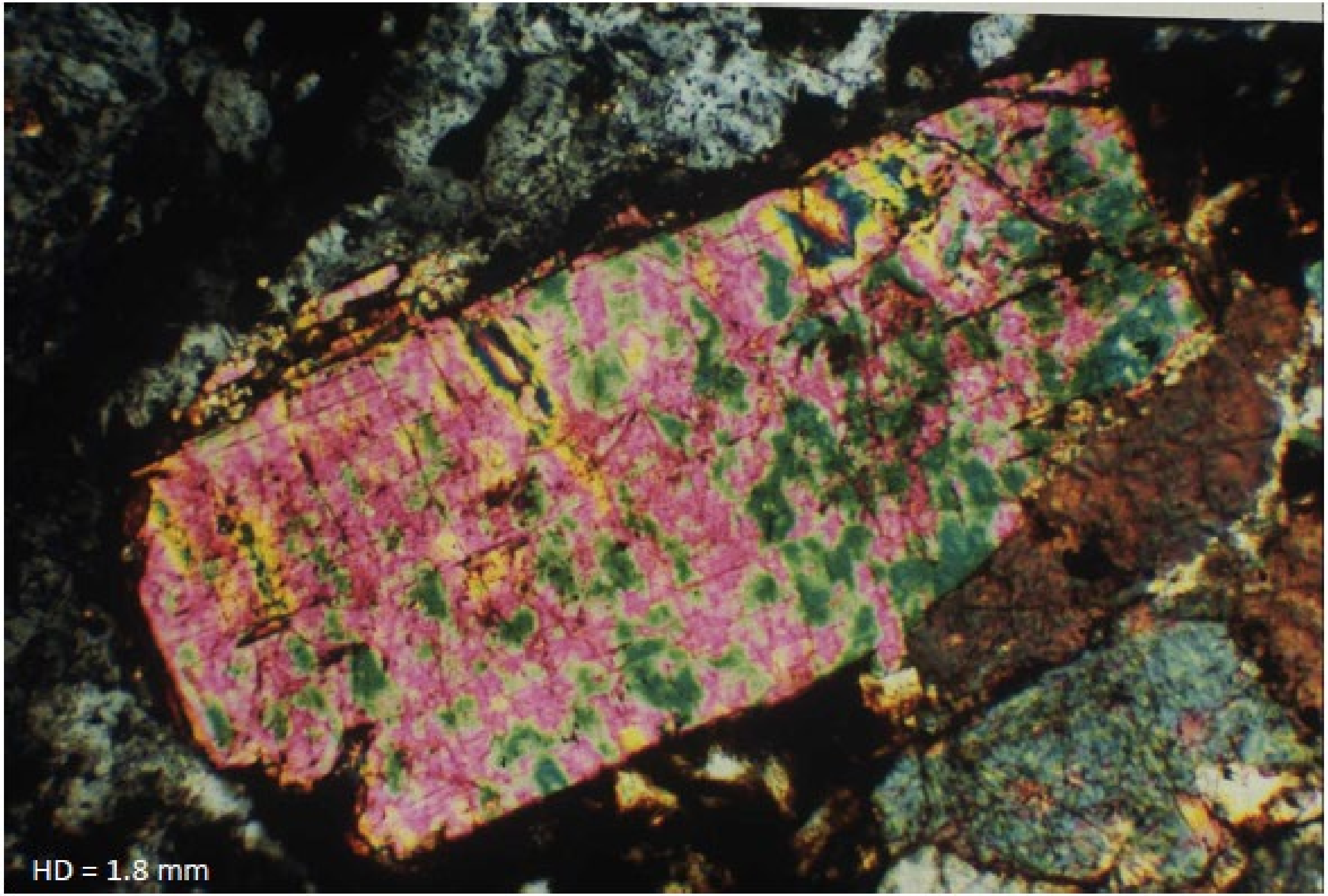


mm scale



mm scale

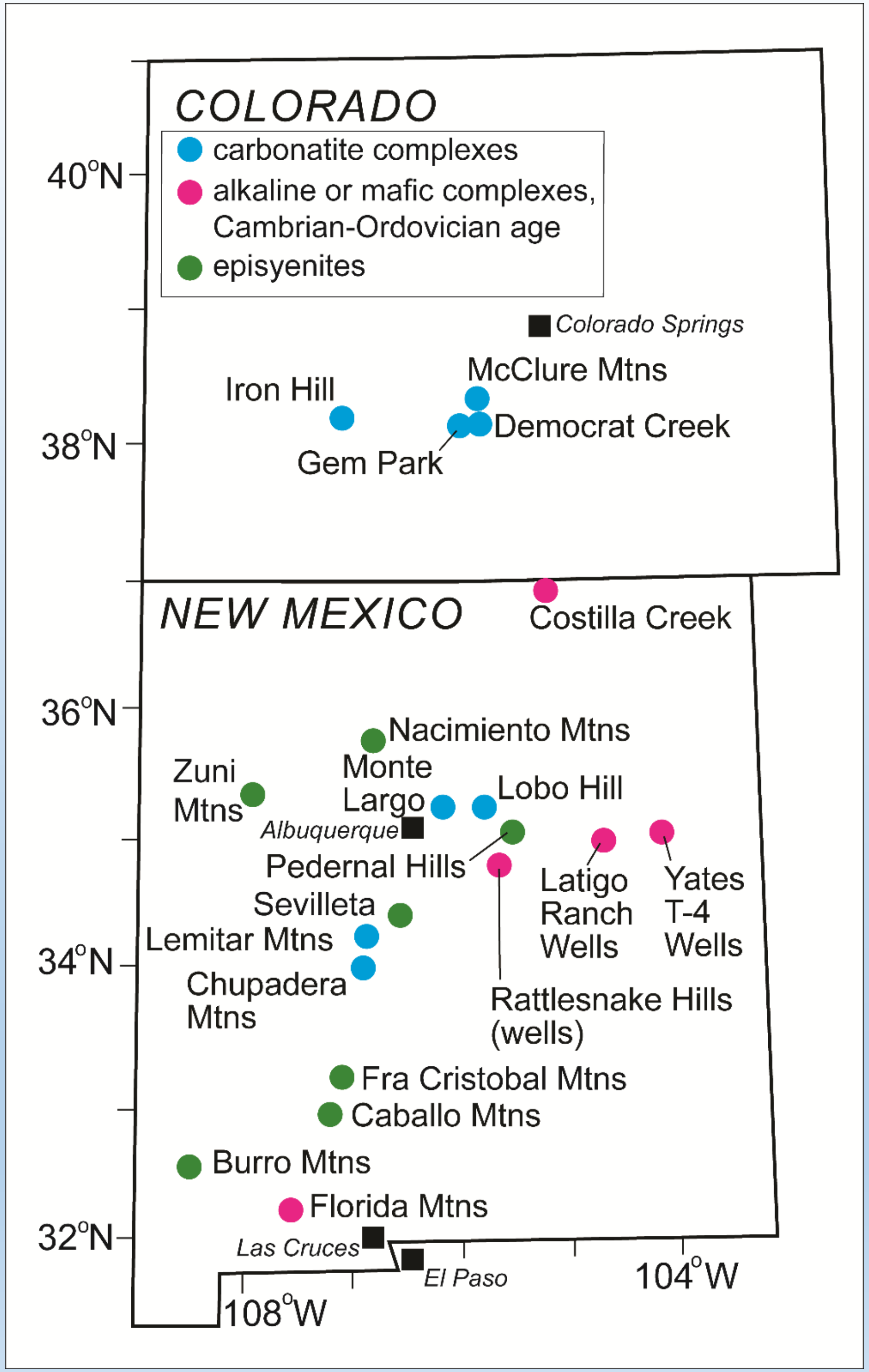
Parisite - $Ca(REE)_2(CO_3)_3F_2$ Mountain Pass, CA

