

# ME571/Geol571 Advanced Topics

Geology and Economics of  
Strategic and Critical Minerals  
Spring 2017

Commodities—beryllium

Virginia T. McLemore

# ASSIGNMENT

- **NEXT WEEK (Feb 13, 20) no class, REE Feb 27, March 6**
- Castor, S.B., 2008, The Mountain Pass rare-earth carbonatite and associated ultrapotassic rocks, California: The Canadian Mineralogist, v. 46, p. 779-806,  
<http://canmin.geoscienceworld.org/content/46/4/779.full.pdf+html?sid=180ae325-acd5-4226-9a02-175f7a865e17>
- Long, K.R., van Gosen, B.S., Foley, N.K. and Cordier, D., 2010, The principle rare earth elements deposits of the United States—A summary of domestic deposits and a global perspective: U.S. Geological Survey, Scientific Investigations Report 2010-5220, 104 p., <http://pubs.usgs.gov/sir/2010/5220/> (accessed 5/1/12).
- Mariano and Mariano, 2012, Rare earth mining and exploration in North America: Elements, v. 8, 369-376,  
<http://elements.geoscienceworld.org/content/8/5/369.full.pdf+html?sid=605ebd04-9070-4994-9bce-b1cdd79f349d>

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

# MINERAL COMMODITY SUMMARIES 2017

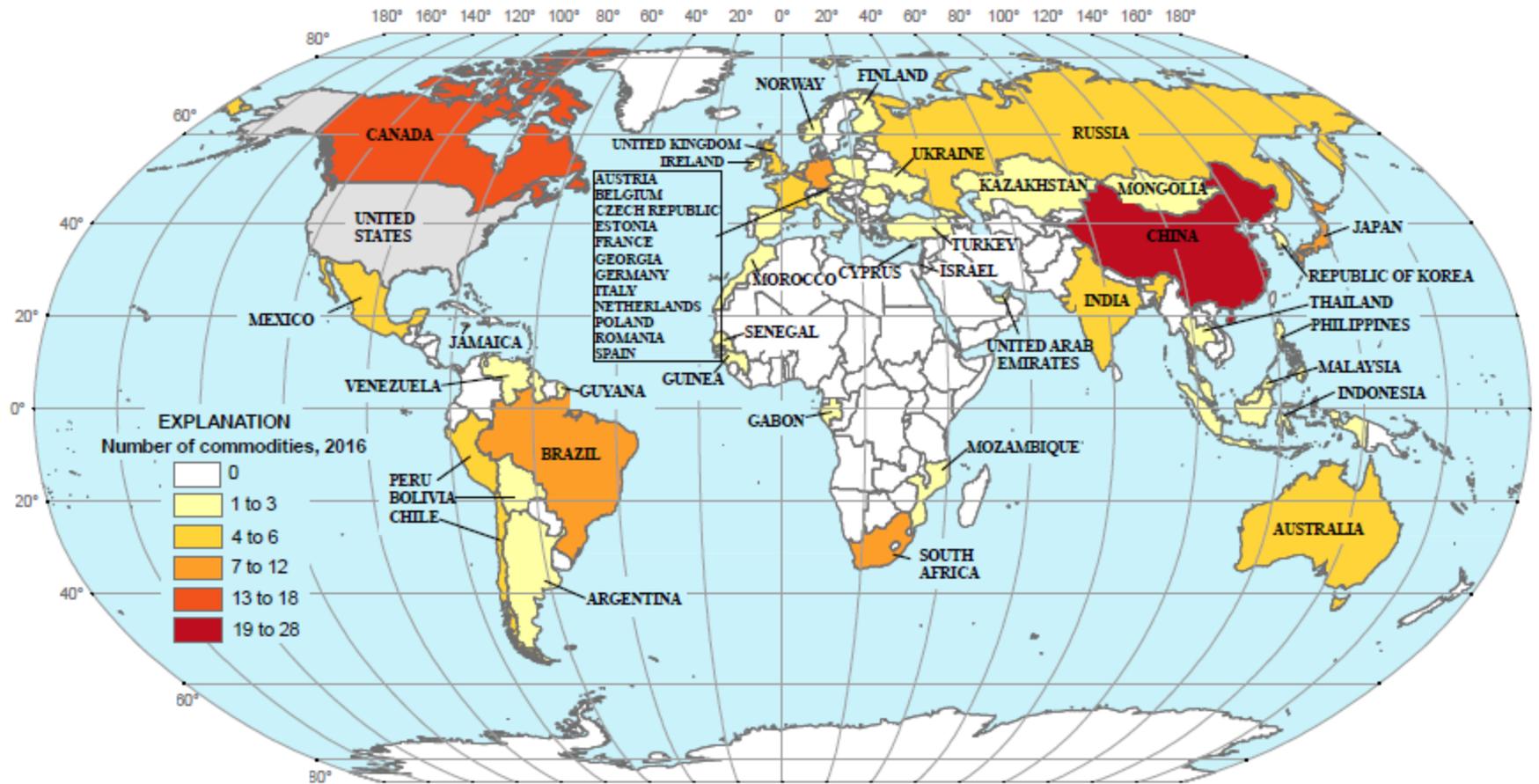
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Abrasives	Fluorspar	Mercury	Silicon
Aluminum	Gallium	Mica	Silver
Antimony	Garnet	Molybdenum	Soda Ash
Arsenic	Gemstones	Nickel	Stone
Asbestos	Germanium	Niobium	Strontium
Barite	Gold	Nitrogen	Sulfur
Bauxite	Graphite	Palladium	Talc
Beryllium	Gypsum	Peat	Tantalum
Bismuth	Hafnium	Perlite	Tellurium
Boron	Helium	Phosphate Rock	Thallium
Bromine	Indium	Platinum	Thorium
Cadmium	Iodine	Potash	Tin
Cement	Iron and Steel	Pumice	Titanium
Cesium	Iron Ore	Quartz Crystal	Tungsten
Chromium	Iron Oxide Pigments	Rare Earths	Vanadium
Clays	Kyanite	Rhenium	Vermiculite
Cobalt	Lead	Rubidium	Wollastonite
Copper	Lime	Salt	Yttrium
Diamond	Lithium	Sand and Gravel	Zeolites
Diatomite	Magnesium	Scandium	Zinc
Feldspar	Manganese	Selenium	Zirconium

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<https://minerals.usgs.gov/minerals/pubs/mcs/2017/mcs2017.pdf>

## MAJOR IMPORT SOURCES OF NONFUEL MINERAL COMMODITIES FOR WHICH THE UNITED STATES WAS GREATER THAN 50% NET IMPORT RELIANT IN 2016



Source: U.S. Geological Survey

# DEFINITIONS

**A mineral occurrence** is any locality where a useful mineral or material is found.

**A mineral prospect** is any occurrence that has been developed by underground or by above ground techniques, or by subsurface drilling to determine the extent of mineralization.

