ME589/Geol571/GEOC 589-04D/GEOL 589-04/GEOL 589-04D Advanced Topics

Mineral Deposits in New Mexico

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Safety

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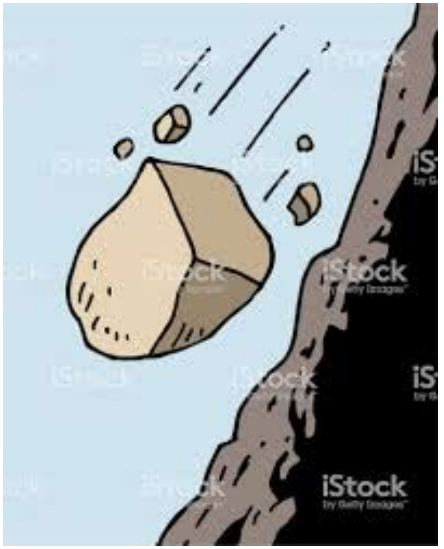
Safety in Entering Inactive/Abandoned Underground Workings during Exploration

Common Hazards

- Low Oxygen
- Carbon Monoxide
- Loose Rock
- Open Holes
- Unsafe ladders
- Poor Visibility
- Animals
- Deep Water



Equipment Needed

- Oxygen detector
- Toxic/Flammable gas detector
- Safety lines
- Scaling Bars
- Bear deterrent
- Each Crew Member must also have a safety belt with a safety lanyard, a hard hat, boots, gloves and a battery-powered underground cap lights

Entering an Abandoned Mineshaft

- Use extreme caution in understanding that hazards could result in loss of life.
- Prior to entry, examine state of ventilation, if there are other entrances/exits and if there is presence of water.
- Any indication of hazards (dangerous atmosphere, collapsed timbers/workings, recent fallen rock) should result in rethinking the necessity of mapping/sampling in the mine

Sampling

- If the mineshaft is deemed to be void of hazards and permission is given to attain samples, caution must still be used.
- Be mindful of cracks/breaks in the rock that extend from floor to ceiling and take samples away from these locations.
- In Western Canada a certified shift-boss is required to be on-site during any rock extraction. This shift-boss must hold a valid BC Mines Shiftboss certificate.
- Similar restrictions are in place in the United States.

Reference

- Safety Guidelines for Mineral Exploration in Western Canada 5th Edition. AME BC. 2013, https://amebc.ca/wp-content/uploads/2017/06/AME-BC-Safety-Guidelines_5th-Ed-2014-Rev_Web.pdf

Lemitar carbonatites field trip Sunday Feb 7, 2021

- My handout is on my web site
- Will likely be able to take those that missed it later—let me know when is good for you

- WHEN IN APRIL IS GOOD FOR EVERYONE?
  - Weekends?
  - Fridays?
  - April 2 (Good Friday—school holiday)

  - Steeplerock (Grant Co), pegmatites/Pecos (San Miguel, Rio Arriba), Chino/Tyrone, Hillsboro, Gallinas Mountains (Lincoln County), Rosedale (Socorro), others?
  - VOLUNTEER to find out?

COVID Testing

- NMT is testing every Thursday and results are generally by Sunday
- Request that you test frequently as an added precaution
  - Test Feb 11

Field trip Feb 19

- Monticello diatomite
- St. Cloud zeolite
- Kline Mountain kaolinite deposit
- Taylor Creek tin deposits
- Chloride district fluorite (Ag?) volcanic epithermal deposits

- Camp overnight at Taylor Creek?

- Volunteer to organize the trip?
- Director Dr. Nelia Dunbar will be joining us!
- Masks required and social distancing

- I leave for Phoenix March 4
- Mid term before then (probably March 1)
- If you have any questions concerning your midterm or your project and need to see me—do it before March 4
- I will not be available March 12-21—you may be lucky and get an email answer from me, but no promises
- I return to Socorro March 22, but I start a 2 week quarantine and will not be in class until April 5
  - I will have class March 22, 29—details before I leave (probably a combination of pre-recorded and zoom)
  - Those whose safety presentations will be due those 2 days—in person or record
  - OTHER IDEAS

- If you need a recommendation from me for the NMGS scholarship—ask sooner rather than later

- Field trip reports due March 5, if you did not go on a field trip, then do a virtual trip or report on a paper from a guidebook or other article
- Bureau Mineral Museum is now open and I will accept a field trip report to there

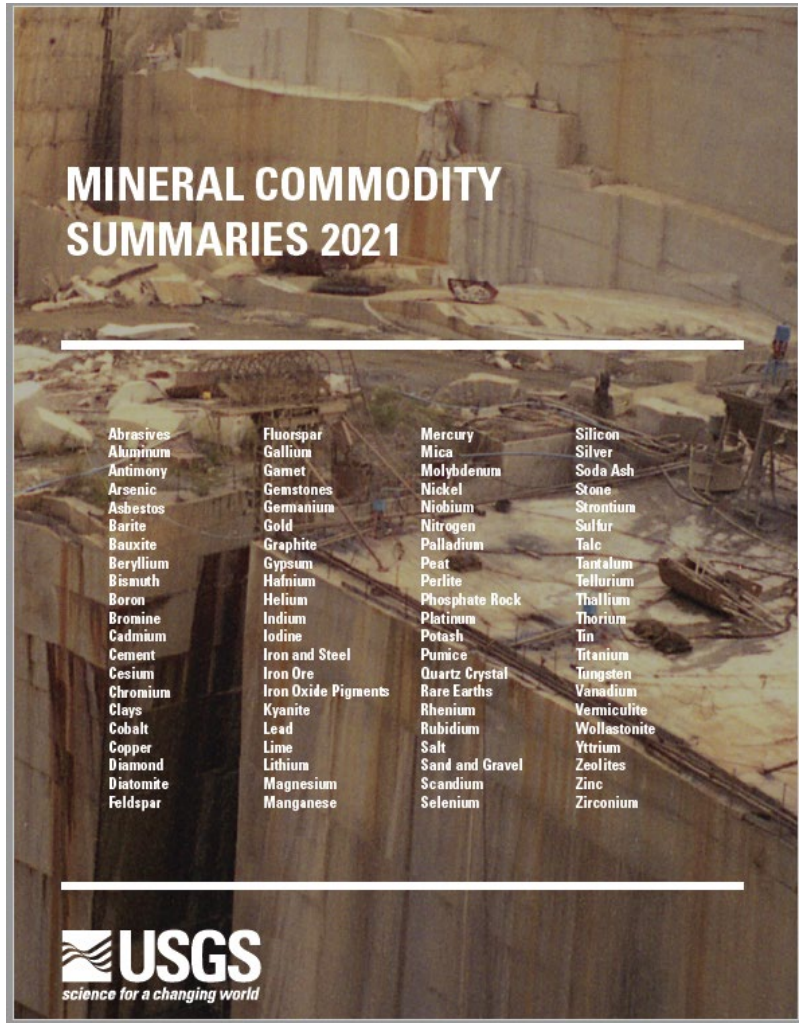


Table 1.—U.S. Mineral Industry Trends

	2016	2017	2018	2019	2020[e]
Total mine production (million dollars):					
Metals	23,700	26,800	28,200	26,900	27,700
Industrial minerals	47,700	52,600	56,100	56,900	54,600
Coal	22,300	26,100	27,200	25,500	18,800
Employment (thousands of workers):					
Coal mining, all employees	51	52	52	52	46
Nonfuel mineral mining, all employees	130	134	140	140	136
Chemicals and allied products, production workers	516	525	546	558	533
Stone, clay, and glass products, production workers	306	305	311	315	301
Primary metal industries, production workers	293	292	295	300	268
Average weekly earnings of workers (dollars):					
Coal mining, all employees	1,441	1,486	1,546	1,617	1,510
Chemicals and allied products, production workers	950	1,010	1,072	1,067	1,060
Stone, clay, and glass products, production workers	851	873	945	968	978
Primary metal industries, production workers	1,002	995	1,036	1,025	1,010

[e]Estimated.

State	Value (millions)	Rank[2]	Percent of U.S. total[3]	Principal commodities[4]
Nebraska[5]	$215	38	0.26	Cement (portland), lime, sand and gravel (construction), sand and gravel (industrial), stone (crushed).
Nevada	9,140	1	11.10	Copper, diatomite, gold, lime, silver.
New Hampshire	110	47	0.13	Sand and gravel (construction), stone (crushed), stone (dimension).
New Jersey	345	40	0.42	Sand and gravel (construction), sand and gravel (industrial), stone (crushed).
New Mexico	864	31	1.05	Cement (portland), copper, potash, sand and gravel (construction), stone (crushed).

https://pubs.usgs.gov/periodicals/mcs2021/mcs2021.pdf

2019 State	Value (millions)	Rank[2]	Percent of U.S. total	Principal commodities[3]
Nebraska[4]	$214	39	0.25	Cement (portland), lime, sand and gravel (construction), sand and gravel (industrial), stone (crushed).
Nevada	8,190	1	9.49	Copper, diatomite, gold, lime, sand and gravel (construction).
New Hampshire	156	44	0.18	Sand and gravel (construction), stone (crushed), stone (dimension).
New Jersey	377	40	0.44	Peat, sand and gravel (construction), sand and gravel (industrial), stone (crushed).
New Mexico	1,090	28	1.26	Cement (portland), copper, potash, sand and gravel (construction), stone (crushed).

2020 State	Value (millions)	Rank[2]	Percent of U.S. total[3]	Principal commodities[4]
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Does not include coal

Arrastra in action with John and Jake Long at Piños Altos, New Mexico, 1892

Mineral Resources: Reserves, Peak Production and the Future Meinert et al. https://www.mdpi.com/2079-9276/5/1/14

- What did you think about this article?
- When will we achieve peak production of a commodity?
- Effect of continued exploration?
- Will we run out of commodities?
- Why is resources + reserves ≠ all there is?
- Are the models sound?
- Any other comments?

Mineral Resources: Reserves, Peak Production and the Future Meinert et al. https://www.mdpi.com/2079-9276/5/1/14

- Earth has a finite mass and eventually resources will be used up

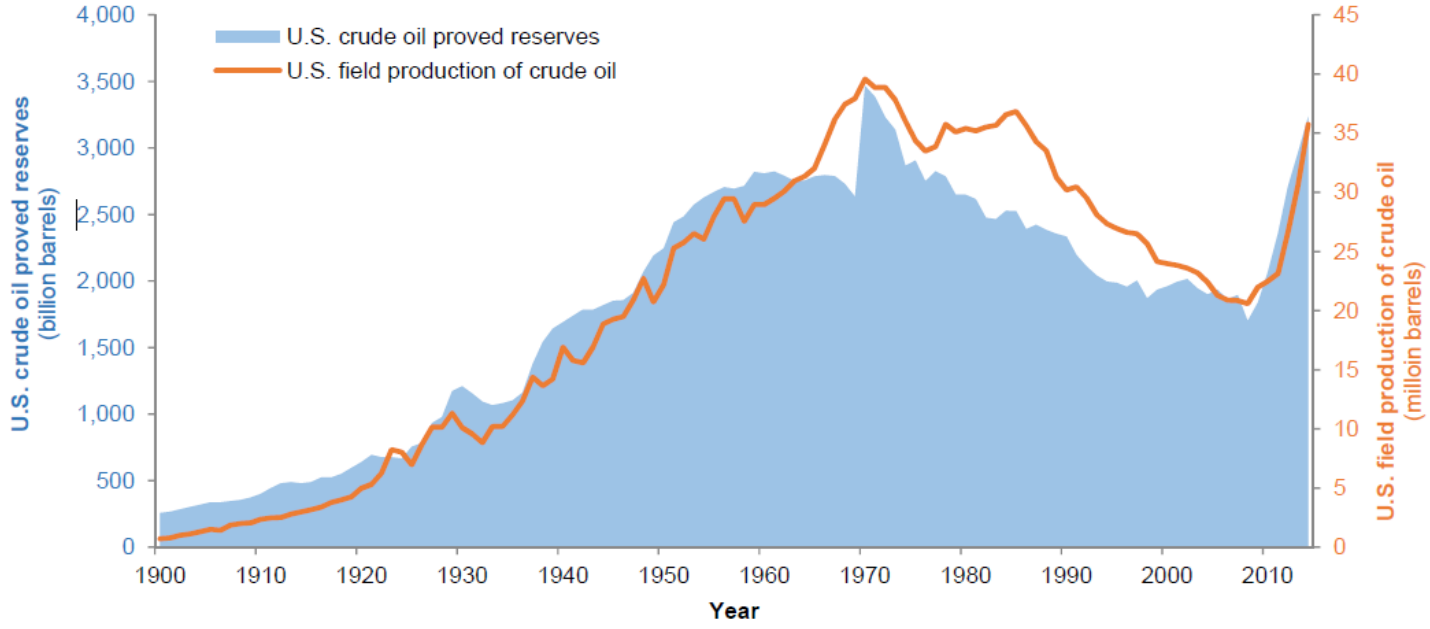


Figure 1. U.S. crude oil reserves and production showing apparent "peak oil" for conventional petroleum reserves in 1972 and growth in reserves in the past ~10 years as a result of the application of new drilling technology. U.S. barrels are equivalent to approximately 0.159 cubic meters. Data source: [47].

Mineral Resources: Reserves, Peak Production and the Future Meinert et al. https://www.mdpi.com/2079-9276/5/1/14

- Will we reach peak copper production?

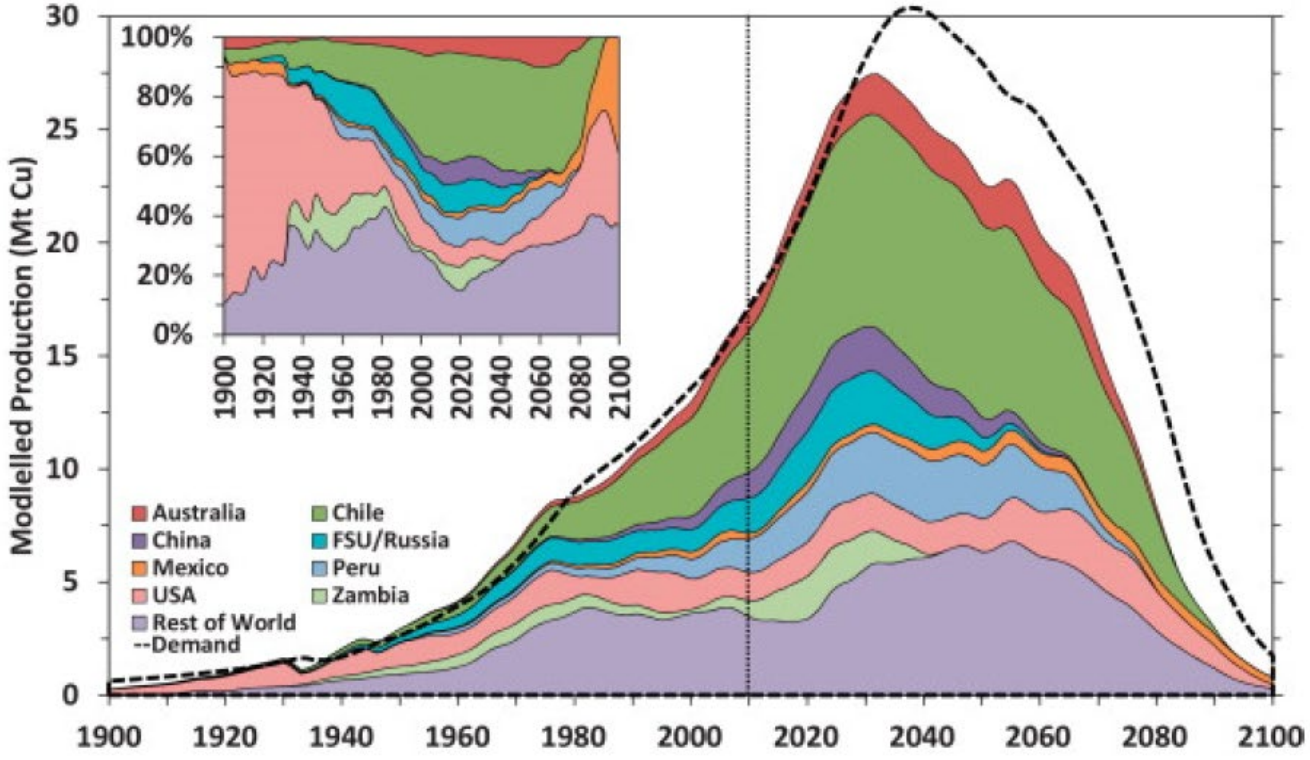


Figure 3. World copper production: historical and projected based on the modeling in [9].

Rare earth elements (REE)

57	58	59	60	62	63	64	65	66	67	68	69	70	71	39
La	**Ce**	**Pr**	**Nd**	**Sm**	**Eu**	**Gd**	**Tb**	**Dy**	**Ho**	**Er**	**Tm**	**Yb**	**Lu**	**Y**
138.91	140.12	140.91	144.24	150.36	151.96	157.25	158.93	162.5	164.93	167.26	168.93	173.04	174.97	88.906
Light rare earths				**Heavy rare earths**										

La - Lanthanum
Ce - Cerium
Pr - Praseodymium
Nd - Neodymium
Sm - Samarium
Eu - Europium
Gd - Gadolinium
Tb - Terbium
Dy - Dysprosium
Ho - Holmium
Er - Erbium
Tm - Thulium
Yb - Ytterbium
Lu - Lutetium
Y - Yttrium

Figure 2.2: Sub-groups of the rare-earth metals, per industry (not scientific) norms (sources: TMR, industry sources).

If we plotted the REE according to concentration, you would get a jagged pattern like Figure 1 that is difficult to interpret.

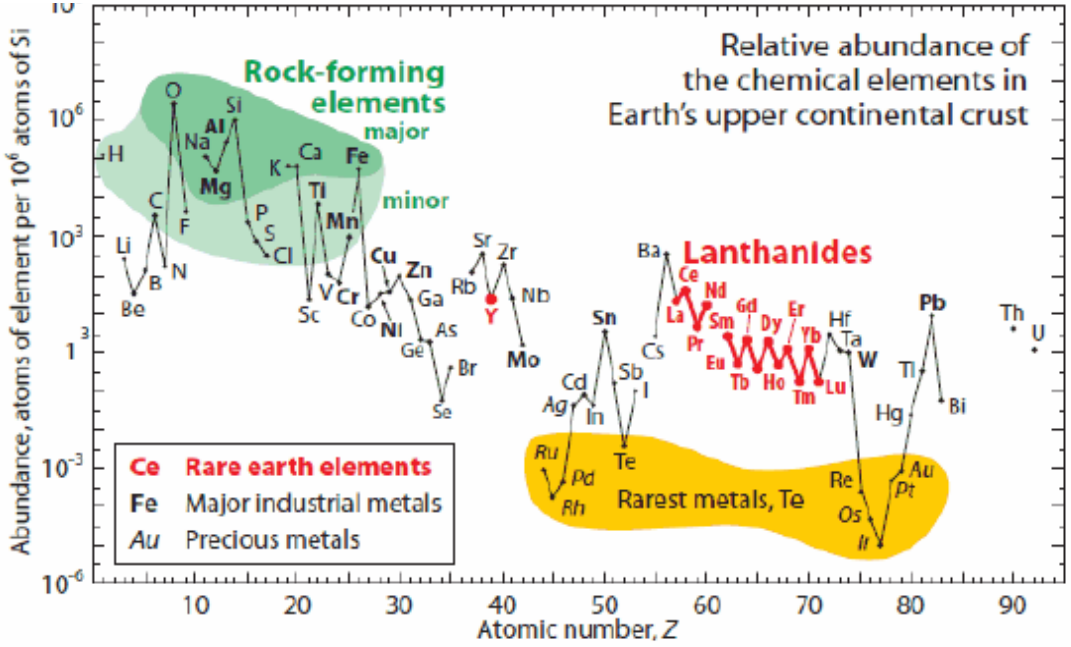


Figure 1 Relative abundance of rare earths (highlighted in red). Figure courtesy of Gordon Haxel, USGS.

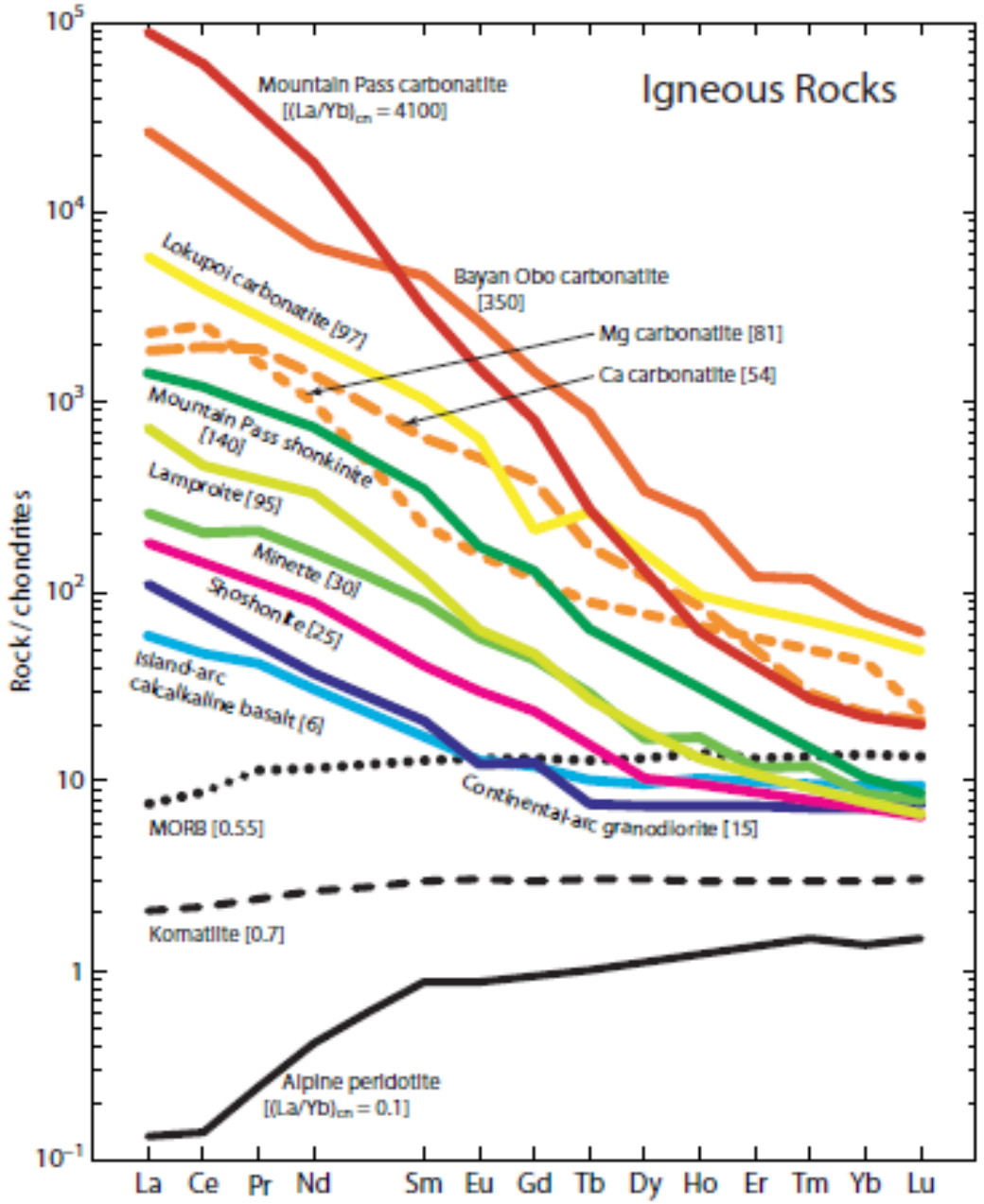


Figure 3. Chondrite-normalized (Table 1; Nakamura, 1974) REE spectra for average (labeled in italic) or representative compositions (labeled in upright type) of several common suites of ultramafic to intermediate, tholeiitic and calcalkaline

So we plot the concentration of the sample (rock)/concentration of chondrite (Fig. 3). We use chondrite (meteorite) simply by convention agreed by geochemists decades ago. Here you can see chondrite-normalized patterns for many deposits. Mt. Pass is in CA and is in production. Byan Obo is the China deposit.

PRECAMBRIAN DEPOSITS

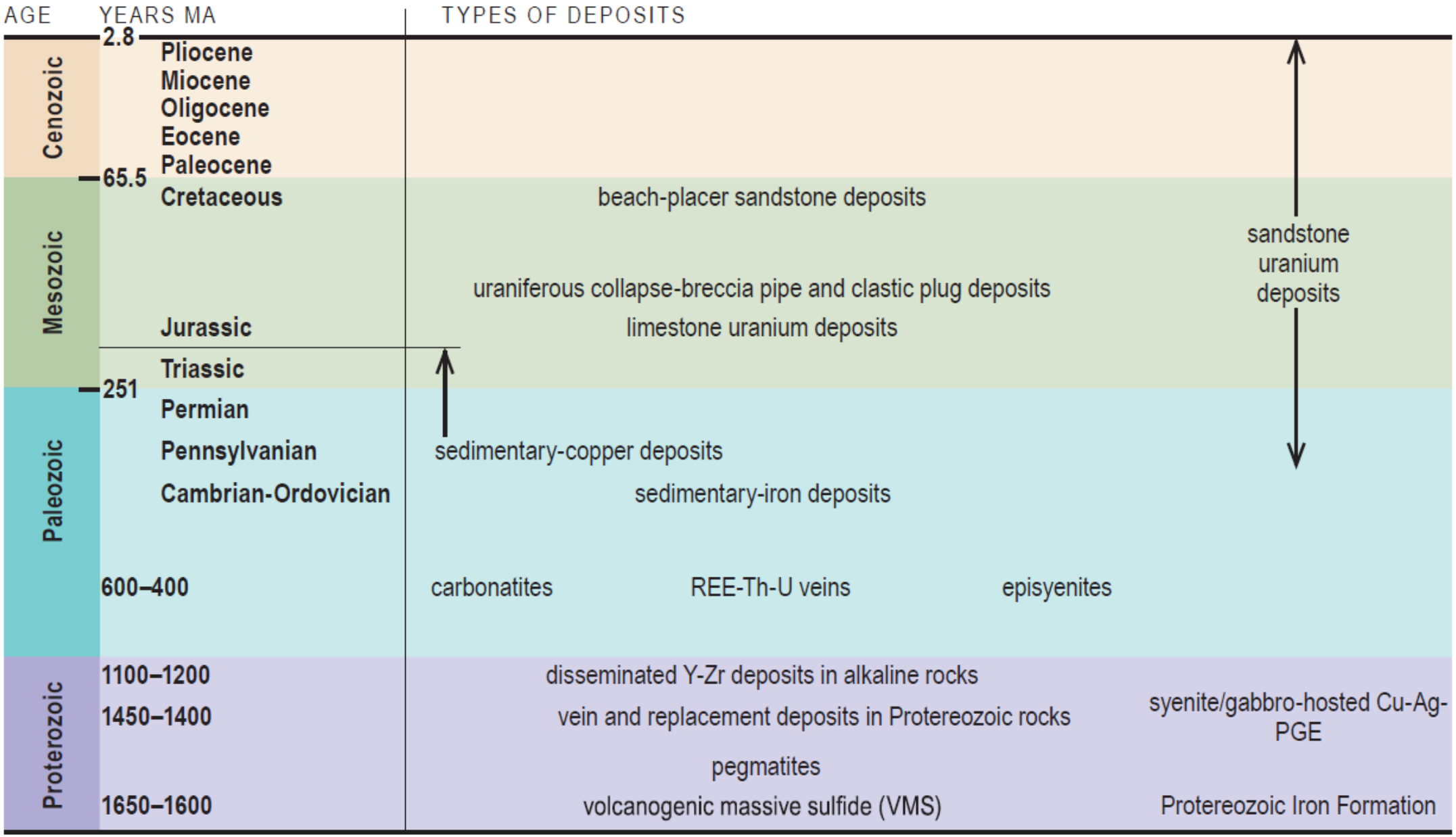


Figure 2. Distribution of Proterozoic-Mesozoic metallic mineral and uranium deposits in New Mexico through time. Arrows delineate the time period sedimentary-copper and sandstone uranium deposits span.

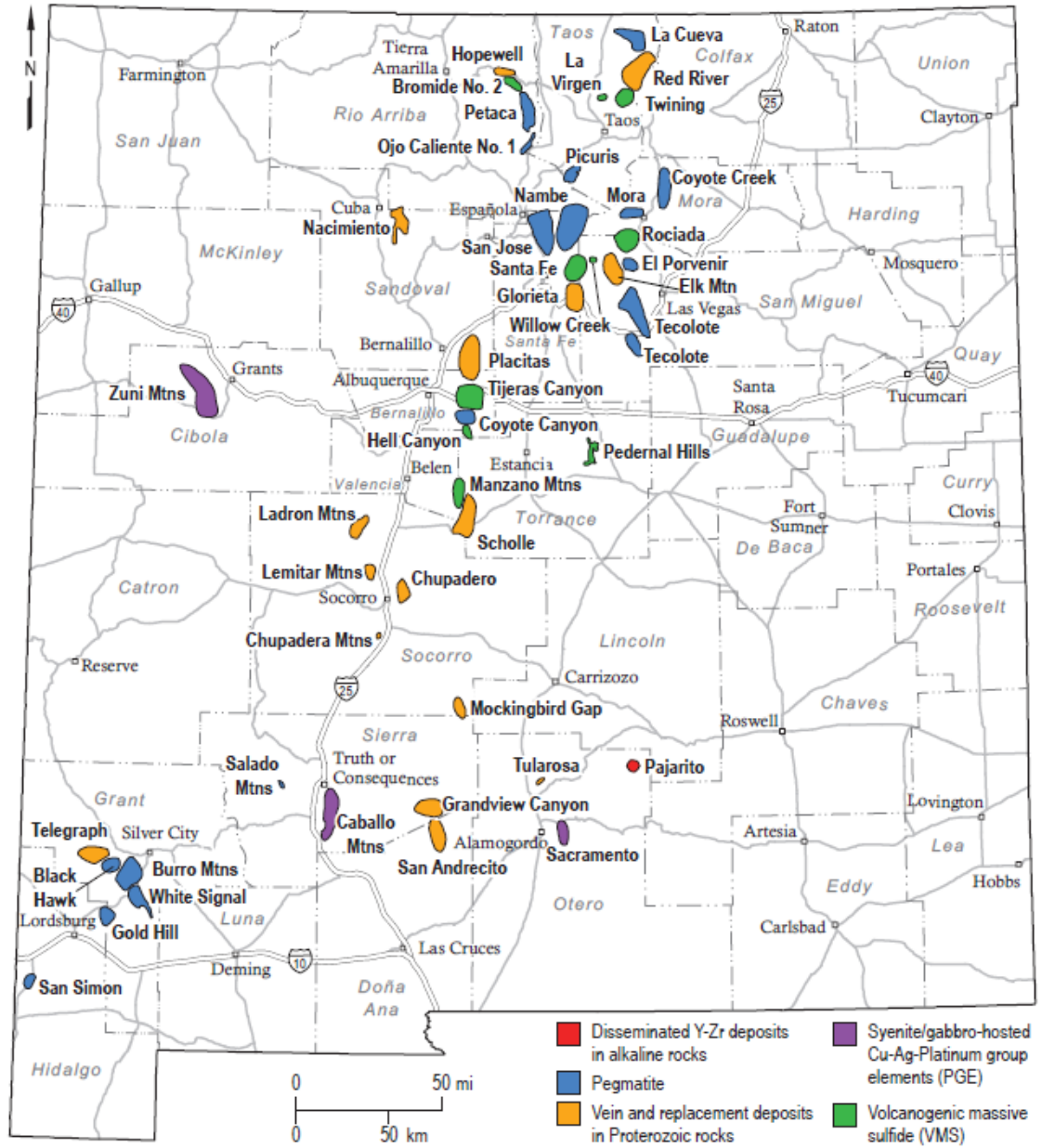
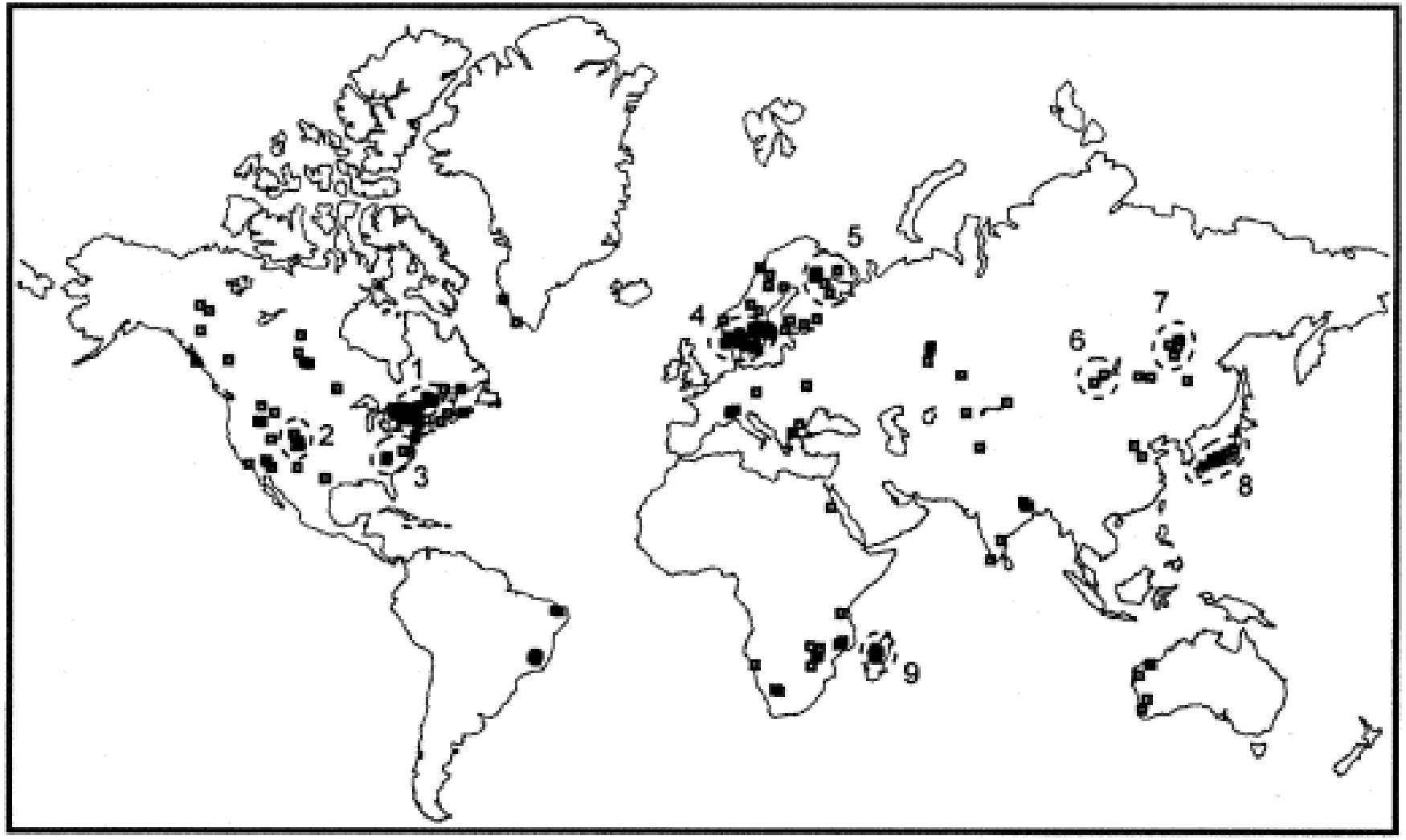


Figure 4. Proterozoic age mineral deposits in New Mexico. Some districts contain more than one type of deposit. Iron formation deposits are found in two districts, Hopewell and Bromide No. 2, in northern New Mexico.