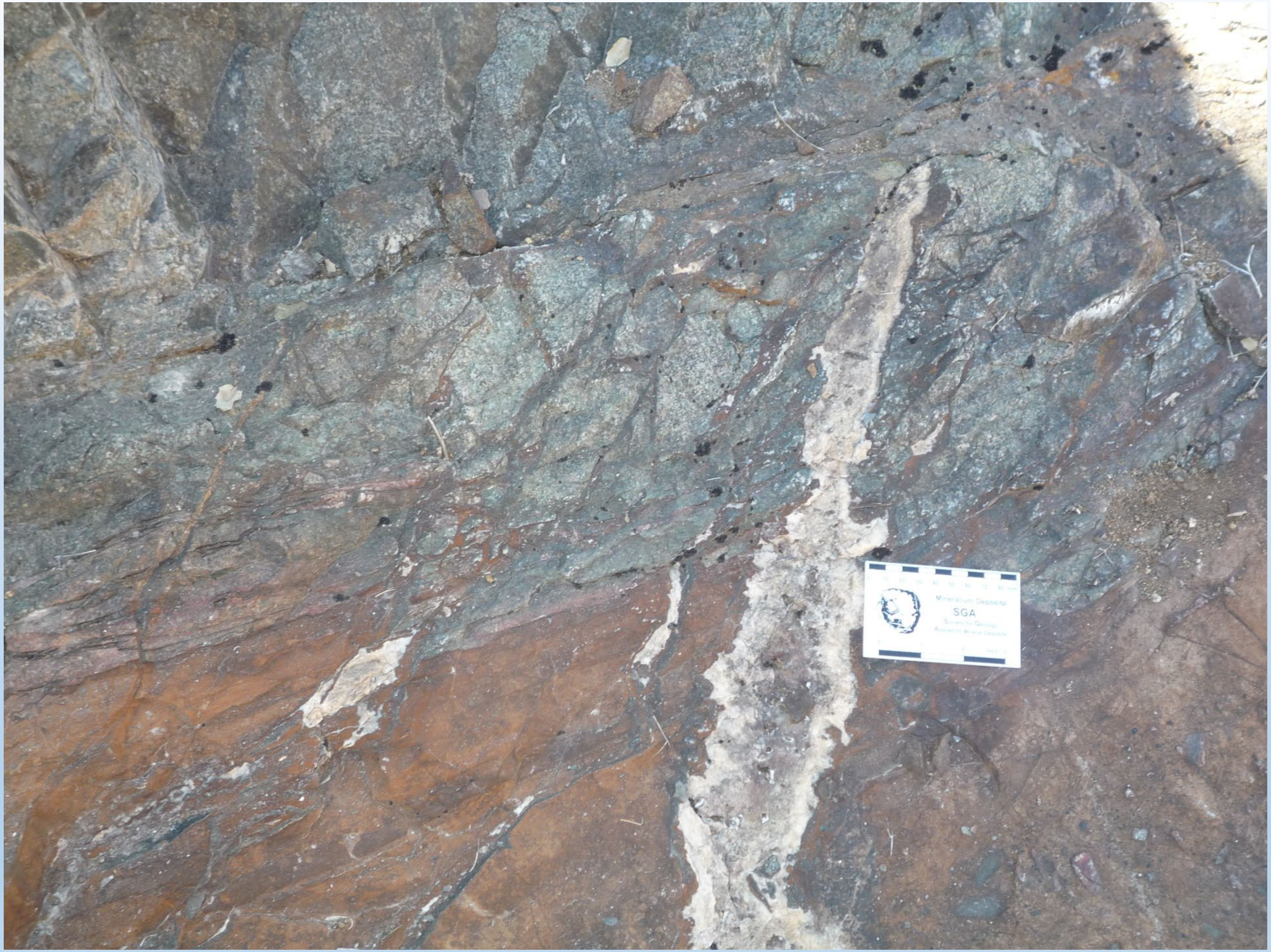



Mineralium Deposita
SGA
Society for Geology
Applied to Mineral Deposits
mm
Inch

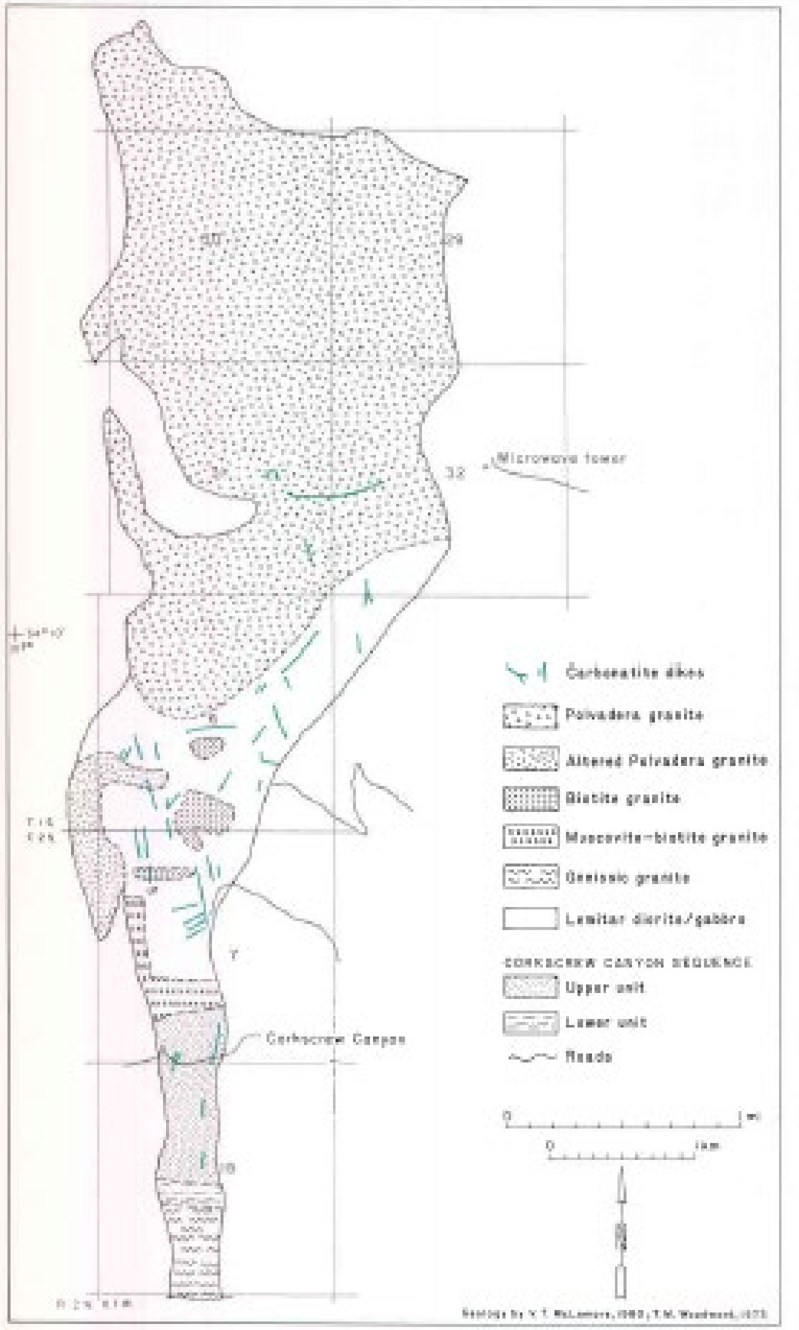
Mineralium Deposita
SGA
Society for Geology
Applied to Mineral Deposits
0 10 20 30 40 50 60 70 80 mm
Inch
0 1 2 3

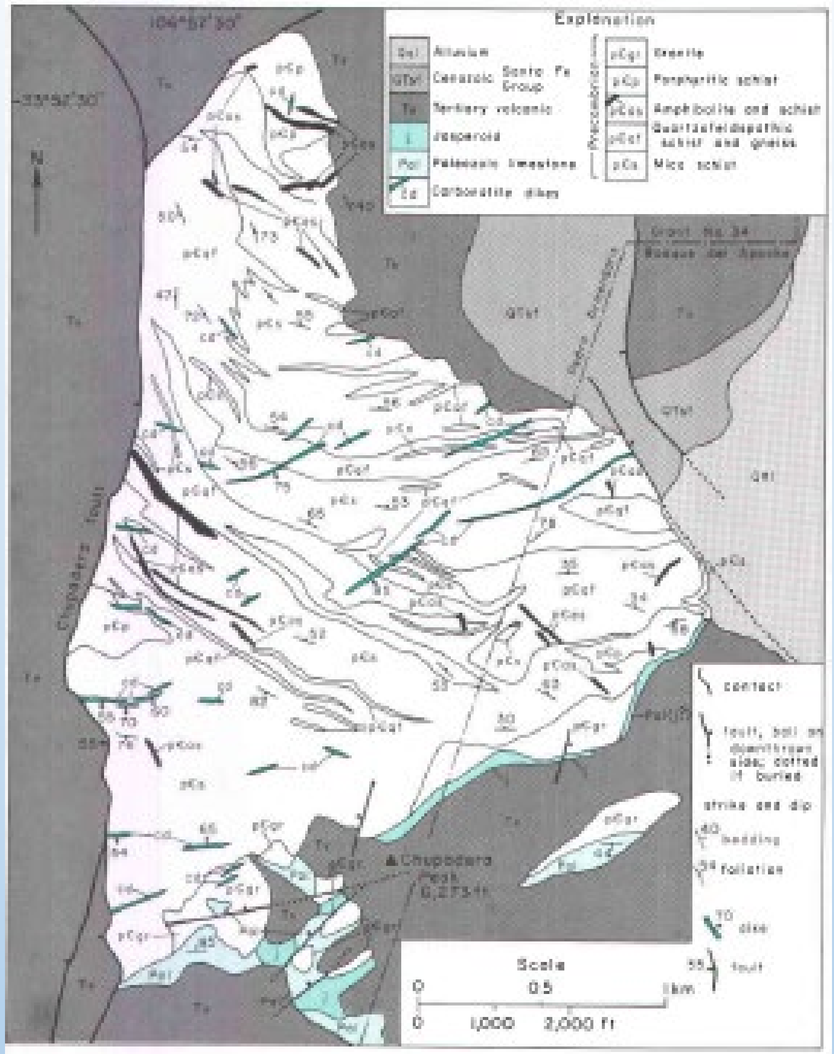
Cambrian-Ordovician carbonatites, syenites, alkali granites, episyenites