The terms **mineral occurrence** and **mineral prospect** do not have any resource or economic implications.

**A mineral deposit** is any occurrence of a valuable commodity or mineral that is of sufficient size and grade (concentration) that has potential for economic development under past, present, or future favorable conditions.

An **ore deposit** is a well-defined mineral deposit that has been tested and found to be of sufficient size, grade, and accessibility to be extracted (i.e. mined) and processed at a profit at a specific time. Thus, the size and grade of an ore deposit changes as the economic conditions change. **Ore refers to industrial minerals as well as metals.**

# *Mineral Deposits* versus *Ore Bodies*

mineral deposit  $\neq$  ore body

ore body = reserves

mineral deposit =  
+ reserves  
+ unmineable  
+ uneconomic  
+ mined



**Gangue – the unwanted part of the ore, comprises minerals such as calcite, quartz and iron pyrite**





**Grade – Refers to the proportion of the ore that is the ore mineral or actual elemental metal content that can be extracted from it - expressed as a percentage**

**The grade of the Cornish tin ore is between 0.5 and 1.5 % cassiterite ( $\text{Sn O}_2$ ) This means there is between 98.5 and 99.5% gangue in the ore**

**Tenor – Refers to the percentage of the ore mineral that is actual metal to be extracted**



**The tenor of iron ores vary considerably:  
Limonite 35% Fe, Haematite 57% Fe, Magnetite 70%**

# Calculating Ore Grade as % Mineral Content and % Elemental Metal Content

Using Chalcopyrite as an example:

Chemical Formula is  $\text{Cu, Fe, S}_2$

Relative atomic masses are:

$\text{Cu} = 63.5, \text{Fe} = 56 \text{ and } \text{S} = 32$

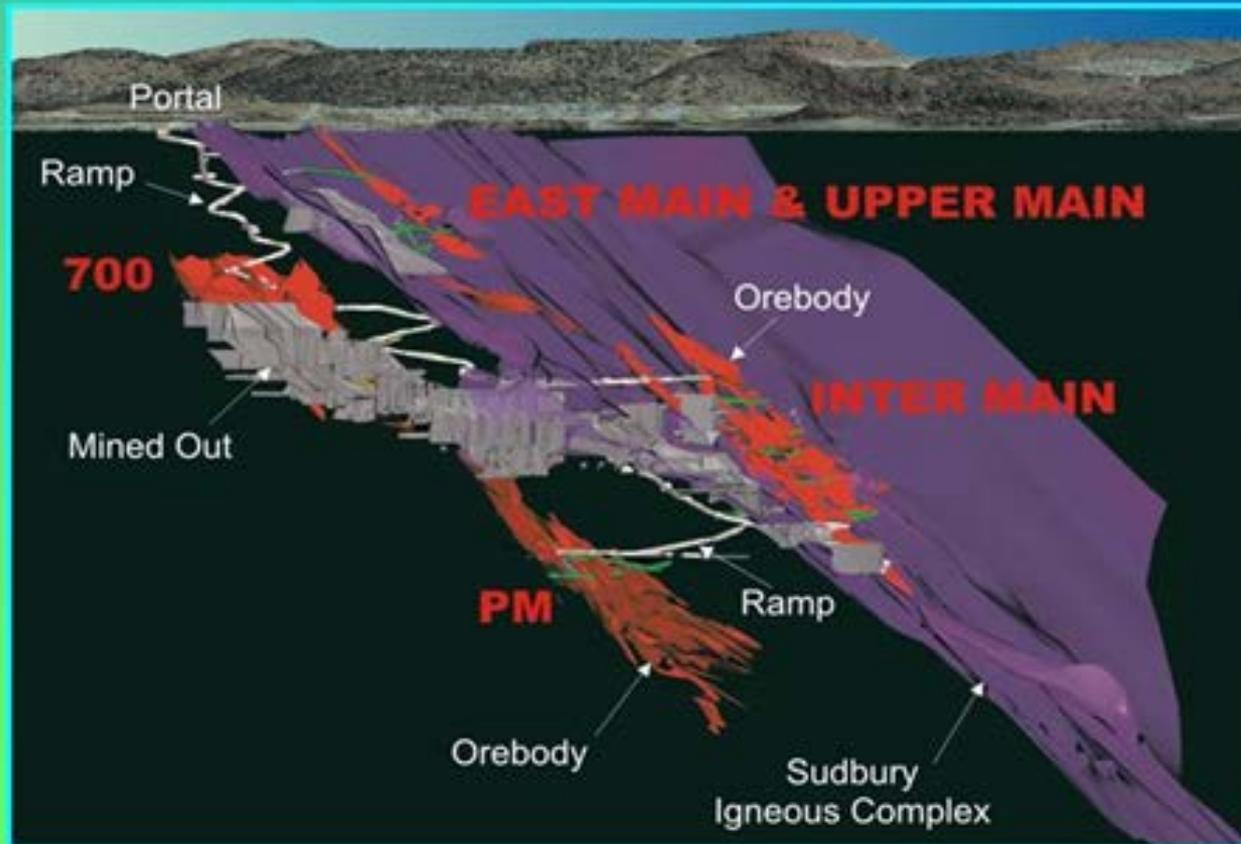
So 1kg of copper will be found in:

$$63.5 + 56 + (2 \times 32)/63.5$$

This equals 2.9 kg of Chalcopyrite

If the ore contained 2% copper then it would have  $2 \times 2.9 = 5.8\%$  Chalcopyrite

**Tonnage – Refers to the total amount of metal that can be extracted from any particular ore deposit.**



**Tonnage is calculated by taking into account the volume of the ore deposit, the grade of the ore and the tenor of the ore mineral**

**CLASSIFICATION OF  
MINERAL RESOURCES  
ON U.S. FEDERAL LAND**

**Locatable Minerals** are whatever is recognized as a valuable mineral by standard authorities, whether metallic or other substance, when found on public land open to mineral entry in quality and quantity sufficient to render a claim valuable on account of the mineral content, under the United States Mining Law of 1872. Specifically excluded from location are the leasable minerals, common varieties, and salable minerals.