PEGMATITES

>551 pegmatites in world with REE



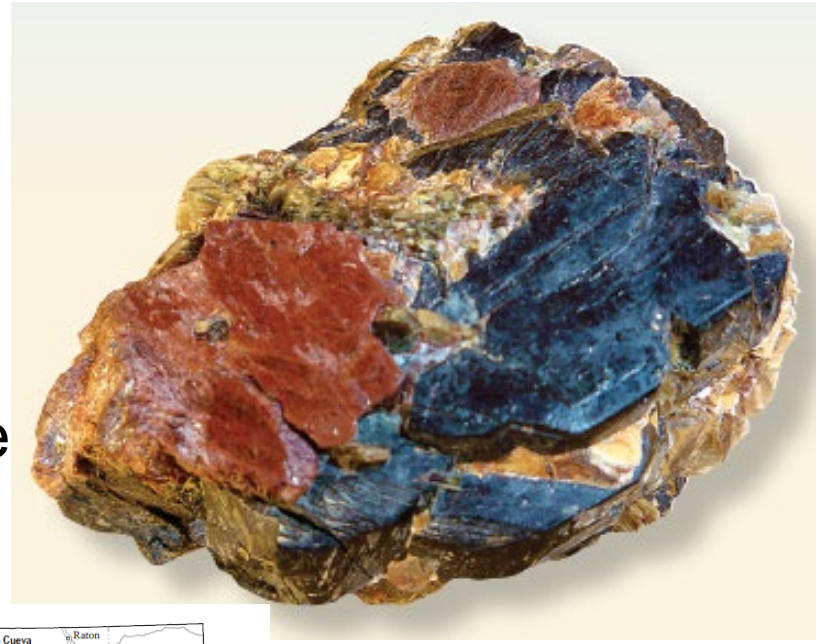
Pegmatites

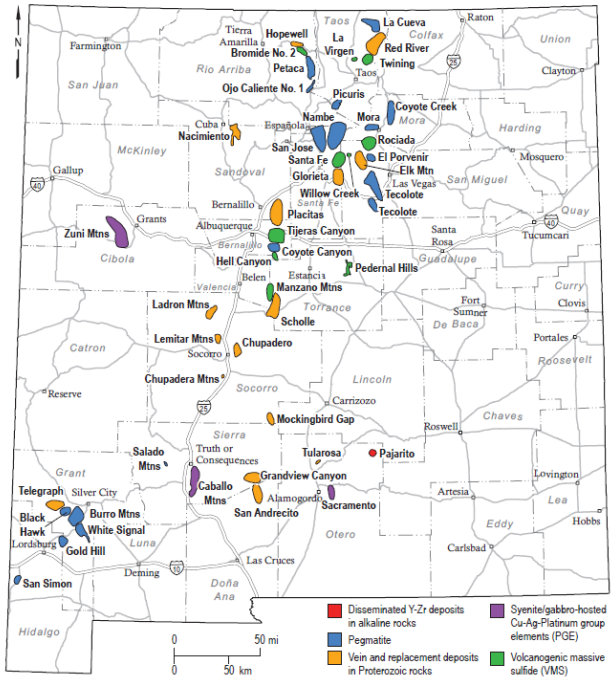
- “an essentially igneous rock, commonly of granitic composition, that is distinguished from other igneous rocks by its extremely coarse but variable grain-size, or by an abundance of crystals with skeletal, graphic, or other strongly directional growth-habits.” (London, 2008)
- Products of magmatic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

- Potential commodities include feldspar, mica, garnet, quartz, REE, lithium, niobium, beryllium, tantalum, uranium, thorium, gemstones

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





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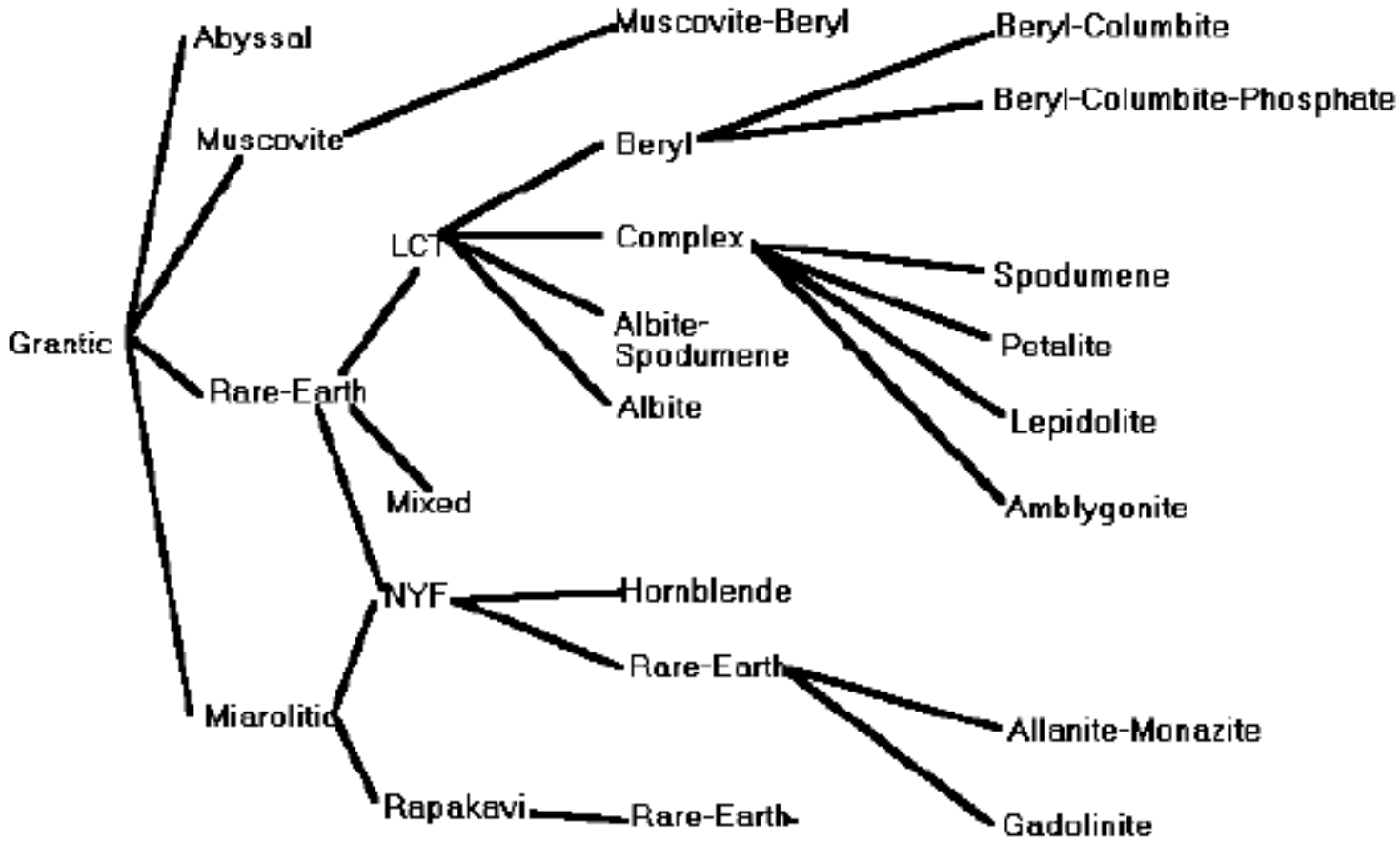
Pegmatites

- 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 =H_2O, 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)

Pegmatite Classes



(Cerny 1992)

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	**Li**,Rb, **Cs**,Be,Sn,Ga **Ta** > 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	**Nb** > 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)

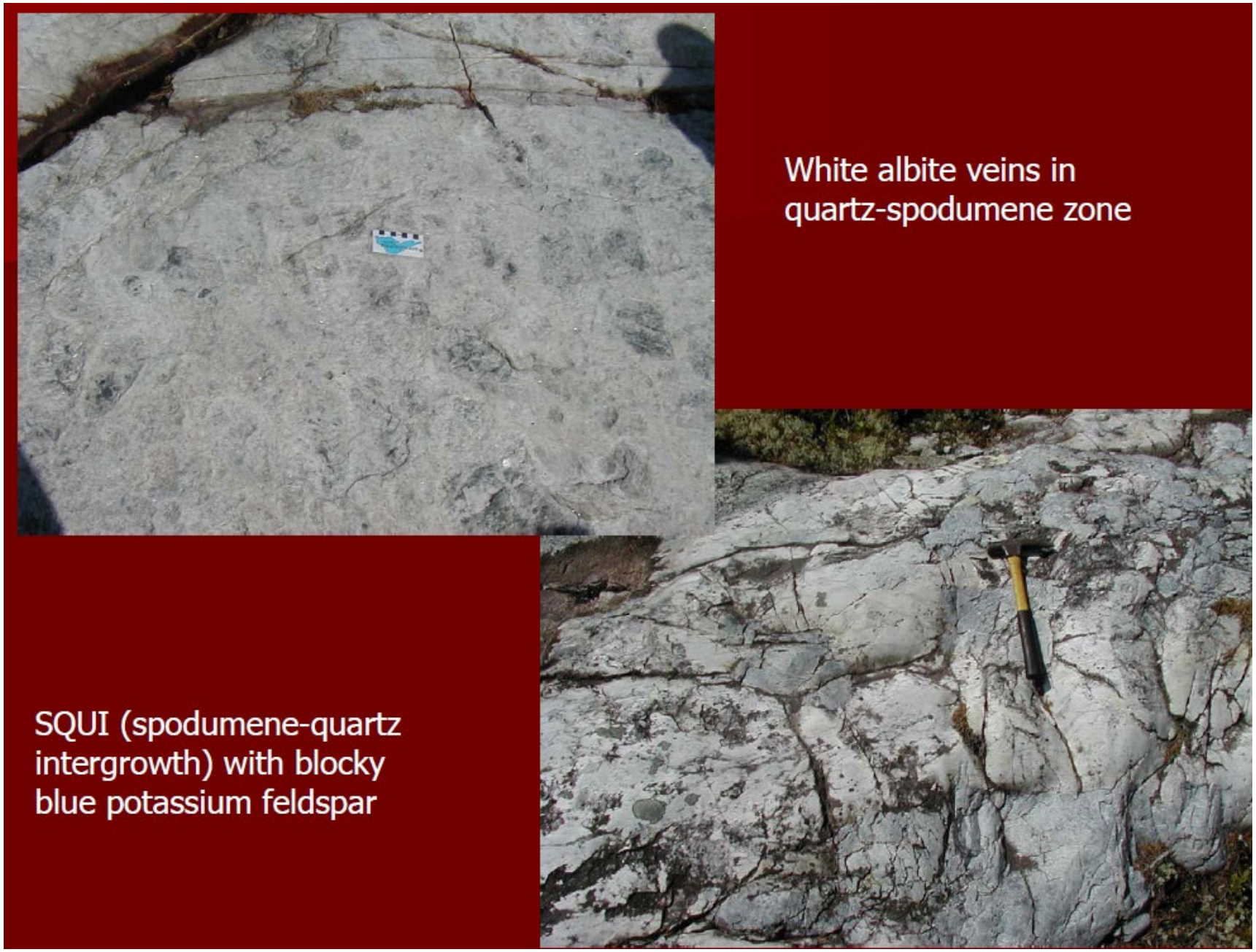
Figure 1. World map showing the locations of LCT pegmatite deposits or districts, including smaller districts in the United States. The symbols are color-coded by age. Giant deposits are represented by larger symbols.

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



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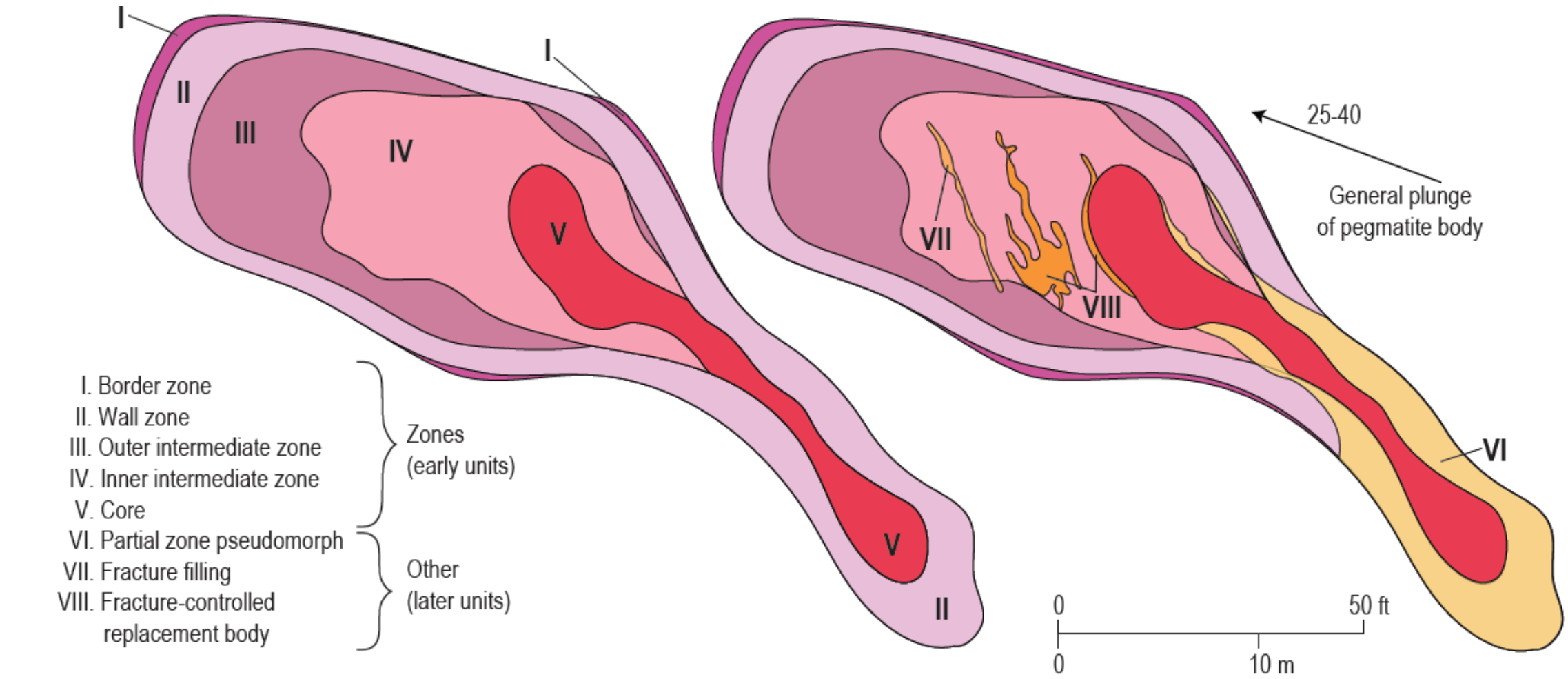
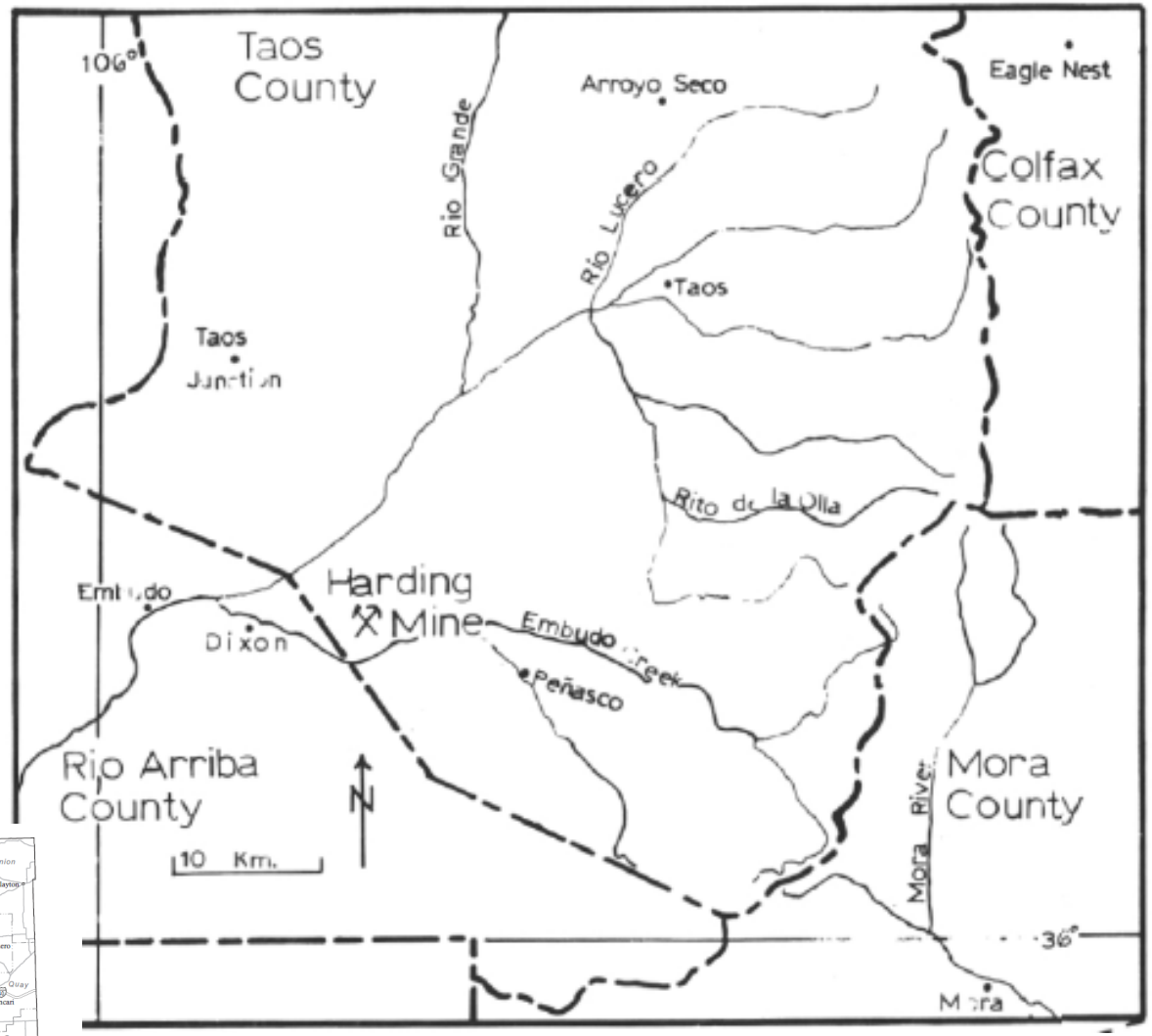


Figure 6. Idealized pegmatite body (modified from Jahns, 1946).

Harding mine, New Mexico

- Pegmatite in Picuris district
- Age 1337 Ma
- Resources remain
- L-C-T with Nb
- Discovered 1910



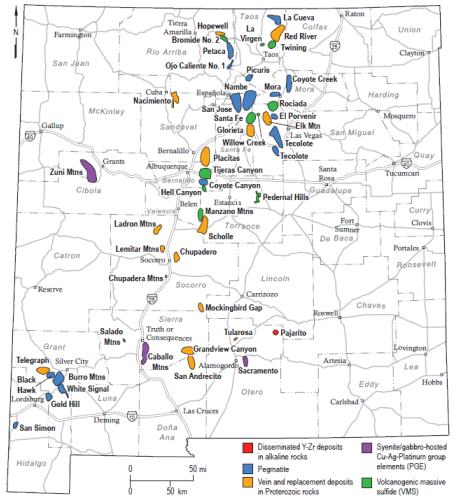
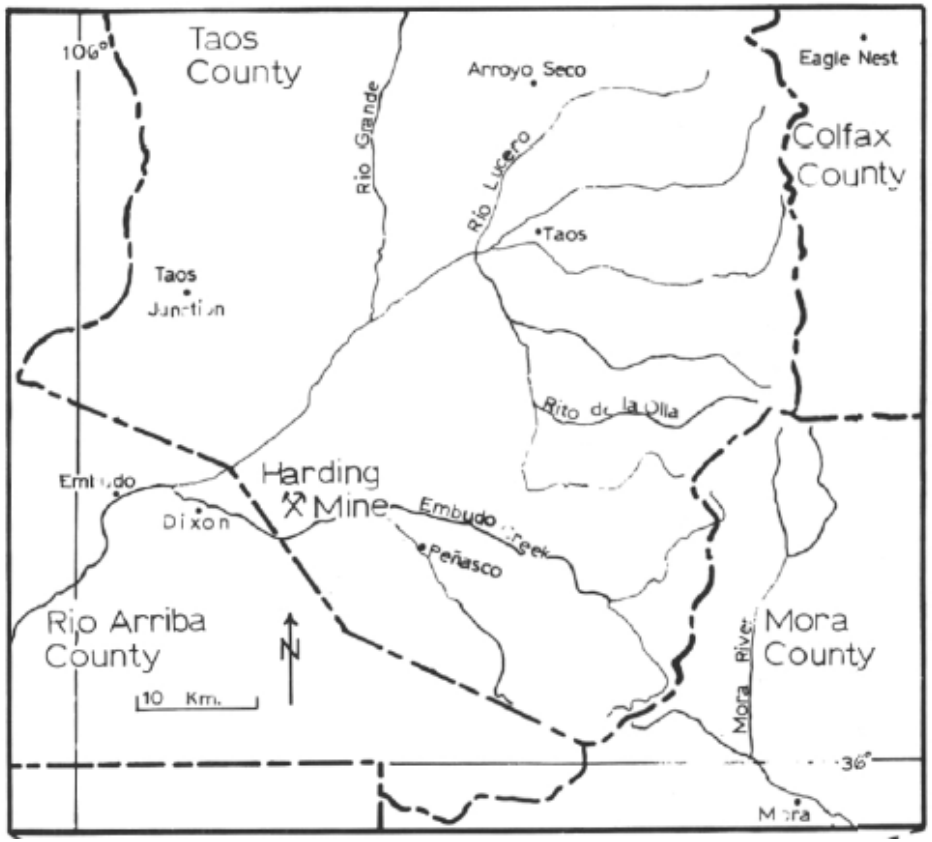
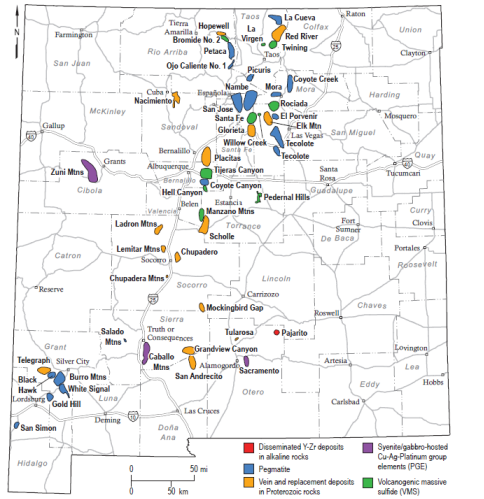


Figure 4. Proterozoic age mineral deposits in New Mexico. Some districts contain more than one type of deposit. Iron formation deposits are found in two districts, Hopewell and Bromide No. 2, in northern New Mexico.

Harding mine, New Mexico

- Lepidolite mining 1919-1930
  - 12,000 tons of lepidolite-spodumene ore, averaging 3.5% LiO_2
- Microlite 1942-1947
  - more than 22,000 lbs of tantalum concentrates, averaging 68% Ta_2O_5 and 7% Nb_2O_5, were produced
  - 41 short tons of spodumene and 558 short tons of lepidolite were produced
  - 464 lbs of placer tantalite and columbite averaging 43% Ta_2O_5 and 36% Nb_2O_5
- Beryl 1950-1959
  - 848.3 short tons of beryl that averaged 10% BeO were produced
  - 806 short tons of lepidolite and 249 short tons of spodumene were produced





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Harding mine, New Mexico

Sorting beryl-from left to right: Art Montgomery, Faudio Griego, A. E. Archuleta, Juan Romero, Eliseo Geigo and Pablo Rendo. (Laura Gilpin, 1953)

Drilling deep underground in bery stope. (Laura Gilpin, 1953)

"Dumping" a small car-load of beryl ore down the chute to sorting platform. (Laura Gilpin, 1953)

Harding mine, New Mexico

Figure 2. Southwestward view of Harding quarry from North Knob, showing the sharp, irregular hanging wall of the main pegmatite body as exposed by open-cut mining prior to 1943. The body dips gently away from the observer, and its footwall is exposed near portal of main entry in right foreground. Active workings for microlite ore are at left in quarry, beyond the northeast entry. Temporary structure of U.S. Bureau of Mines camp appears on the wooded slope in center distance.

Looking into mine adits from top of North Knob

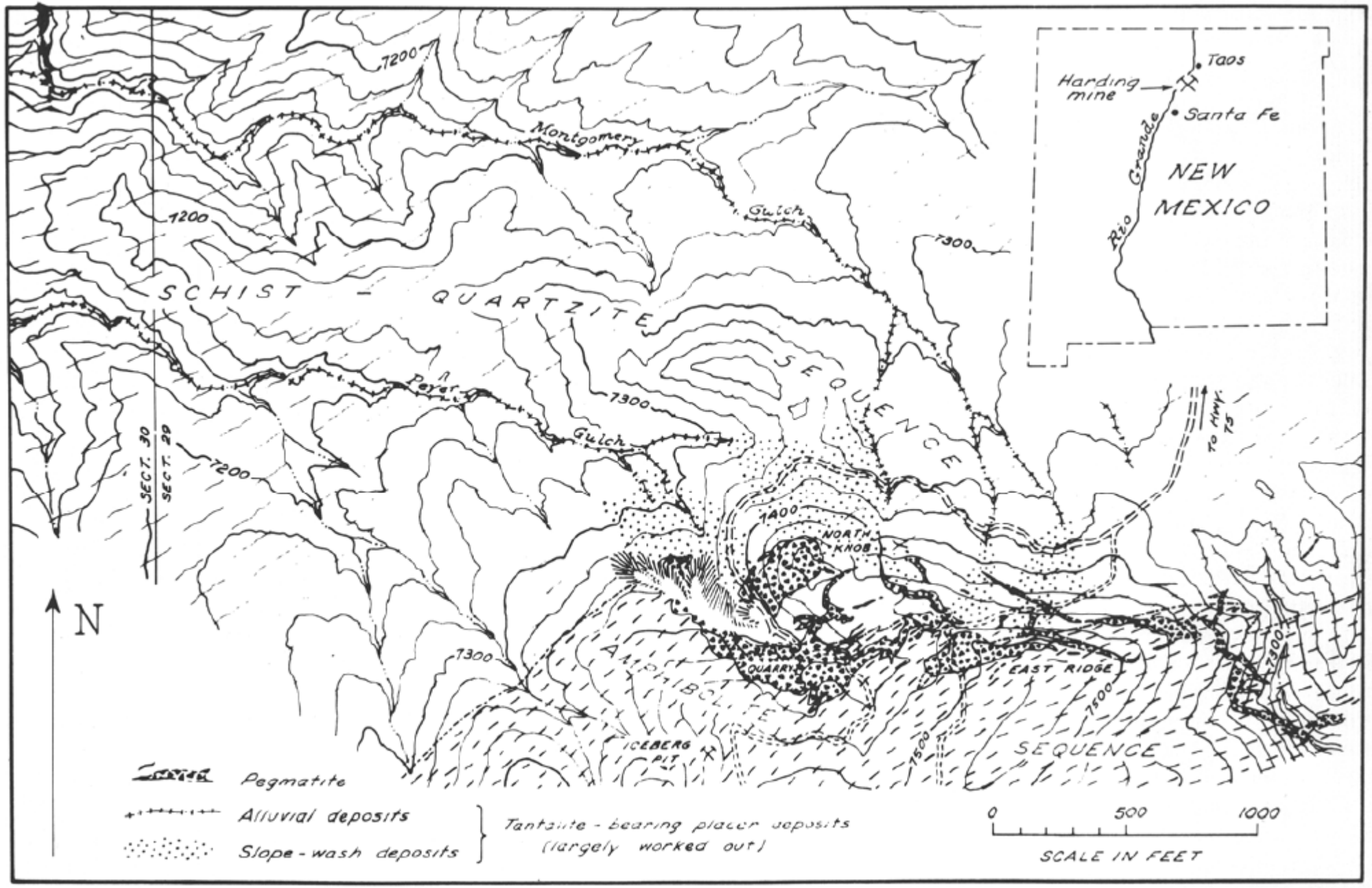


Figure 1. Generalized map of Harding pegmatite bodies. Insert shows location within the State of New Mexico.

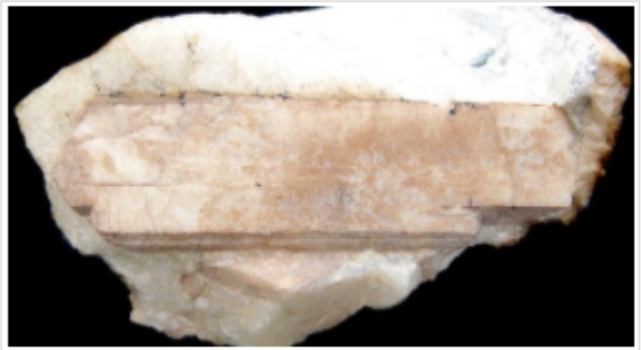
Jahns and Ewing, 1976

TABLE 5. MINOR ACCESSORY MINERALS OF THE HARDING PEGMATITE

Silicates		Oxides	Carbonates	Phosphates	Sulfides Arsenides	Other
allanite	eucryptite	bismite	azurite	amblygonite	bismuthinite	bismuth
amphibole	illite	cassiterite	beyerite	lithiophilite	chalcocite	fluorite
andalusite	kaolinite	gahnite	bismutite	monazite	chalcopyrite	
bertrandite	montmorillonite	ilmenite	calcite	wavellite	loellingite	
biotite	pyrophyllite	limonite	malachite		pyrite	
chloritoid	thorite	magnetite				
chrysocolla	topaz	pyrolusite				
cordierite	tourmaline	rutile				
epidote	zircon	sphene				
		tenorite				

Jahns and Ewing, 1976

Spodumene $LiAlSi_2O_6$



Harding Mine, Picuris District, Taos Co., New Mexico, USA

Spodumene, terminated crystal (12.3 x 3.6 cm) in quartz.

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Microlite Group $A_{2-m}Ta_2X_{6-w}Z_{-n}$ **, Lepidolite**

Harding Mine, Picuris District, Taos Co., New Mexico, USA

Microlite [probably not analysed - zircon?] in lepidolite. Specimen size:4,5x3cm

Photo and collection; Jorge M. Alves

Copyright: © Jorge Moreira Alves Photo ID: 77957 Uploaded by: Jorge Moreira Alves View Count: 1132 Approval status: Public galleries Type: Photo - 989 x 750 pixels (0.7 Mpix)

https://www.mindat.org/gallery.php?loc=13724

Columbite-Tantalite

Harding Mine, Picuris District, Taos Co., New Mexico, USA

Waterworn crystals on display at the University of New Mexico Geology Museum. P. Cristofono photo.

https://www.mindat.org/gallery.php?loc=13724

Copyright: © 2008 Peter Cristofono Photo ID: 154888 Uploaded by: Peter Cristofono View Count: 1151 Approval status: Public galleries Type: Photo - 400 x 357 pixels (0.1 Mpix)

Microlite Group $A_{2-m}Ta_2X_{6-w}Z_{-n}$

TT8-V5R

Harding Mine, Picuris District, Taos Co., New Mexico, USA

Field of View: 4.0 mm
Largest Crystal Size: 3.0 mm

Brown microlite group crystal (EDS confirmed) hosted in spodumene and albite matrix with minor 'rose muscovite' (Mn-rich muscovite). Brown staining of the host matrix is due to radiation damage. Self collected 3/21/2018. Chris Emproto collection and photo.

Photo ID: 929225 Uploaded by: Christopher Emproto View Count: 36 Approval status: Public galleries Type: Photo - 1242 x 1024 pixels (1.3 Mpix)

In the Mine

Harding Mine, Picuris District, Taos Co., New Mexico, USA

The Harding Pegmatite is a Precambrian aged, zoned pegmatite. The distinct zones are the beryl zone, cleavelandite zone, and quartz-lath spodumene zone.

The pegmatite was discovered around 1910. From 1919 to 1930, lepidolite was mined. During the Second World War, microlite, tantalite-columbite, beryl, and spodumene were extracted. From 1950 to 1955, four men and a mule named Beryl mined the abundant beryl of the pegmatite.

Photo taken: 17 July 2000
Camera: Nikkormat FS

Film: Kodak Gold 100

Copyright: © Nathalie Brandes Photo ID: 395930 Uploaded by: Nathalie Brandes View Count: 369 Approval status: Public galleries Type: Photo - 1765 x 1200 pixels (2.1 Mpix)

Beryl (Var: Morganite) $Be_3Al_2(Si_6O_{18})$ WUF-45N

Harding Mine, Picuris District, Taos Co., New Mexico, USA

Largest Crystal Size: 6 inches

New Mexico Bureau of Geology Mineral Museum no. 10851, gift of Ramon S. DeMark, and no. 17931, gift of Jesse Kline (detail in child image).

Copyright: © Erin Delventhal Photo ID: 814632 Uploaded by: Erin Delventhal View Count: 265 Approval status: Public galleries Type: Photo - 2448 x 3264 pixels (8.0 Mpix)

https://www.mindat.org/gallery.php?loc=13724

Harding mine—zones

- biotite + muscovite + quartz ± garnet ± margarite ± schorl
- quartz + albite + muscovite ± perthite
- quartz ± albite ± muscovite
- quartz + lath spodumene
- microcline + spodumene + lepidolite + albite + muscovite + quartz
- cleavelandite + rose muscovite ± quartz
- cleavelandite + quartz ± muscovite
- blocky perthite ± quartz ± albite
- quartz + aplitic albite ± muscovite

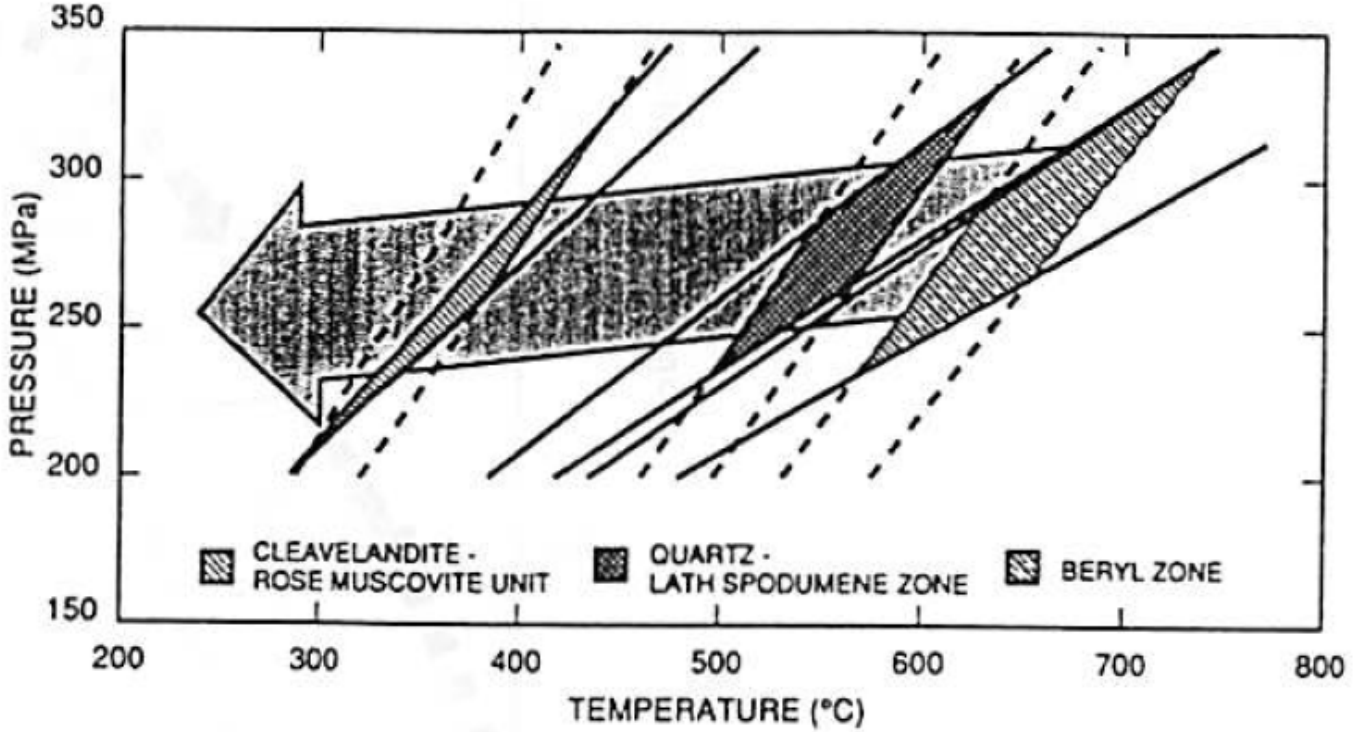


FIG. 5. Isochores for fluid inclusions in Harding pegmatite quartz and beryl. CO_2-H_2O isochores (solid lines) for the beryl zone (0.77–0.79 g/cm^3), quartz - lath spodumene zone (0.81–0.83 g/cm^3), and rose muscovite – cleavelandite unit (0.91–0.93 g/cm^3), including for each lithologic unit a range in $X(CO_2)$ of 0.75–1.0. CO_2-H_2O-NaCl isochores (dashed lines) (all 1.0–1.1 g/cm^3) for the beryl zone, quartz - lath spodumene zone, and rose muscovite - cleavelandite unit, including for each lithologic unit a range in $X(CO_2)$ of 0.0–0.1 and X(NaCl) of 0.0–0.1. The original data are from Cook (1979). The regions of intersection for the two types of isochores are shaded for each lithologic unit. The large shaded arrow shows the crystallization sequence.