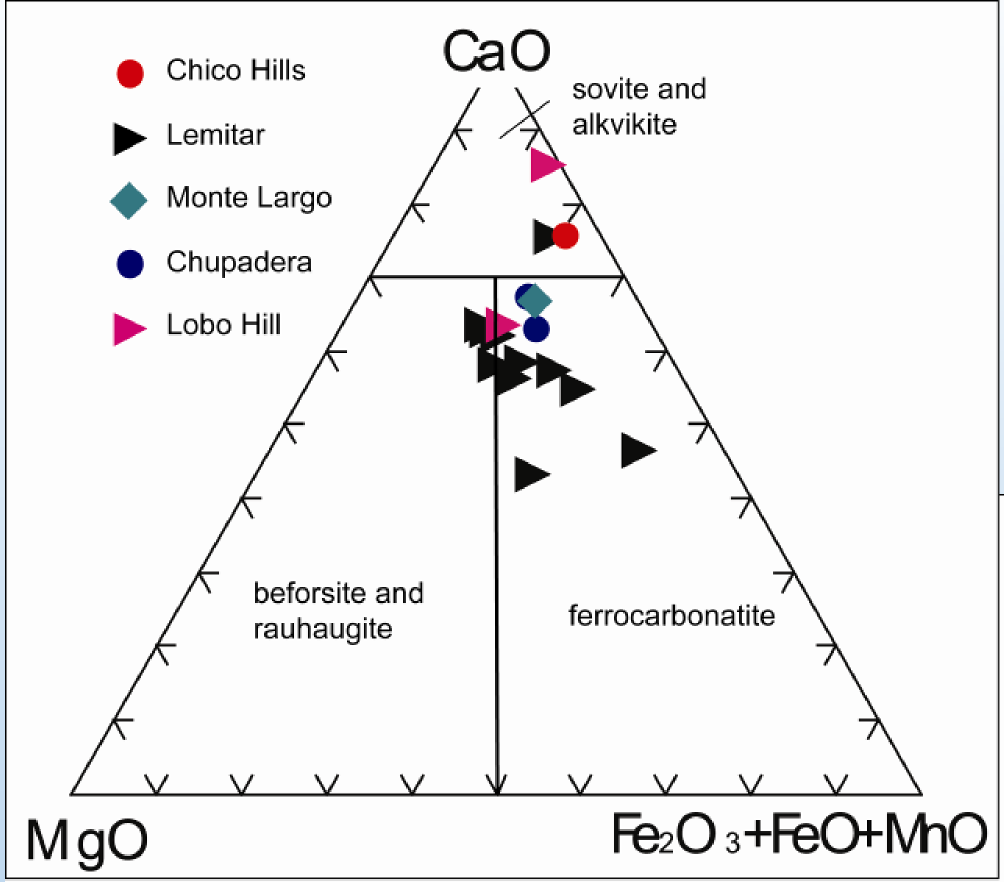
Lemitar carbonatite

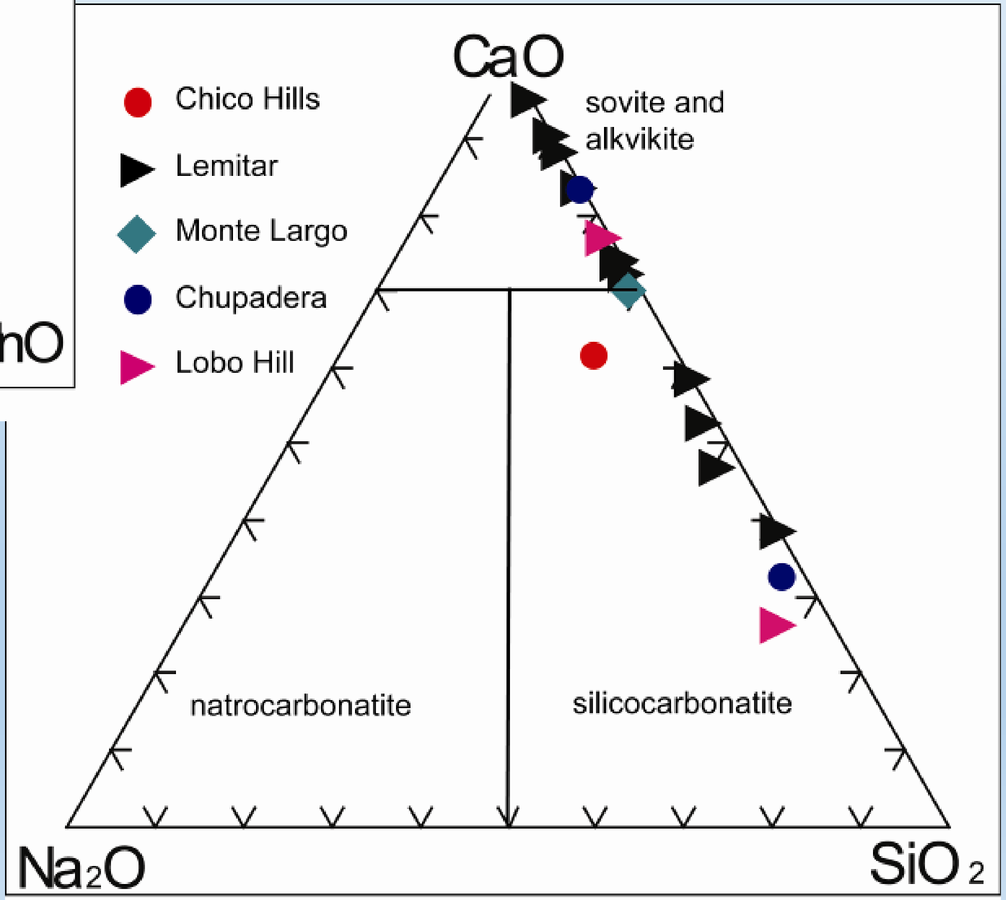


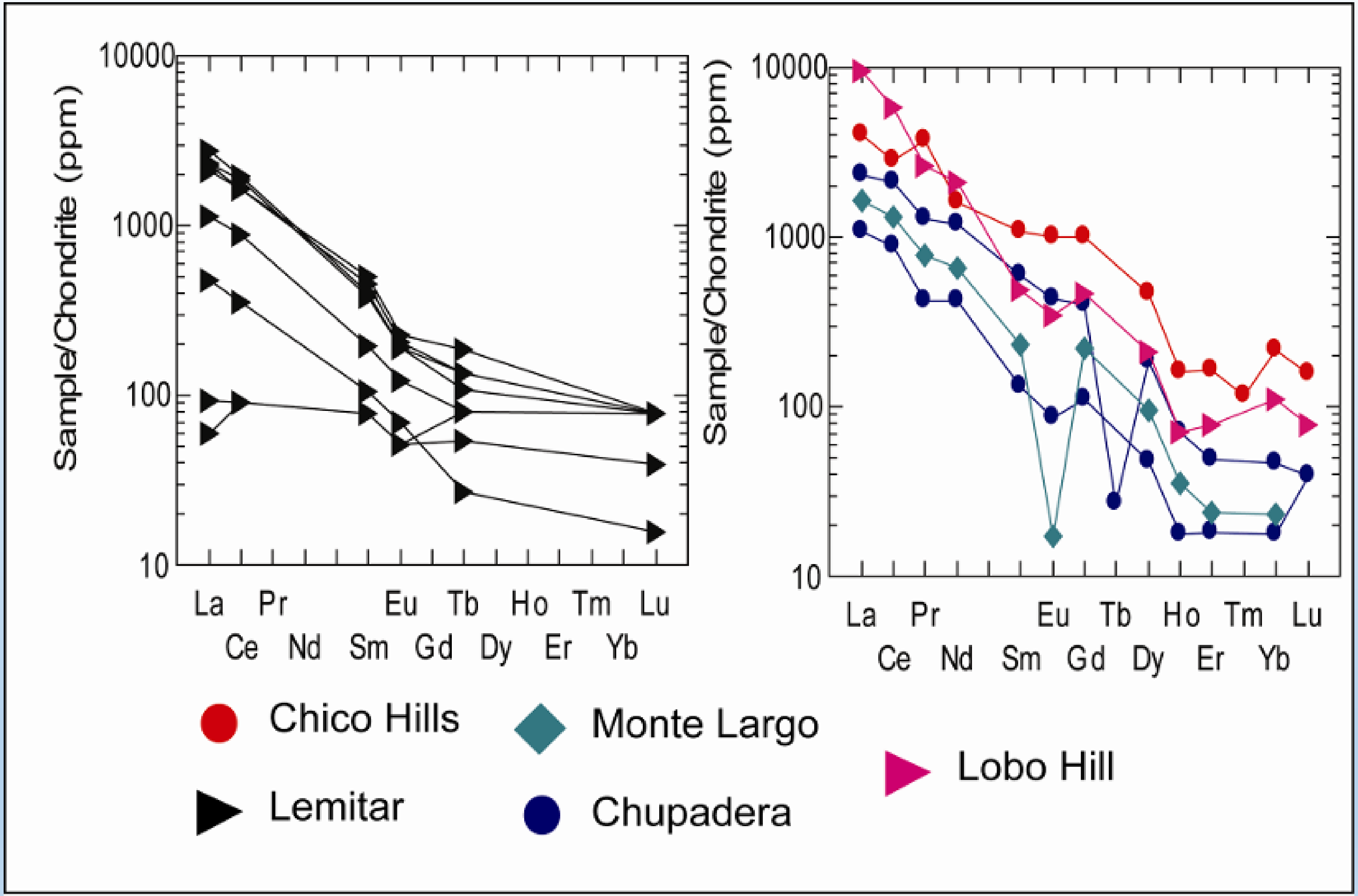


Chupadera carbonatites (van Allen et al., 1986)

Lemitar carbonatites (McLemore, 1983)


Chico Hills
Lemitar
Monte Largo
Chupadera
Lobo Hill
CaO
sovite and alkvikite
beforsite and rauhaugite
ferrocarbonatite
MgO
Fe2O3+FeO+MnO


CaO
Chico Hills
Lemitar
Monte Largo
Chupadera
Lobo Hill
sovite and alkvikite
natrocarbonatite
silicocarbonatite
Na2O
SiO2

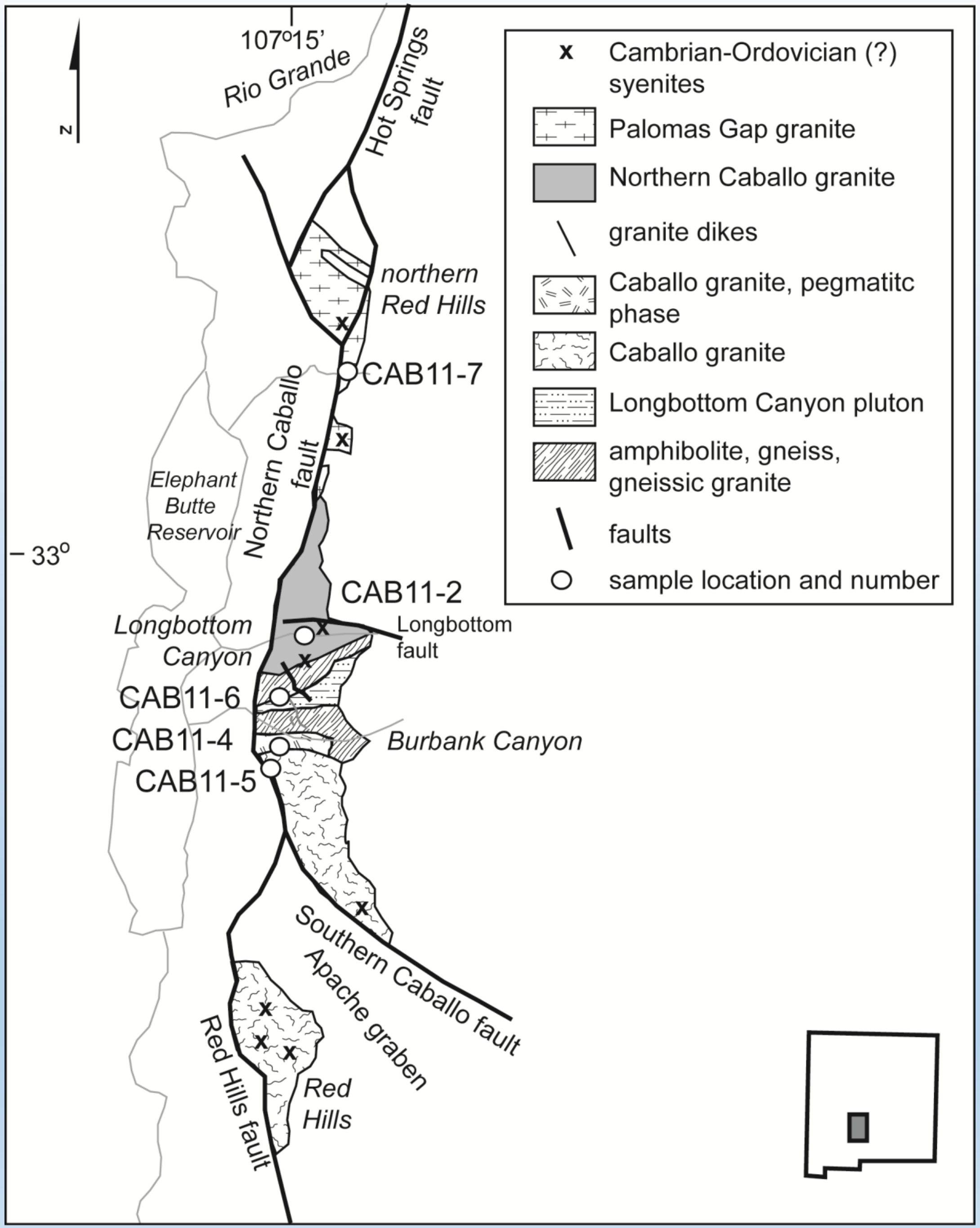


10000
1000
100
10
Sample/Chondrite (ppm)
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
10000
1000
100
10
Sample/Chondrite (ppm)
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Chico Hills
Monte Largo
Lobo Hill
Lemitar
Chupadera