**Leasable Minerals** The passage of the Mineral Leasing Act of 1920, as amended from time to time, places the following minerals under the leasing law: oil, gas, coal, oil shale, sodium, potassium, phosphate, native asphalt, solid or semisolid bitumen, bituminous rock, oil-impregnated rock or sand, and sulfur in Louisiana and New Mexico.

**Salable Minerals** The Materials Act of 1947, as amended, removes petrified wood, common varieties of sand, stone, gravel, pumice, pumicite, cinders, and some clay from location and leasing. These materials may be acquired by purchase only.

# Other terms

# Canadian Instrument 43-101

- Set of rules and guidelines for reporting information relating to a mineral property in order to present these results to the Canadian stock exchange
  - created after the Bre-X scandal to protect investors from unsubstantiated mineral project disclosures
  - gold reserves at (Bre-X's) Busang were alleged to be 200 million ounces (6,200 t), or up to 8% of the entire world's gold reserves FRAUD
- Similar to JORC (joint ore reserves committee code, Australia)
- South African Code for the Reporting of Mineral Resources and Mineral Reserves (SAMREC)

# Other terms

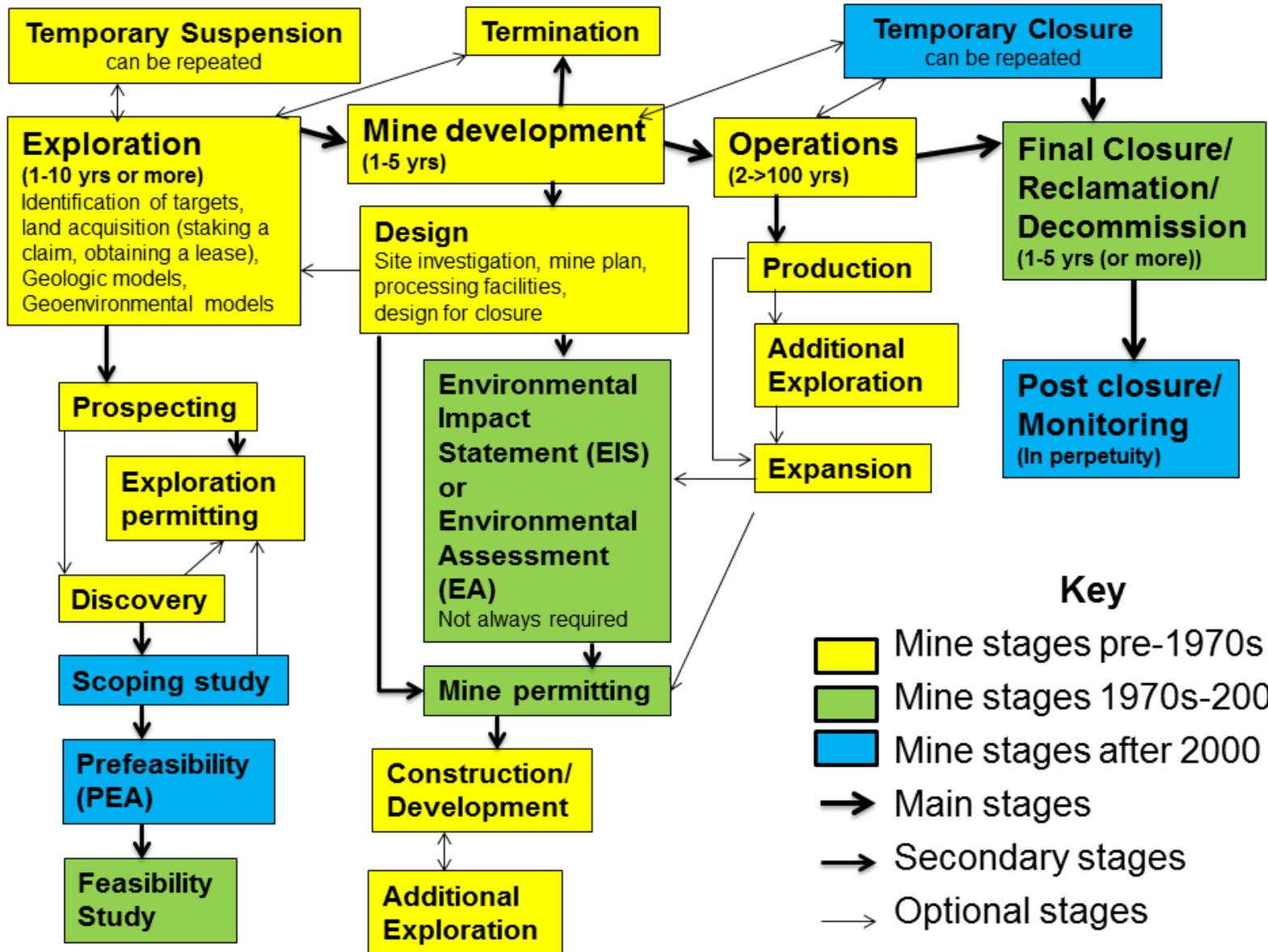
- Adjacent property
  - Company has no interest
  - Boundary close to project
  - Geologic characteristics similar to project
- Advanced property
  - Mineral reserves
  - Minerals resources with a PEA or feasibility study
- Early stage exploration property