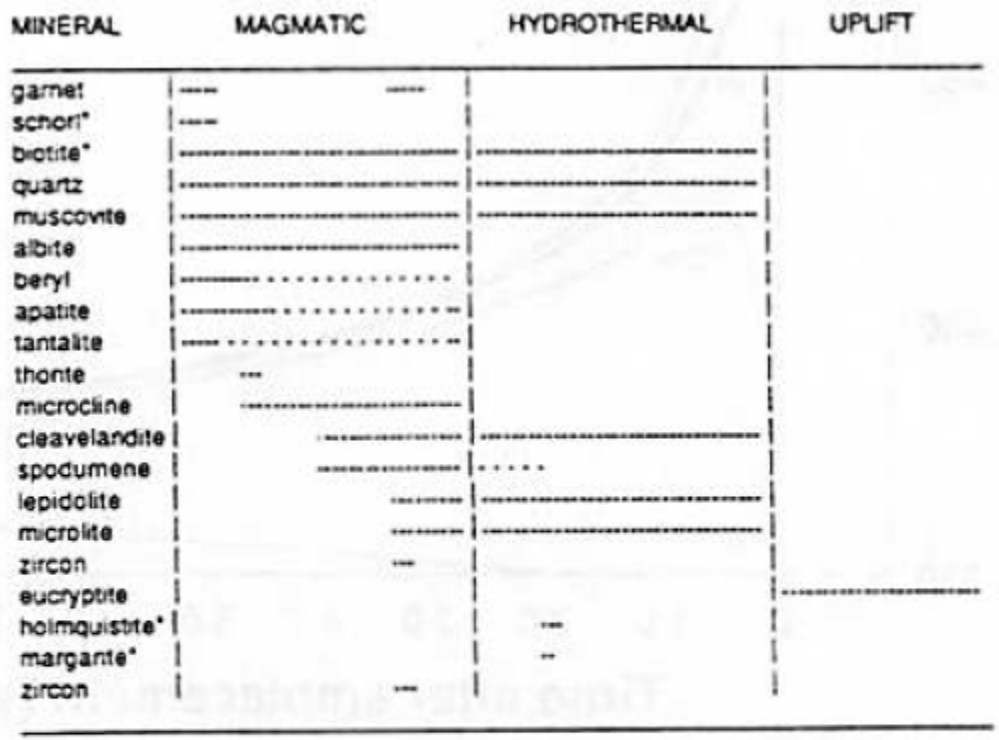
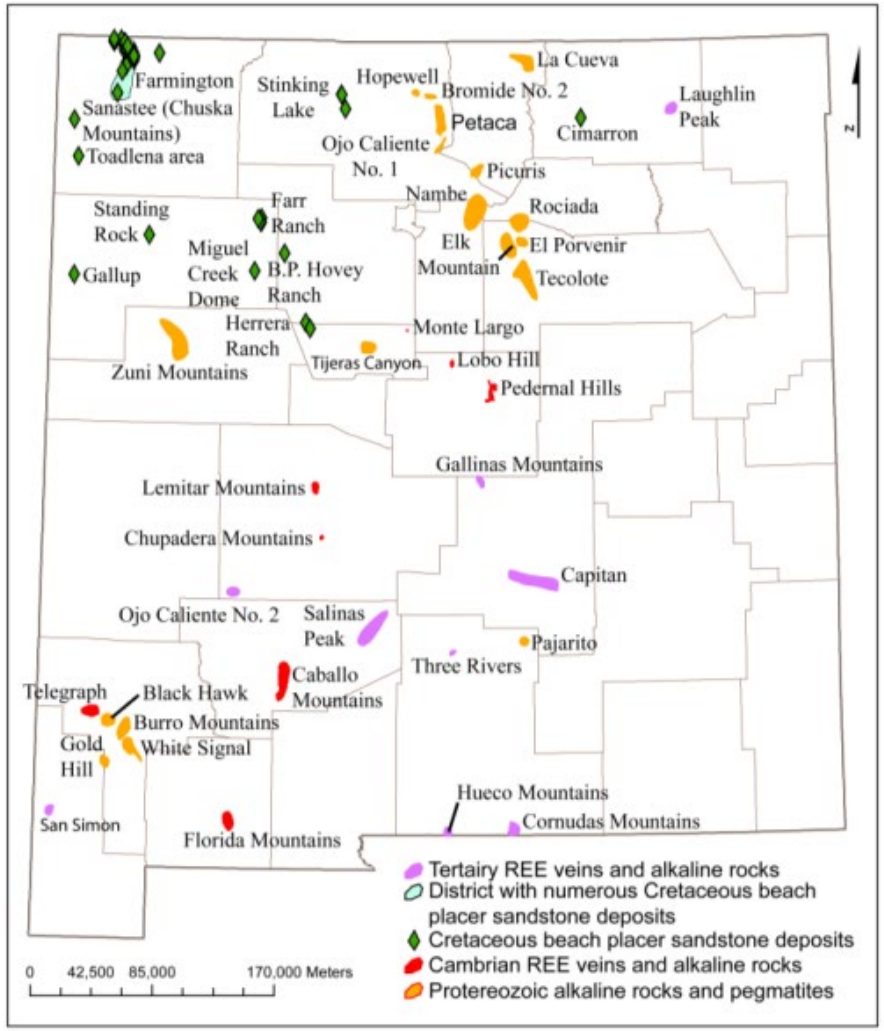


FIG. 8. Crystallization sequence of major and minor minerals in the Harding pegmatite and its metasomatic aureole. The magmatic, hydrothermal, and uplift stages of crystallization correspond to the crystallization path shown in Figure 6. Minerals marked with an asterisk occur only in the metasomatic aureole.

Chakomakos and Lumpkin (1990)

- University of New Mexico owns it since 1978 as a field laboratory—mineral collecting is allowed
- Release form
  - More than 10 people need to pay $50 and have form in 3 weeks before visit
- https://eps.unm.edu/research/harding/release-form.html

- You can visit this mine on your own before the end of April and include it as a field trip report for this class



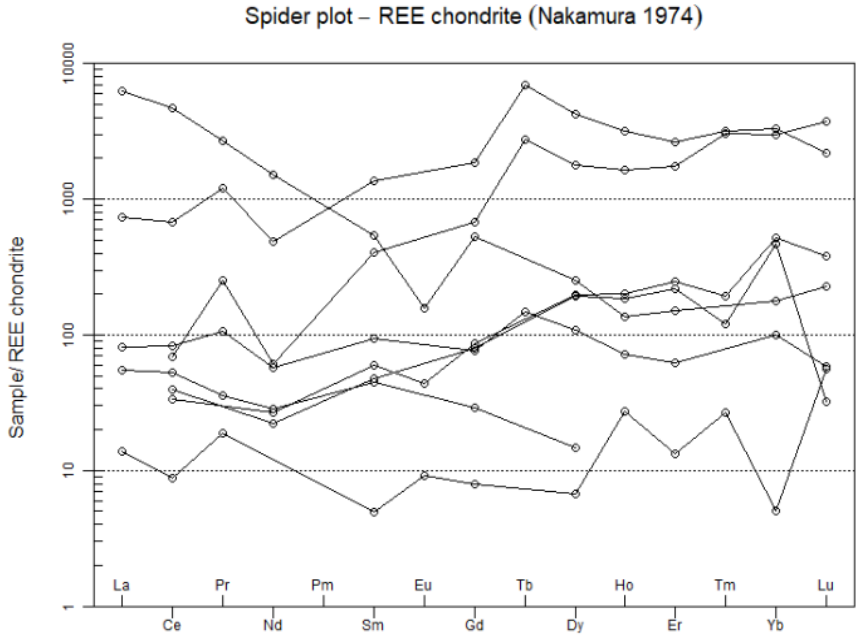
Petaca

Burro Mountains

Other Pegmatites

Other Pegmatites

- Production from the Petaca and Ojo Caliente No. 1 mining districts, Rio Arriba County w=production data withheld.
- Nb content of 0.04 percent in 87 pegmatites of the Petaca district



Commodity	Production	Years of production
Beryl	12,748	
Columbite-tantalite (lbs)	5,092-12,000	
Sheet mica (lbs)	604,927	
Scrap mica(short tons)	15,191	1899-1963
Feldspar	w	
Lithium (short tons)	w	1920-1963
Bismuth (lbs)	100	1943
Rare earth elements (samarskite) (lbs)	5,000	
Kyanite (short tons)	1,500	1928
Uranium	2 lbs	1954

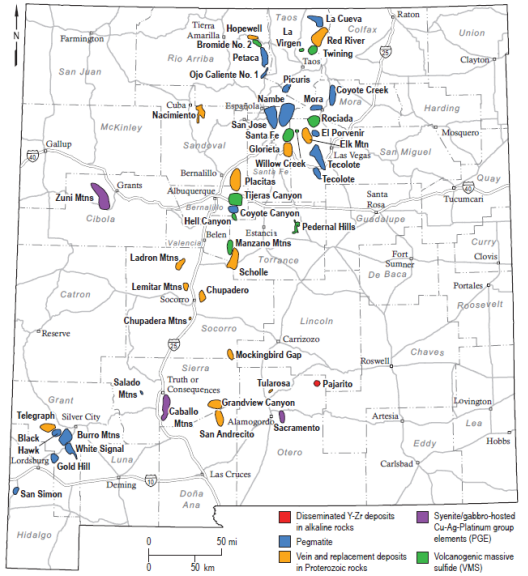


Figure 4. Proterozoic age mineral deposits in New Mexico. Some districts contain more than one type of deposit. Iron formation deposits are found in two districts, Hopewell and Bromide No. 2, in northern New Mexico.

REE production from Proterozoic deposits in New Mexico

DISTRICT NAME	PRODUCTION
Gallinas Mountains	146,000 lbs of bastnasite concentrate
Petaca	112 lbs of samarskite, few hundred lbs of monazite, 12,000 lbs of Ta-Nb-REE ore
Elk Mountain	500 lbs of Ta-U-REE concentrate
Rociada	Several thousand tons of REE-Ta ore
Tecolote	$10,000 worth of beryl, tantalite-columbite and monazite
Gold Hill	REE production in the 1950s

Production of rare earth elements (REE) in New Mexico, to date.

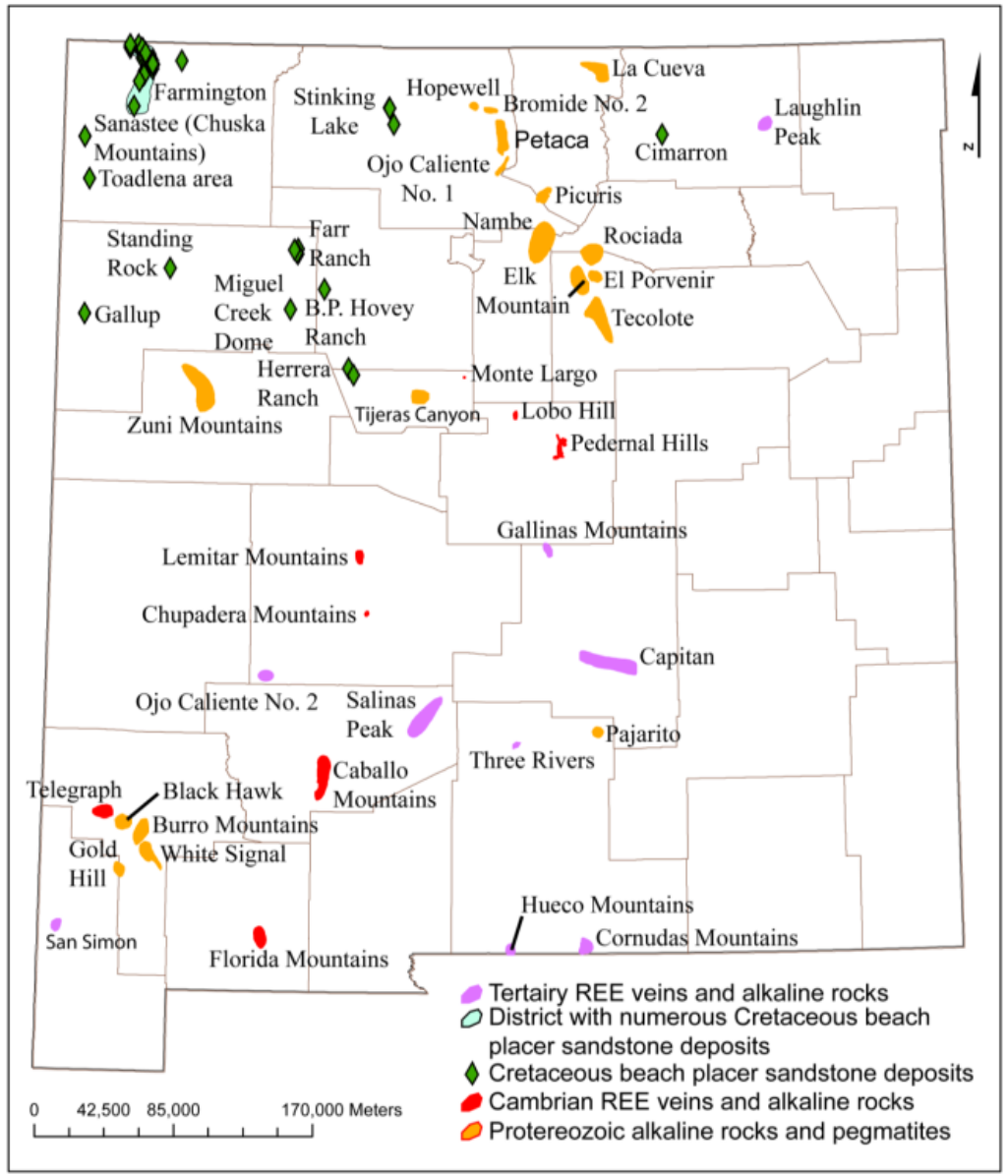
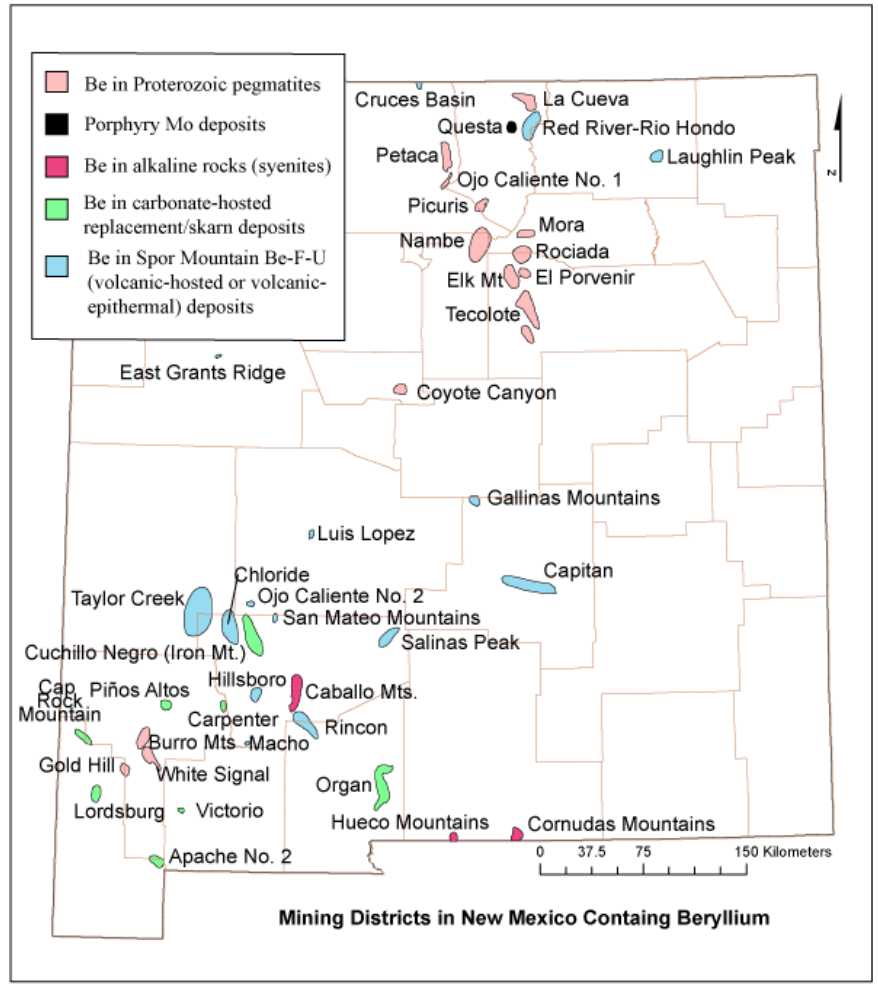


TABLE 4. Beryllium production from Proterozoic pegmatites in New Mexico (Meeves et al., 1966). Additional production in 1963-1969 is withheld. Additional production from Iron Mountain in the Cuchillo Negro district, Santa Fe district, and Mora district is unknown.

County	Year	Beryl (pounds)
Rio Arriba	1951-1963	12,748
San Miquel	1951-1963	49,015
Taos	1951-1963	1,678,054
Harding, Taos	1950-1959	1,696,600
TOTAL	1950-1963	1,739,817



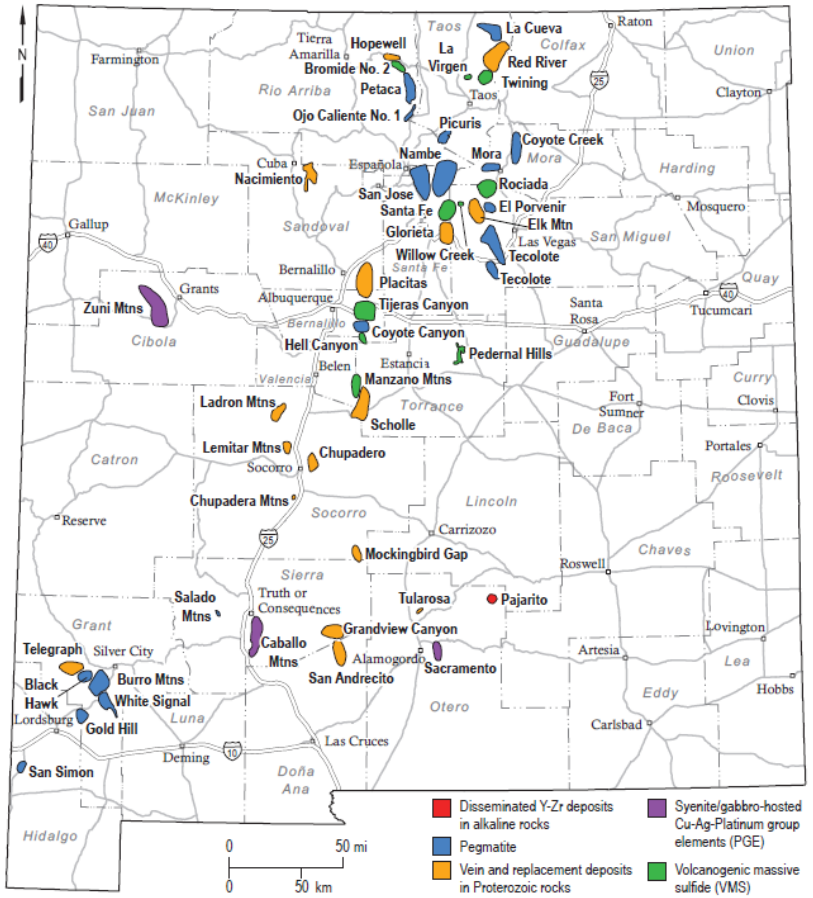


Figure 4. Proterozoic age mineral deposits in New Mexico. Some districts contain more than one type of deposit. Iron formation deposits are found in two districts, Hopewell and Bromide No. 2, in northern New Mexico.

Elk Mountain

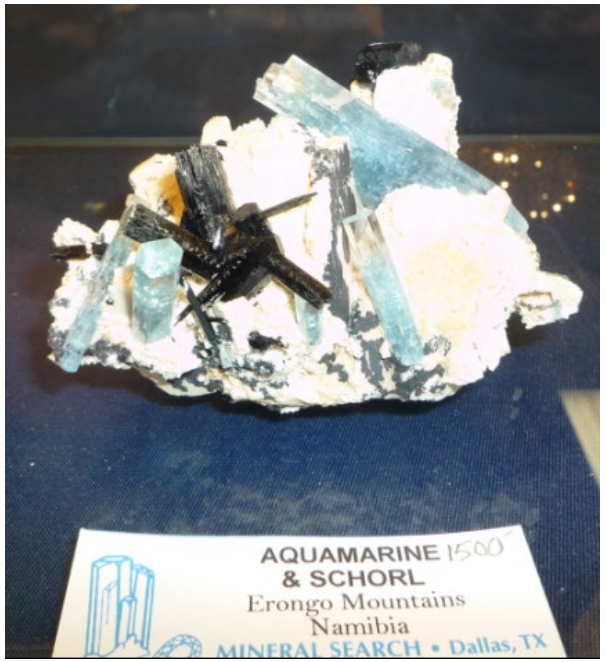
Other Pegmatites

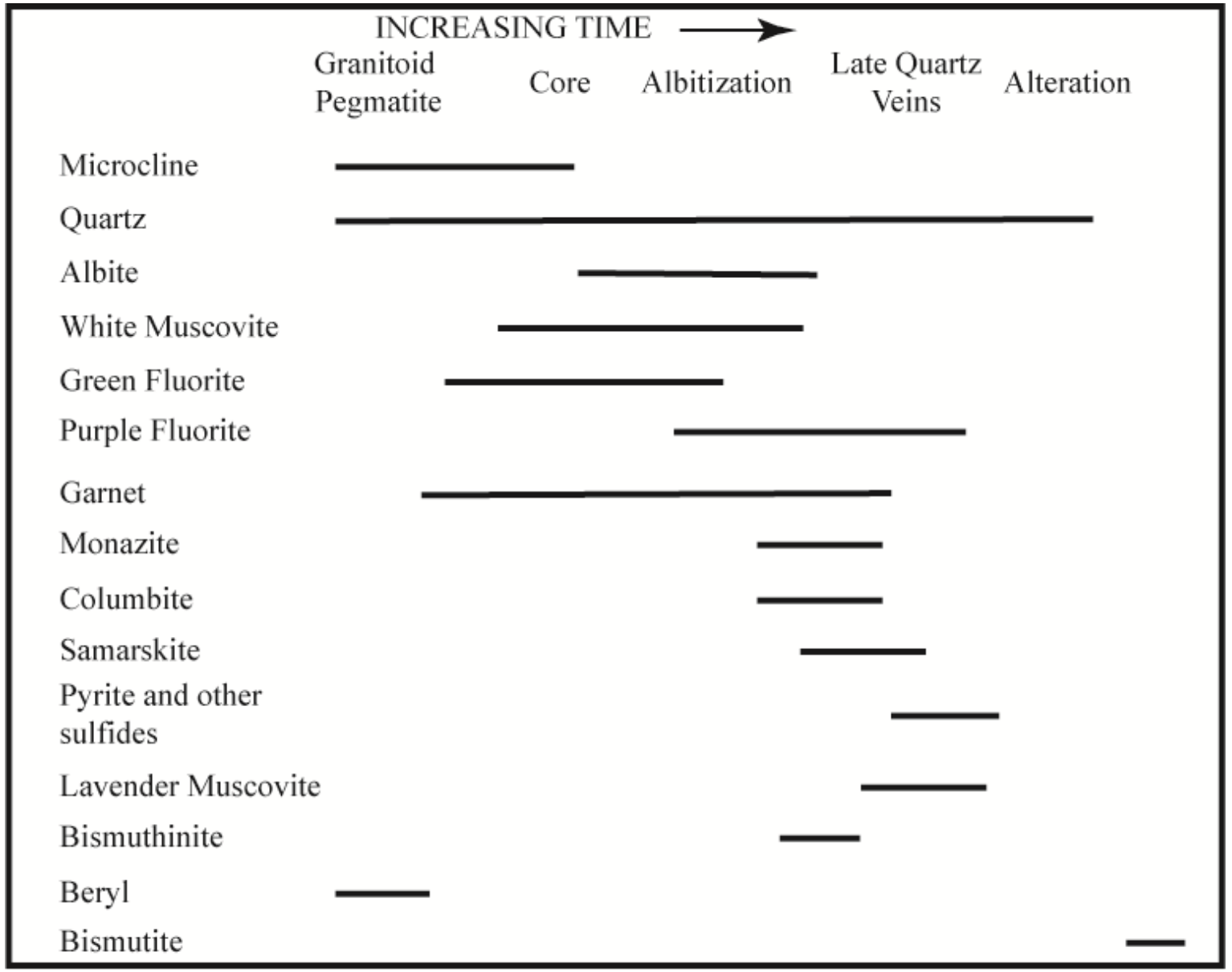
REE minerals in pegmatites

- Garnet
- Fluorite
- Columbite
- Beryl
- Gadolinite
- Euxenite
- Uraninite
- Microlite
- Allanite
- samarkite
- Cyrtolite
- Zircon
- Monazite

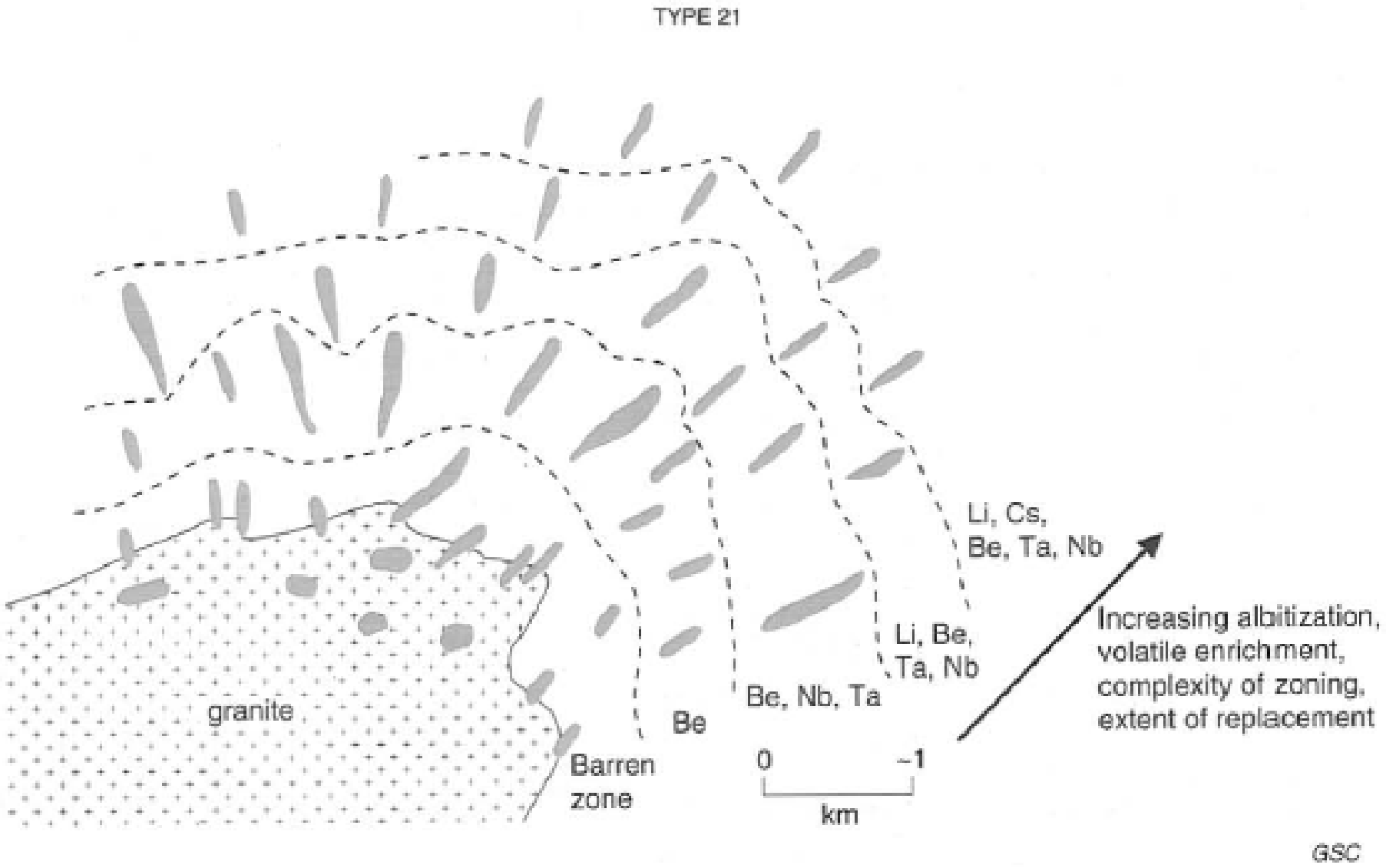
Gemstones

- Gems known to ancient man
  - Romans had emerald mines >2000 yrs ago in Egypt
- Emerald (green)
- Aquamarine (blue, gree)
- Chrysoberyl (golden beryl)=alexandrite
- Beryl
- Goshenite (colorless)
- Helliodor (yellow)
- Morganite (pink, orange)





Paragenesis, Globe pegmatite (Petaca)



Sinclair, 1996

Figure 21-4. Schematic representation of the regional zonation of pegmatites (red) around a granite intrusion (modified from Trueman and Černý, 1982).

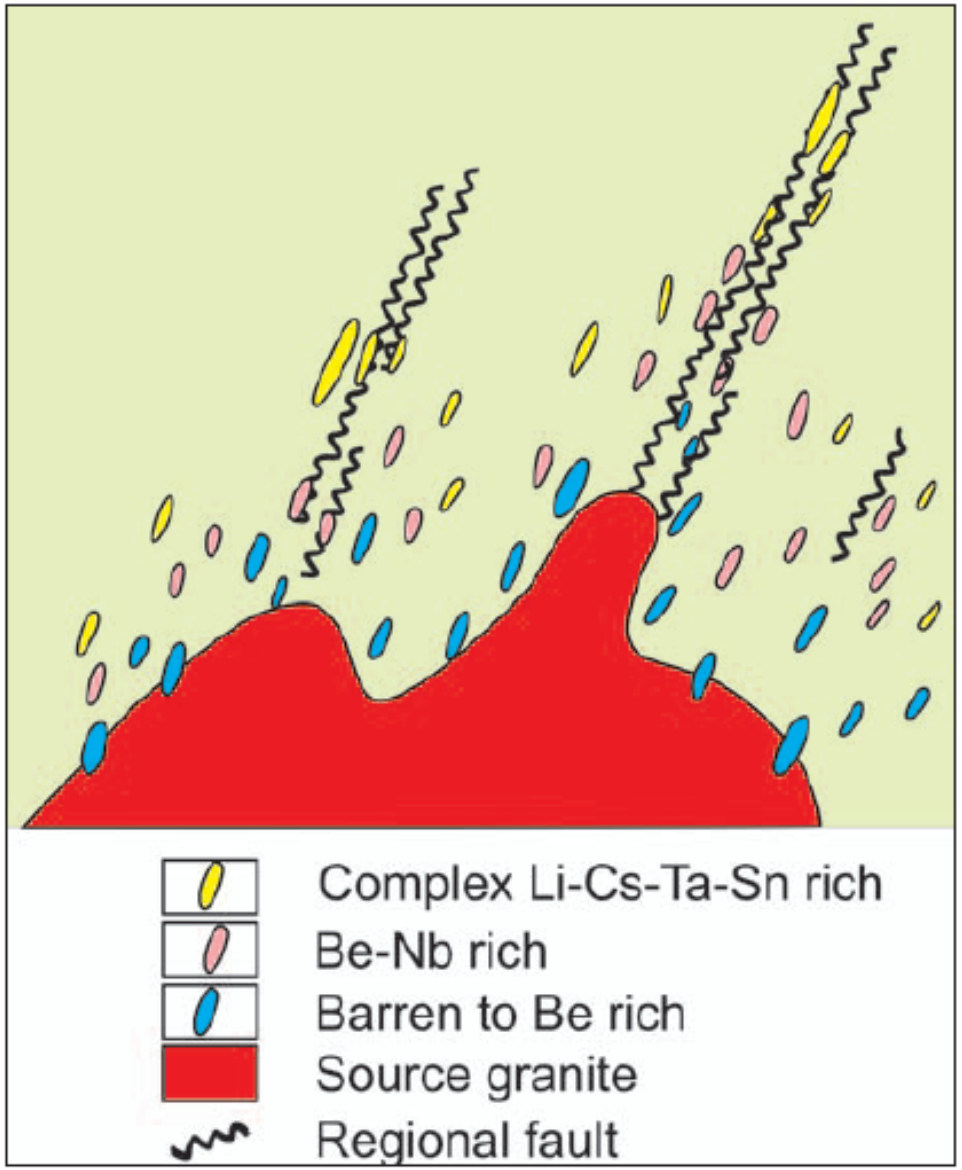


FIGURE 1 Idealized zoned pegmatite field around a source granite. The maximum distance of pegmatites from the source granite is on the order of kilometers or, at most, tens of kilometers. MODIFIED FROM ČERNÝ (1989)

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

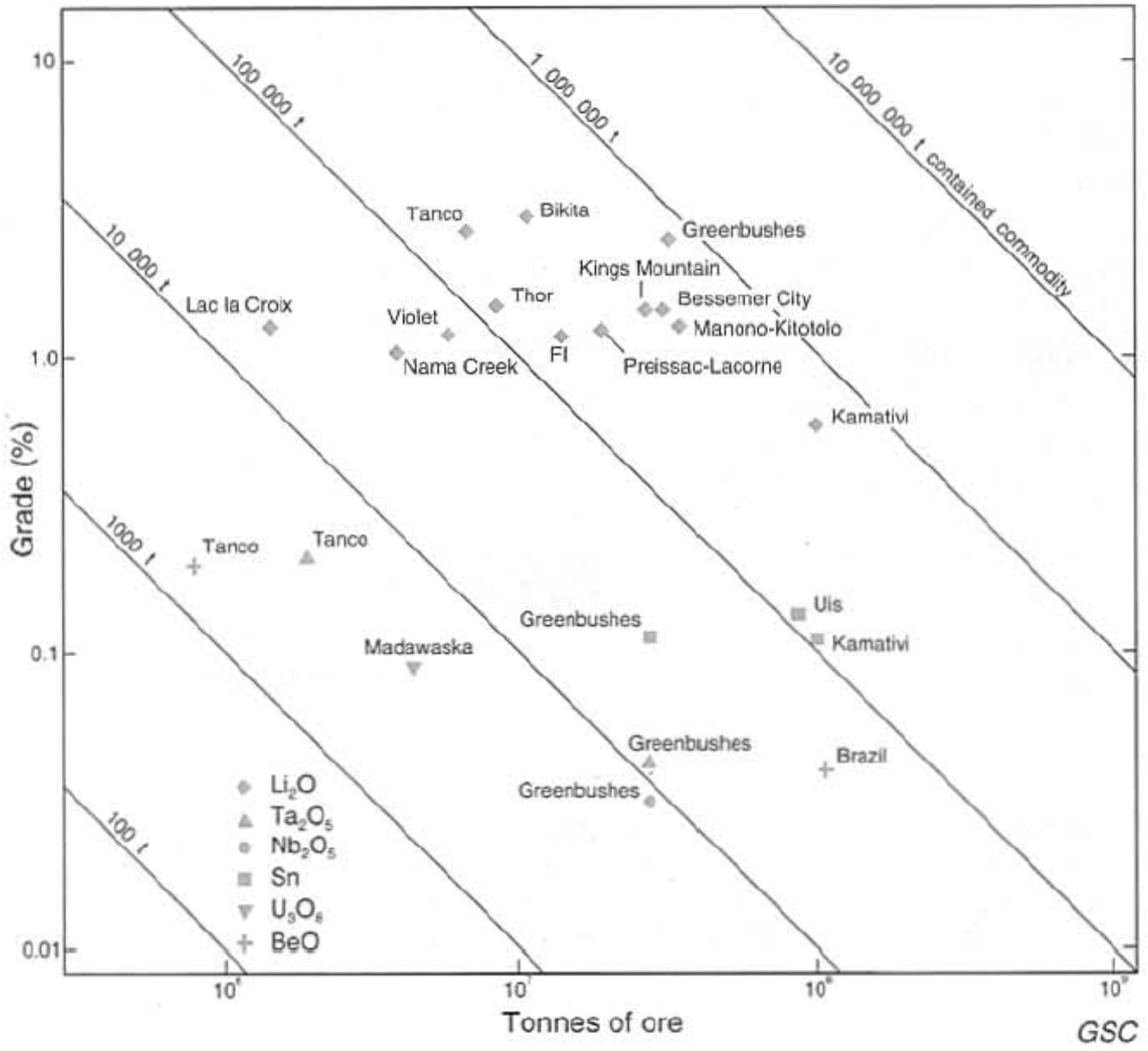


Figure 21-2. Grade versus tonnage diagram for pegmatite deposits (data are from Table 21-2).