Metamorphic/metasomatic

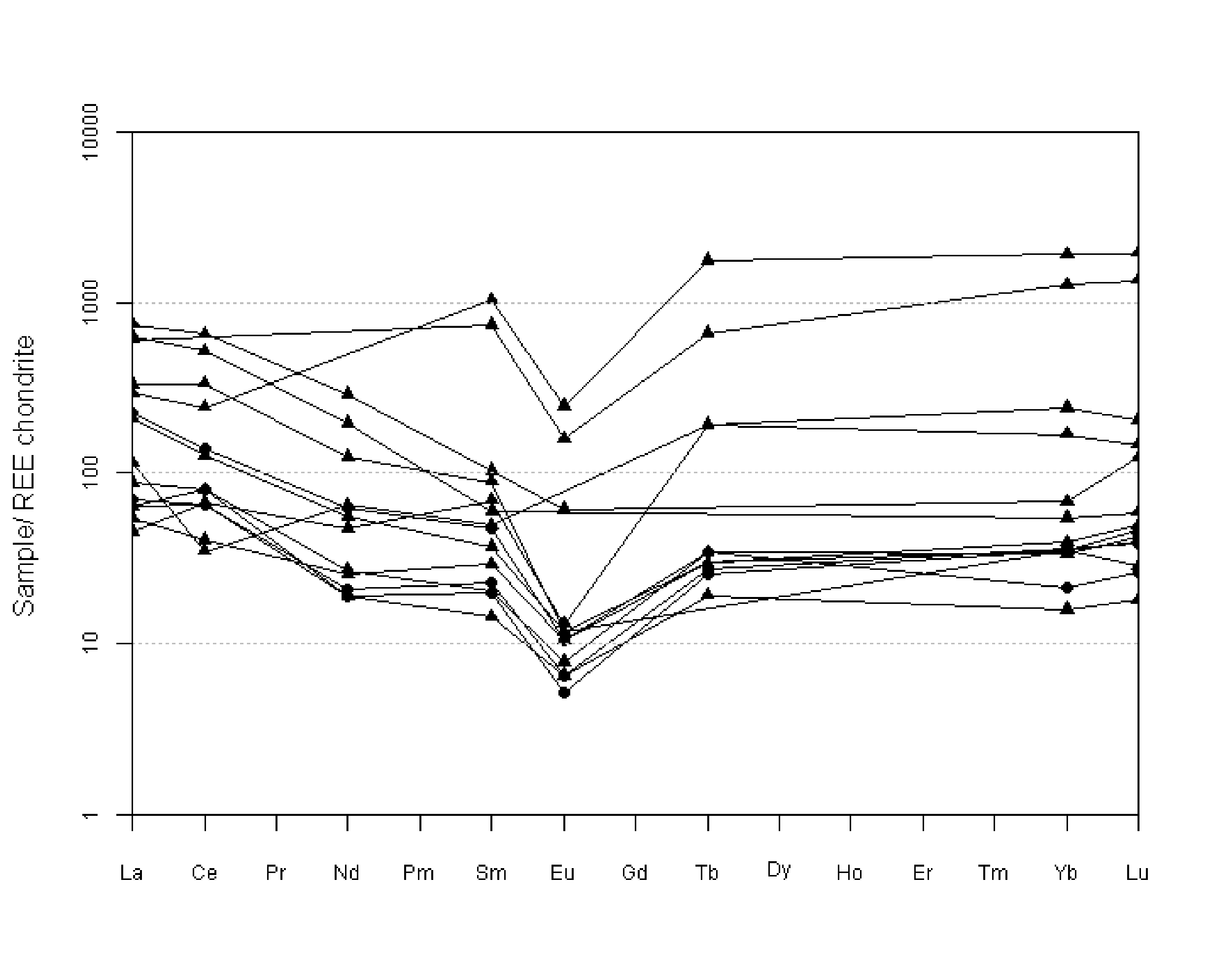
The term *episyenite* was originally used to describe metasomatic syenites whose magmatic protolith was not certain (Lacroix, 1920). These deposits are also known for their uranium content and called metasomatite deposits by the International Atomic Energy Agency (2018). Episyenites are quartz-depleted, K-feldspar-rich altered rocks that were desilicified and metasomatized by alkali-rich fluids (Leroy, 1978; Recio et al., 1997; Boulvais et al., 2007; Suikkanen and Rämö, 2019). The metasomatic rocks in several areas in New Mexico, including the Caballo, Burro, and Zuni Mountains and Lobo Hill were erroneously called magmatic syenites and alkali granites (McMillan and McLemore, 2004), but are actually metasomatic in origin and not primary igneous rocks (Fig. 1; McLemore, 2013, 2020; Riggins, 2014; Riggins et al., 2014). Elsewhere in the world, these alkali-rich metasomatic rocks are associated with U and Th deposits (Costi et al., 2002; Condomines et al., 2007; Cuney et al., 2012; International Atomic Energy Agency, 2018; Suikkanen and Rämö, 2019), gold deposits (López-Moro et al., 2013) and tin-tungsten deposits (Charoy and Pollard, 1989; Costi et al., 2002; Borges et al., 2009), but unmineralized episyenites are found as well (Petersson and Eliasson, 1997; Recio et al., 1997; Hecht et al., 1999). Episyenites are similar to altered rocks formed by fenitization and would be called fenites by some geologists. Fenitization is the alkali-metasomatism associated with carbonatites or alkaline igneous activity (LeBas, 2008). However, we are reluctant to use the term fenite for these rocks studied here because there is no definitive spatial association with carbonatite or alkaline igneous rocks.

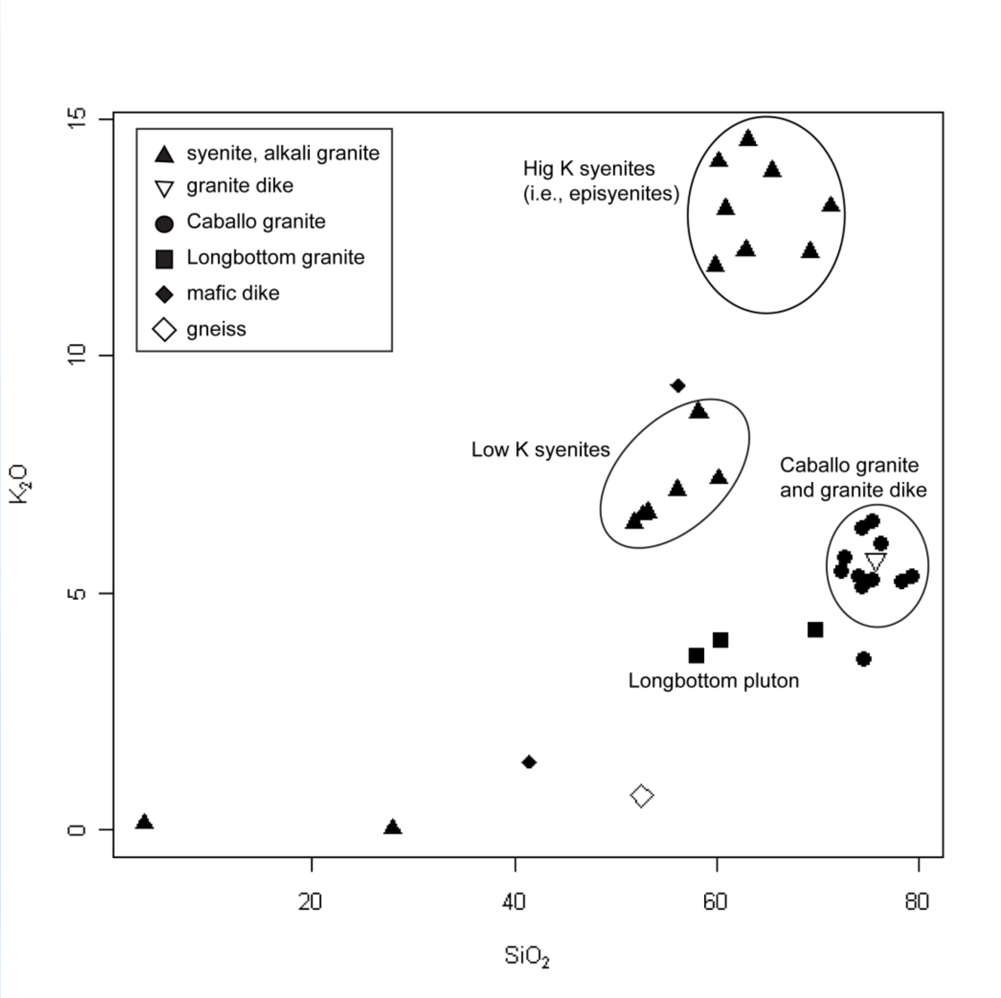
Episyenites in Longbottom Canyon, Caballo Mountains