# Qualified person (43-101)

- engineer/geoscientist with a university degree, or equivalent accreditation, in an area of geoscience, or engineering, relating to mineral exploration or mining
- has at least five years of experience
- has experience relevant to the subject matter of the mineral project and the technical report
- is in good standing with a professional association

# **LIFE CYCLE OF A MINE**

# Phases of Mining



# Stages of Mining

- Exploration (discovery, premining, undisturbed)
  - Mineral resource potential
  - Prefeasibility/Feasibility study
- Mine development (inc. continued exploration)
- Operations (extraction/production/expansion)
  - Processing/beneficiation/milling/smelting/refining
  - Mine expansion/standby
- Marketing
- Closure/postclosure/post-mining use

**What is beryllium?**

# What is beryllium?

- Beryllium
  - Average of 0.52 mg/kg in soil
  - Occurs as minerals, trace concentrations in other minerals



Beryllium metal



Beryllium ore



Beryllium oxide



Beryllium alloys

Beryllium is a rare metal with unique characteristics.

It is used as a pure metal or as an alloy with copper and aluminum.

Bertrandite and beryl pegmatite are the two most common beryllium ores.



# Beryllium

- 4<sup>th</sup> element on the periodic table
- 44<sup>th</sup> element in abundance
- Gemstone
- low density (1.85 grams/cubic centimeter)
- it has a very high melting point: 1,278° C
- resistance to creep, shear strength, tensile strength, comprehensive yield strength and just its fracture toughness

# Beryllium—Properties

- Low absorption cross-section with respect to thermal neutrons
- Light element
- Ability to withstand extreme heat
- Remain stable over a wide range of temperatures
- Function as an excellent thermal conductor
- Transparent to x-rays
- Light
- Non-sparking
- High heat capacity
- Stronger than steel
- In small amounts prevents metal fatigue failure in alloys with other metals

# Beryllium—Uses

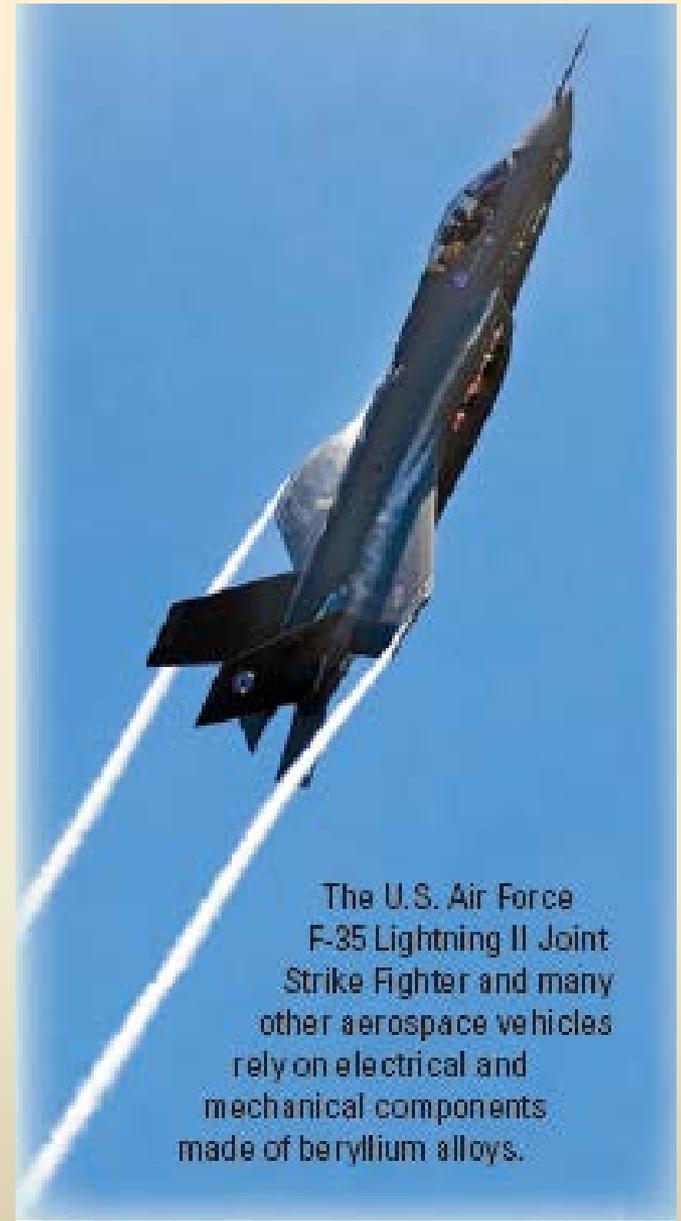
- Electronic and electrical components
- Aerospace and defense applications
- Used as pure metal
- Mixed with other metals to form alloys
- Processed to form salts that dissolve in water
- Excellent refractory=processed to form oxides and ceramic materials
- Reflector of neutrons=application in nuclear reactors

# Beryllium—Uses

- Air bag sensors
- Ignition
- Power steering and electronic auto systems
- Fire extinguishers
- Sprinkler heads
- Pacemakers
- lasers
- Military electronic targeting and infrared countermeasure systems
- Circuits controlling electric windows in cars
- computer chip heat sinks
- Nuclear fuel
- Wind turbine components
- Golf club shafts
- Engine blocks
- Disc drives
- Wheel rims
- Cellular phones
- Home temperature controls
- Ceramics



View of the back of one of the 18 beryllium mirror segments for the James Webb Space Telescope. The ribs at the back of the mirror help to maintain the mirror's strength and ability to hold its shape under extreme conditions. The front of the mirror is completely smooth and coated in a thin film of gold. Photograph courtesy of the National Aeronautics and Space Administration.