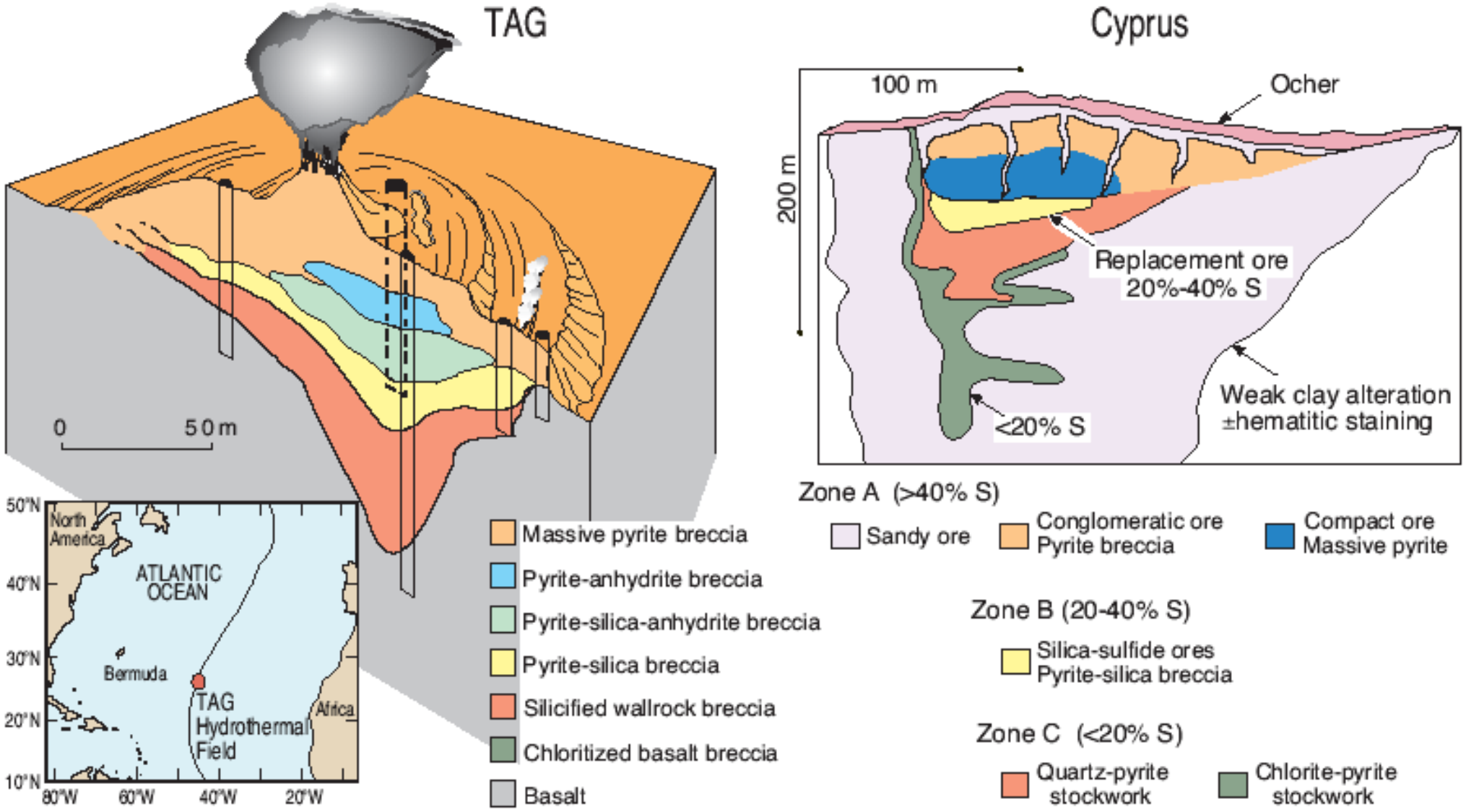
Sinclair, 1996

VOLCANOGENIC MASSIVE SULFIDE DEPOSITS

VOLCANOGENIC MASSIVE SULFIDE DEPOSITS

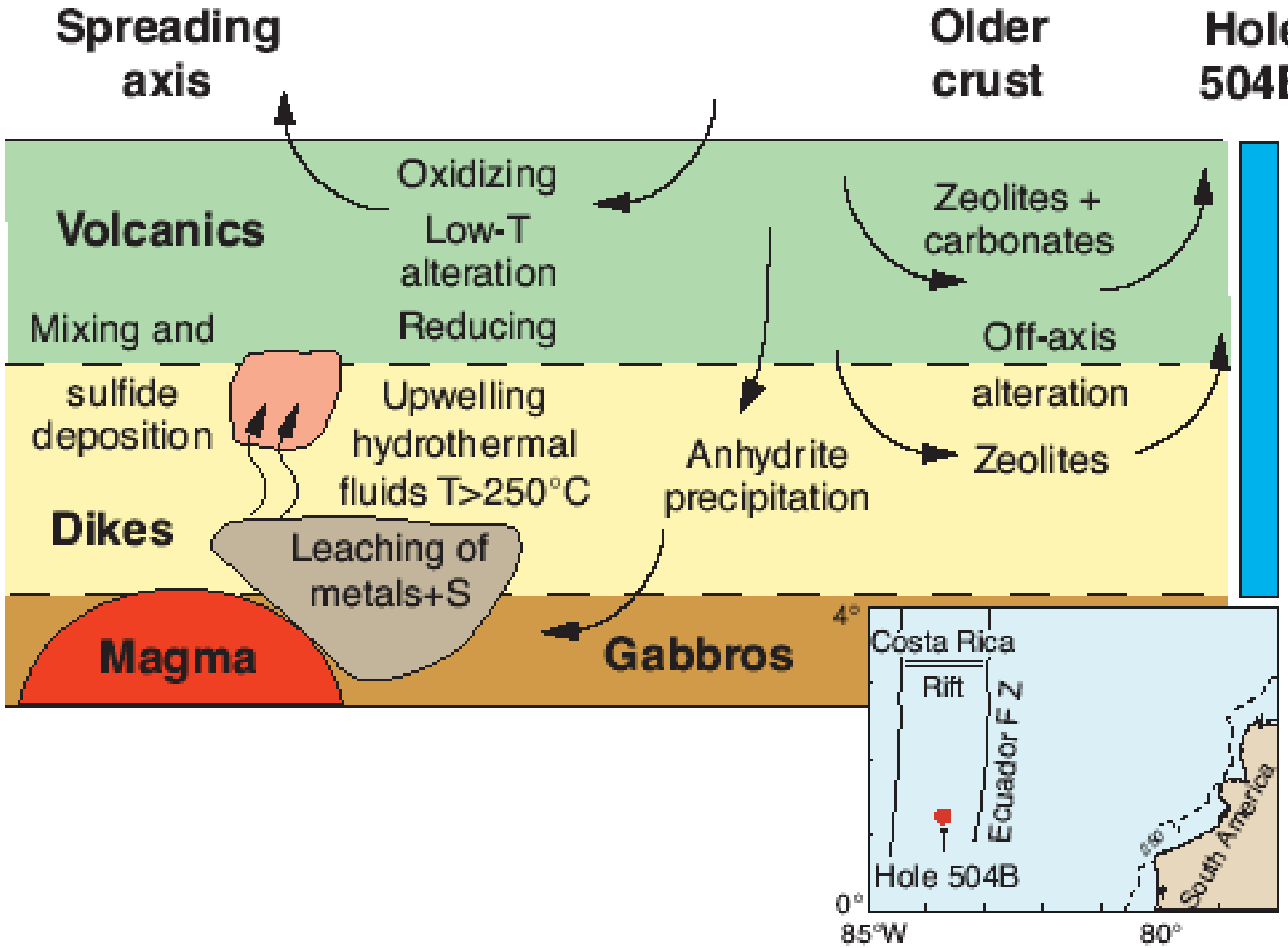
- Known as VMS ore deposits
- copper-lead-zinc sulfides
- volcanic-associated hydrothermal events in submarine environments
- Also called Kuroko, Cyprus, and Besshi deposits
- collisional environments (ocean-ocean or ocean-continent convergence) during periods of extension and rifting
- controlled by
  - Temperature, a_S, pH of fluids in the reaction zone
  - adiabatic cooling of the fluid during its ascent (related to water depth
  - amount of subsea-floor fluid mixing

- Bimodal mafic settings (e.g., Noranda, Urals) occur in incipient-rifted subduction oceanic arcs, typified by flows and <25 percent felsic strata (Cu-Zn)
- Mafic settings (e.g., Cyprus, Oman) occur in primitive oceanic backarcs, ophiolite sequences with <10% sediment (Cu-Zn)
- Pelite-mafic (e.g., Windy Craggy, Besshi) settings occur in mature oceanic backarcs, typified by subequal amounts of pelite and basalt (including mafic sills (Cu-Zn)
- Bimodal-felsic (e.g., Skellefte, Tasmania) settings occur in incipient-rifted subduction epicontinental arcs, typified by 35 to 70% felsic volcaniclastic strata (Cu-Zn-Pb)
- Siliciclastic-felsic settings (e.g., Iberia, Bathurst) occur in mature epicontinental backarcs, typified by continent-derived sedimentary and volcaniclastic strata (Cu-Zn-Pb)



Volcanic massive sulfide deposits

http://joides.rsmas.miami.edu/files/AandO/Humphris_ODPLegacy.pdf



http://joides.rsmas.miami.edu/files/AandO/Humphris_ODPLegacy.pdf

Shape and mineralogy

- Tabular
- Tubular
- Disseminated
- Irregular replacement
- Stratabound
- Open-space filling

- Chalcopyrite
- Galena
- Sphalerite
- Native gold
- Silver sulfides
- Co, Ni, V locally

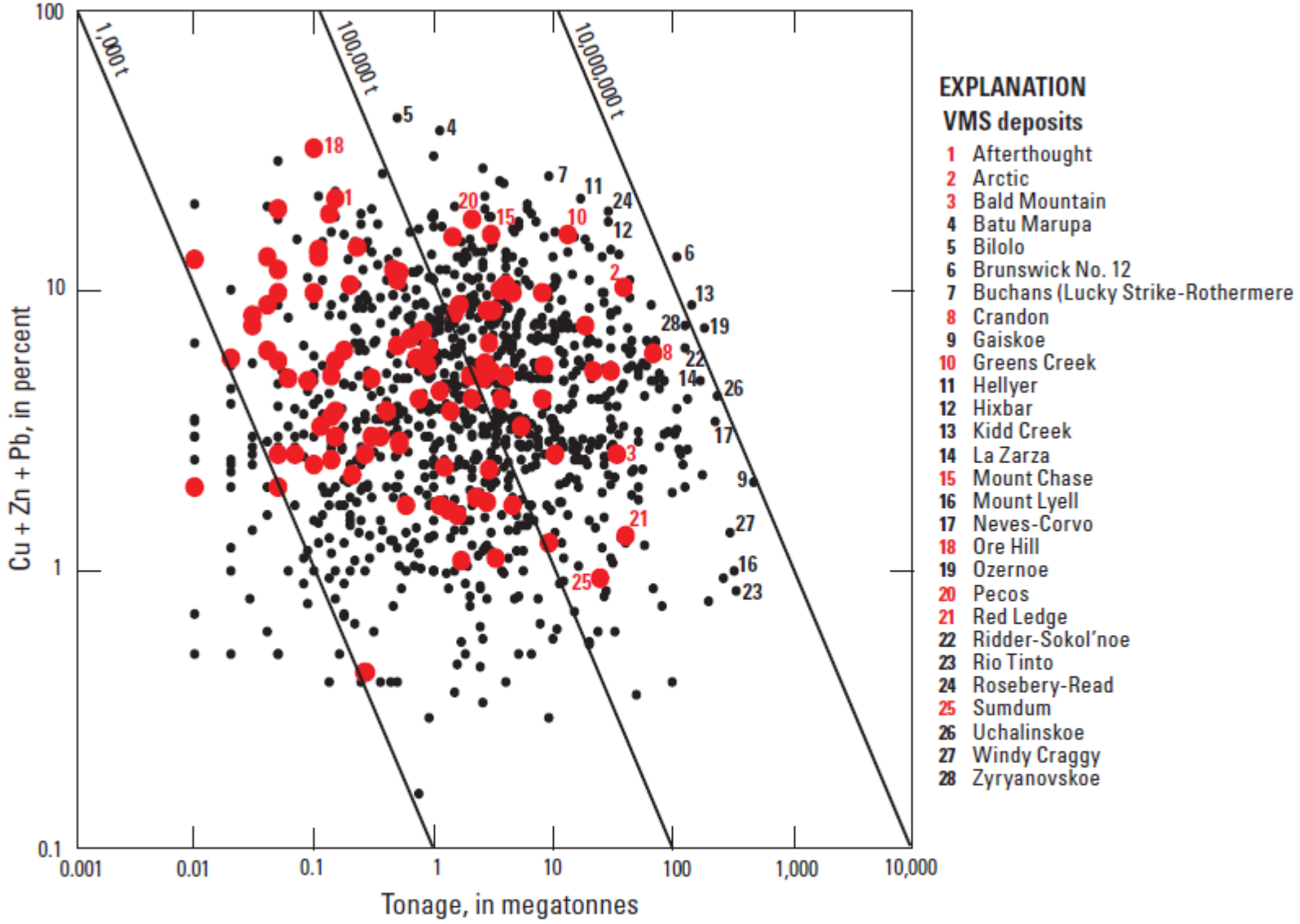


Figure 2–1. Grade and tonnage of volcanogenic massive sulfide deposits. Data are shown for 1,021 deposits worldwide. U.S. deposits are shown as red dots. Data from Mosier and others (2009) (Cu, copper; Zn, zinc;.Pb, lead).

Shanks and Thurston, 2012

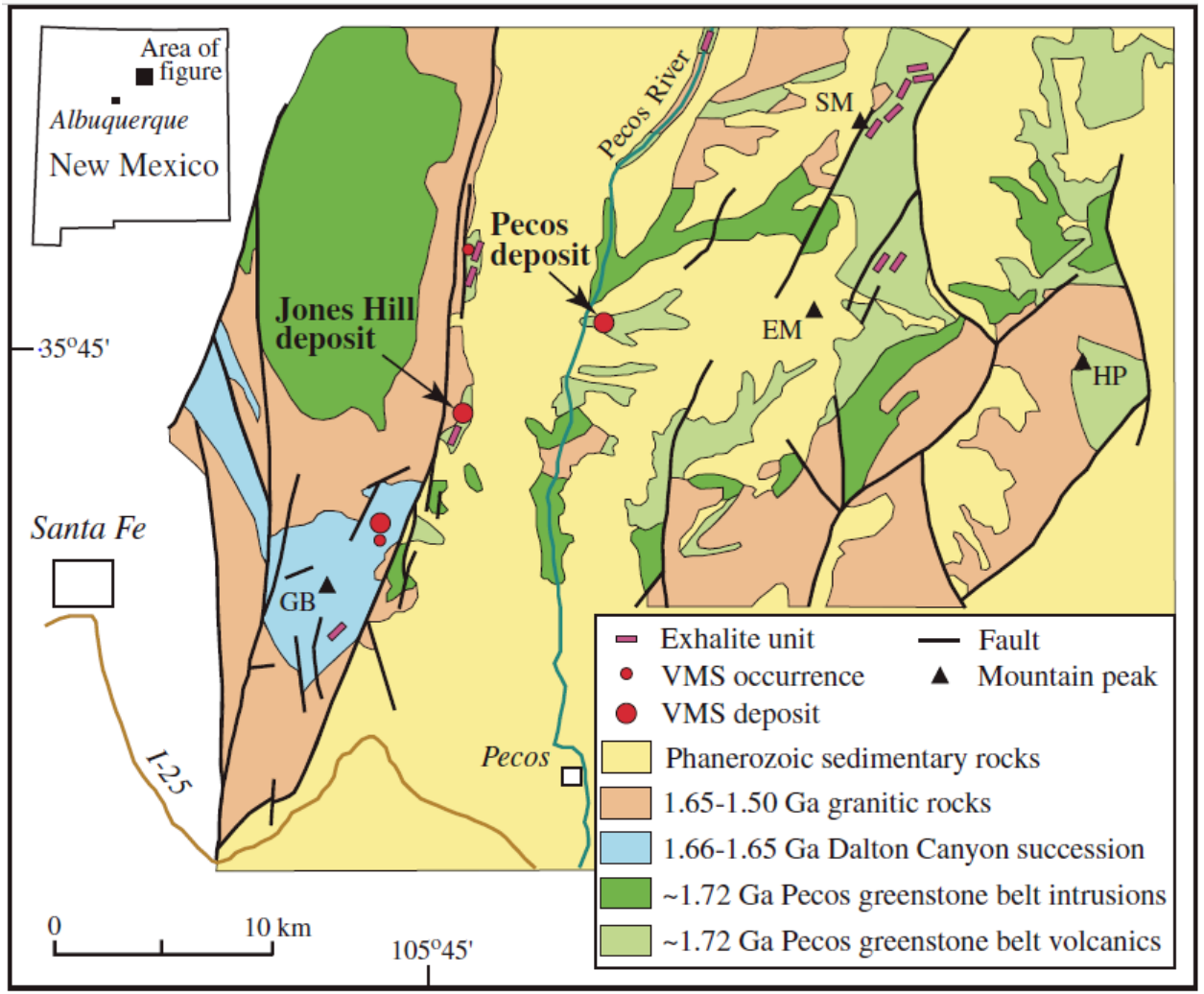


Figure 1. Simplified geologic map of the Pecos greenstone belt and vicinity showing locations of volcanogenic massive sulfide (VMS) deposits and occurrences and bedded exhalite units (iron formation, jasper). Geology from Robertson and Condie (1989). VMS deposits and occurrences and exhalite units from Riesmeyer (1978), Fulp (1982, 1996), and Moench et al. (1988). EM—Elk Mountain; GB—Glorieta Baldy; HP—Hermit Peak; SM—Spring Mountain.

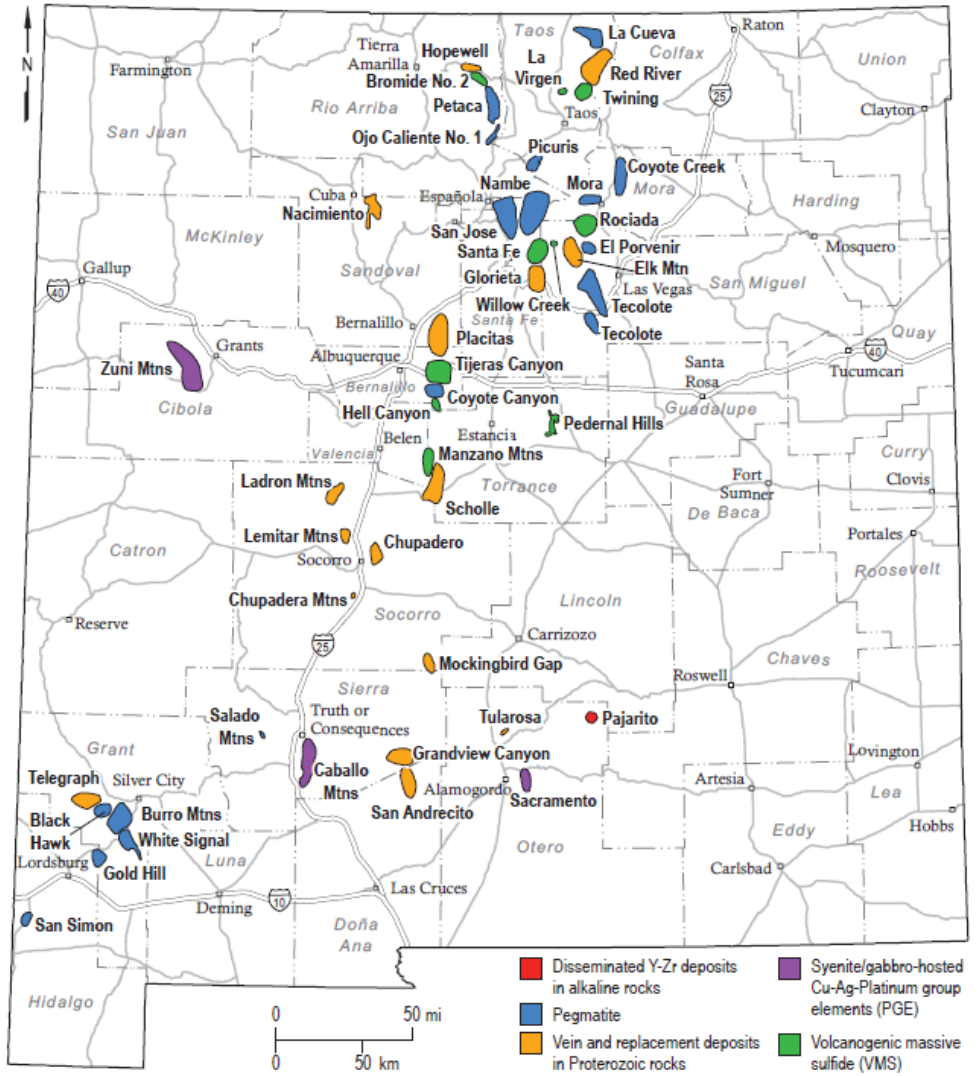


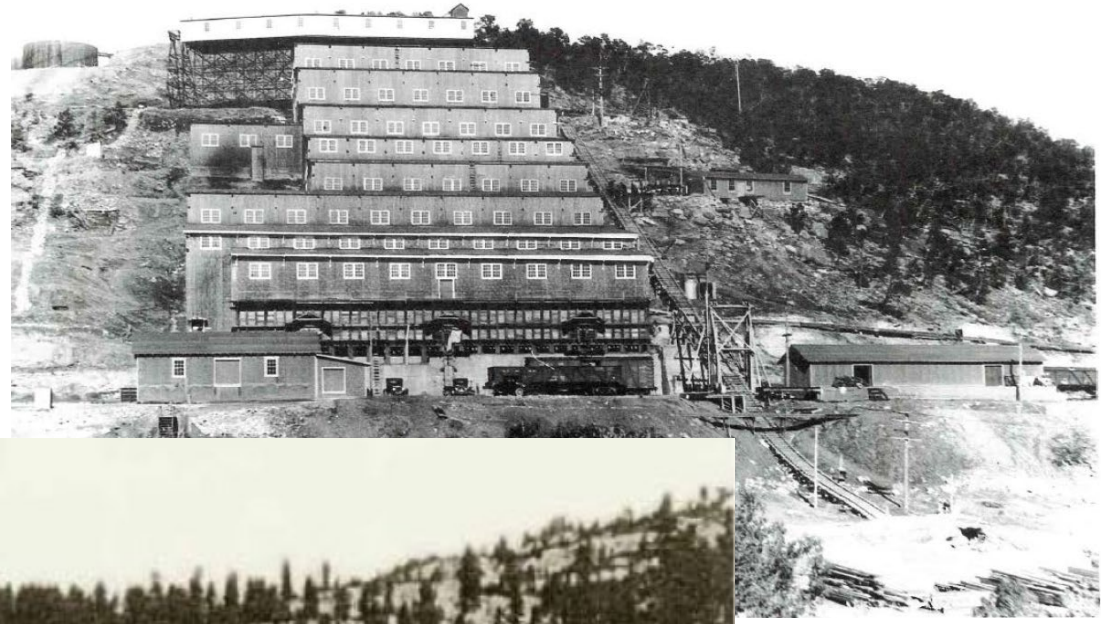
Figure 4. Proterozoic age mineral deposits in New Mexico. Some districts contain more than one type of deposit. Iron formation deposits are found in two districts, Hopewell and Bromide No. 2, in northern New Mexico.

Slack et al., 2009

Pecos (Willow Creek, Terrero) mine

- Sphalerite, galena, chalcopyrite, gold, silver minerals
- Largest producers of Pb and Zn at that time in the US, largest employer in NM
- 1927-1944
  - 2,302,753 short tons ore
  - 18,687,426 lbs Cu
  - 178,858 troy ounces Au
  - 5,477,760 troy ounces Ag
  - 133,042,500 lbs Pb
  - 421,543,000 lbs Zn
  - Worth >$40 million

El Molino Mill



Pecos Mine

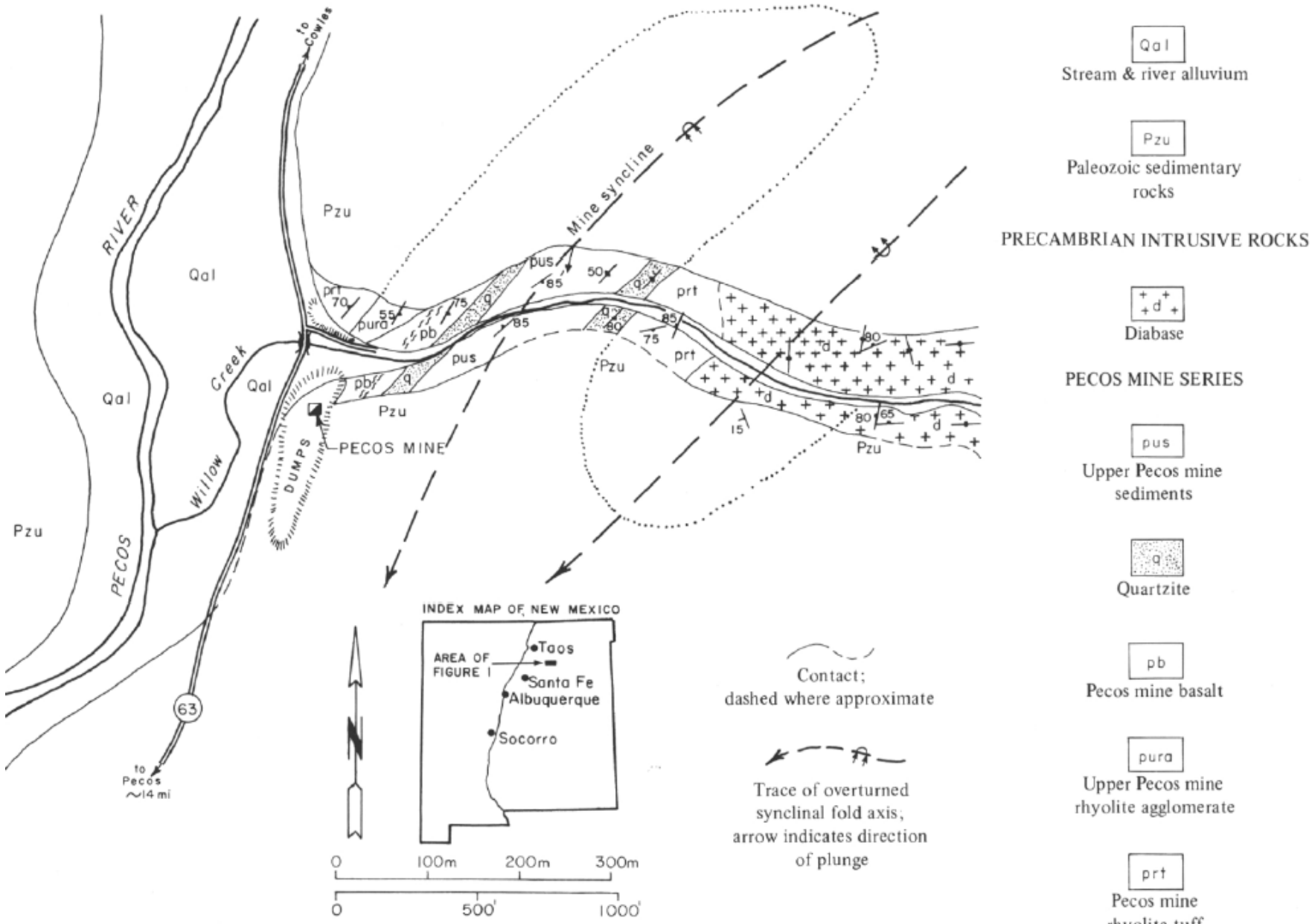


Figure 1. Geologic map of the Pecos mine area. Modified from Riesmeyer (1978).

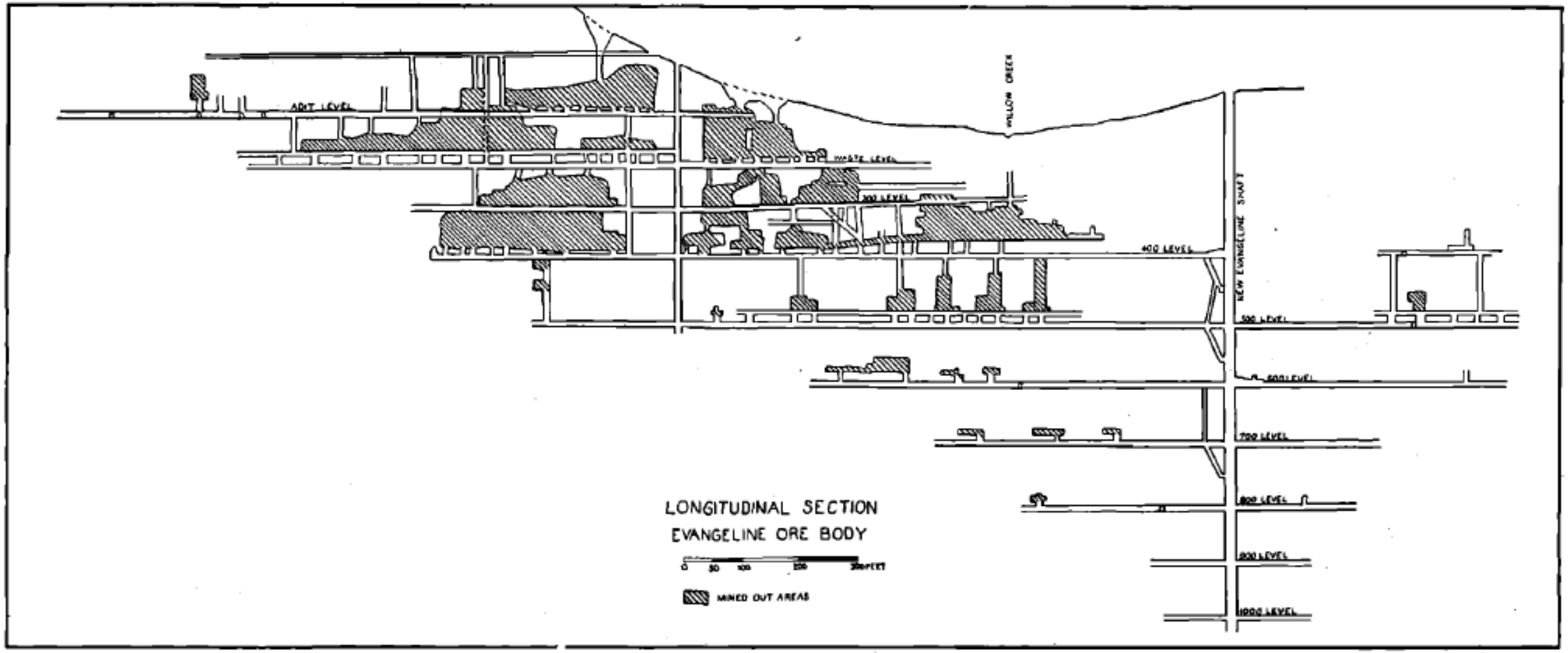
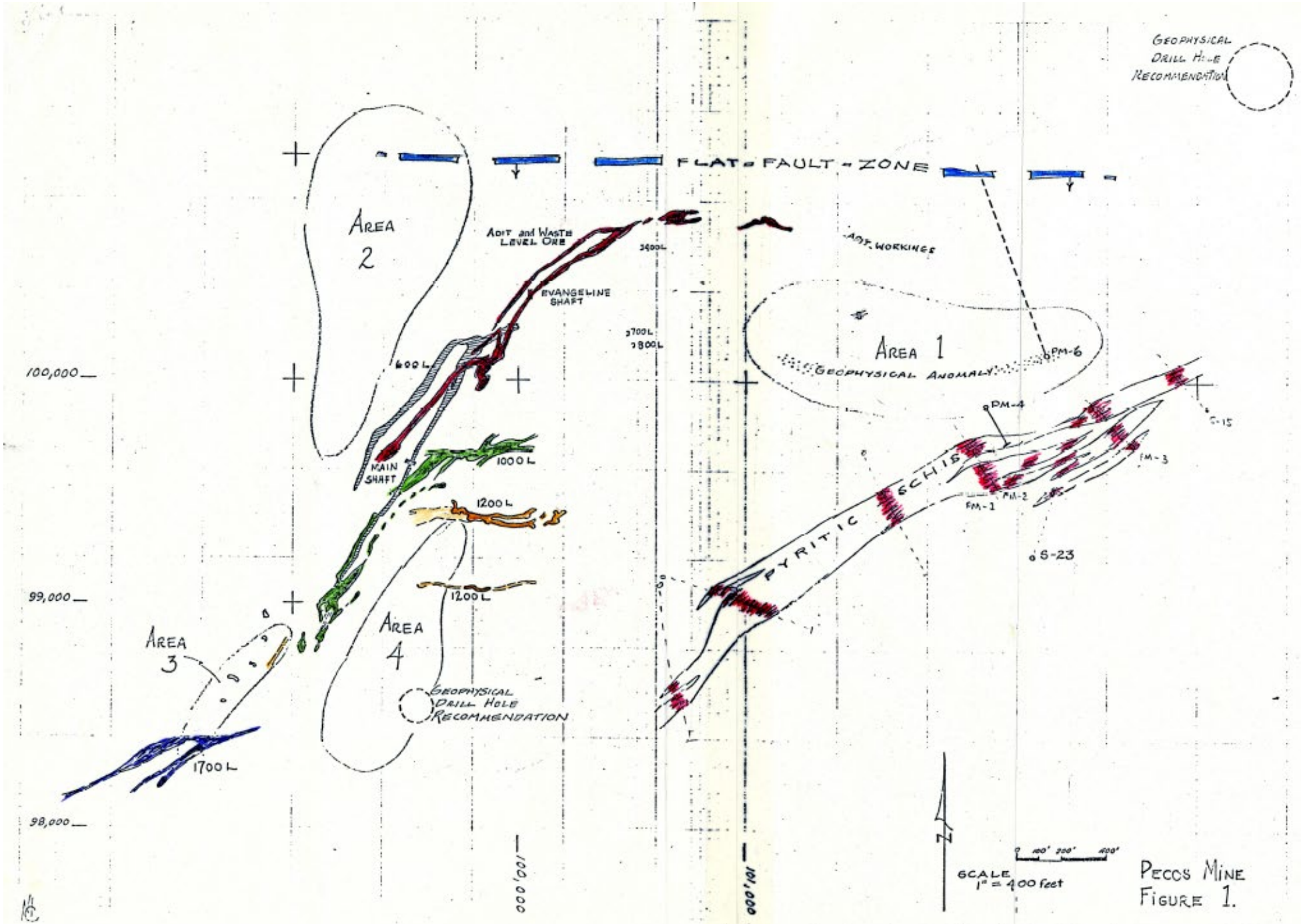


FIG. 10. Longitudinal section of the Evangeline ore body, showing the plunge toward the southwest.

Krieger, 1932



Area 1—continuation of Katydid ore body on north side of fault
Area 2—NW extension of Katydid ore body
Area 3—ore left in mine at 1350 and 1700 levels (mine flooded in 1938)
Area 4—geophysical anomaly

Colburn, unpub, 1975

Mine Site Contamination

- Waste rock from was deposited into Willow Creek and in to the Pecos River floodplain. Runoff from the mine site contained acidic metal-laden ARD, and suspended solids with elevated metals.

- Runoff from the mine site flowed into beaver-created wetlands, before emptying into the Pecos River.

- Under normal flow conditions, solids settling and microbial metal reduction in the beaver wetlands, greatly reduced the impact of mine runoff on the Pecos River.

- During high runoff, however, the ability of the beaver wetlands to attenuate contaminants was diminished, and higher levels of metals entered the Pecos River.

Dennis McQuillan

Mine Contamination—cont.