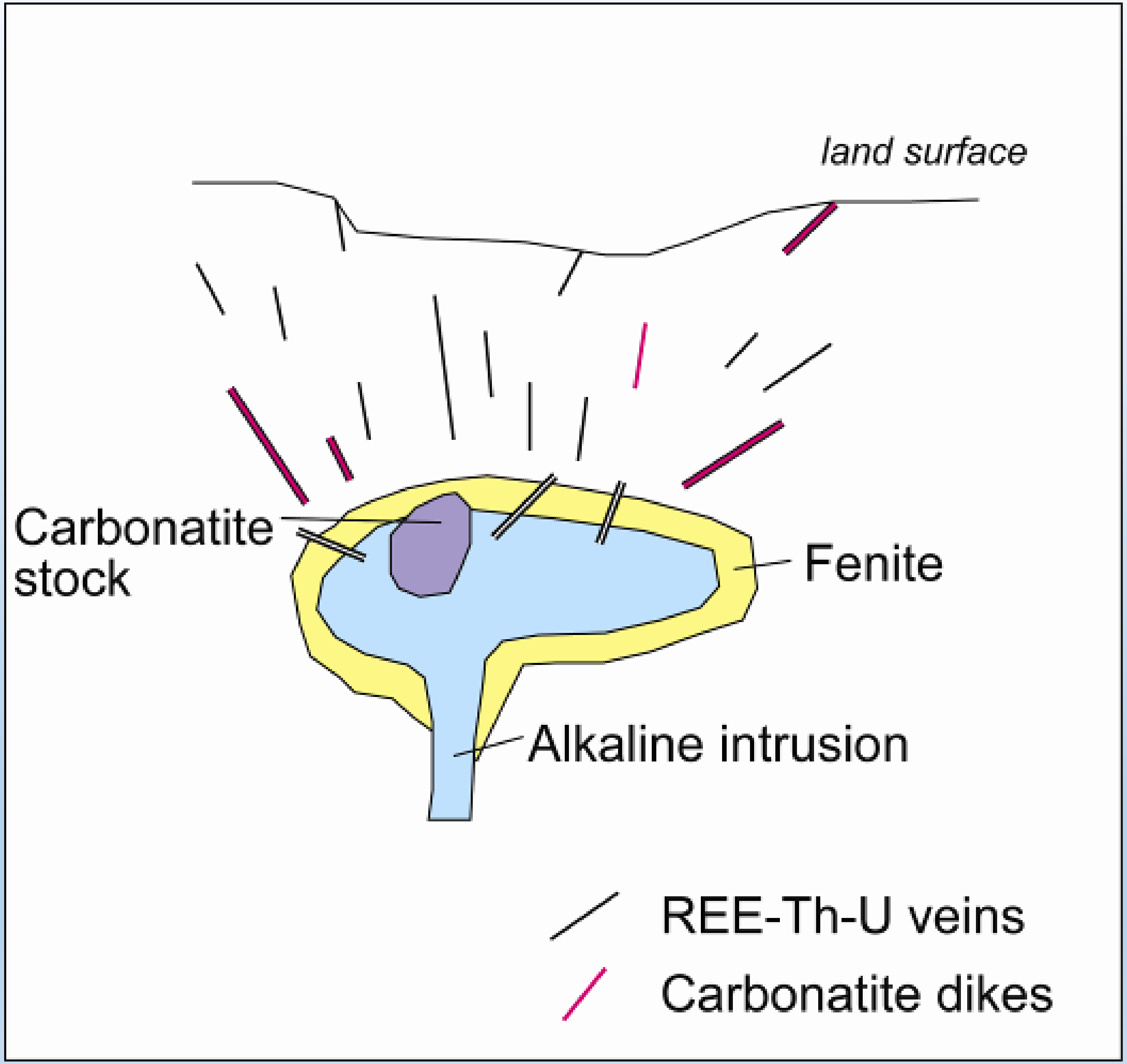


Episyenites in Caballo Mountains

Chemistry of Caballo Episyenites



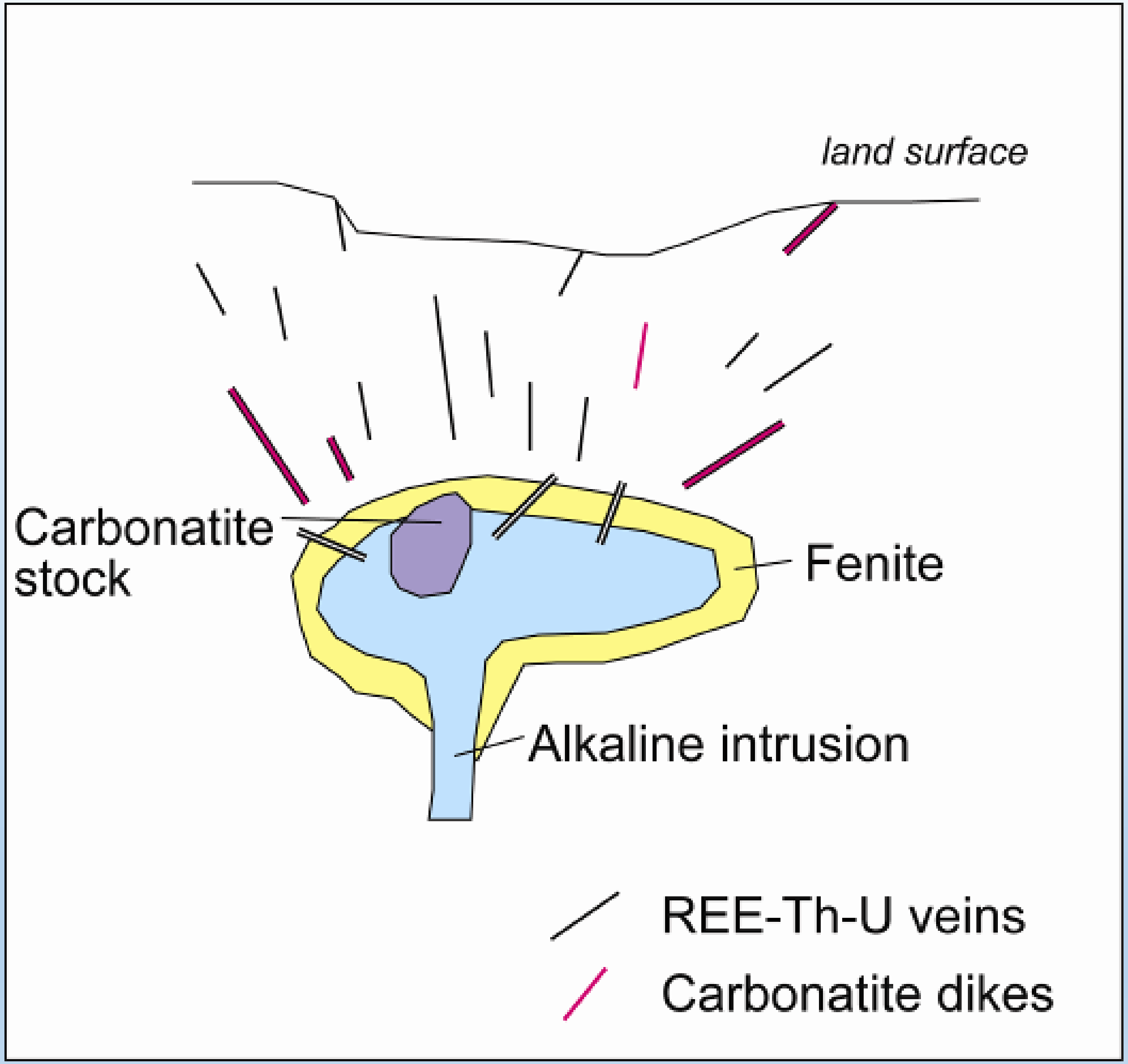


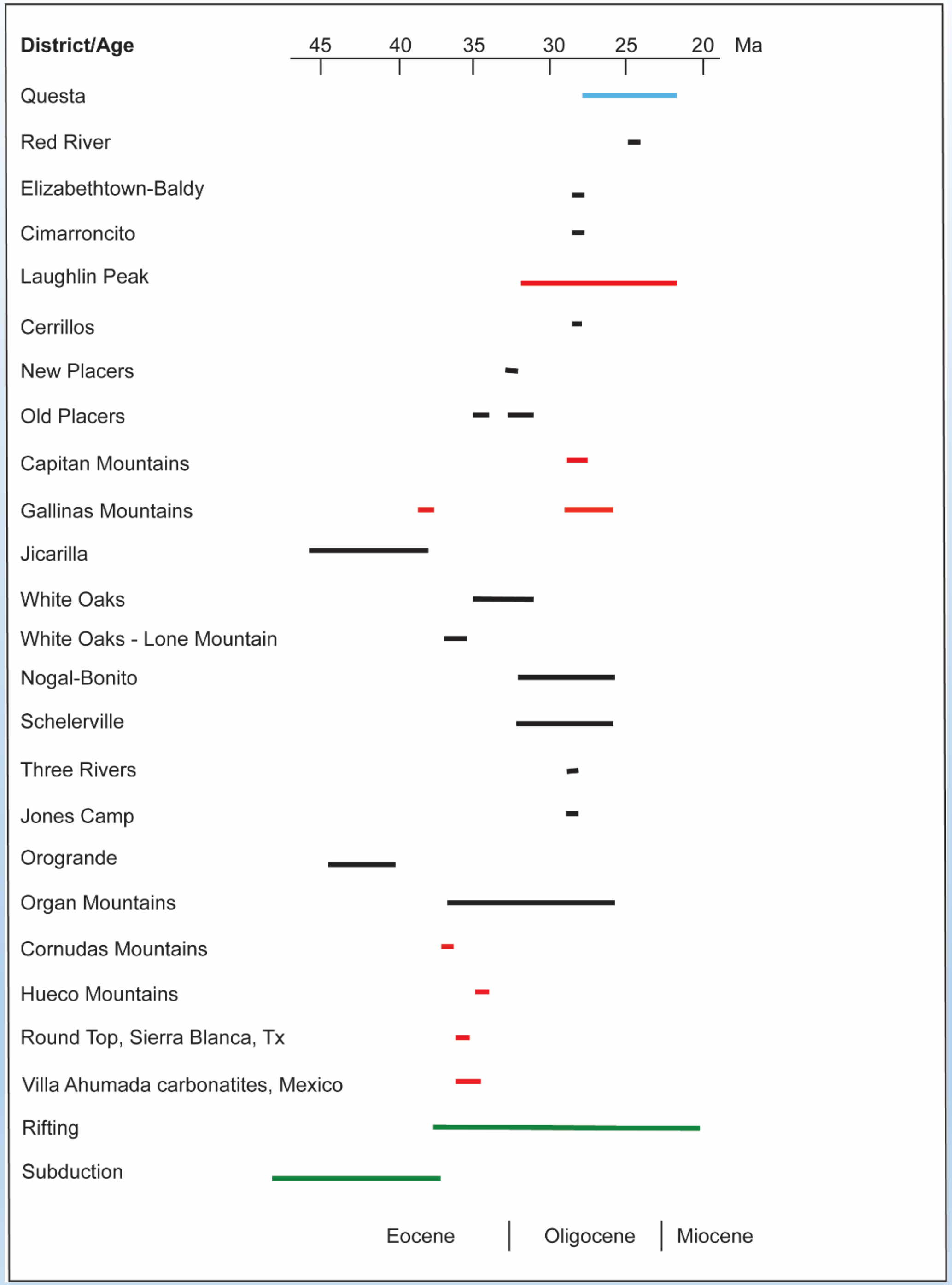

land surface
Carbonatite stock
Fenite
Alkaline intrusion
REE-Th-U veins
Carbonatite dikes

REE-Th-U Hydrothermal Veins

REE-Th-U Hydrothermal Veins

- various Th and REE minerals found in hydrothermal veins and are commonly associated with alkaline igneous rocks and carbonatites
- tabular bodies, narrow lenses, and breccia zones along faults, fractures and shear zones

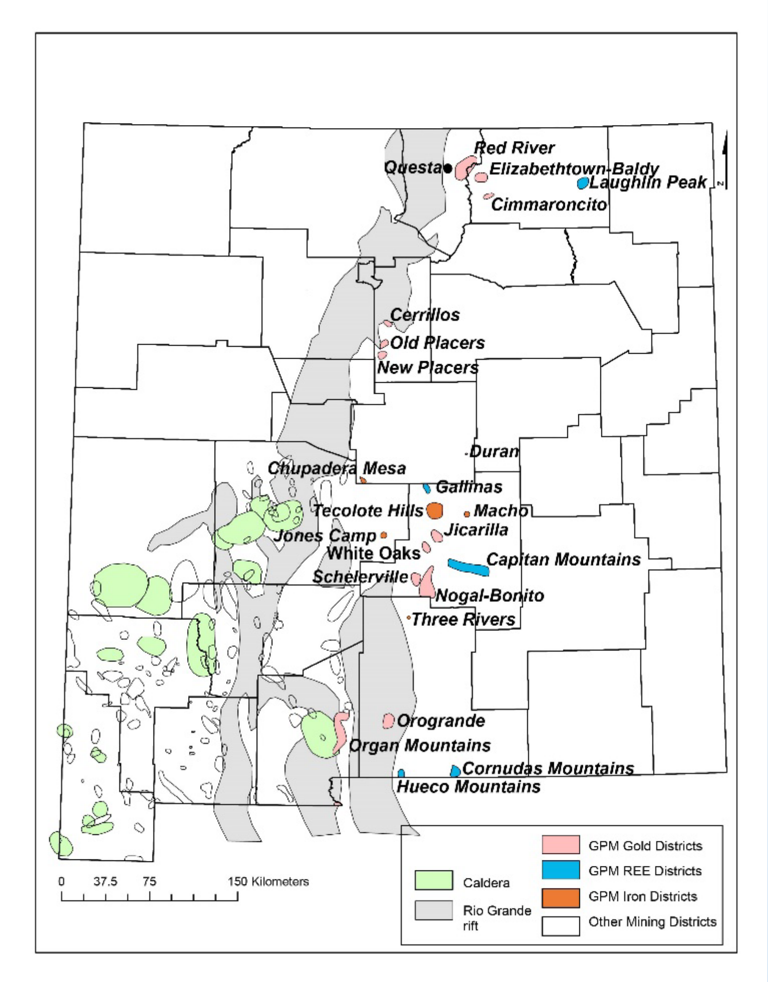

land surface
Carbonatite stock
Fenite
Alkaline intrusion
REE-Th-U veins
Carbonatite dikes



blue line=predominantly porphyry Mo deposits

black lines=primary Au and base metals districts

red lines= predominantly REE districts



Ages of igneous rocks associated with North American Cordilleran alkaline-igneous belt in NM, TX, and Mexico, arranged from north to south. Small- to medium-sized volcanic/magmatic fields or porphyry systems, with ages ranging from 22 to 46 Ma (updated from McLemore, 2018)