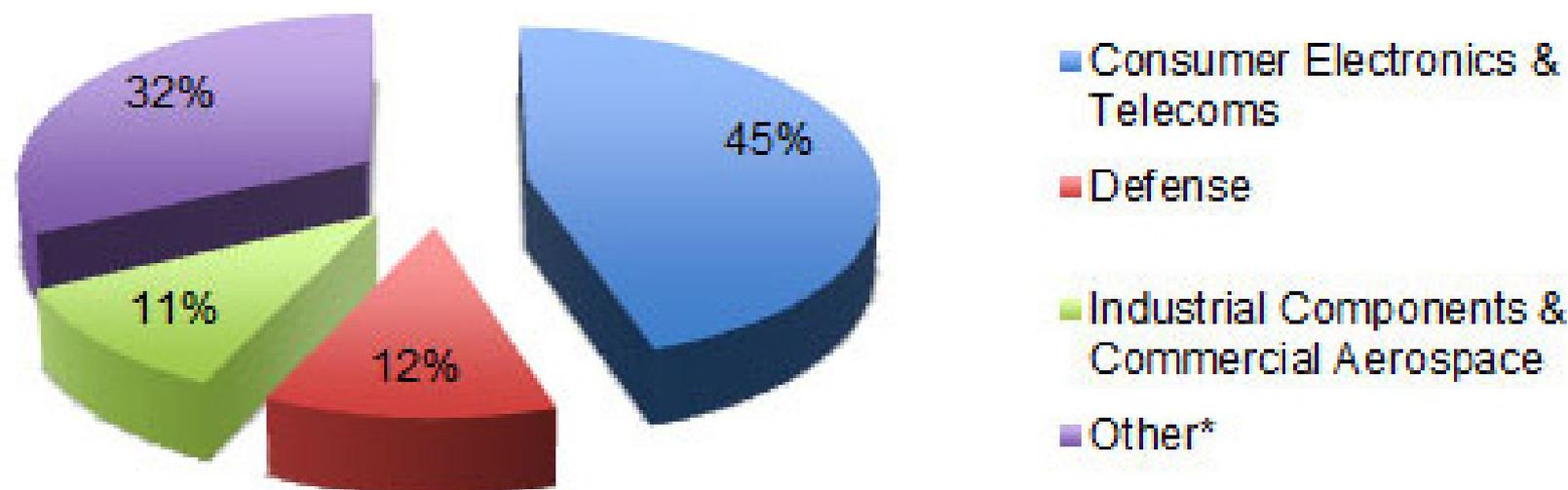


The U.S. Air Force F-35 Lightning II Joint Strike Fighter and many other aerospace vehicles rely on electrical and mechanical components made of beryllium alloys.

USGS

Because the number of beryllium producers is limited and the use of substitute materials in specific defense-related applications that are vital to *national security* is inadequate, several studies have categorized beryllium as a critical and strategic material (National Research Council, 2008, p. 170).

## Beryllium Use in the U.S. – 2011 (based on sales revenues)



Source: USGS \*Appliances, automotive electronics, energy, medical devices and other applications

# Beryllium—Substitutions

- Be is used in applications in which its properties are crucial, so few substitutions for many applications
- Graphite
- Steel
- Titanium
- Aluminum nitride
- Phosphor bronze

# Beryllium—Production

Metric tons

USGS Minerals Yearbook 2017

## Salient Statistics—United States:

	<u>2012</u>	<u>2013</u>	<u>2014</u>	<u>2015</u>	<u>2016<sup>g</sup></u>
Production, mine shipments	225	235	270	205	190
Imports for consumption <sup>1</sup>	100	57	68	66	51
Exports <sup>2</sup>	55	35	26	29	32
Government stockpile releases <sup>3</sup>	( <sup>4</sup> )	10	1	1	1
Consumption:					
Apparent <sup>5</sup>	265	262	318	233	210
Reported, ore	220	250	280	220	200
Unit value, annual average, beryllium-copper master alloy, dollars per pound contained beryllium <sup>6</sup>	204	208	215	220	231
Stocks, ore, consumer, yearend	15	20	15	25	25
Net import reliance <sup>7</sup> as a percentage of apparent consumption	15	10	15	12	10

## World Mine Production and Reserves:

	Mine production <sup>g</sup>	
	<u>2015</u>	<u>2016</u>
United States	205	190
China	20	20
Madagascar	5	5
Other countries	<u>1</u>	<u>1</u>
World total (rounded)	230	220

## Reserves<sup>g</sup>

The United States has very little beryl that can be economically hand sorted from pegmatite deposits. The Spor Mountain area in Utah, an epithermal deposit, contains a large bertrandite resource, which is being mined. Proven bertrandite reserves in Utah total about 14,000 tons of contained beryllium. World beryllium reserves are not available.

Brazil ships beryl to Utah  
Russians opened Malyshevsky emerald mine

# Be consumption 2013

## 250 mt, \$114 million

### Be alloy

- 32% aerospace applications
- **20% consumer electronics applications (computers)**
- **14% automotive electronics applications**
- 12% energy applications
- **12% telecommunications infrastructure applications**
- 8% appliance applications
- 2% defense and medical applications

### Be metal

- 52% defense and science applications
- 26% industrial components and commercial aerospace applications
- 8% medical applications
- 7% telecommunications infrastructure applications
- 7% other