- Sediments panned from Willow Creek contained grains of sphalerite, galena, chalcopyrite, pyrite and other minerals associated with the mine site.
- Pecos River sediments downstream of the mine site contained elevated concentrations of metals.
- Elevated metals also were detected in benthic macroinvertebrates, fish tissue and in small mammals.
- The Pecos River and Lisboa Springs Fish Hatchery, 11 miles downstream of the mine, had a history of major fish kills that coincided with runoff events in the watershed.
- High levels of zinc and aluminum are believed to have been at least partly responsible for some of the fish kills.

Dennis McQuillan

Pecos ARD Seep

The white and brown precipitates and froths consist of iron, copper and zinc sulfates, and iron and aluminum oxides and hydroxides. From McLemore and Brandvold (2001).

Mill Site Contamination

- Mill tailings were deposited into two impoundments in Alamitos Creek.
- Lead concentrations in the tailings ranged from 2,800 to 13,000 ppm
- The tailings dams failed in 1973 resulting in tailings dispersal downstream in Alamitos Creek and most likely into the Pecos River.
- After dam failure, erosion of the tailings by Alamitos Creek provided an ongoing source of contamination into the watershed.
- Surface water contained cadmium, lead, iron and manganese in excess of state and federal standards.
- Stream sediments contained elevated iron, copper, lead and zinc.
- Groundwater in monitoring wells near the tailings piles contained sulfate, manganese and total dissolved solids in excess of state standards.

Dennis McQuillan

Mine Waste Used as Fill Fish Kill

- Up until the 1970s, waste had been removed from the mine and mill sites and used as fill material for roads, campgrounds, camping pads, a trailhead, and at the Lisboa Springs Fish Hatchery.
- Spring runoff in 1991 caused a massive fish kill. More than 90,000 trout died at the hatchery, alone.
- The fish kill brought attention to contamination from the mine and mill.

Dennis McQuillan

1992 AOC

The Administrative Order on Consent (AOC) was signed on December 2, 1992 by:

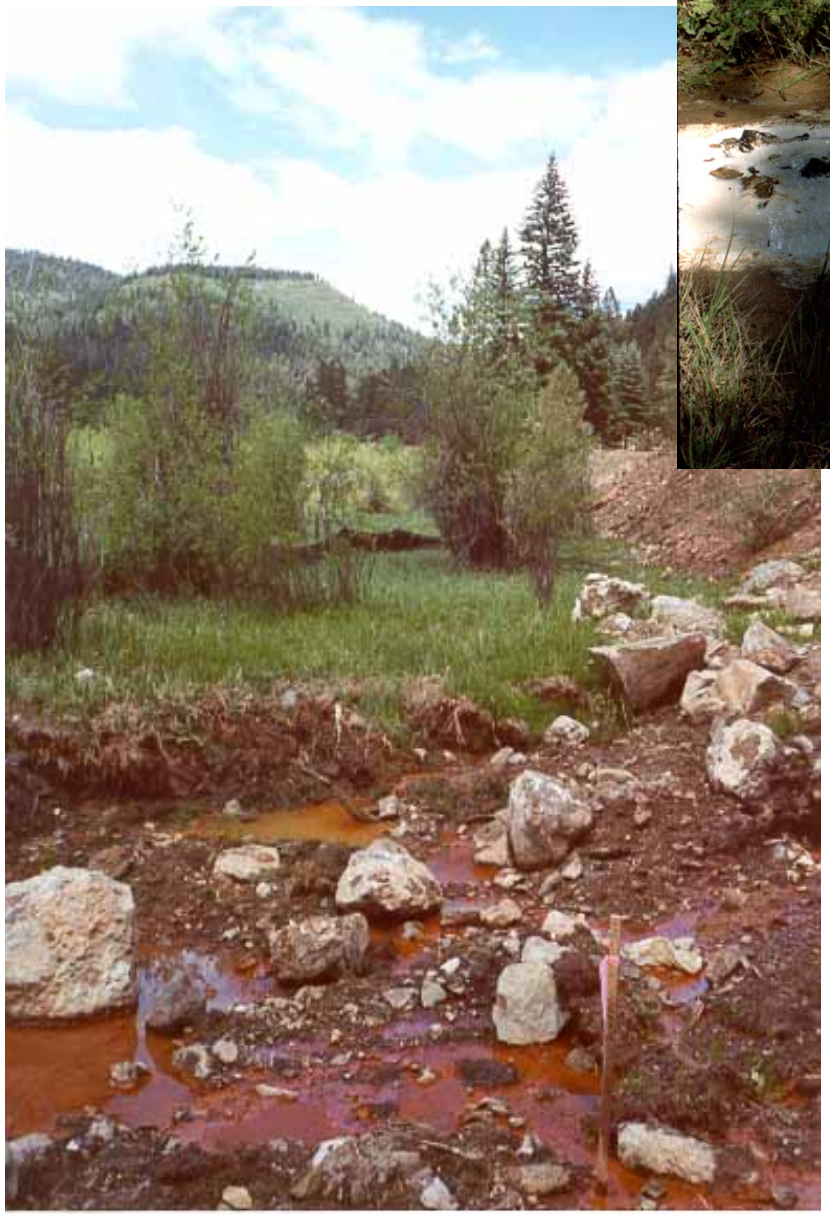
- NMED
- N.M. Natural Resource Damage Trustee
- N.M. Department of Game and Fish
- N.M. Highway and Transportation Department, and by
- AMAX Resource Conservation Company.

The AOC included a Cost Sharing Agreement where AMAX was responsible for 80% of the total cost of investigation, remediation and natural resource damages for the mine and mill, and the State of N.M. was responsible for 20%.

The U.S. Forest Service was not a party to the AOC, but allocated $1.2 million to remove or cap mine waste that had been used as fill at roads and campgrounds.

Willow Creek Acid Rock Drainage next to Pecos mine

Before Cleanup



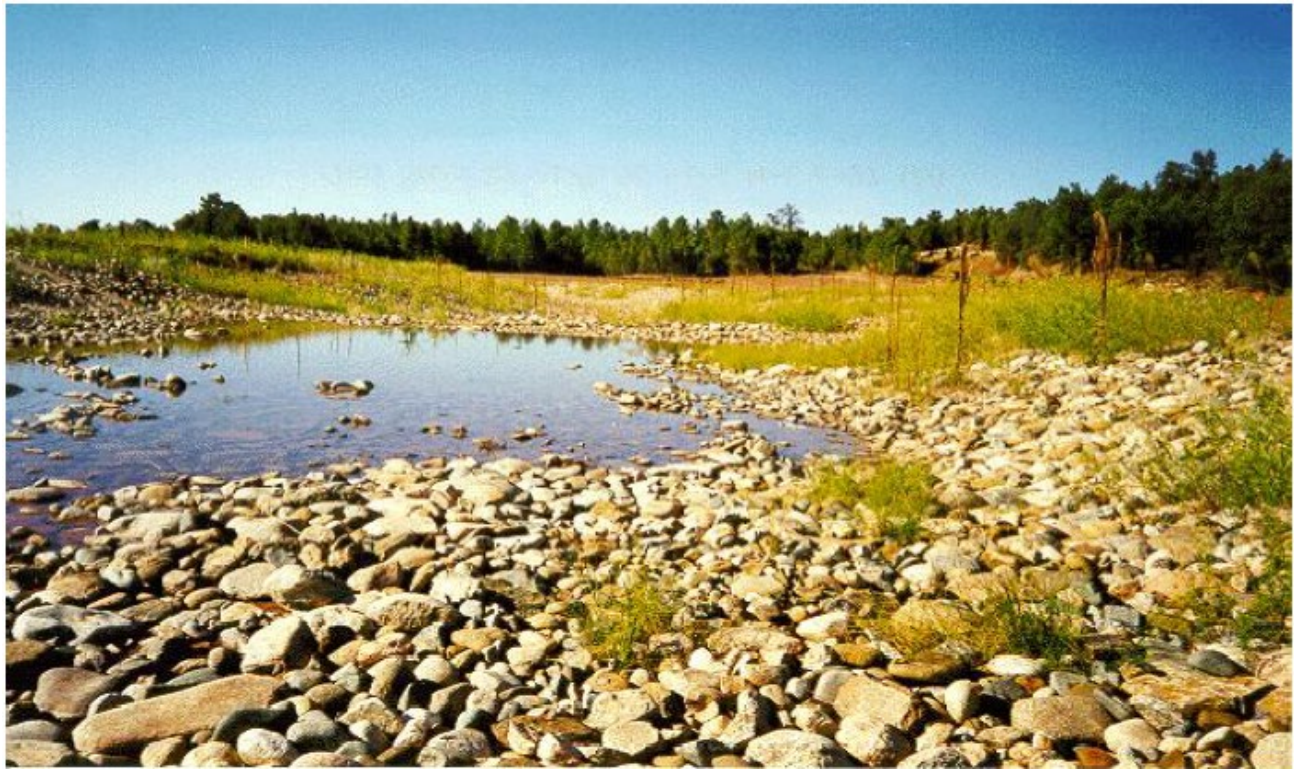
Pecos Mine Waste Piles Before and After Cleanup

A lead cleanup target of 500 mg/Kg (parts per million) was used.

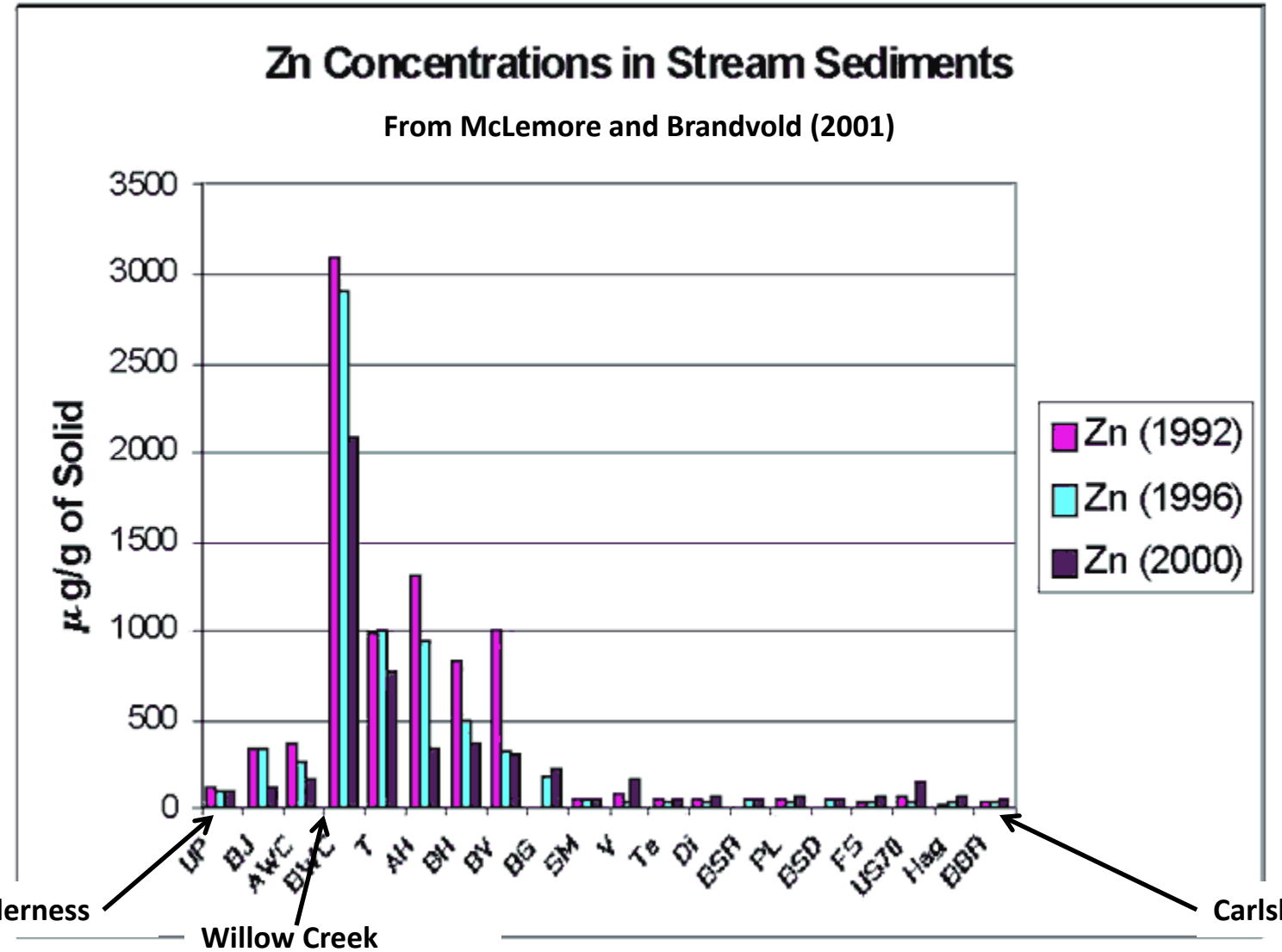
Dennis McQuillan

Dennis McQuillan

El Molino Mill Tailings Before and After Cleanup



Zinc Attenuation in Pecos River Stream Sediment after

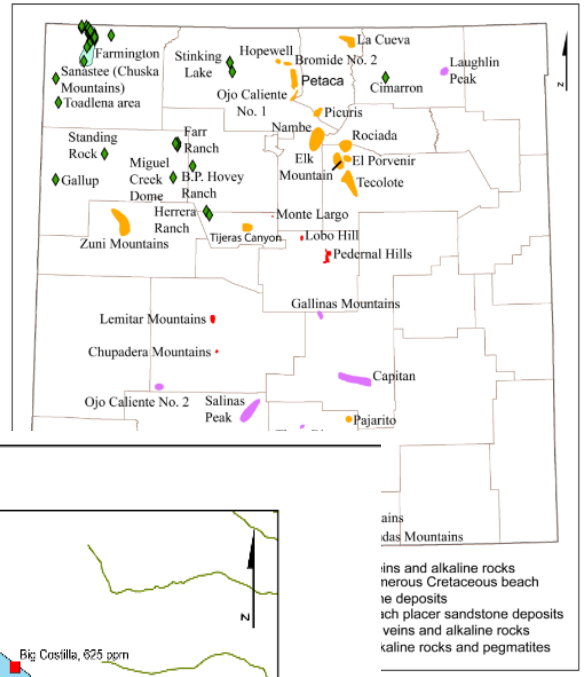


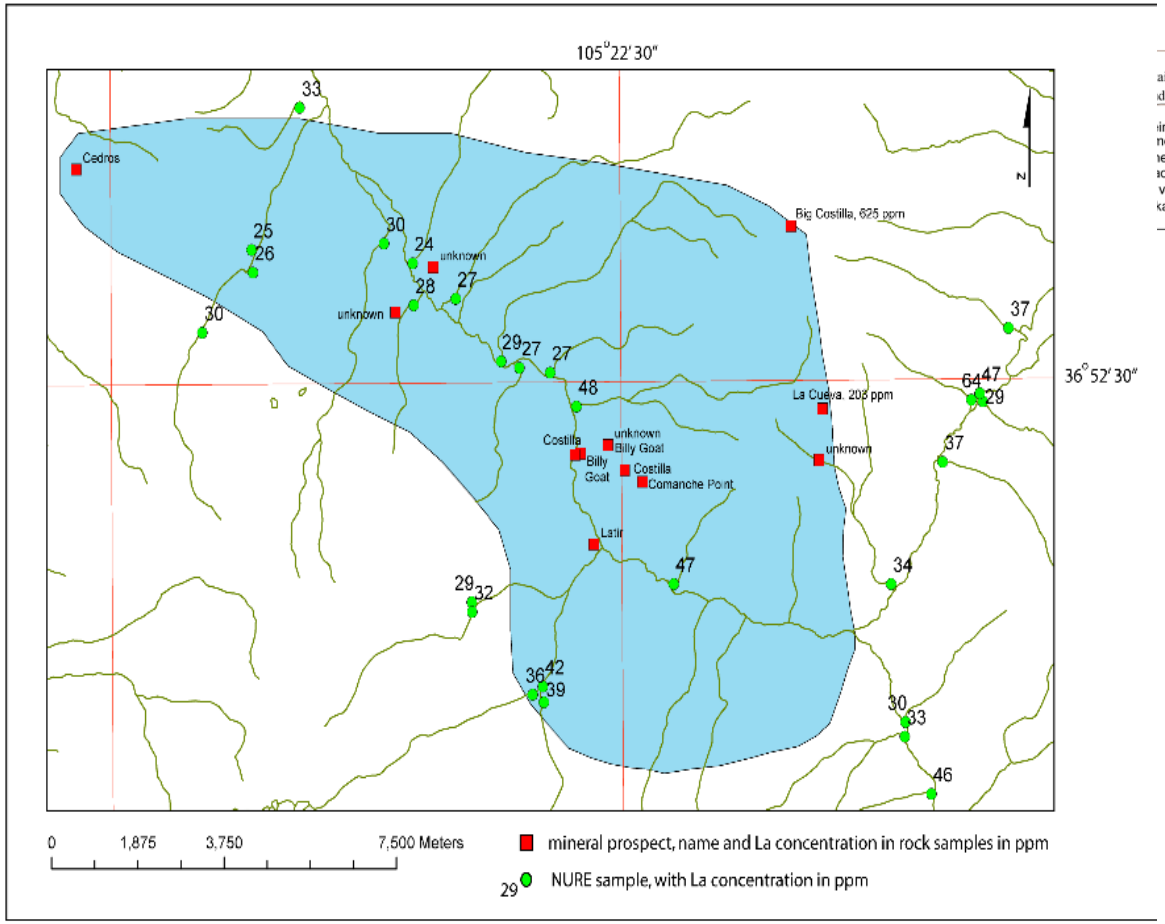
VEIN AND REPLACEMENT DEPOSITS IN PROTEROZOIC ROCKS

OTHER DEPOSITS IN PRECAMBRIAN ROCKS

Costilla massif, La Cueva district, Taos County

- Radioactive pegmatites intrude the granite and both intrude a complex Proterozoic metamorphic terrain of metamorphic and igneous rocks
- The granitic rocks are subalkaline, metaluminous to peraluminous.
- 1560 ppm Ce and 625 ppm La, potential for U, Th





Mineralogy of Costilla massif (Zelenka, 1984)

- Uraninite UO_2 (with Ce)
- Thorite $ThSiO_4$ (with Ce)
- Uranothorite $(Th,U)SiO_4$
- Magnetite Fe_3O_4 (with U, Th)
- Zircon $ZrSiO4$ (with U, REE)
- Allanite $(Ce,Ca,Y)_2(Al,Fe^{+++})_3(SiO_4)_3(OH)$
- Apatite $Ca_5(PO_4)_3(OH,F,Cl)$ (with U, Th)
- Titanite $CaTiSiO_5$ (with U, Th)
- Thorogummite $Th(SiO_4)_{1-x}(OH)_{4x}$
- Uranophane $Ca(UO_2)_2SiO_3(OH)_2•5(H_2O)$

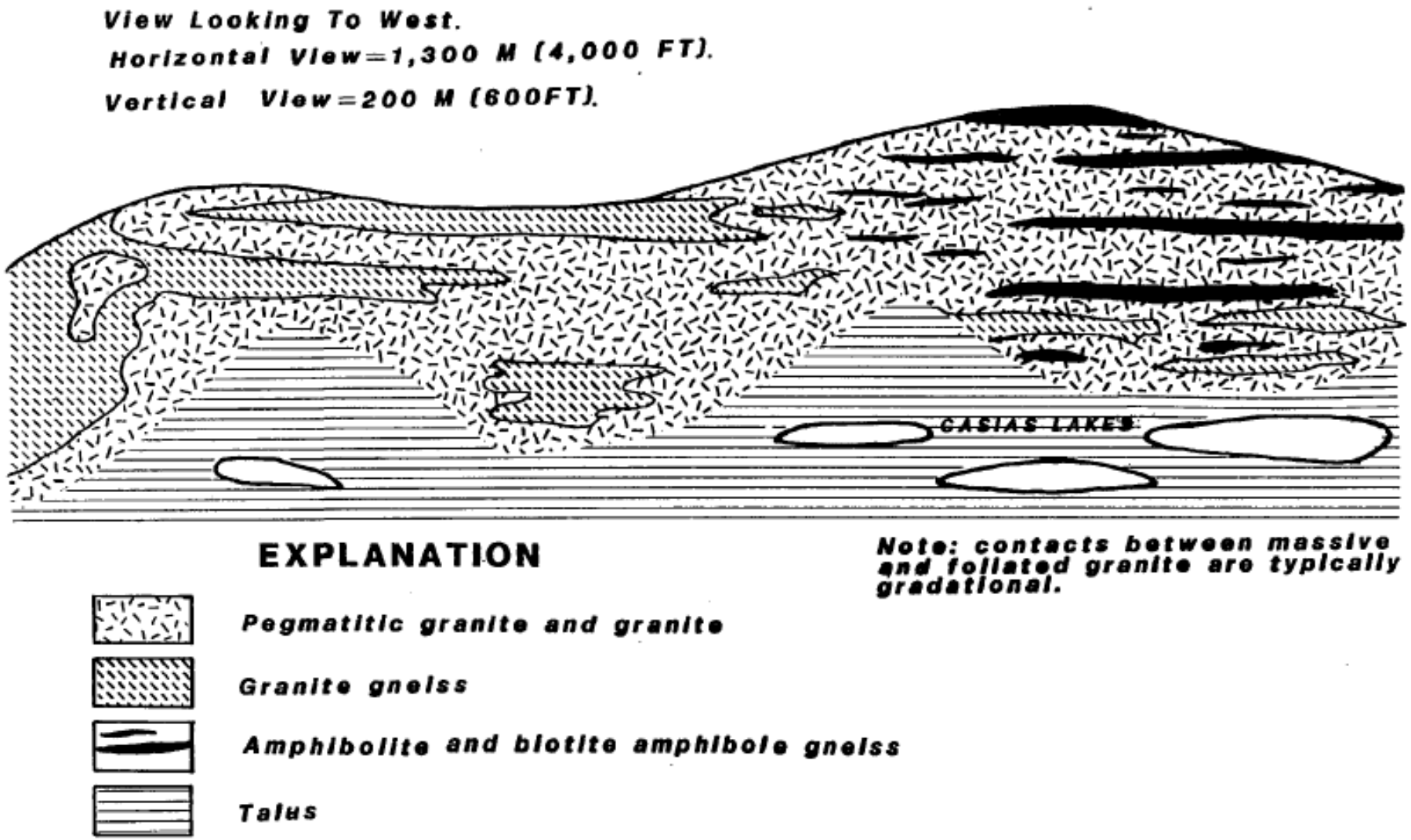


Figure 4. Sketch map of relations observed in outer cupola of Costilla massif, looking west towards ridge line south of Big Costilla Peak. Amphibolite, and biotite-amphibole gneiss represent roof pendants intruded by the granite massif.

Zelenka, 1984

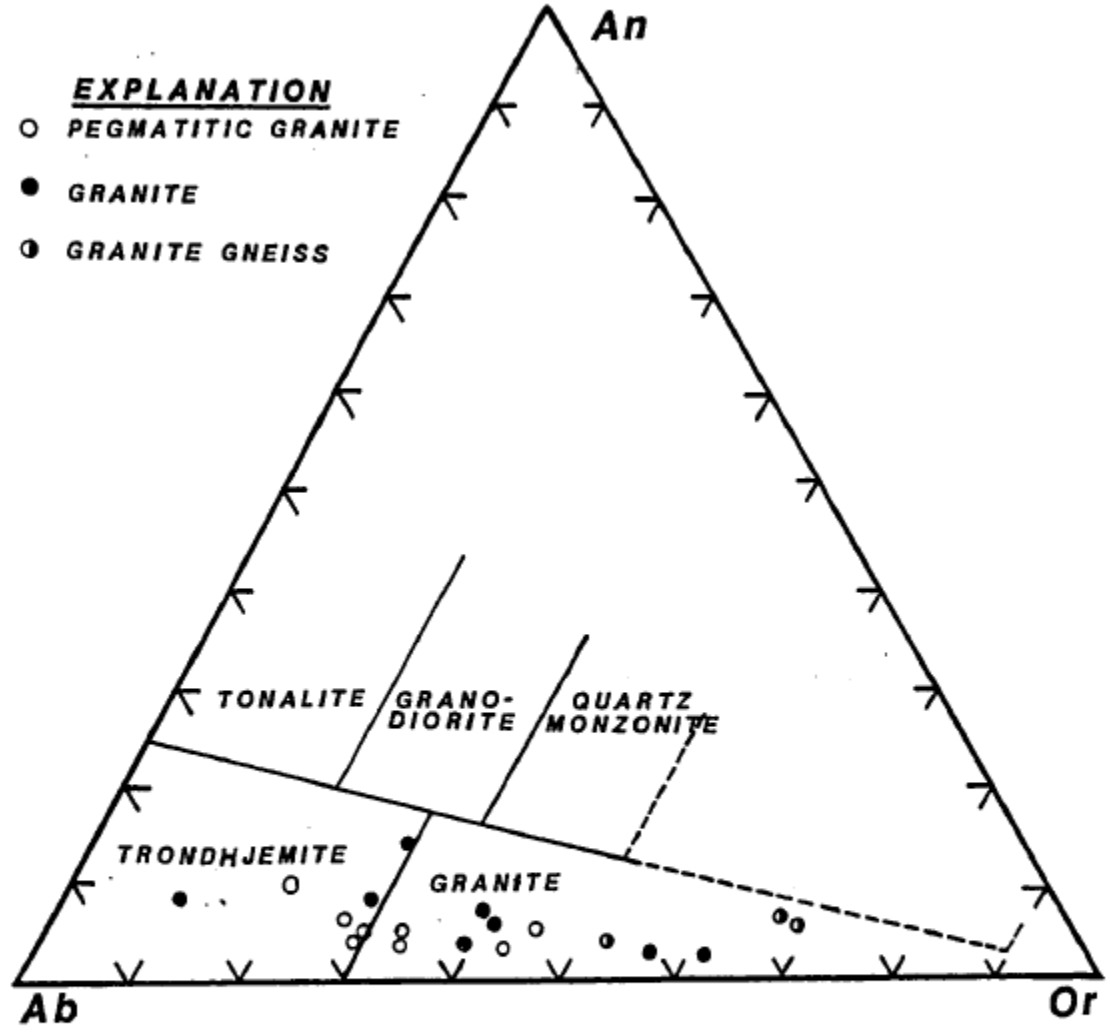
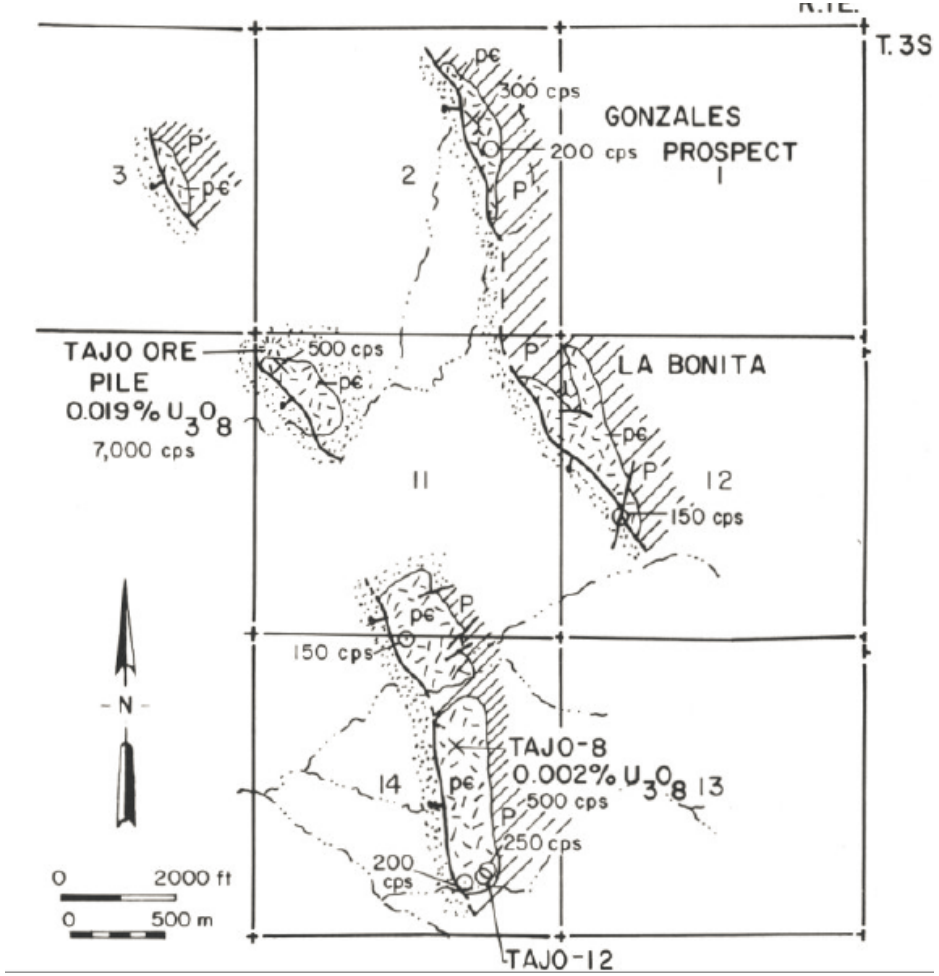
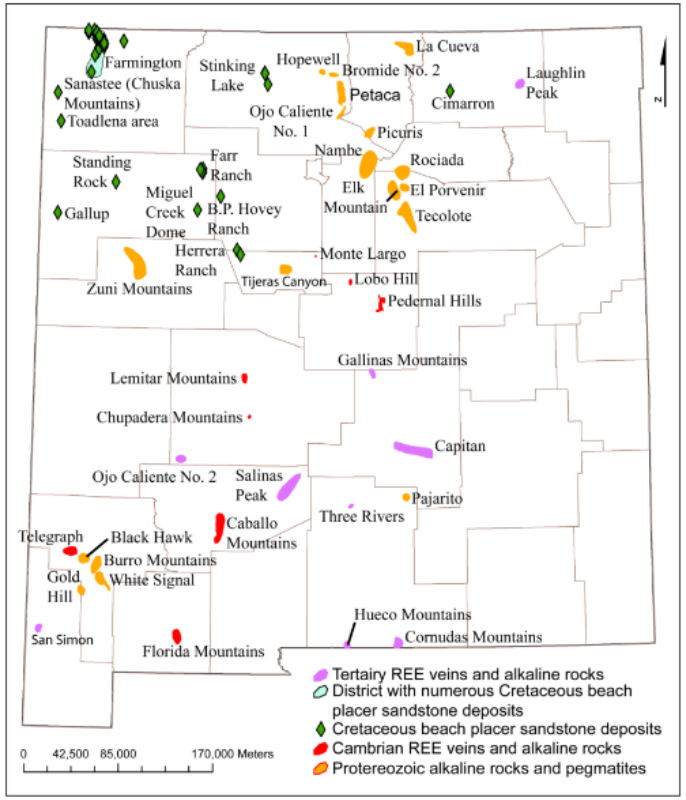


Figure 5. Normative granitic rock classification (O'Connor, 1965), showing distribution of typical granitoids from study area.

Tajo Granite, Chupadero district, Socorro County

- Mineralogy
  - Hematite
  - Fluorite
  - Uranophane?
- Chemistry
  - 0.4350% U_3O_8
  - <1200 ppm Y
  - Total REE 281 ppm





Tajo Granite

Copper Hill Cu-Ag-Sb deposit, Picuris district, Taos County

Copper Hill Cu-Ag-Sb deposit, Picuris district, Taos County

- Contact between orthoquartzite (Ortega Fm) and Ribconada Formation schists
- Fracture controlled, quartz veins along north-striking faults in the Ortega end at the contact
- At the contact veins merge to mushroom-shaped deposits

Minerals

- Chalcocite
- Chlorite
- Chrysocolla
- Covellte
- Cuprite
- Cupromeite
- Hematite
- Stibiconite
- Tetrahedrite
- Tourmaline
- Volborthite
- Acanthite
- Andalusiite
- Wolframite

Volborthite, etc.

Copper Hill deposits, Picuris District, Taos Co., New Mexico, USA

https://www.mindat.org/loc-50467.html

Retrograde metamorphic mineralization in a brittle-ductile trap (Williams and Fulp, 1995)

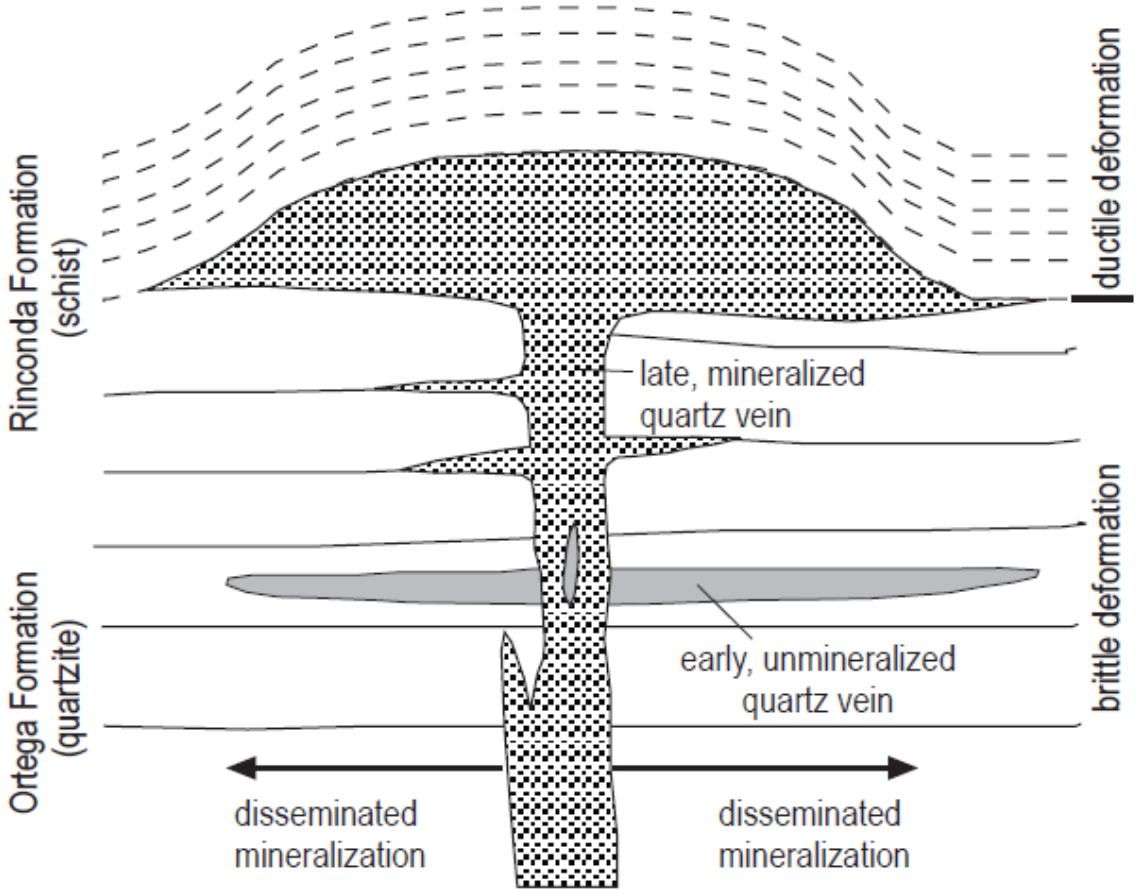
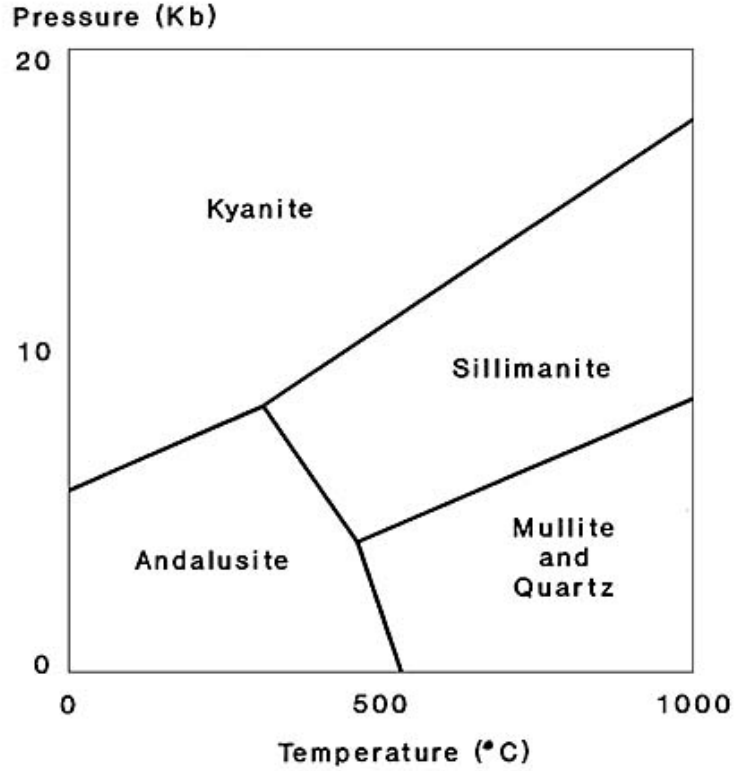


Figure 7. Schematic model of retrograde mineralization in the Copper Hill deposit (NMTA0014), Picuris district (simplified from Williams and Bauer, 1995). Early, unmineralized quartz veins were emplaced during regional retrograde metamorphism of the Ortega Group. Cu-Sb-Ag-quartz veins were emplaced after early quartz veins emplacement, but before the final recrystallization of the Ortega quartzite and late quartz veins.