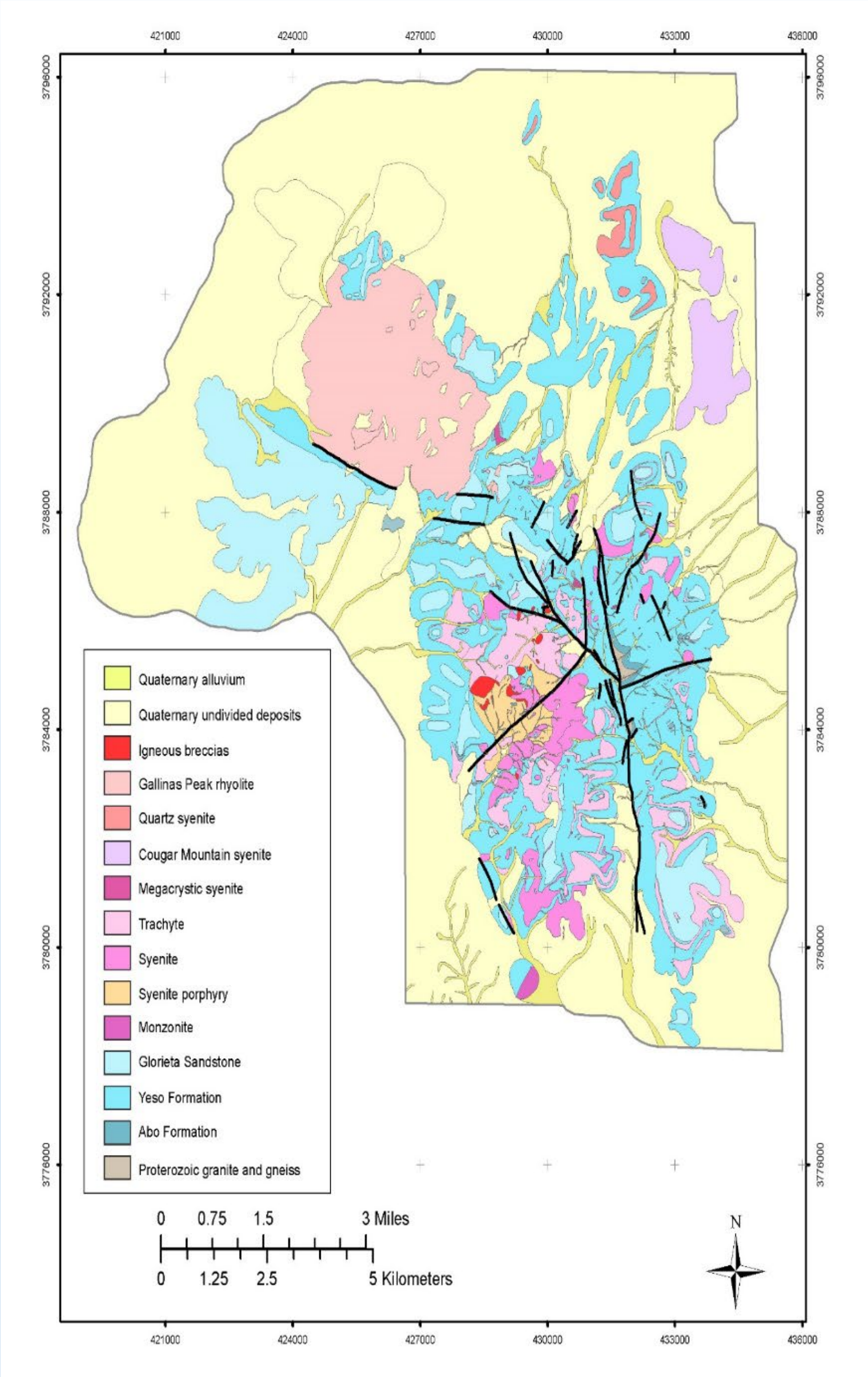
Mineral production from the Gallinas Mountains

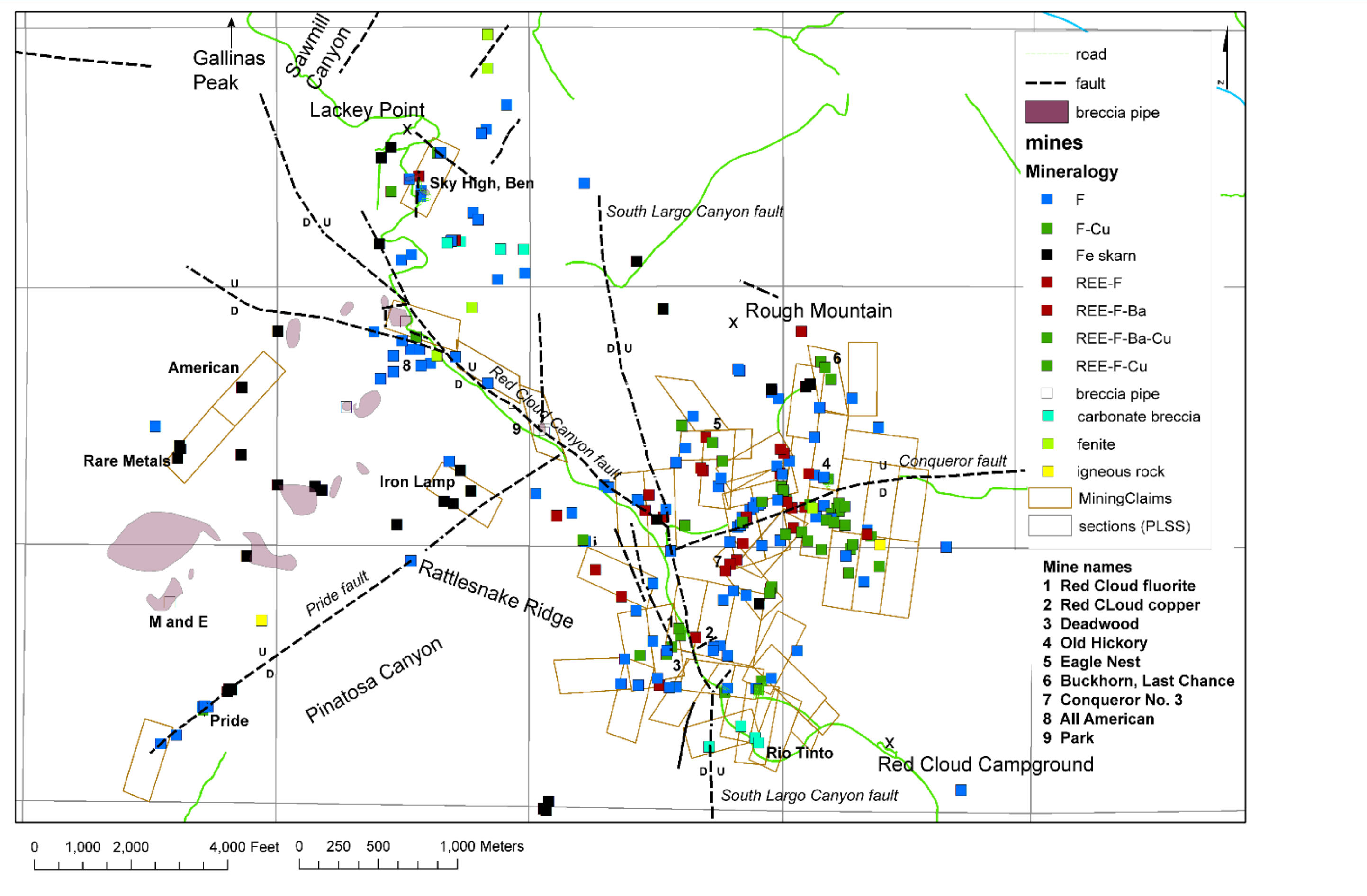
Mineral Produced	Mine name	Years of production	Amount (short tons)	Grade %
Copper	various	1909-1953	192.7	
Gold	various	1913-1955	7 ounces	
Silver	various	1909-1955	23,723 ounces	
Lead	various	1909-1055	863.4	
Zinc	various	1948-1953	8.7	
Iron ore	American	1942-1943	3,944	55.7
	Gallinas	1942	6,410	48.7
	Other mines		3,326	
Total iron ore		1942-1943	11, 540	
Fluorite	All American	1951-1954	129	
	Conqueror (Tinto)	1951-1954	300	
	Red Cloud	1951-1954	1,000	
Total fluorite		1951-1954	1,608	
Bastnäsite	Conqueror No. 9	1954-1955	60	
	Conqueror No. 10	1956	11	
	Red Cloud	1980	600	
Total bastnäsite		1954-1956	671	

Gallinas Mountains, New Mexico

More than 30 units (22 intrusive) have been mapped. Additional faults have been recognized and mapped.

District produced Cu, Ag, Pb, Zn, Fe, F, and REE (bastnäsite)





Gallinas Mountains, New Mexico

- Host rocks are dikes, sills, and laccoliths that have intruded the Permian Glorieta, Yeso and Abo formations and Proterozoic granites
  - Andesite
  - Trachyte to trachydacite to trachyandesite
  - Syenite
  - Rhyolite
  - Intrusive breccia pipes

Andesite dike near Sky High mine

Rapikivi texture in syenite (Gal1006)

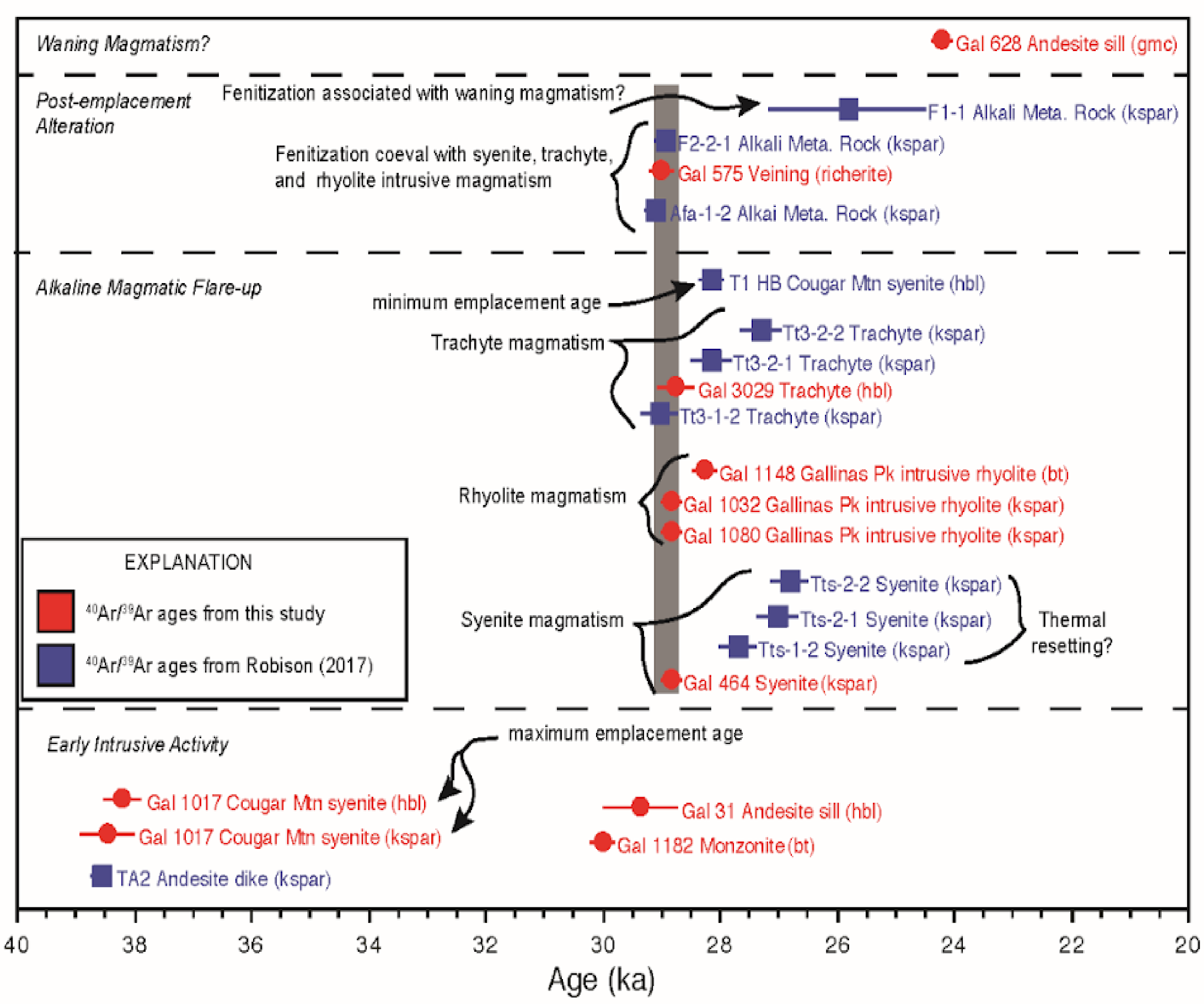
Miarolitic cavity with quartz, orthoclase in rhyolite (Gal1150)

Mafic xenolith in trachyte (Gal131)

Clear evidence of complicated system of multiple pulses of magmas

$^{40}Ar/^{39}Ar$ Geochronology Results

- Early magmatic activity (38.5 to 29.3 Ma)
- Alkaline intrusive flare-up (28.8 to 28.0 Ma)
- Alteration and implied younger intrusions (25.8 to 24.4 Ma)