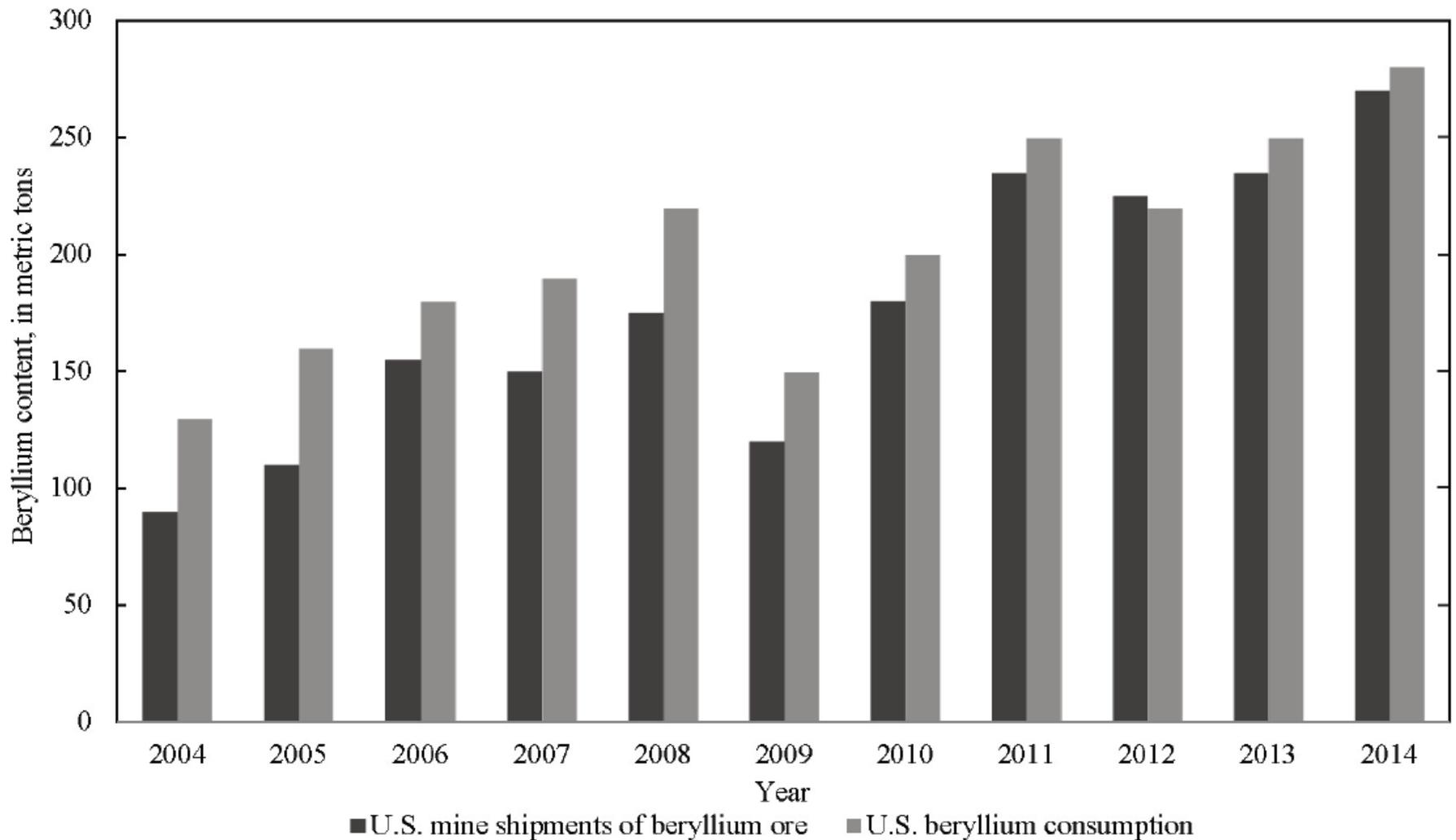
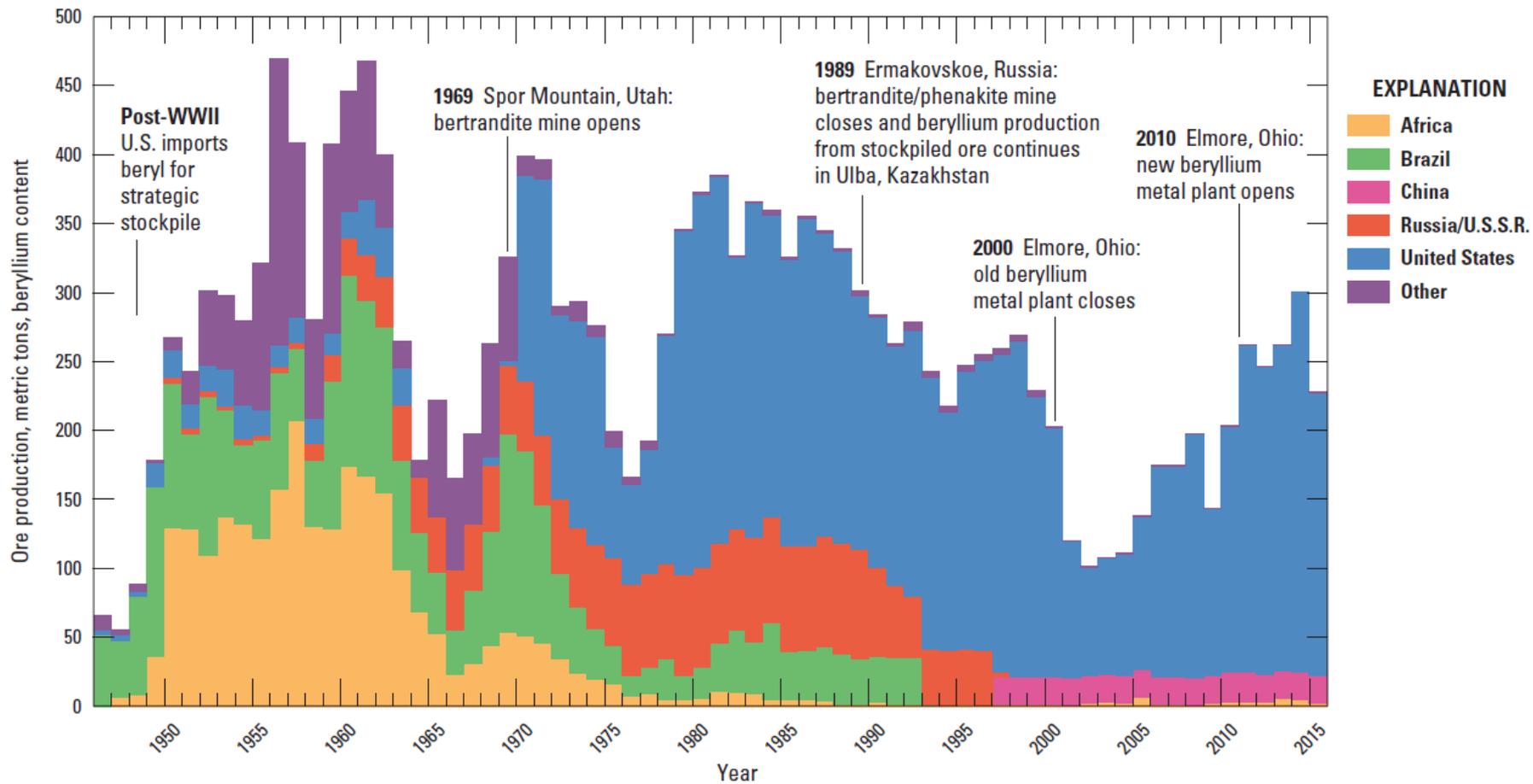