Kyanite

- conversion to mullite ($Al_6Si_2O_{13}$) and SiO_2 at 1400-1500 deg C, expands irreversibly by up to 18%, thereby offsetting the firing shrinkage of other raw materials, especially clay, in ceramic bodies and refractories
- 1 metric ton (t) of aluminosilicate concentrate yields approx 0.88 t of mullite
- Refractories, 90% (high melting points)
  - iron and steelmaking
  - manufacture of chemicals, glass, nonferrous metals, and other materials
- 10% in other uses
  - Dimension stone

Fig. 2. Mineral phases within the Al2P3 ¥ SiO2.



Anon., 1985.

Kyanite

- Approximately 1500 short tons of kyanite ore were produced from the Big Rock mine (NMRA0177), Petaca district in 1925-1928 by P.S. Hoyt
- quartz-kyanite pods has been attributed to weathering (i.e., paleosol), hydrothermal Al-Si alteration (Barker, 1958), metamorphic differentiation of siltstone (Corey, 1960), or metasomatism along shear zones
- Geochemical, oxygen isotopic, and metamorphic petrographic evidence presented by Simmons (1999) and Simmons and Larson (2001) support a hydrothermal alteration that was subsequently sheared and metamorphosed
- remaining kyanite resources are low in grade and tonnage, no potential

ANORTHOSITES AND RICOLITE, RICOLITE DISTRICT

Anorthosites

- Anorthosite—monomineralic plutonic rock consisting of plagioclase feldspa
  - Gabbroic anorthosite contains 1-22% dark minerals, 78-90% plagioclase
- Economically anorthosites account fo much of the world's production of titanium with by-product vanadium and iron
  - Also dimension stone
- Found in the Ricolite district, near Redrock, Burro Mountains
- No economic potential

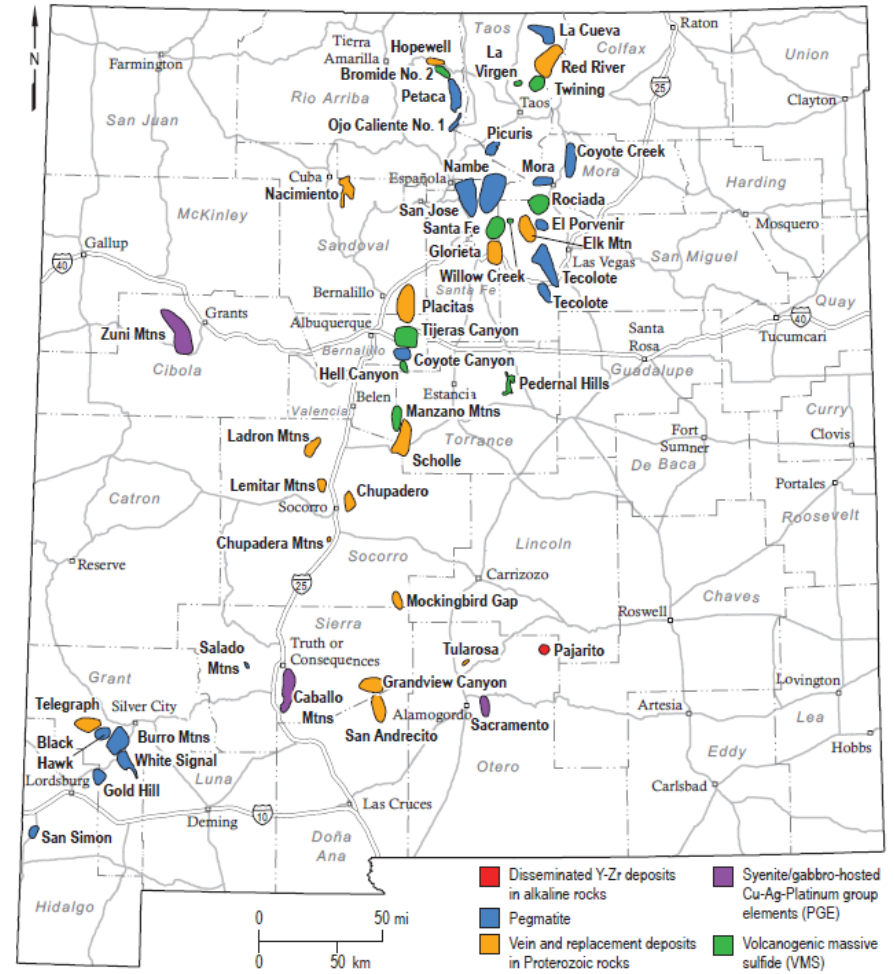
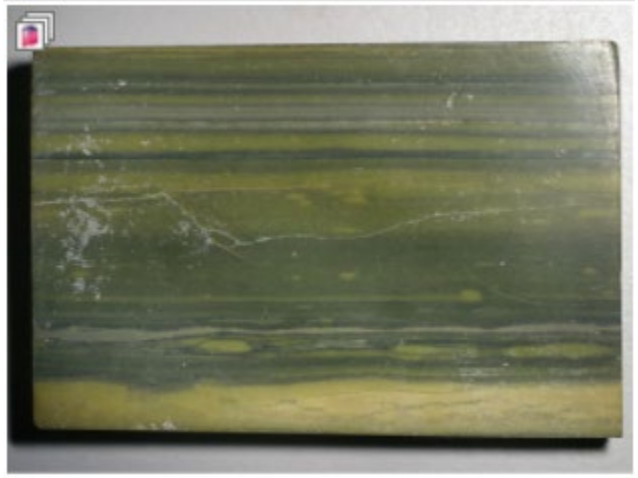


Figure 4. Proterozoic age mineral deposits in New Mexico. Some districts contain more than one type of deposit. Iron formation deposits are found in two districts, Hopewell and Bromide No. 2, in northern New Mexico.

Ricolite veins

- Nonfibrous ricolite (a form of banded talc serpentine) has been produced from the district for carving, decorative, and dimension stone
- Contact metamorphic adjacent to the Redrock Granite
- Various shades of yellow and green produced by alternating bands of talc and serpentine with flakes of chlorite, fracture fillings of calcite and quartz, and cross-fiber veins of the asbestiform serpentine, chrysotile
- 1878 shipped to Chicago
- New Mexico Ricolite Co. in 1945-1946
- Mineral collecting only
- Redrock Wildlife Refuge and withdrawn from mineral entry



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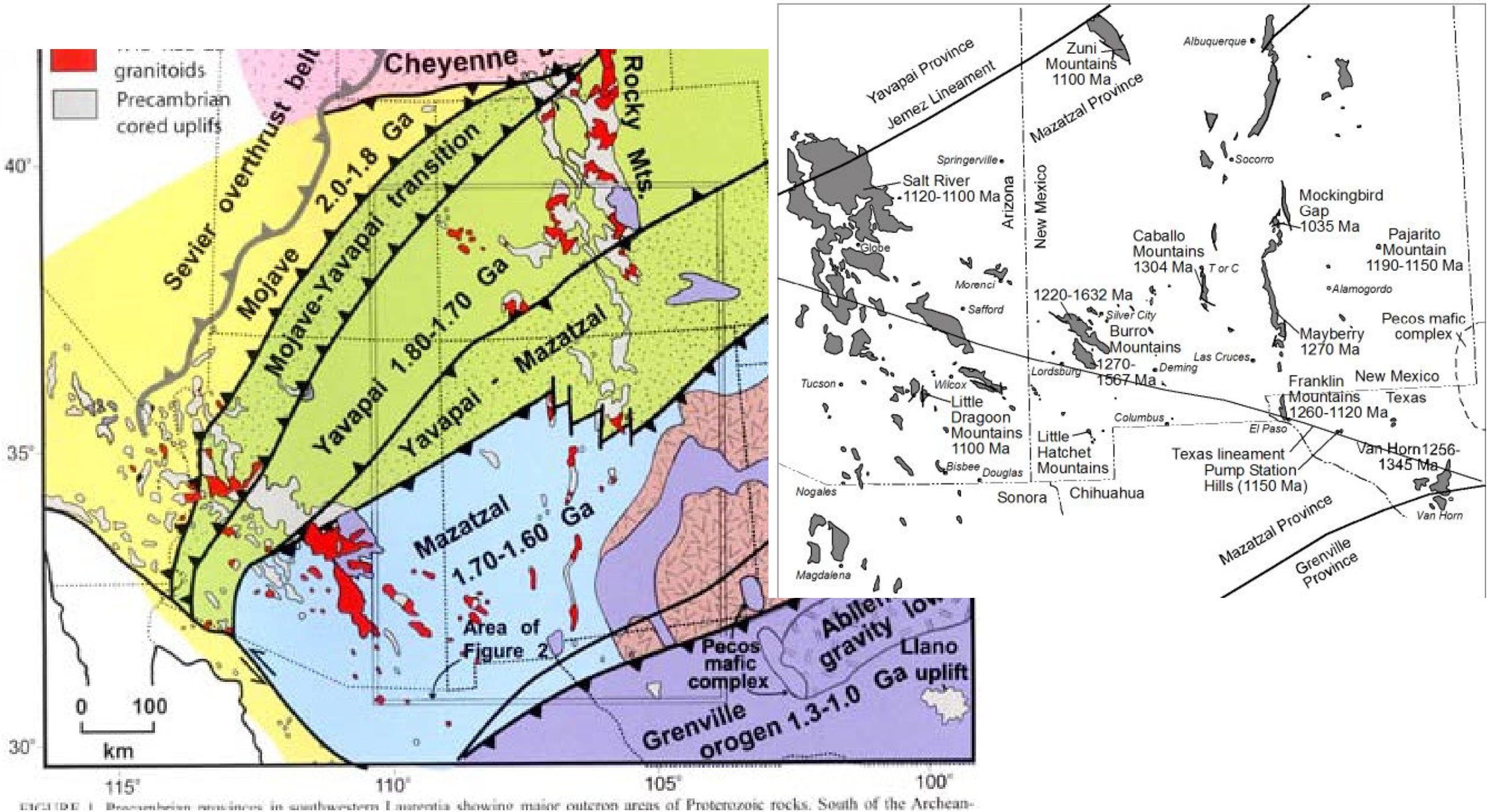
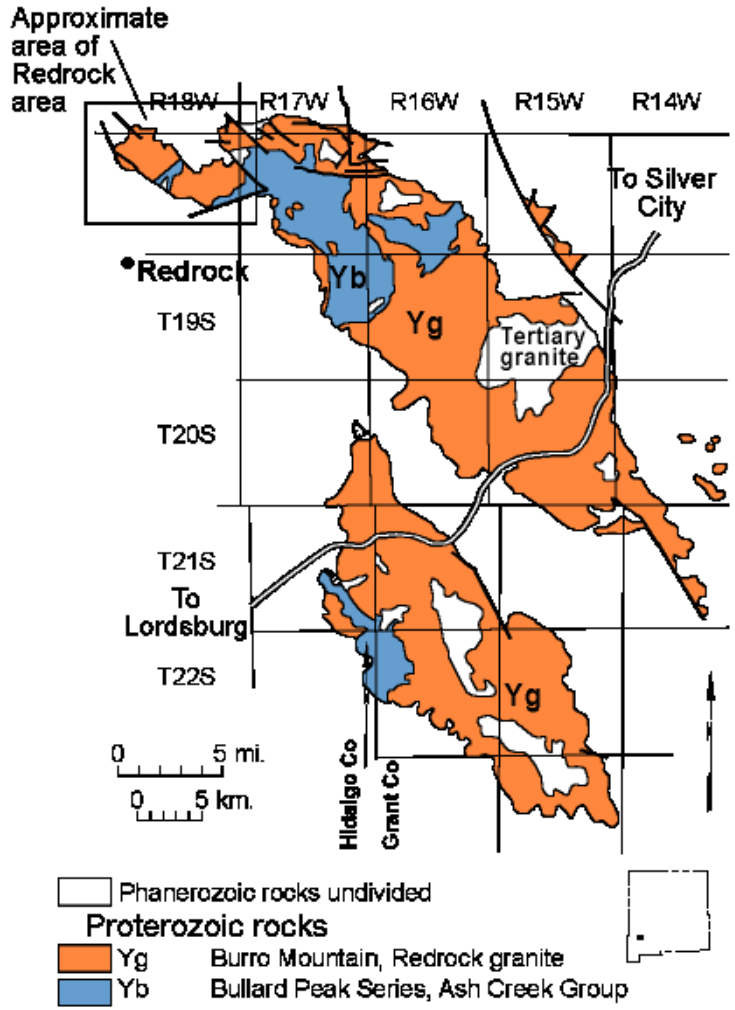


FIGURE 1. Precambrian provinces in southwestern Laurentia showing major outcrop areas of Proterozoic rocks. South of the Archean-

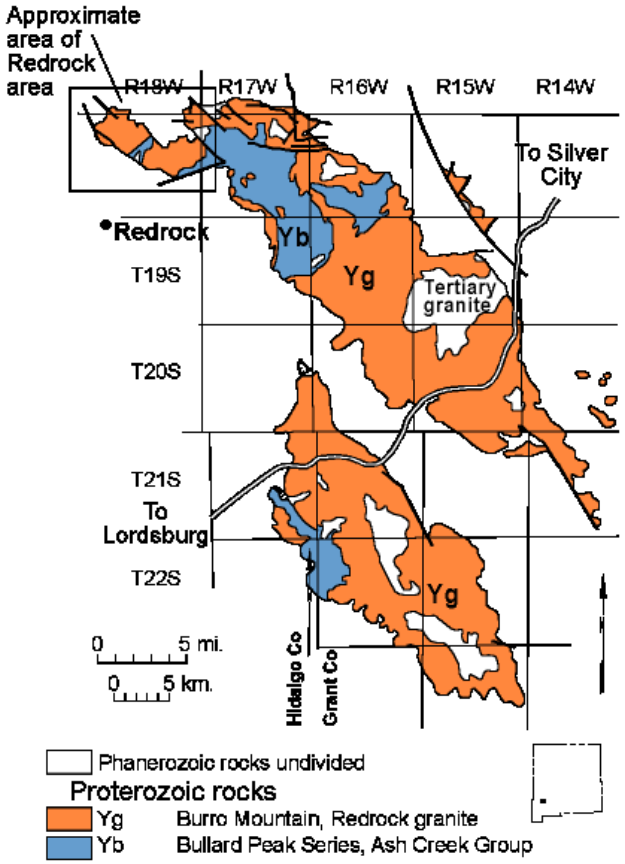
Importance of the Redrock Area of the Burro Mountains

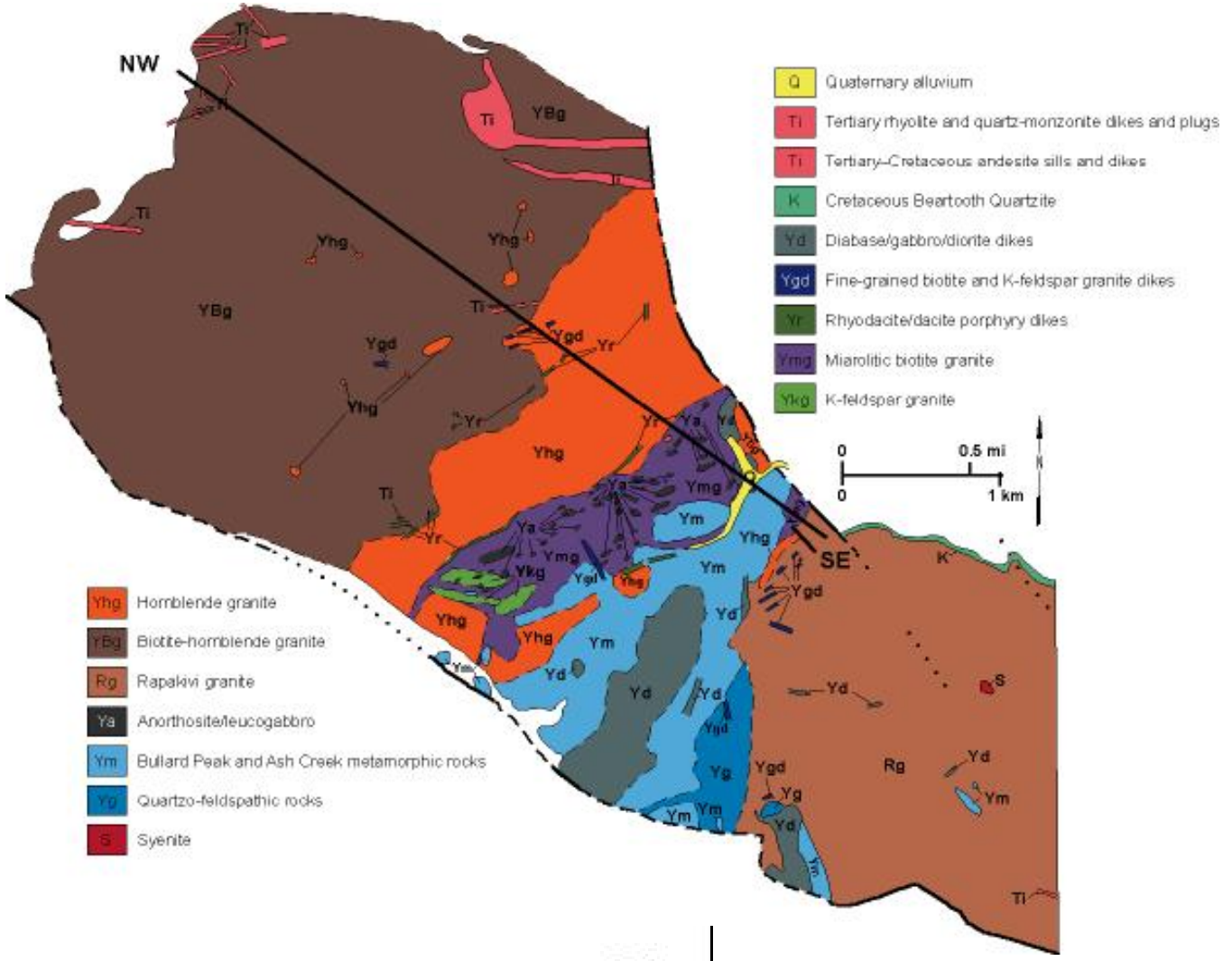


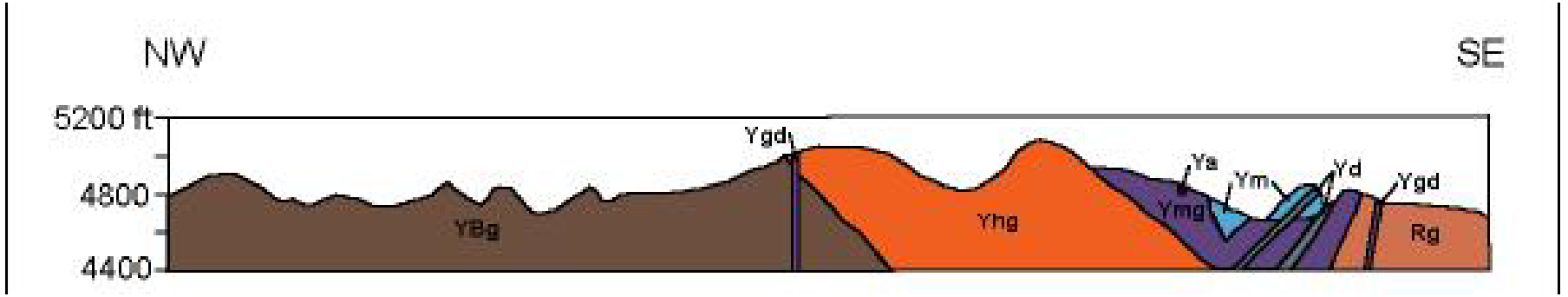
- Three distinct mid-Proterozoic magmatic events (at 1633 Ma, 1460 Ma, and 1220 Ma).
- Association of anorthosites and A-type granites.
- Association of co-mingled rapakivi granite and minette, which is rare in the world.

Proterozoic Stratigraphy

- Dikes (granitic 1200-1220 Ma, gabbro 1000-1100?, rhyodacite-dacite porphyry?, pegmatite?)
- Redrock Granite (1220 Ma)
  - Ricolite veins
- Anorthosite/leucogabbro (1225 Ma)
- Jack Creek Rapakivi Granite (1465 Ma)
- Minette (1465 Ma)
- Gneissic granite/granodiorite (1440-1450 Ma)
- Burro Mountain granite (1440-1460 Ma?)
- Diabase/diorite/gabbro (1633 Ma)
- Bullard Peak and Ash Creek Metamorphic rocks, including granitic rocks (>1633 Ma, 1550-1570 Ma)


Approximate area of Redrock area
R18W
R17W
R16W
R15W
R14W
To Silver City
Redrock
Yb
Yg
Tertiary granite
T19S
T20S
T21S
To Lordsburg
T22S
Yg
0 5 mi.
0 5 km.
Hidalgo Co
Grant Co
Phanerozoic rocks undivided
Proterozoic rocks
Yg Burro Mountain, Redrock granite
Yb Bullard Peak Series, Ash Creek Group


NW
SE
Ti
YBg
Yhg
Ygd
Yr
Ymg
Ya
Ym
Yd
Ykg
K
S
Rg
Yg
0 0.5 mi
0 1 km
Q Quaternary alluvium
Ti Tertiary rhyolite and quartz-monzonite dikes and plugs
Ti Tertiary–Cretaceous andesite sills and dikes
K Cretaceous Beartooth Quartzite
Yd Diabase/gabbro/diorite dikes
Ygd Fine-grained biotite and K-feldspar granite dikes
Yr Rhyodacite/dacite porphyry dikes
Ymg Miarolitic biotite granite
Ykg K-feldspar granite
Yhg Hornblende granite
YBg Biotite-hornblende granite
Rg Rapakivi granite
Ya Anorthosite/leucogabbro
Ym Bullard Peak and Ash Creek metamorphic rocks
Yg Quartzo-feldspathic rocks
S Syenite


NW
SE
5200 ft
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YBg
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Ya
Ym
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Yd
Ygd
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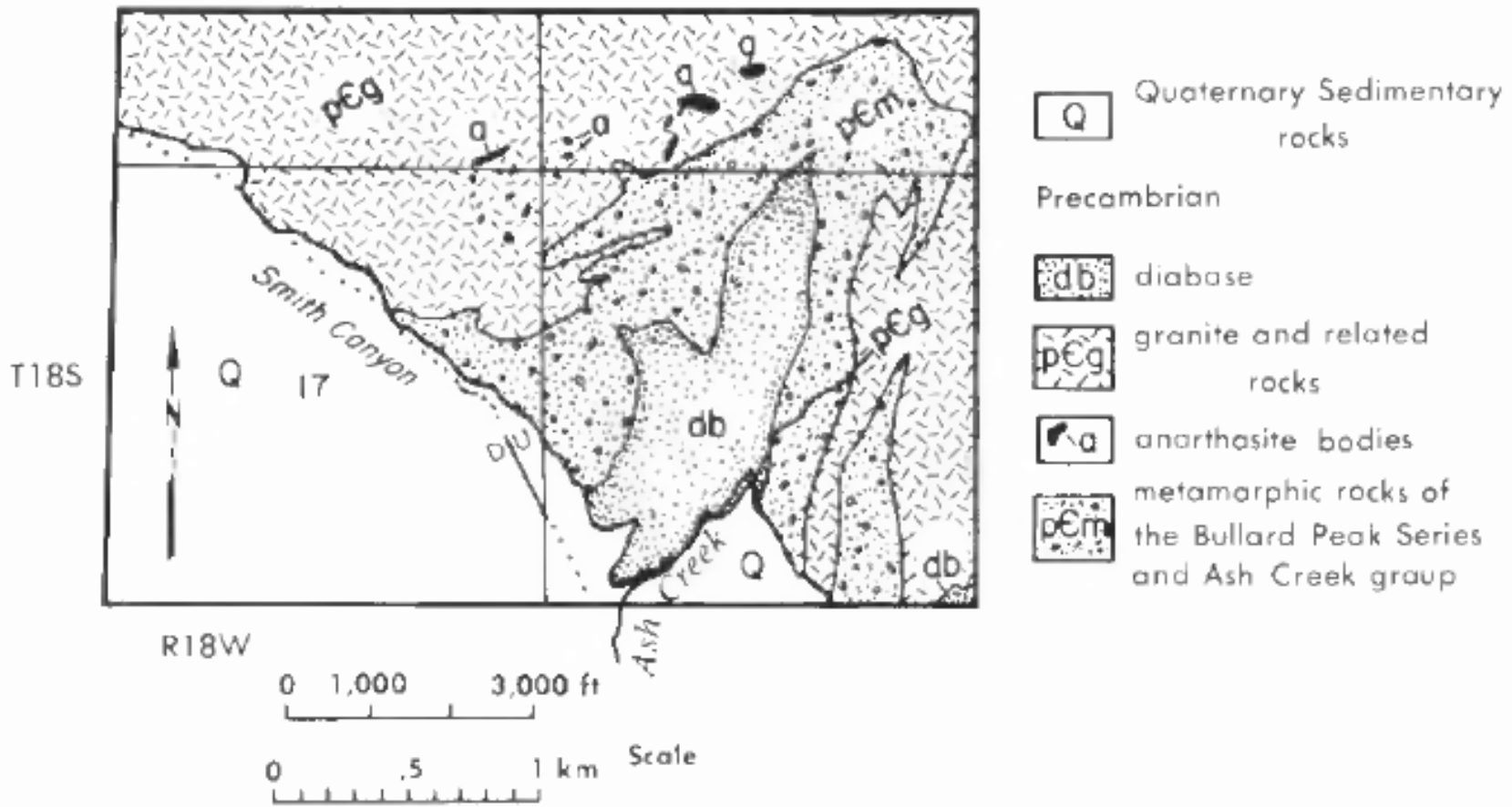
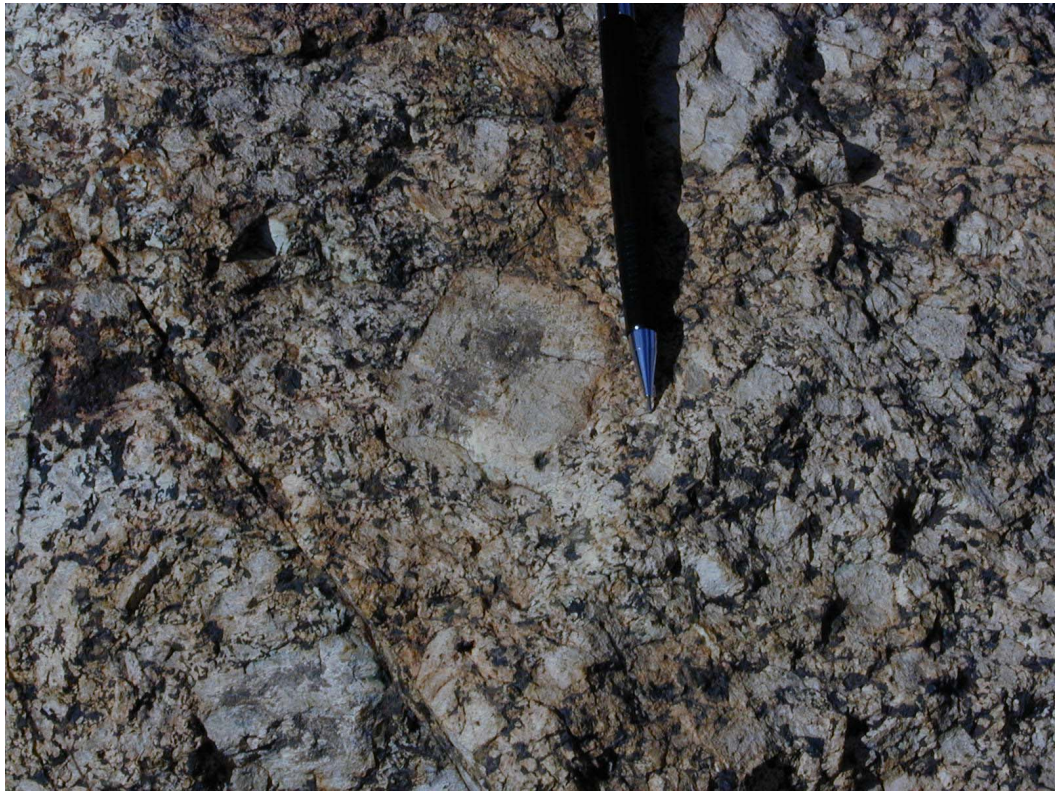
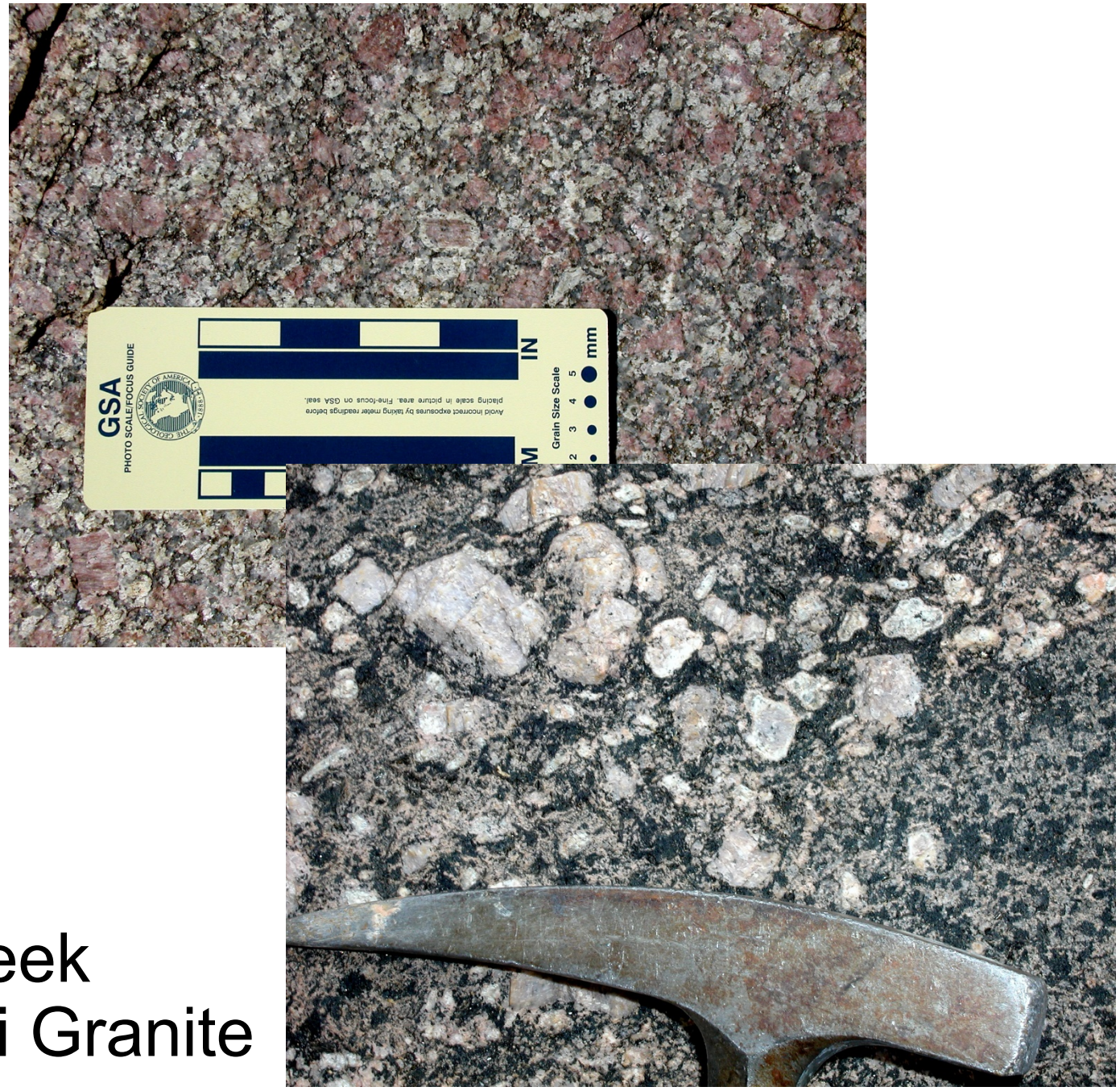


FIGURE 2. Generalized geologic map of the Ash Creek area (secs. 8, 9, 16 and 17, T18S, R18W) near Redrock; from Hewitt (1959), Hedlund (1980) and field reconnaissance by the authors. Aplite dikes are common in the granitic terrain but are not shown.