Preliminary Conclusions

- Detailed mapping coupled with sampling for geochemistry, mineralogy, and geochronology is critical in understanding the field relationships of the mineralization and alteration
  - Major faults are not mineralized with the exception of the Pride and Buckhorn faults
  - Breccia and vein deposits are mostly along faults with small displacements and fracture zones
- $^{40}Ar/^{39}Ar$ geochronology results indicate 2-3 periods of magmatic activity
  - Early magmatic activity (38.5 to 29.3 Ma)
  - Alkaline intrusive flare-up (28.8 to 28.0 Ma)
  - Alteration and younger intrusions (25.8 to 24.4 Ma)
- Five types of mineral deposits are defined in the district distinguished by mineralogy, chemistry, form and host rocks (hydrothermal breccia and fissure veins, F replacements/disseminations, intrusive breccia pipes, Fe skarn-contact replacement deposits, carbonate breccias)
  - The hydrothermal breccia and fissure vein deposits are further subdivided according to mineral and chemistry

COLLAPSE BRECCIA PIPES

COLLAPSE BRECCIA PIPES

- Circular, vertical (up to 1000 metres in vertical extent) pipes filled with down-dropped coarse and fine fragments stopped from the overlying sediments
- Mineralized pipes range from 30 to 200 metres in diameter
- Orphan mine, Arizona, USA
- Mainly U production but some Cu locally
- Poential source of REE, Co, Ni

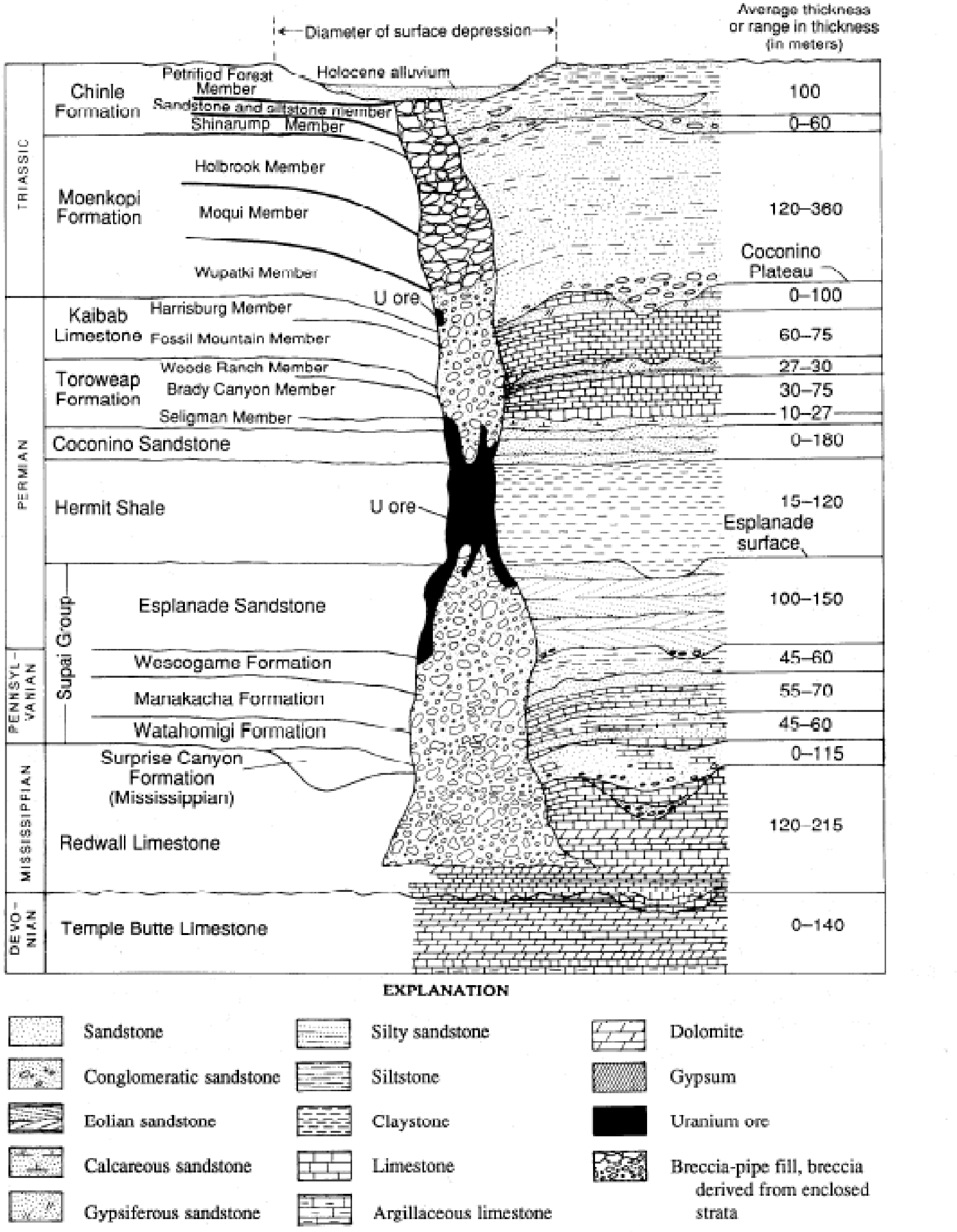
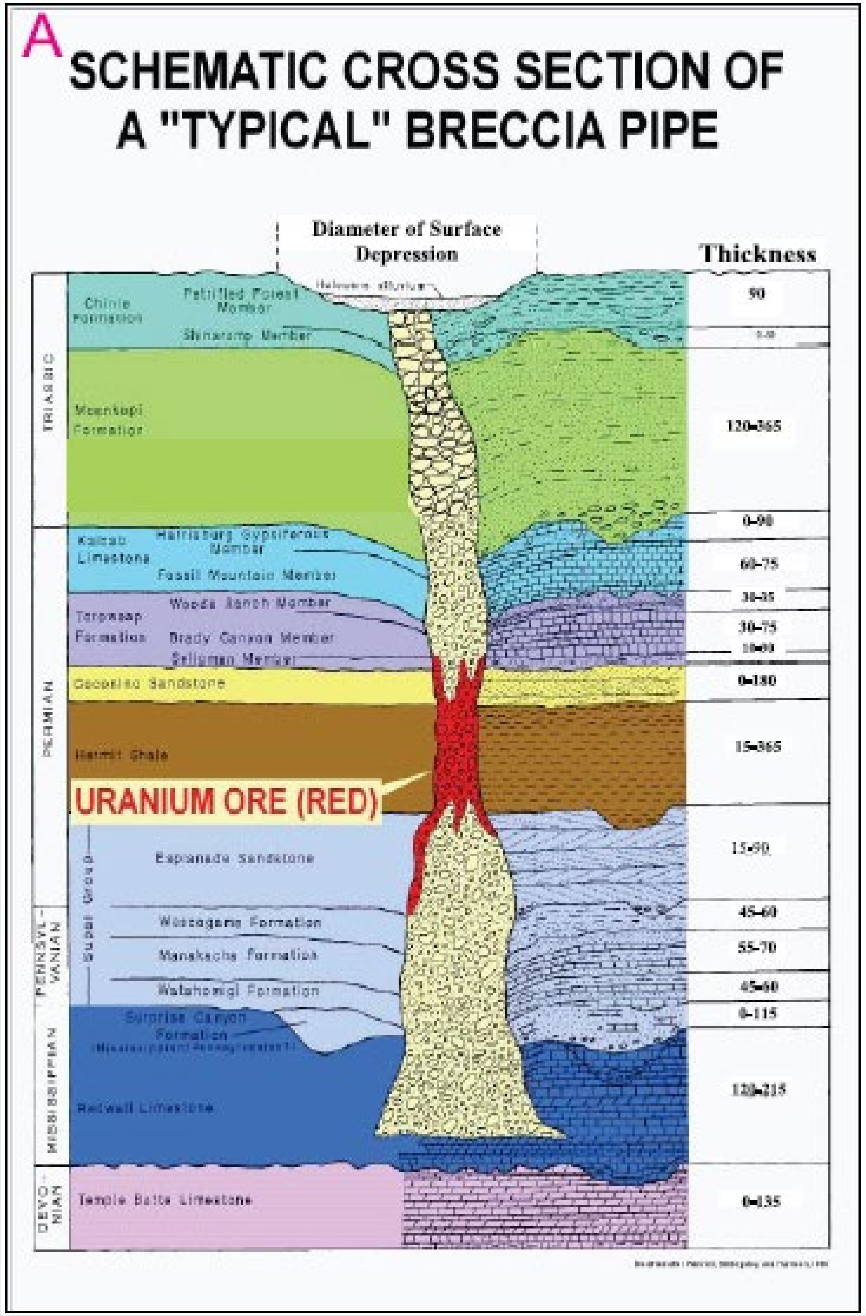
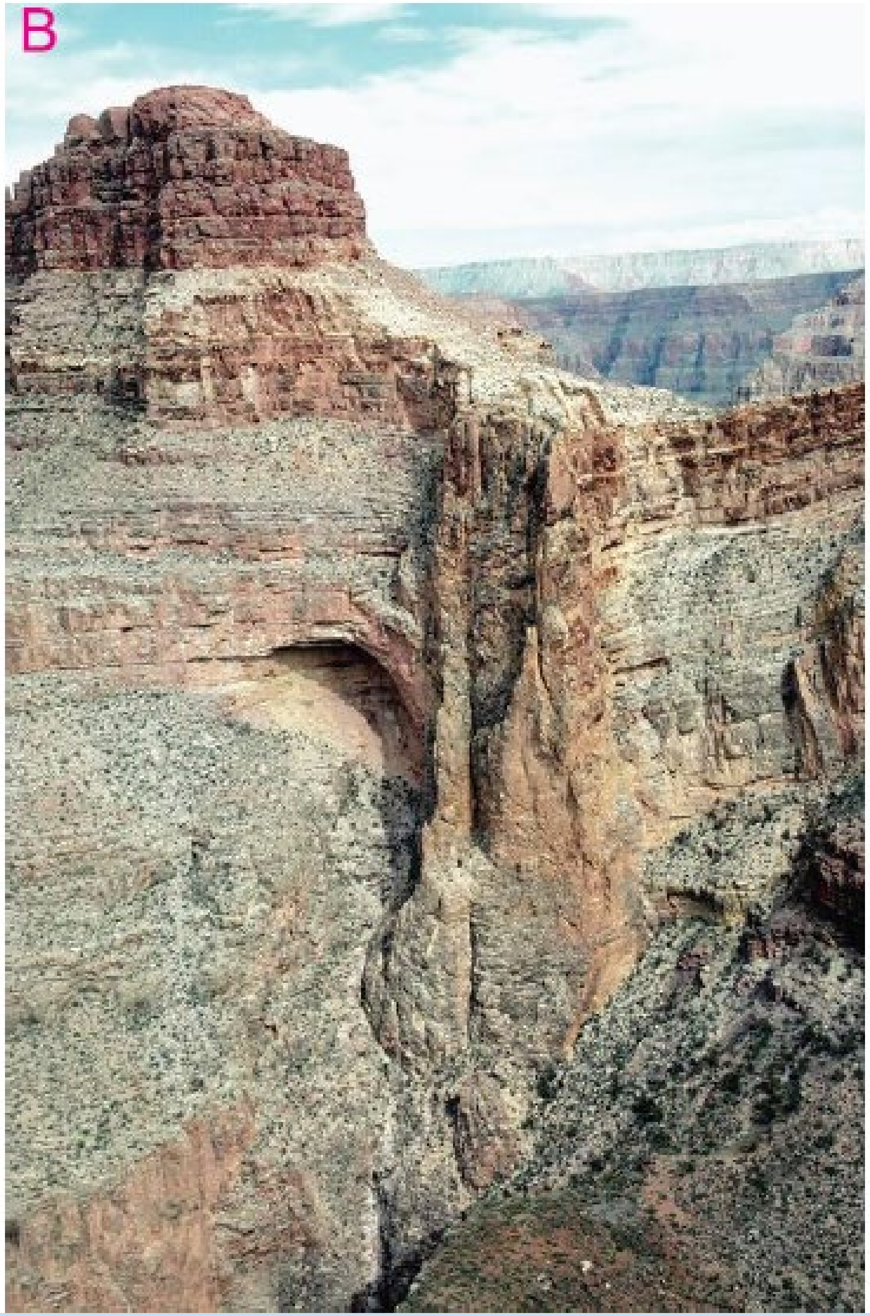


Figure 20. Schematic cross section of a solution-collapse breccia pipe in the Grand Canyon region, showing the general distribution of uranium ore within the pipe (stratigraphic section modified after Van Gosen and Wenrich, 1989).