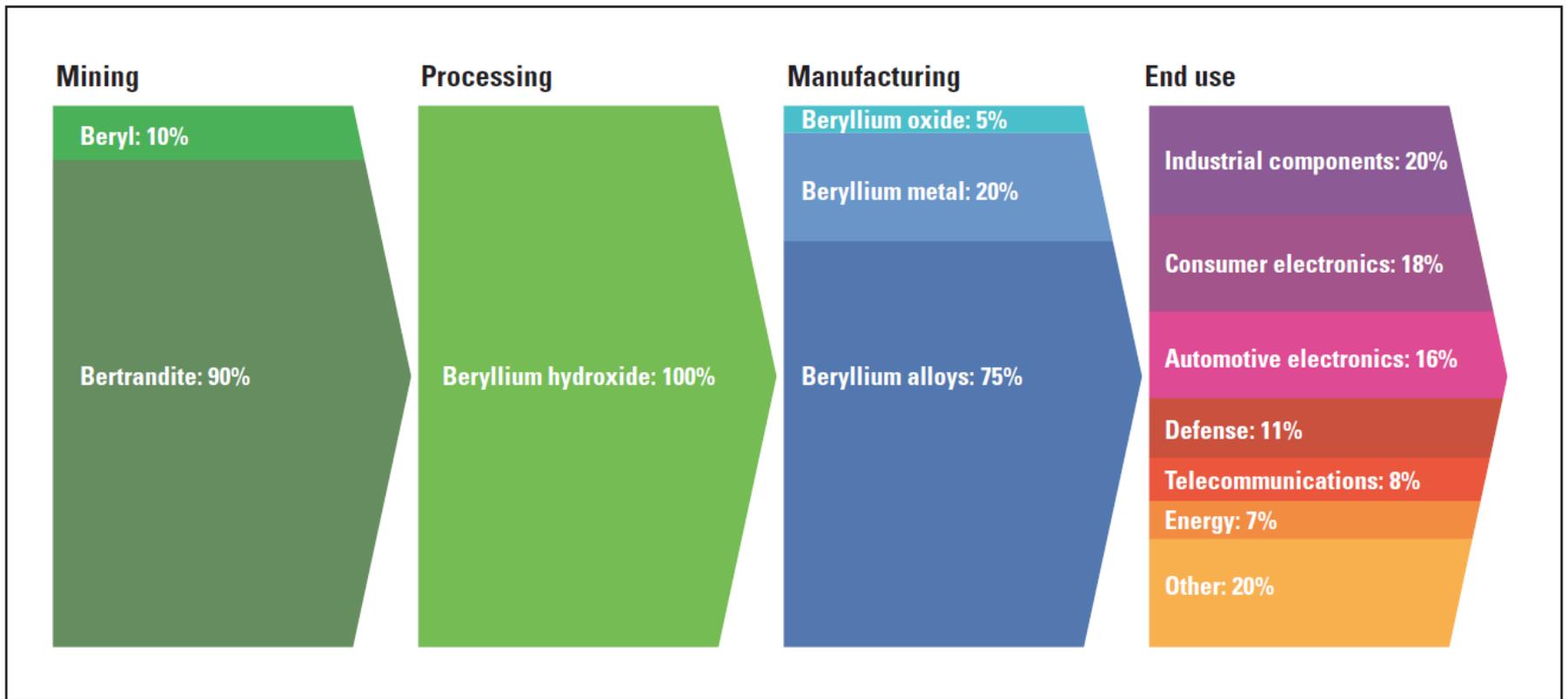