Photograph of anorthosite in Ash Creek

Jack Creek Rapakivi Granite

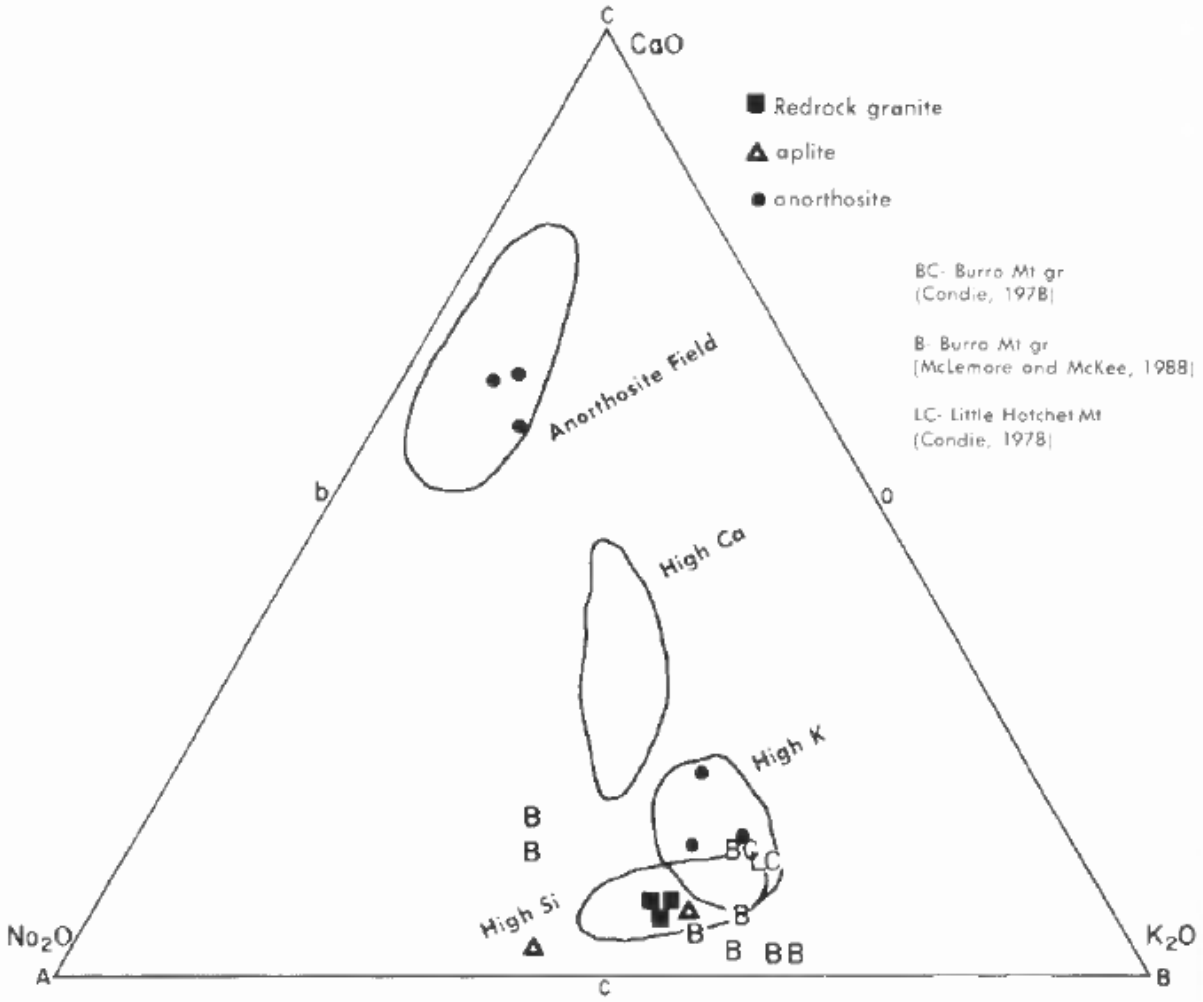
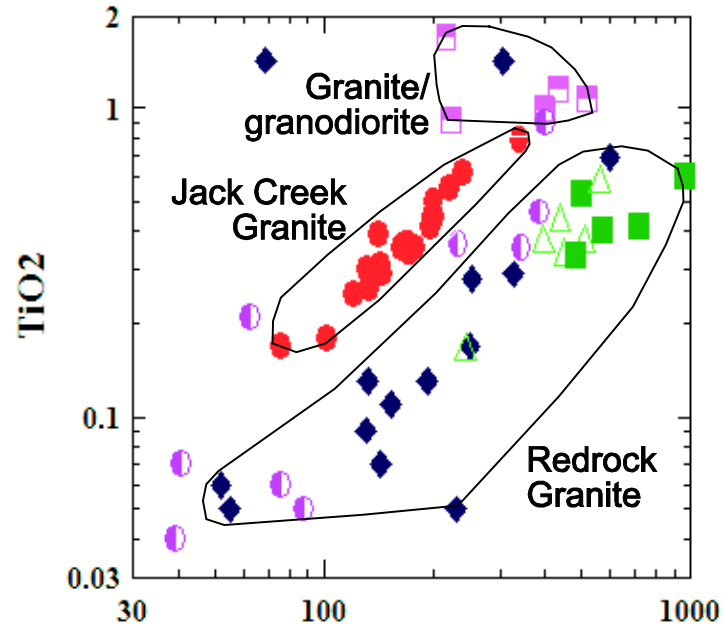
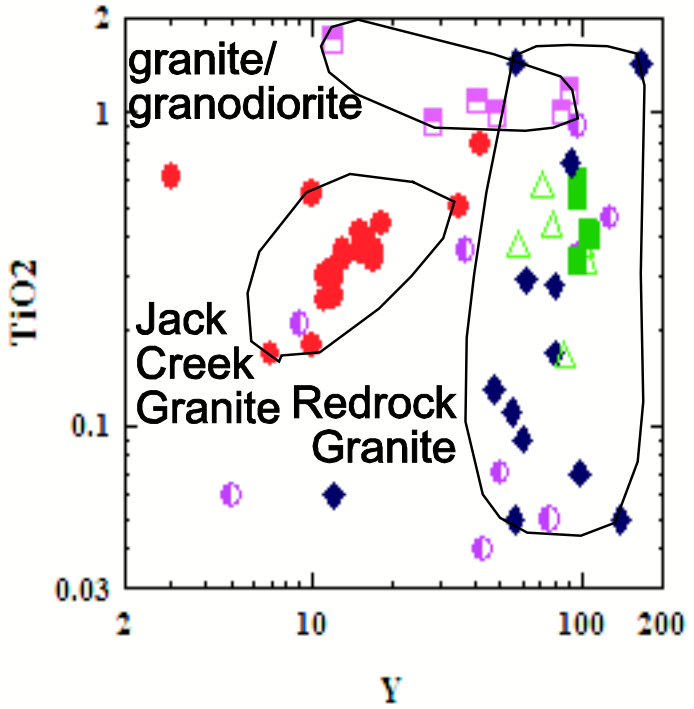
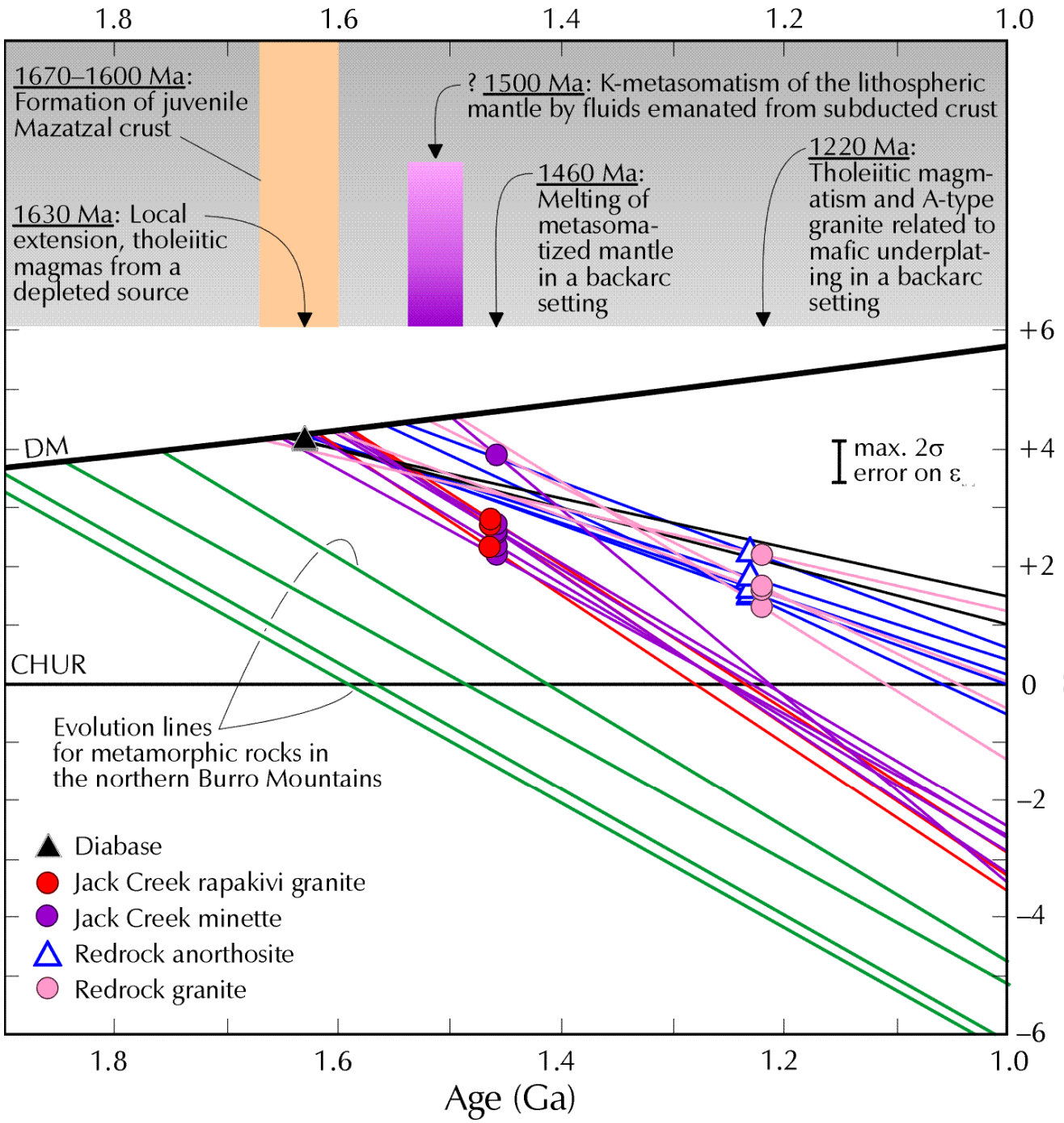


FIGURE 3. CaO-Na_2O-K_2O diagram of granites, aplites and anorthosites from







- Nd isotopic data imply an overall juvenile craton margin and presence of a light-REE-depleted mantle
- Three distinct isotopically mid-Proterozoic magmatic events (at 1633 Ma, 1460 Ma, and 1220 Ma), although more isotopic age determinations are required
- Origin of these granites are related to source heterogeneity and post-accretionary mantle-crust interaction events
- The Jack Creek Rapakivi Granite and minette were presumably emplaced inboard of an extensional arc in response to mafic underplating associated with backarc extension.

SYENITE/GABBRO-HOSTED COPPER-SILVER-PLATINUM GROUP ELEMENTS

Platinum group elements—PGM or PGE

- platinum [Pt]
- palladium [Pl]
- osmium [Os]
- ruthenium [Ru]
- iridium [Ir]
- rhodium [Rh]

- conformable layers or lenses near the base of layered ultramafic and mafic complexes, thin stratiform layers within ultramafic and mafic intrusions, and irregular pipe-like bodies with ultramafic and mafic intrusions
- Archean rocks

Platinum group elements in NM

- No economic PGE deposits in NM
- 4 areas in NM where we find PGE
  - PGE-mineral in Proterozoic syenite and amphibolite bodies in a shear zone in Zuni Mountains
  - sample of Proterozoic age gabbro from the Sacramento Mountains contained 1 ppb Pt and 66 ppb Pd
  - samples of Proterozoic age gabbro from the Caballo Mountains contained 1-3 ppb Pt and 1-2 ppb Pd
  - By-product of porphyry copper deposits—from the smelter anode slimes
- Possibly in VMS/greenstone belts

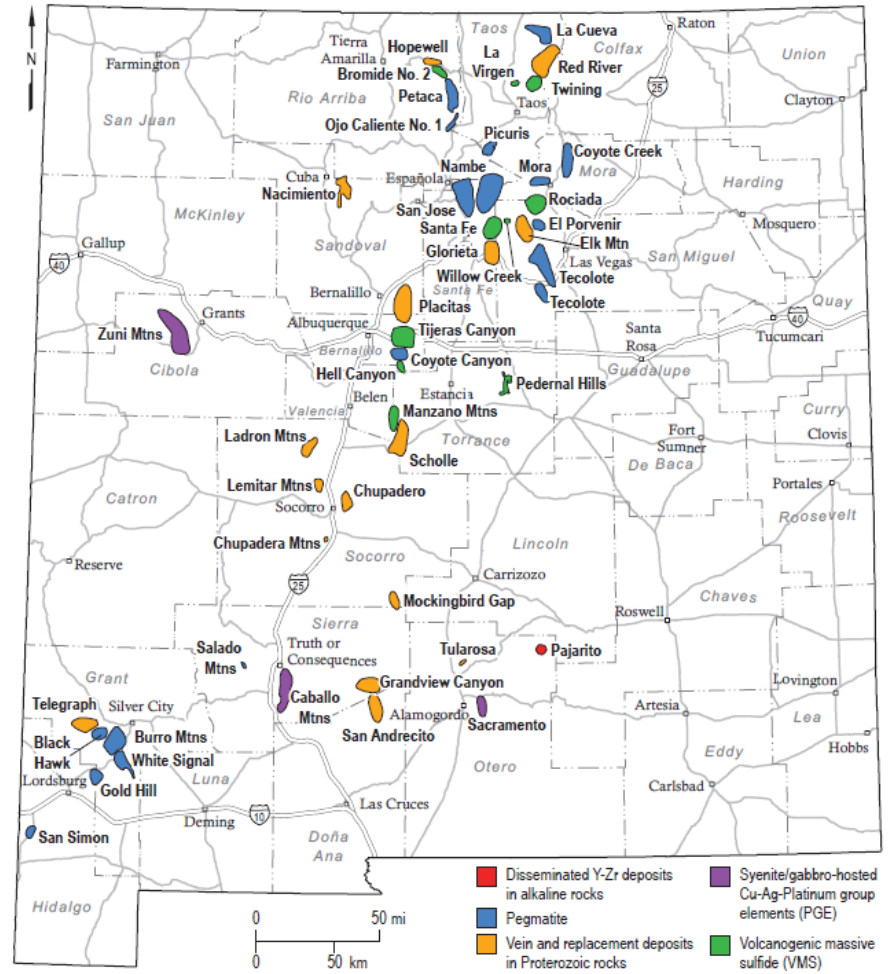


Figure 4. Proterozoic age mineral deposits in New Mexico. Some districts contain more than one type of deposit. Iron formation deposits are found in two districts, Hopewell and Bromide No. 2, in northern New Mexico.

PROTEROZOIC IRON FORMATION

Proterozoic iron formation

- Stratigraphic units composed of layered rocks that contain 15% or more iron, occurring with quartz, chert, and/or carbonate, may contain Mn
- Among the largest iron ore deposits mined for steel in the world
- Moppin Metavolcanic Complex at the Iron Mountain mine (NMRA0181) in the northern Hopewell district and in the Bromide No. 2 district
  - economically interesting, but the grade and size are well below what would be economically feasible today

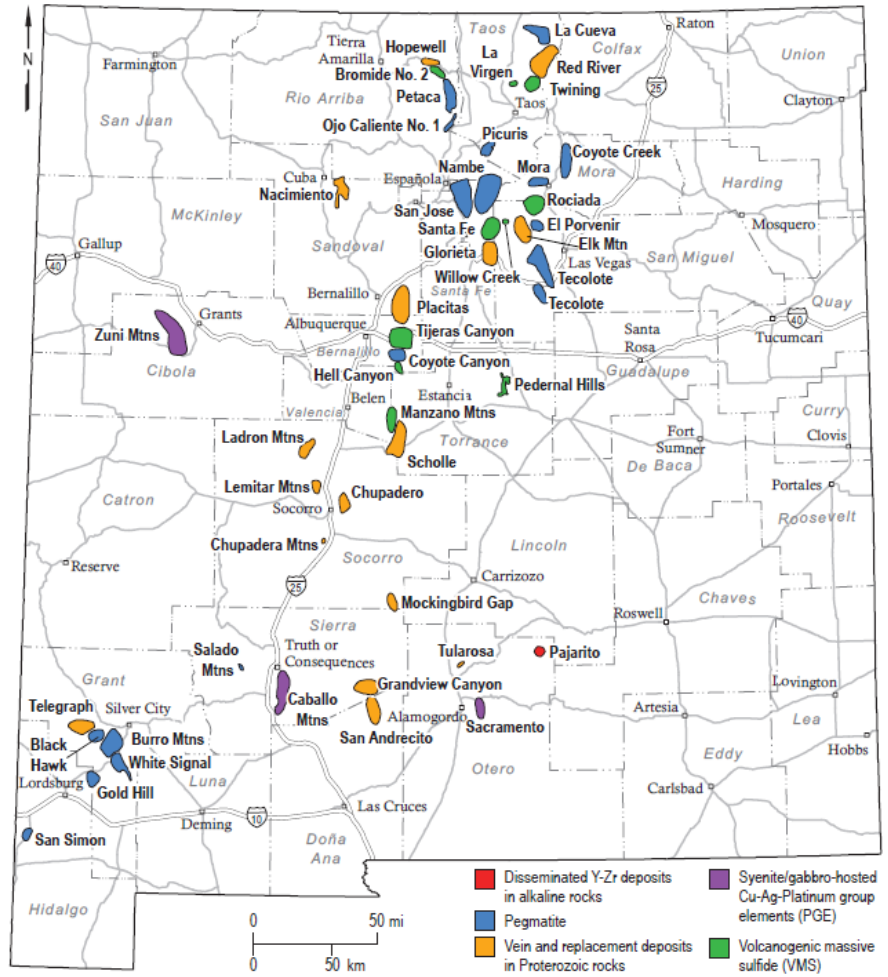


Figure 4. Proterozoic age mineral deposits in New Mexico. Some districts contain more than one type of deposit. Iron formation deposits are found in two districts, Hopewell and Bromide No. 2, in northern New Mexico.

Proterozoic iron formation

- Cabresto Creek area (Taos County)
  - Magnetite-hematite-ilmenite bands
  - Quartzite, schist
  - 25% Fe
  - 50 ft thick
- Iron Mountain (Hopewell)
  - 40% Fe
  - 2 layers magnetite, quartz, chlorite schist
  - 10-20 ft thick, several hundred ft long
- Cleveland Gulch area (Bromide No. 2)
  - 3000 ft long
  - 29.7-37.7% Fe
- No Fe production

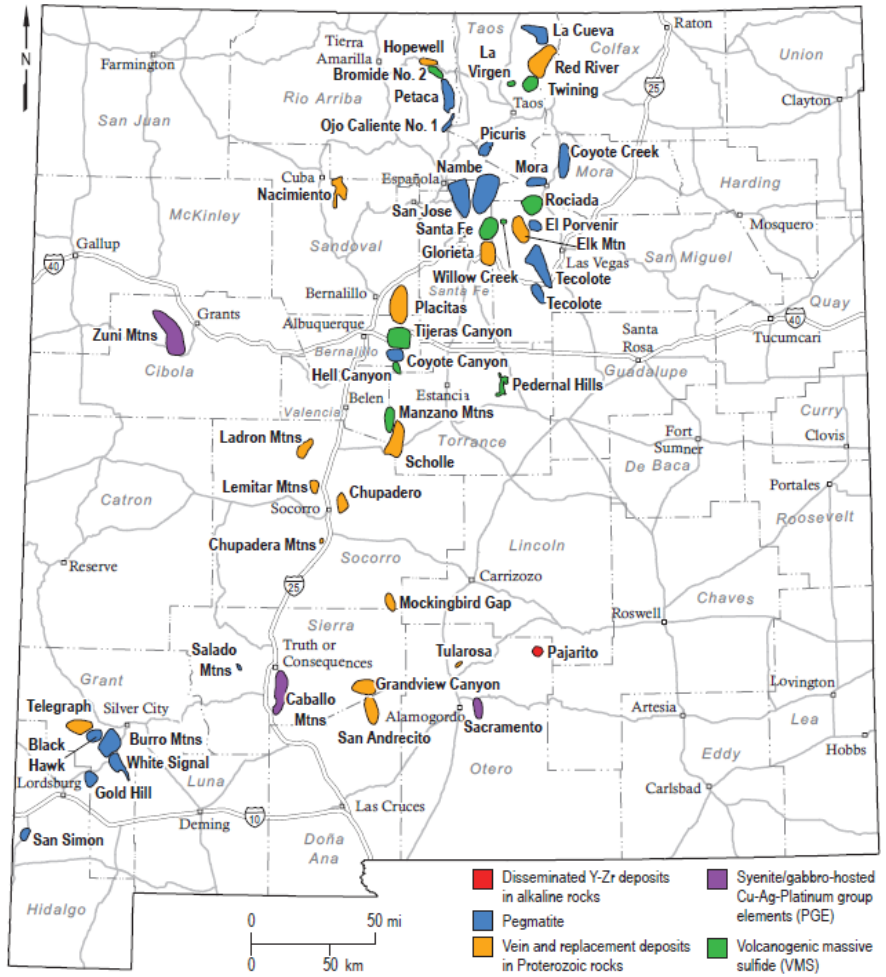
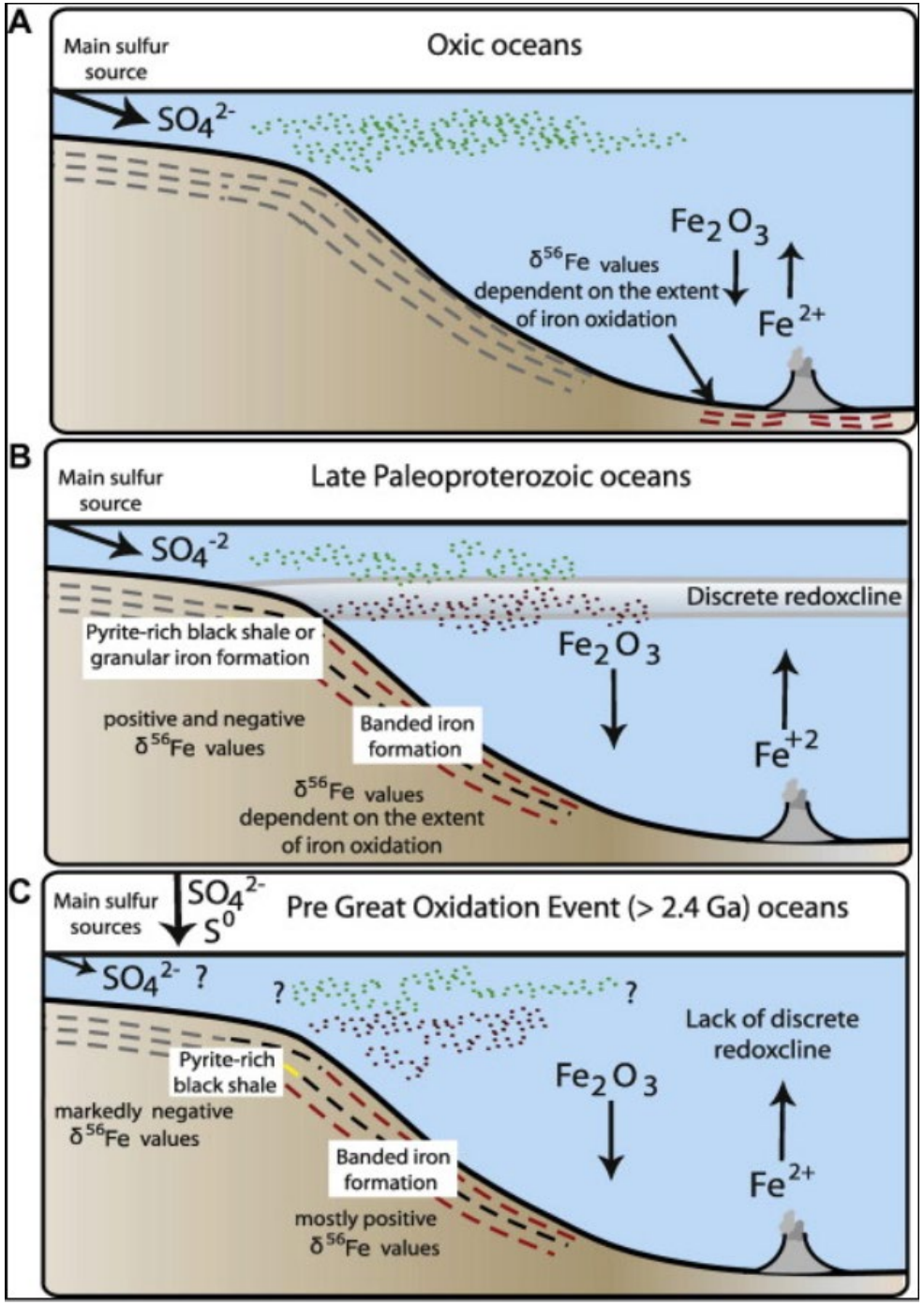


Figure 4. Proterozoic age mineral deposits in New Mexico. Some districts contain more than one type of deposit. Iron formation deposits are found in two districts, Hopewell and Bromide No. 2, in northern New Mexico.

- Earth's atmosphere and oceans did not have the oxygen concentrations we see today
- Fe weathers, enters the oceans, where bacteria reacts to form magnetite
- Magnetite drops to ocean floor (supported by Fe isotope studies)



Planavsky et al., 2012 (https://www.sciencedirect.com/science/article/pii/S0016703711007228)

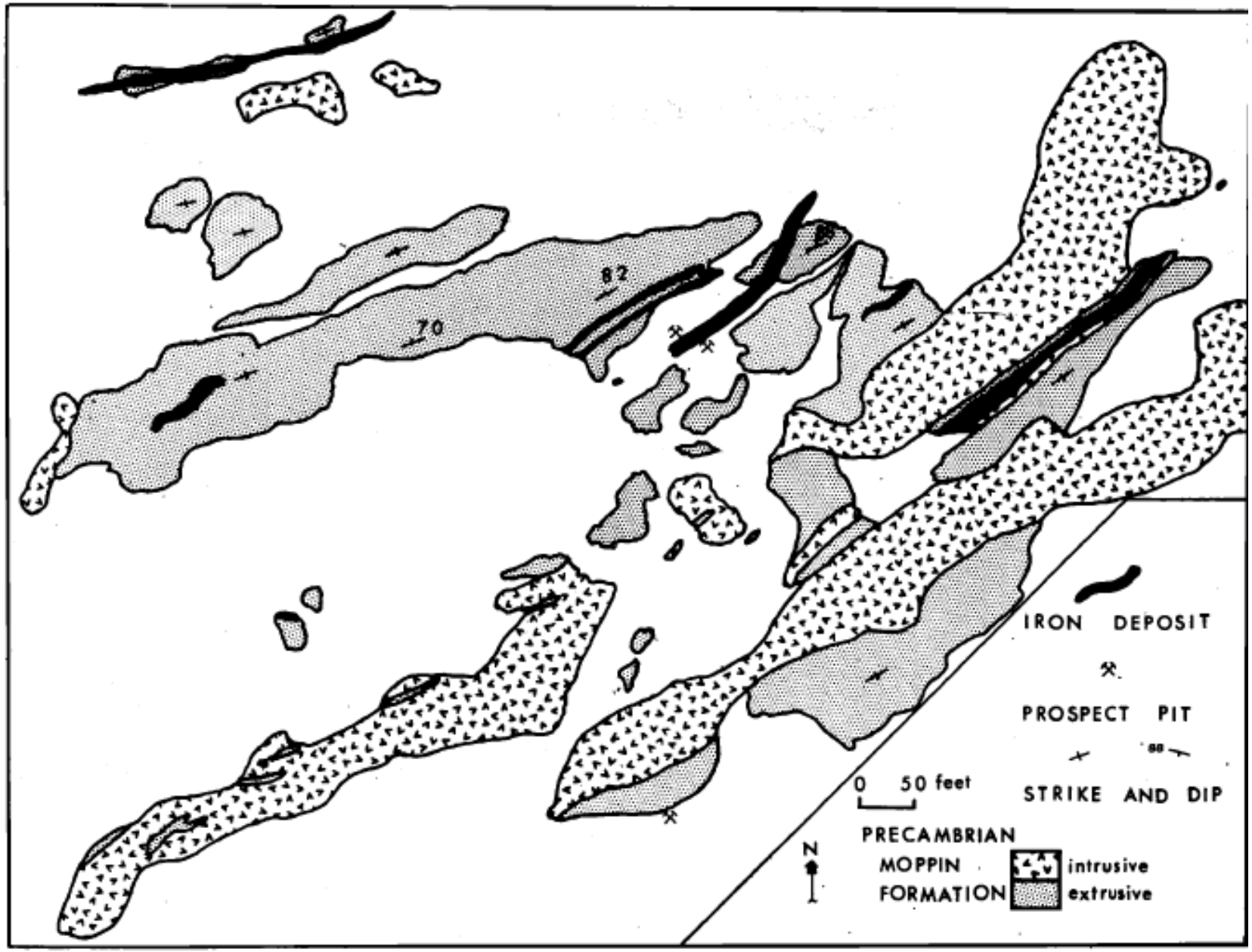
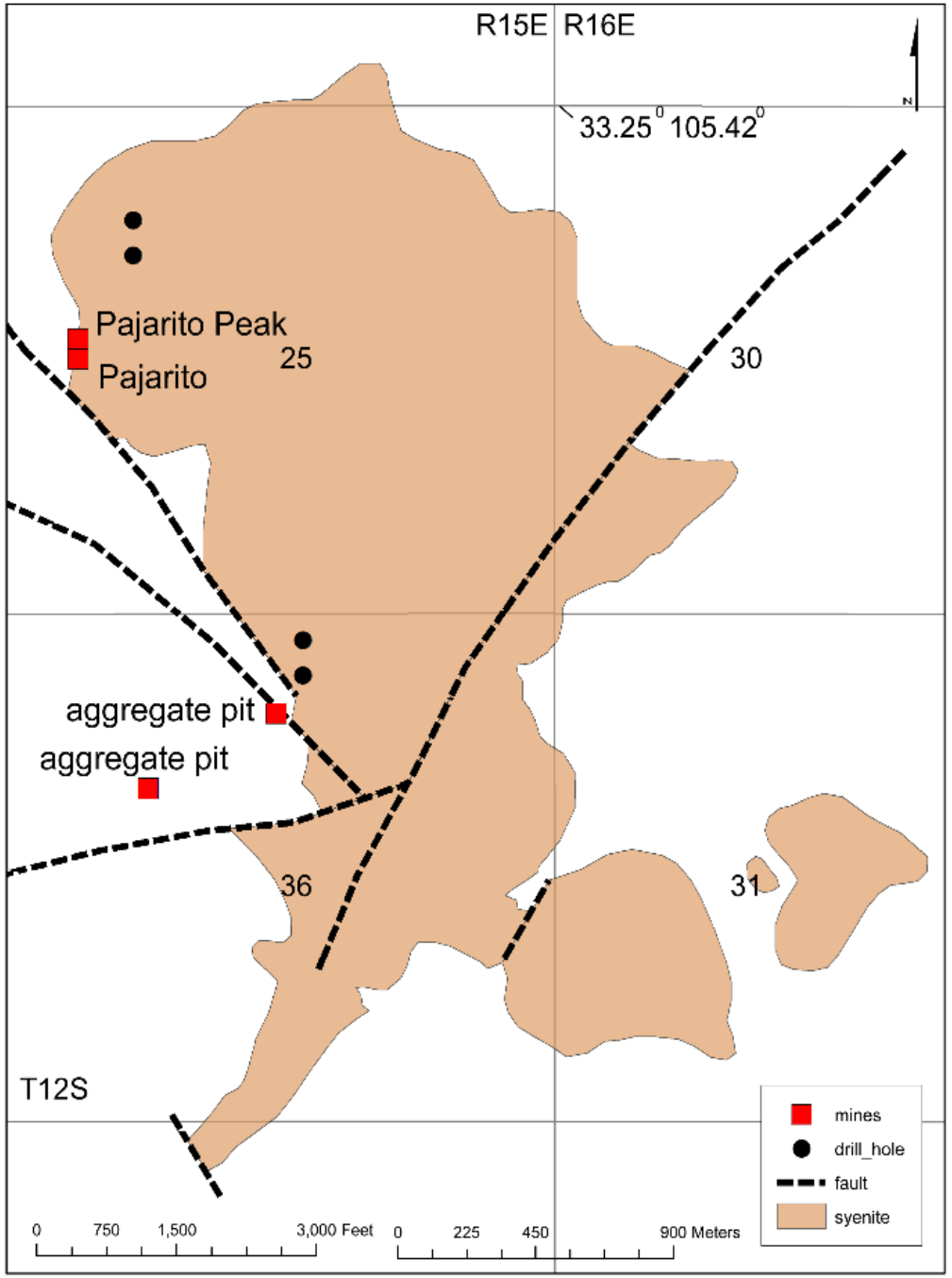
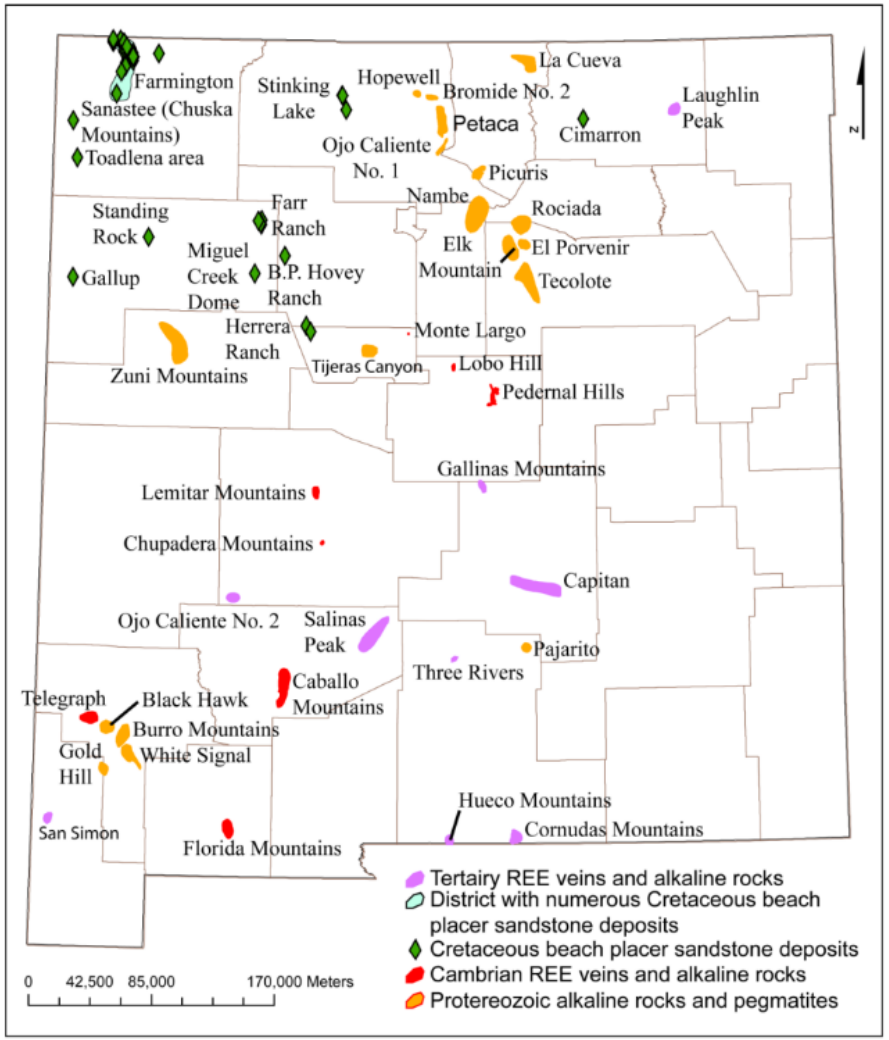


FIG. 4. Geologic outcrop map of part of Iron Mountain, New Mexico.