K.J. Wenrich and S.R. Titley

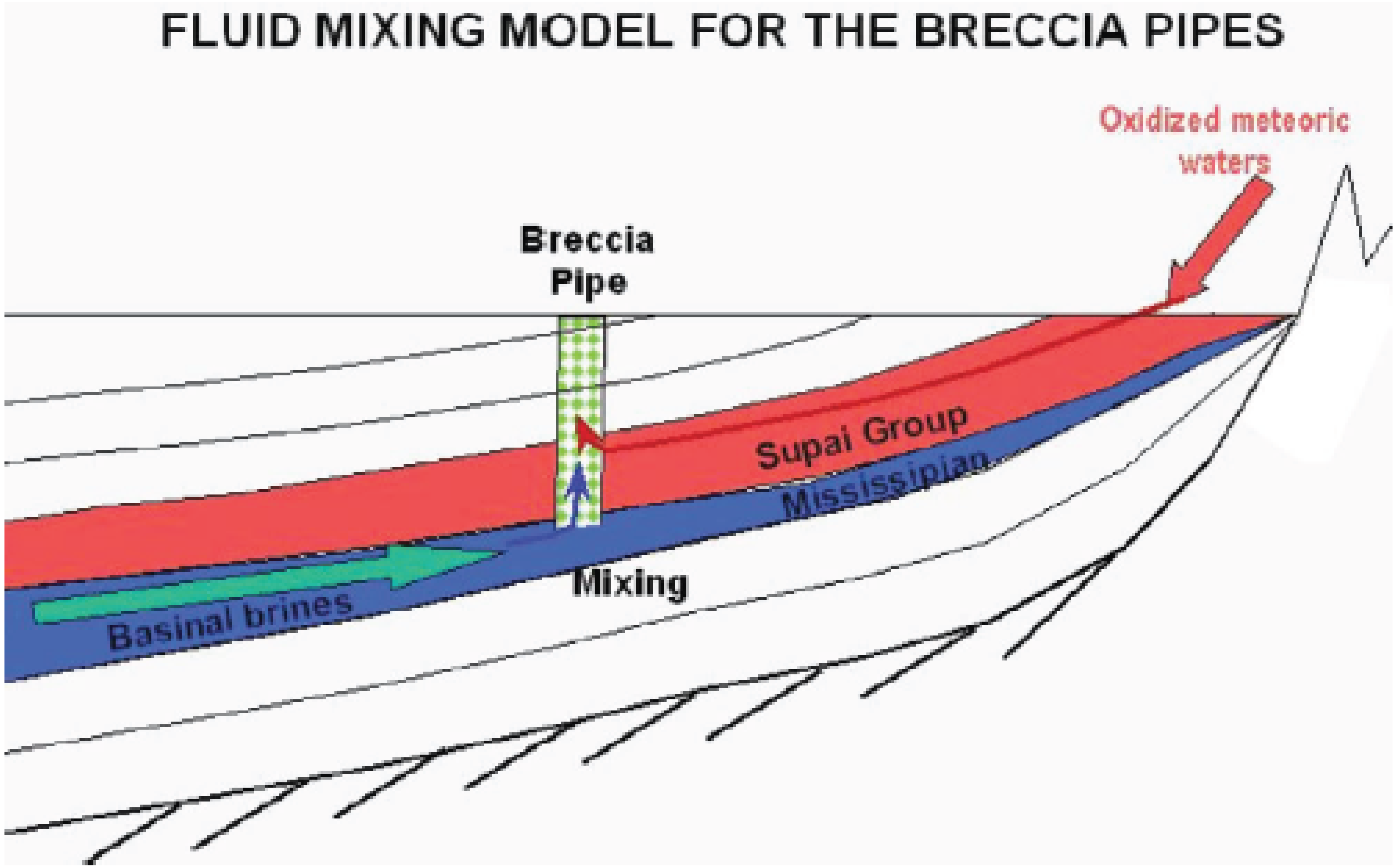


Figure 41. Fluid-mixing model for the breccia pipe ore genesis.

http://www.libertystaruranium.com/wp-content/uploads/2012/04/23AGS22WenrichandTitleyfinal-Protect.pdf

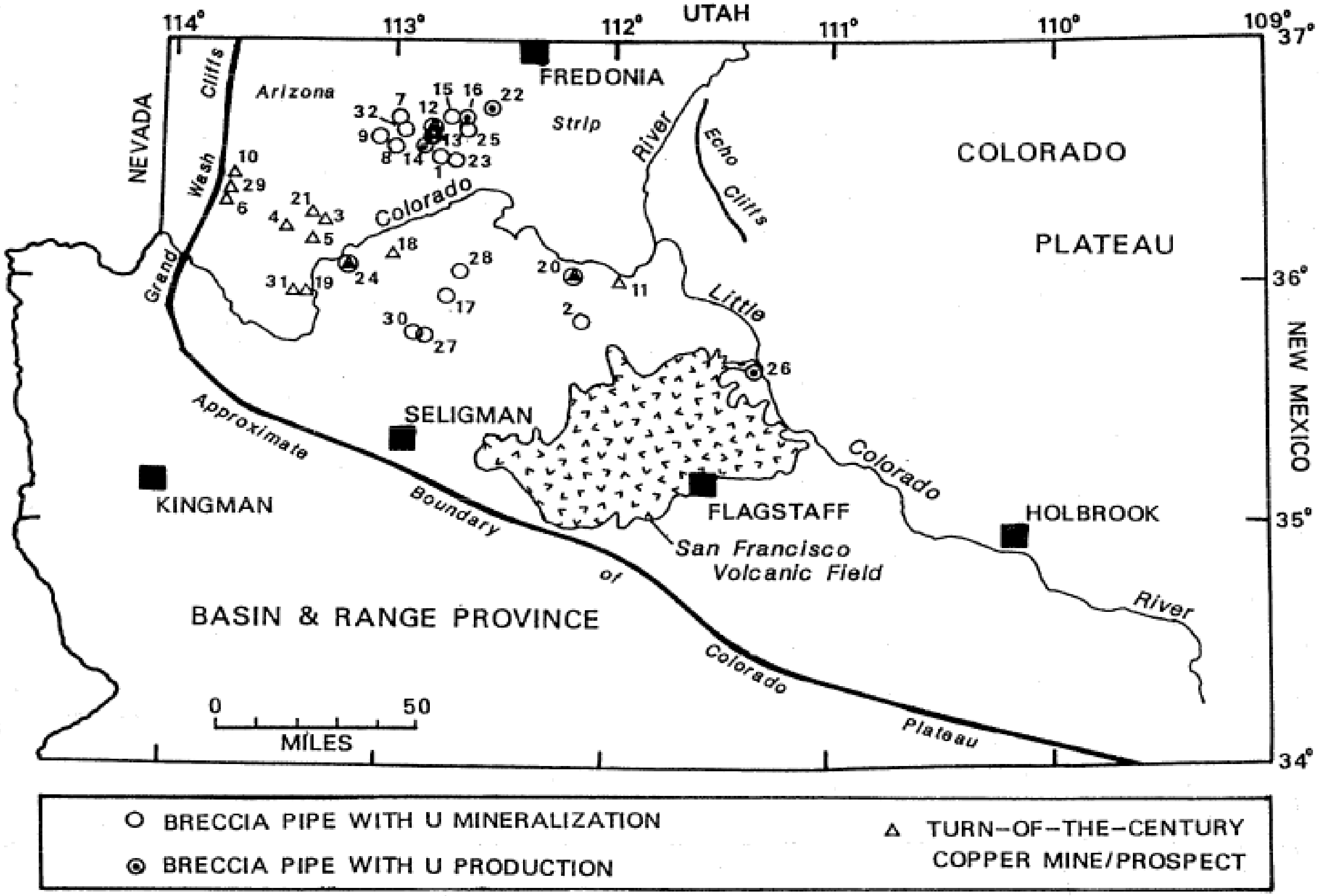


Figure 1. Index map of northern Arizona showing locations of mineralized breccia pipes, and San Francisco volcanic field that buries terrane with high potential for breccia pipes (Wenrich and others, 1989). Numbers refer to the following mines: (1) Arizona 1, (2) Canyon, (3) Chapel, (4) Copper House, (5) Copper Mountain, (6) Cunningham, (7) DB-1, (8) EZ-1, (9) EZ-2, (10) Grand Gulch, (11) Grandview, (12) Hack 1, (13) Hack 2, (14) Hack 3, (15) Hermit, (16) Kanab North, (17) Lynx, (18) Mohawk Canyon, (19) Old Bonnie Tunnel, (20) Orphan, (21) Parashant, (22) Pigeon, (23) Pinenut, (24) Ridenour, (25) Rim, (26) Riverview, (27) Rose, (28) Sage, (29) Savannic, (30) SBF, (31) Snyder, (32) What.

Table 1. Breccia pipe production data for all eight previously producing mines.

Mine*	Average Grade (% U_3O_8)	Production (Pounds U_3O_8)
Hack 1, 2, & 3	0.643	9,542,000
Pigeon	0.695	5,652,000
Kanab North	0.582	2,728,000
Pinenut	1.020	526,350
Hermit	0.760	552,500
Orphan	0.420	4,200,000
Total		**23,200,850**

*All mines except the Orphan mine produced between 1980 and 1994—production figures for those 7 mines are from Donn Pillmore of Energy Fuels Nuclear (written commun., 2008).

Other REE-Bearing Deposits

Other REE-Bearing Deposits

- REE could be recovered as a by-product of uranium, thorium, and phosphate deposits
  - Examine sandstone U deposits for REE contents
- Other placer deposits (fluvial, alluvial placers) could carry anomalous amounts of REE.
- Fluorite veins can carry high concentrations of REE, especially Y.
- Coal??

- Next class MARCH 22, 2022
  - Safety
  - Paper
- Midterm DUE MARCH 15
- Lab exercise DUE MARCH 22

Lab

1. Describe each sample (or group of samples). What are the minerals of economic interest?
2. What is/are the potential critical mineral or minerals?
3. What is the future production of each area? Would you recommend additional exploration?

Look up the papers (some are on my web site Critical (nmt.edu)).

REEinNM (nmt.edu)

McLemore, V.T., Smith, A., Riggins, A.M., Dunbar, N., Rämö, O.T., and Heizler, M.T., 2020, REE-bearing Cambrian-Ordovician episyenites and carbonatites in southern and central New Mexico, USA, *in* Koutz, F.R. and Pinnell, W.M., eds. Vision for discovery: Geology and ore deposits if the Great Basin: Geological Society of Nevada, 2020 Symposium Proceedings, p. 411-428.