McLeroy, 1970

DISSEMINATED YTTRIUM-ZIRCONIUM DEPOSITS IN ALKALINE ROCKS





Proterozoic Pajarito Mountain

Proterozoic Pajarito Mountain

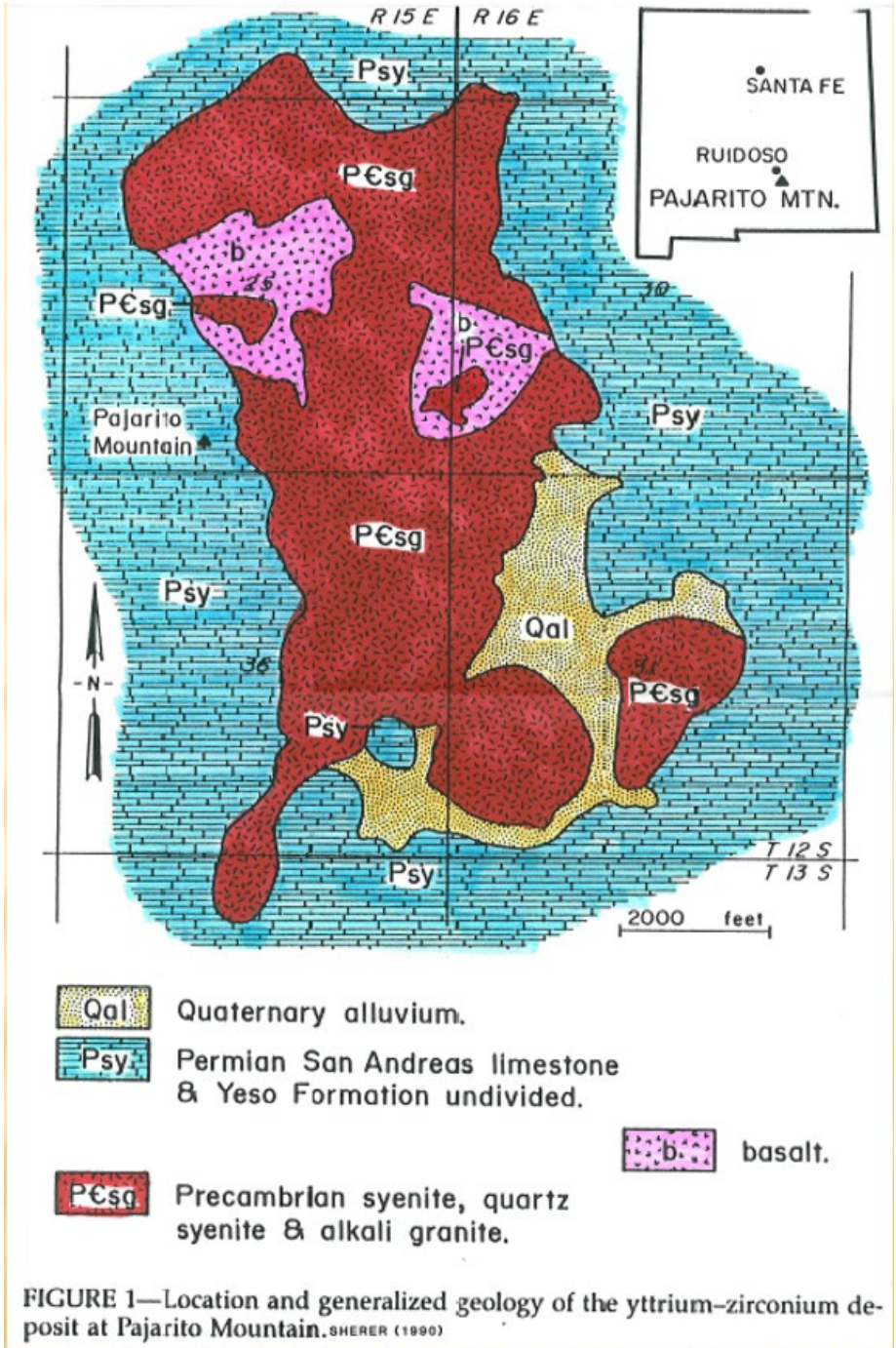
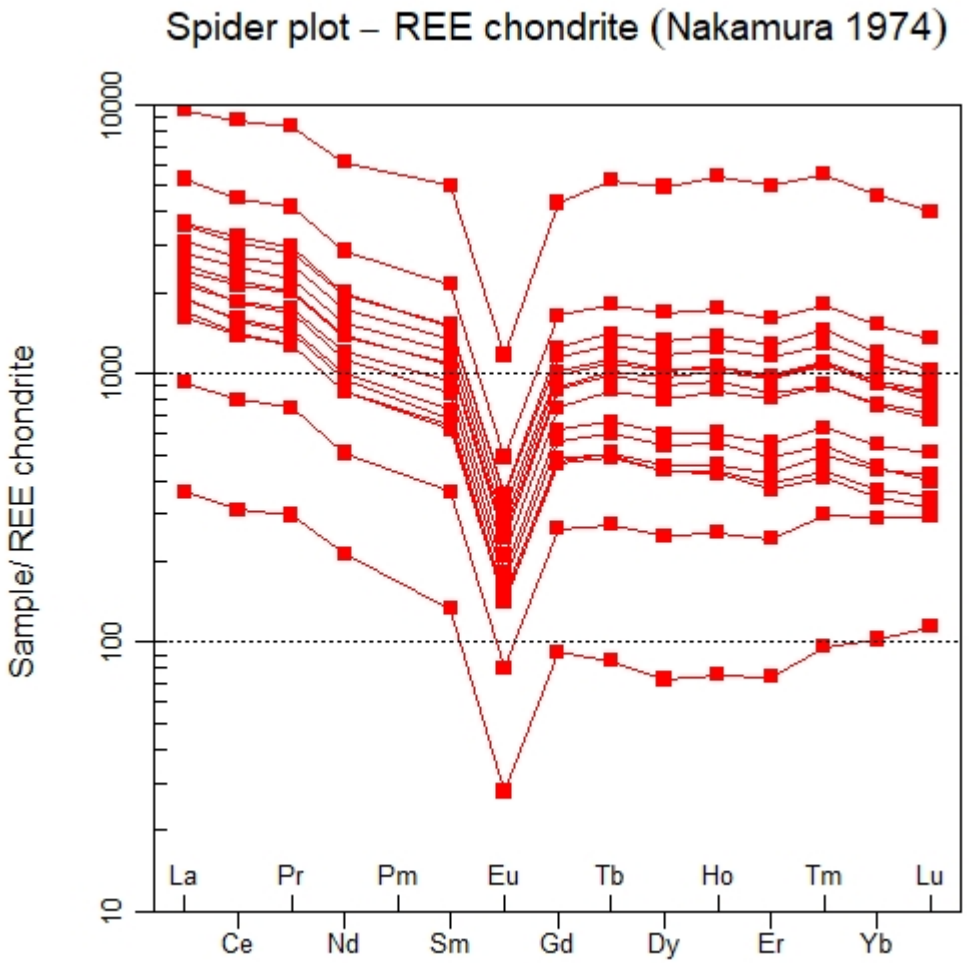


FIGURE 1—Location and generalized geology of the yttrium–zirconium deposit at Pajarito Mountain. SHERER (1990)



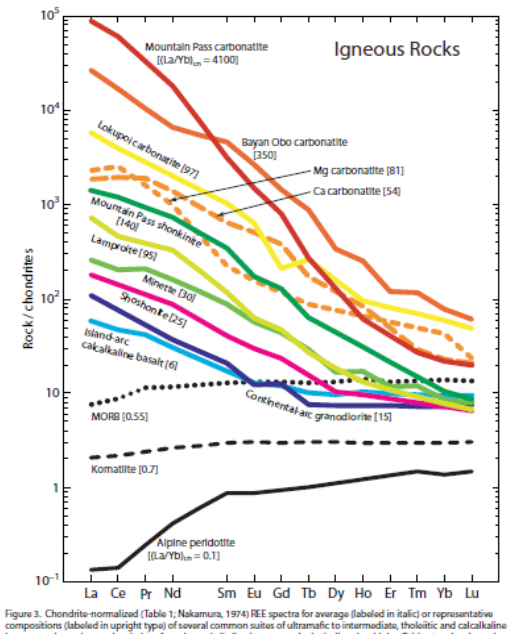


Figure 3. Chondrite-normalized (Table 1; Nakamura, 1974) REE spectra for average (labeled in italic) or representative compositions (labeled in upright type) of several common suites of ultramafic to intermediate, tholeiitic and calcalkaline

- Layered cumulate intrusion—3 stages
- Syenite, nepheline syenite, alkali granite, and gabbro intruded by pegmatites and gabbro dikes
- Recoverable resource of 2.7 million short tons grading 0.18% Y_2O_3 and 1.2% ZrO_2 (historic resources, not NI 43-101 compliant; 1989)
- Market slump in the yttrium and zirconium markets occurred and Molycorp, Inc. dropped the project
- Historic REE resources—537,000 short tons of 2.95% total REE (Jackson and Christiansen, 1993)
- Drilling by Division of Energy & Mineral Development, Office of the Assistant Secretary for Indian Affairs, United States Department of the Interior (DEMD)

Table 2.1. Radiometric dates from previous literature on Pajarita Mountain

Age as given	Lithologic unit	Method	Mineral	Source
1170 ± 24 Ma	"Riebeckite granite"	K-Ar	Riebeckite	Kelley, 1968
1155 ± 25 Ma	"Riebeckite 'granite'"	Rb-Sr	Feldspar	Kelley, 1968
1190 ± 25 Ma	"Syenite pegmatite"	K-Ar	Hornblende	Kelley, 1968
1150 ± 40 Ma	"Quartz syenite-alkali granite"	K-Ar	Amphibole	Moore et al., 1988
1175 ± 15 Ma	"Riebeckite granite"	Rb-Sr	Feldspar	Bauer & Pollock, 1993
1180 ± 25 Ma	"Riebeckite granite"	K-Ar	Riebeckite	Bauer & Pollock, 1993
1200 ± 25 Ma	"Pegmatite/syenite"	K-Ar	Hornblende	Bauer & Pollock, 1993

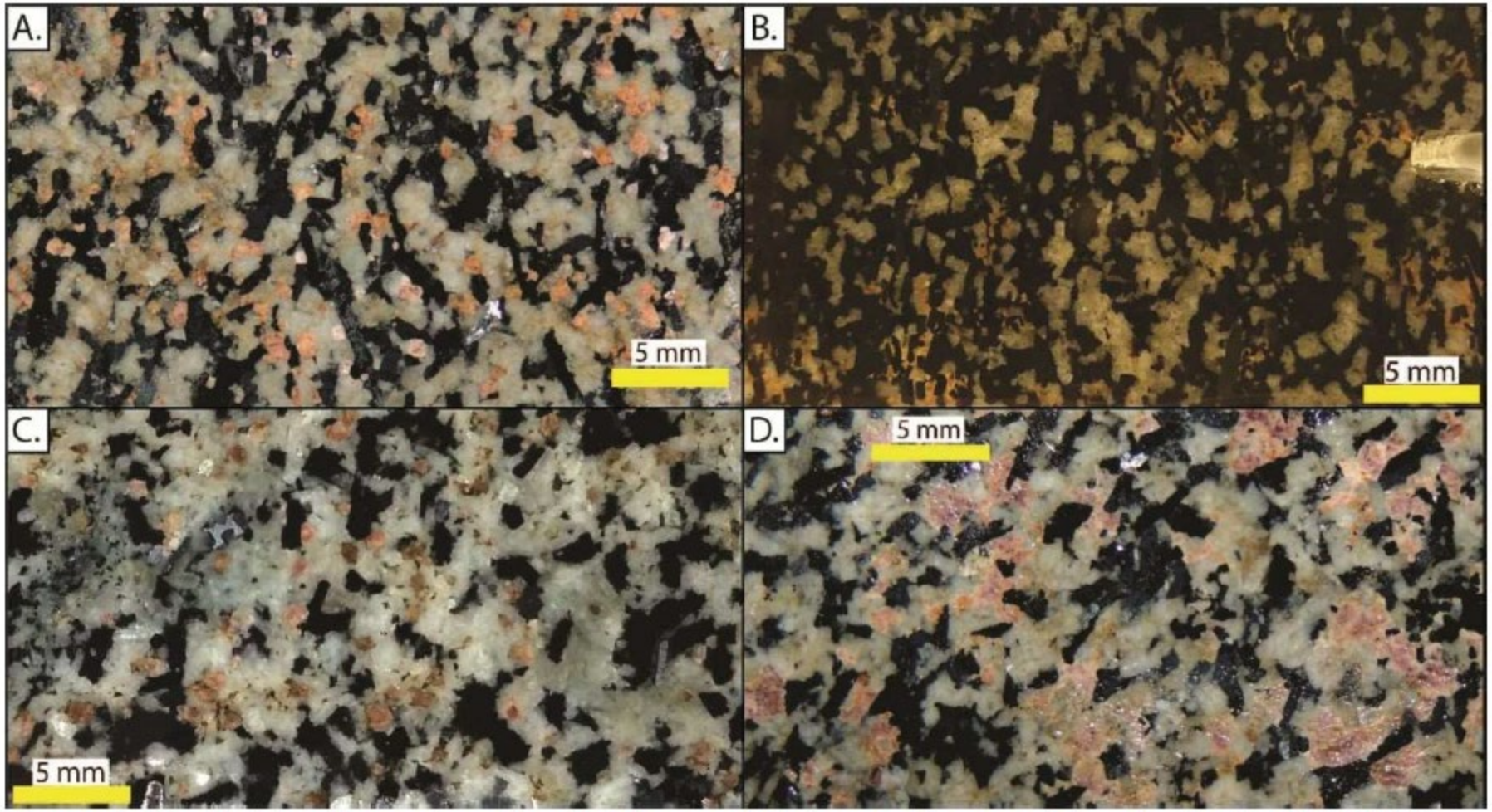
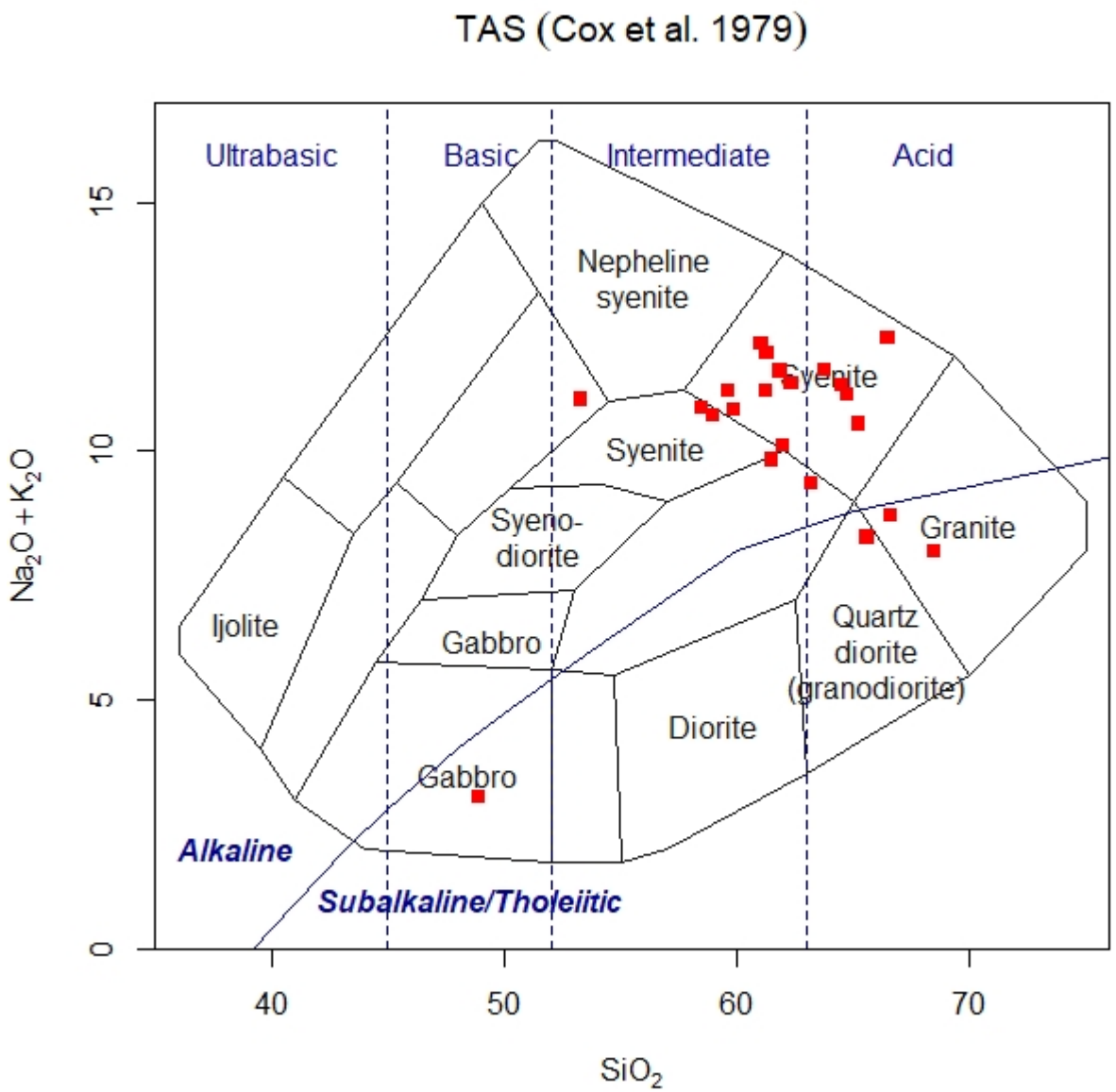


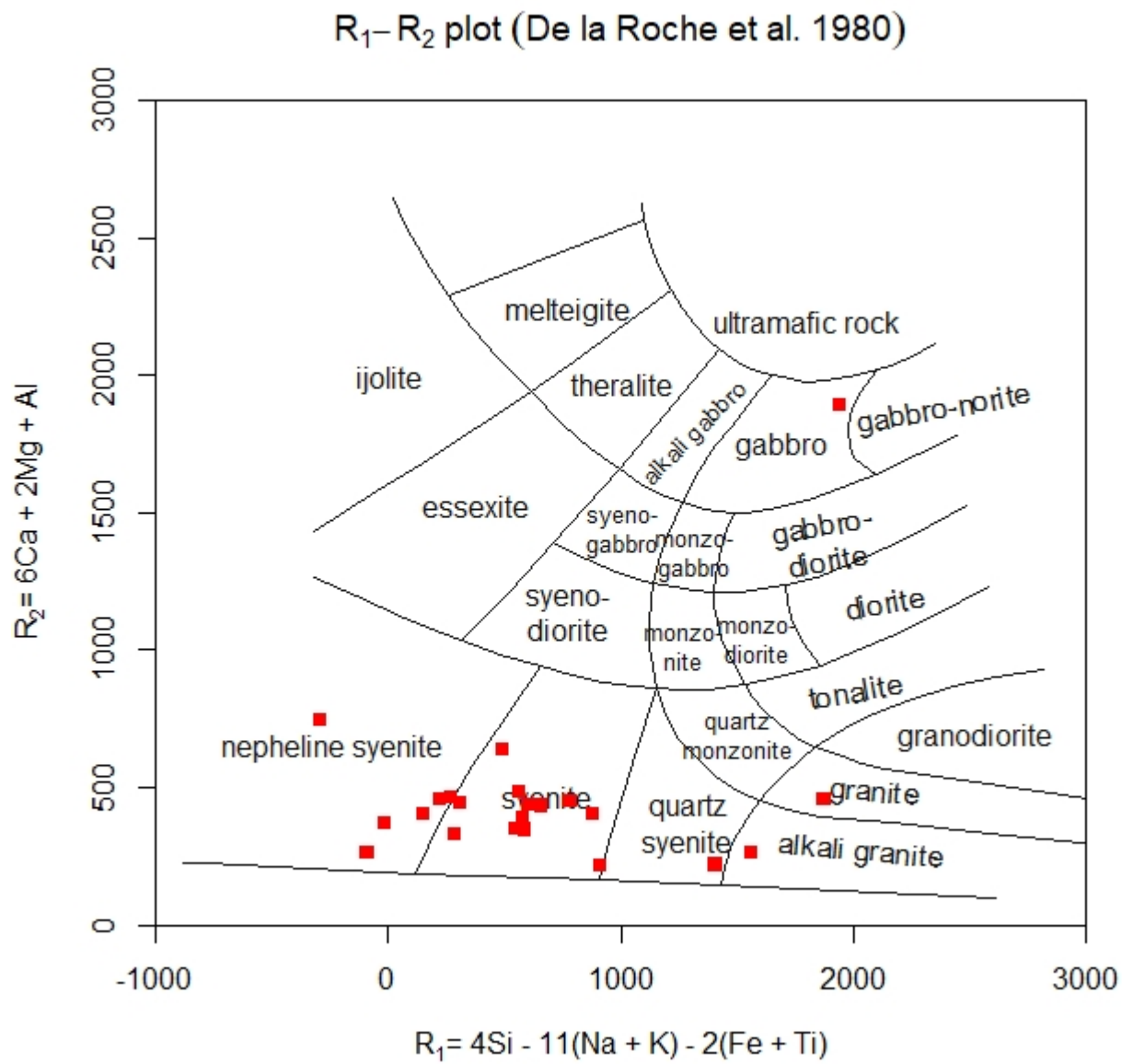
Figure 4.13. Cut hand samples of eudialyte-amphibole syenite cumulate. A. Typical EASC I (South Area) with moderate amphibole. B. EASC with high modal amphibole and fine-grained, dominantly intercumulus eudialyte (orange), North Area. C. EASC with low modal amphibole, North Area. D. EASC with high modal eudialyte, North Area. Note atypically coarse eudialyte grains, some partly enveloping alkali feldspar and amphibole grains.

Berger, 2018

Mineralogy Proterozoic Pajarito Mountain (Berger, 2018)

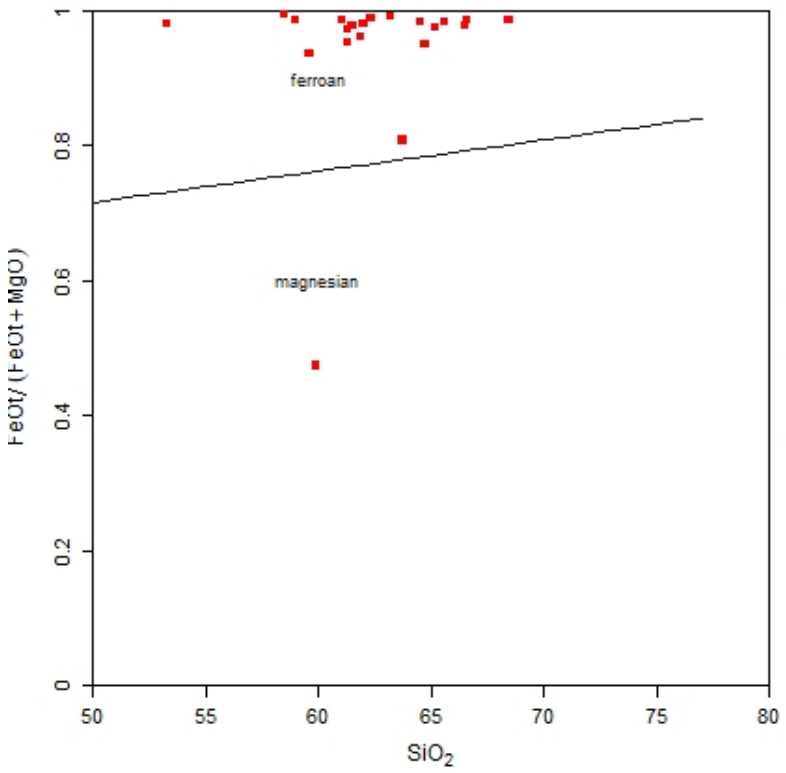
- Eudialyte $Na_4(Ca,Ce)_2(Fe{+}{+},Mn,Y)ZrSi_8O_{22}(OH,Cl)_2$
- Fluorite CaF_2
- Apatite $Ca_5(PO_4)_3(OH,F,Cl)$ (with U, Th)
- Zircon ZrSiO4 (with U, REE)
- 2 REE-bearing silicates

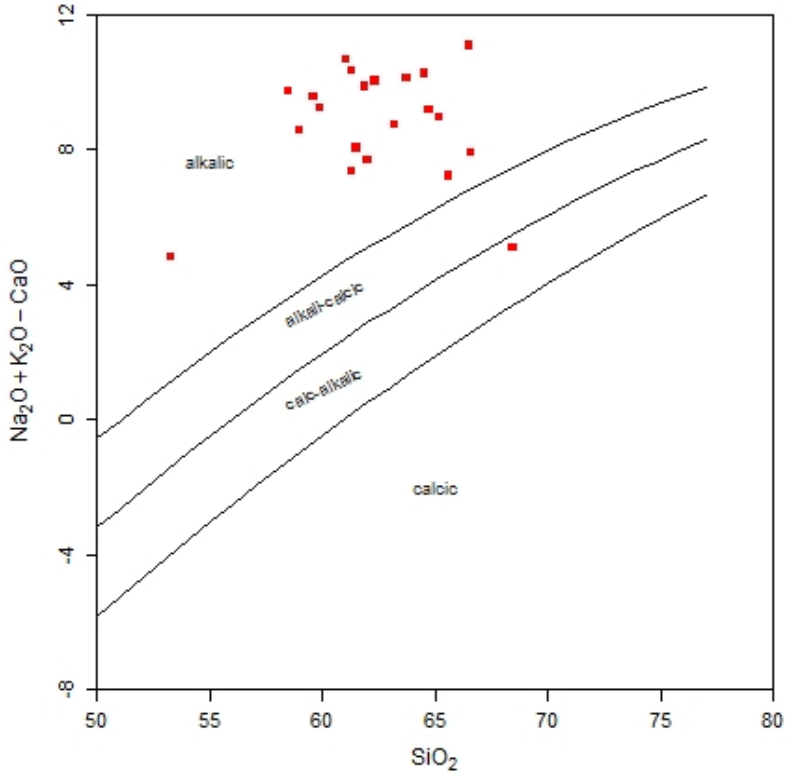


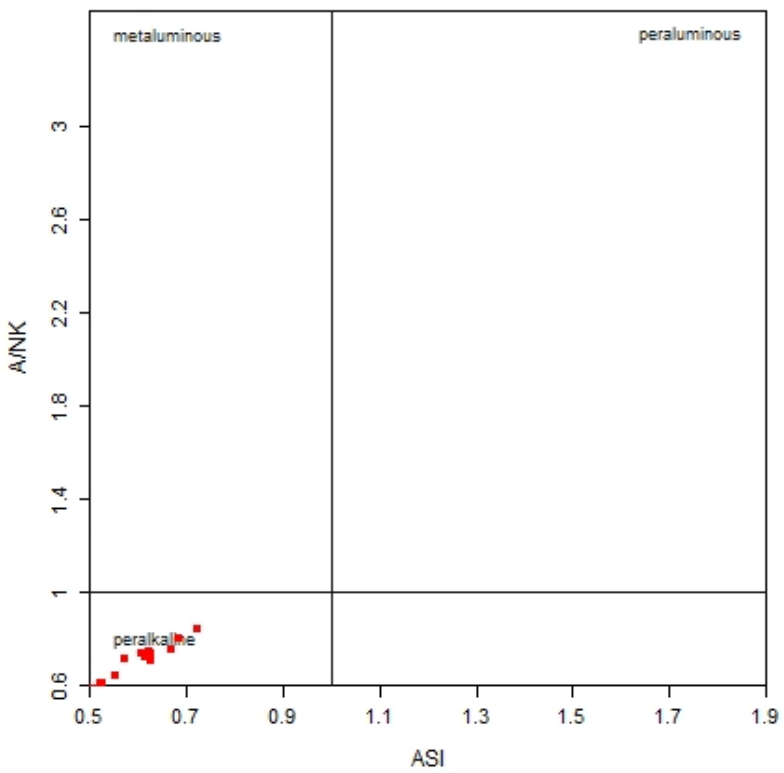


Chemical data by Moore (1989) and Berger (2018)

Granite tectonic discrimination – Frost et al. (2001)

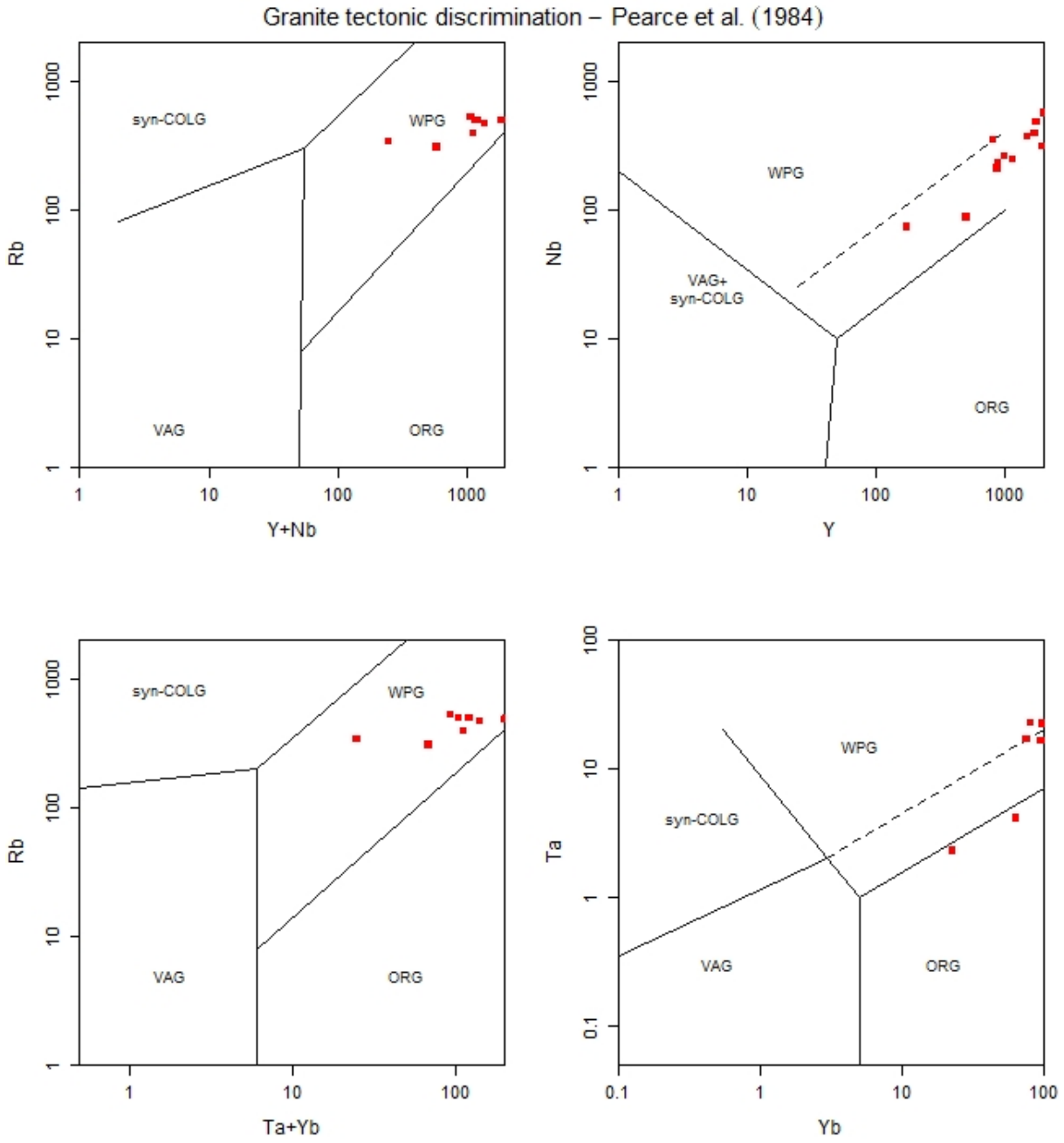






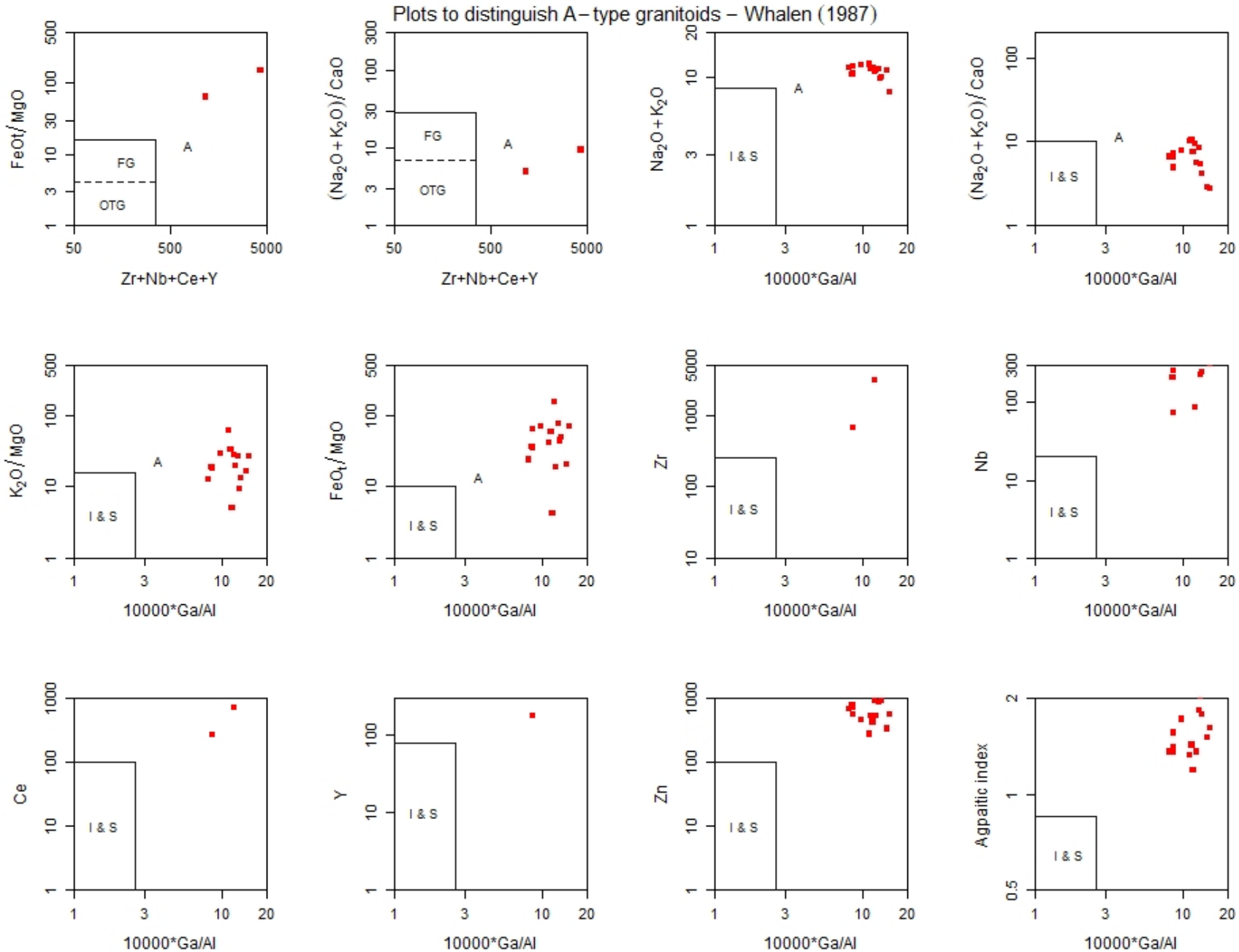
Peralkaline, alkalic

Chemical data by Moore (1989) and Berger (2018)



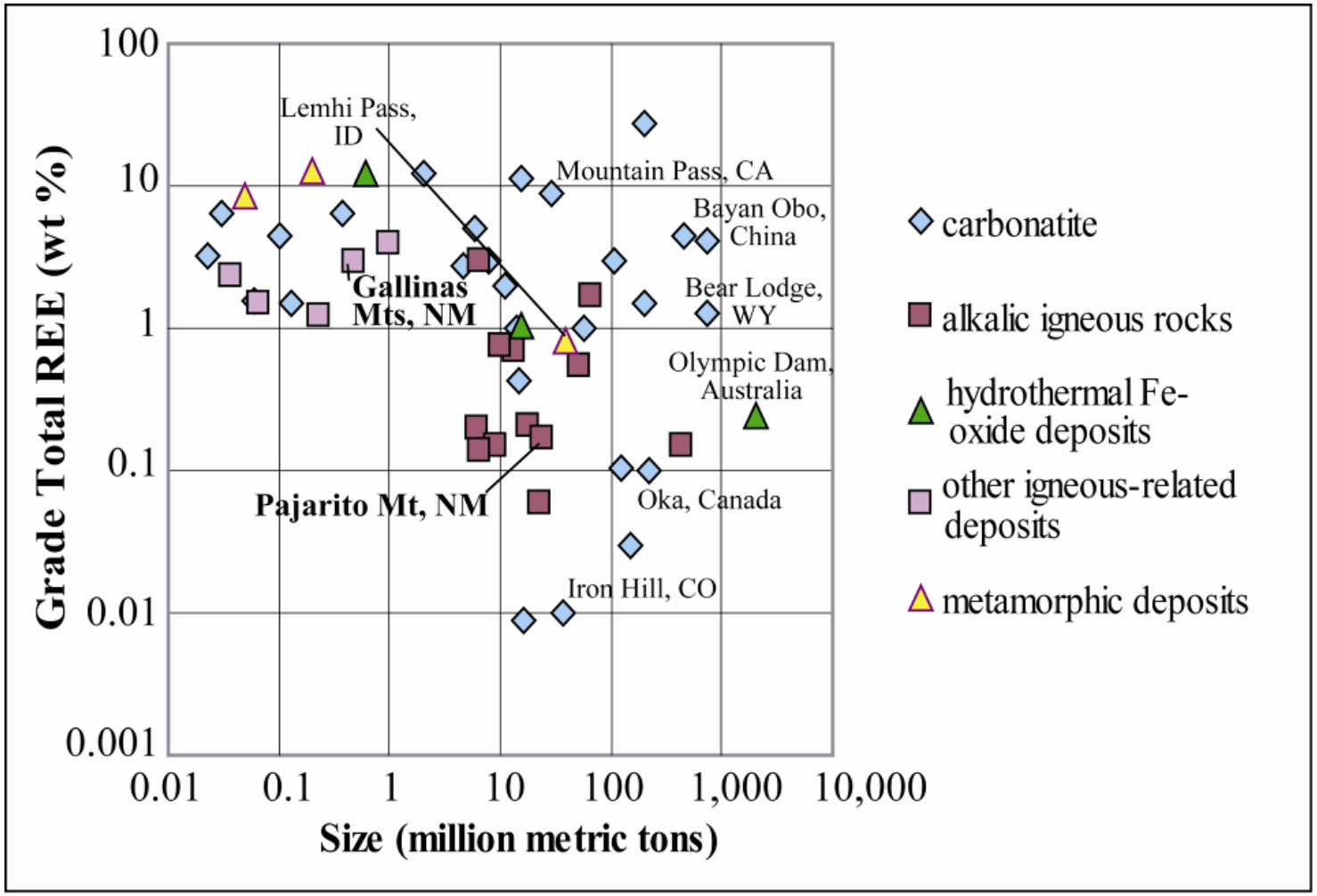
Within Plate Granites

Chemical data by Moore (1989) and Berger (2018)



A-type granite

Chemical data by Moore (1989) and Berger (2018)



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.

ASSIGNMENT

- Safety moment
- REE-Bearing Cambrian-Ordovician Episyenites and Carbonatites in Southern and Central New Mexico, USA
  - https://geoinfo.nmt.edu/staff/mclemore/documents/0411.pdf
- Memoir 50D
  - Chapter 3 Cambrian-Ordovician
  - Chapter 4 Paleozoic to Mesozoic Sedimentary Mineral Deposits