Figure 1. U.S. mine shipments of beryllium ore (Be content) and consumption of beryllium for 2004 through 2014. Source: U.S. Geological Survey.



**Figure 1.** Trends in beryllium mine production from 1946 through 2015 illustrate the dominance of United States production since the opening of the Spor Mountain, Utah, bertrandite mine in 1969. With the exception of Spor Mountain and Ermakovskoe, Russia, beryllium production was derived from beryl mined from pegmatite deposits.



**Figure 2.** Simplified flow diagram of the beryllium industry. Percentages are relative to the total beryllium flow at each stage; flows between stages do not account for losses, changes in stocks, or recycling. End use category labelled “Other” includes 2 percent used in medical applications (Materion Corporation, 2016).

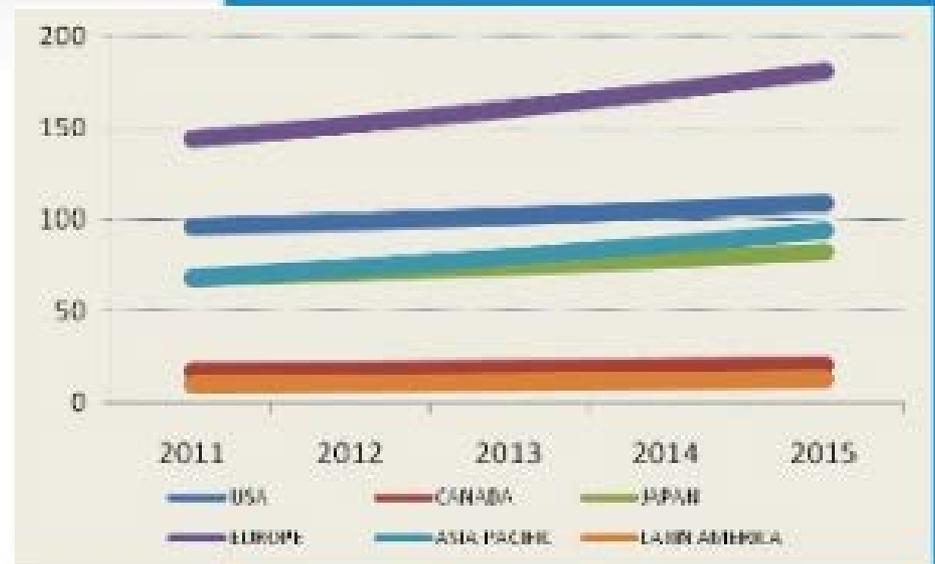
# Beryllium Market Structure

- Brush Resources is currently the sole US producer of beryllium concentrates.
- Spor Mountain and Hogs Back mines produce bertrandite.
- Processing plant at Delta, UT produces beryllium hydroxide from bertrandite and beryl for sale to beryllium markets.
- Can you afford to ship product to Delta, UT at the price Brush will pay?
- Will Delta accept your product?

'Global Beryllium Demand to Reach 465 Metric Tons by 2015" Global Industry Analysts, Inc. 2010

### Growing Be supply/demand imbalance favors suppliers

- Only three primary sources globally (BW, Ulba, US gov't)
- No spot market
- Dramatic price rise (44%) between 2006 and 2008 (up to \$500/kg)
- High price has prevented wider use of Be
- One source (US Govt. stockpile) decreased availability 2008 / 2009



### WORLD BERYLLIUM CONSUMPTION (METRIC TONS)

Source: *Beryllium – A Global Strategic Business Report*, Global Industry Analysts, Inc.

# Supply/Demand

- ◆ The uses for beryllium and thus the market are expanding.
- ◆ The Brush Resources operation has reserves sufficient to meet its needs for many years to come.
- ◆ Mine production is based on the amount of beryllium hydroxide that can be sold and thus varies from year to year.

# Beryllium—Mineralogy

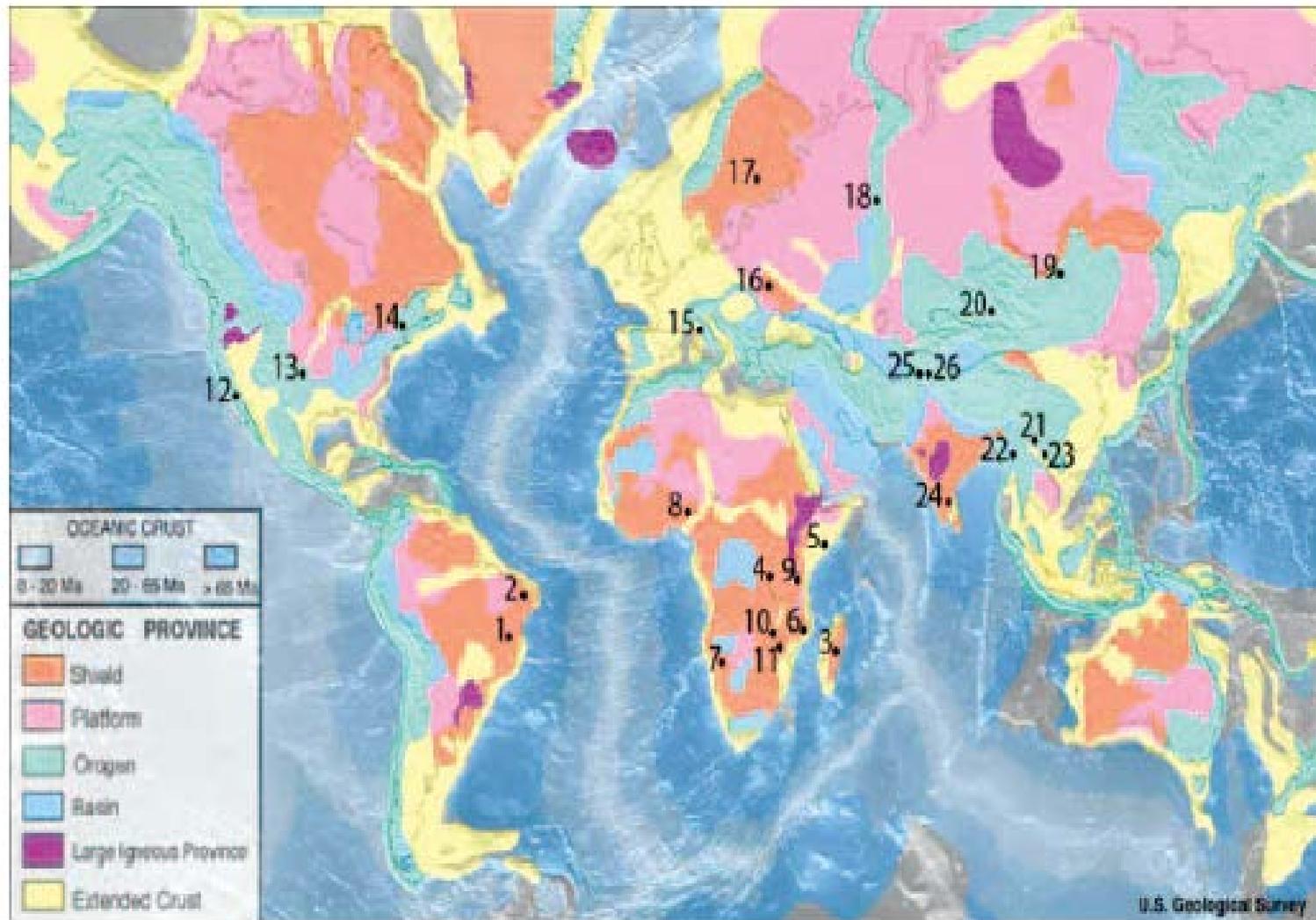


# Gemstones



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





**FIGURE 6** Major gem-pegmatite districts of the world; the numbers correspond to the districts in TABLE 2.  
 Geologic Province Map of the World, U. S. Geological Survey  
 (<http://earthquake.usgs.gov/research/structure/crust/maps.php>)

Simmons et al., 2012

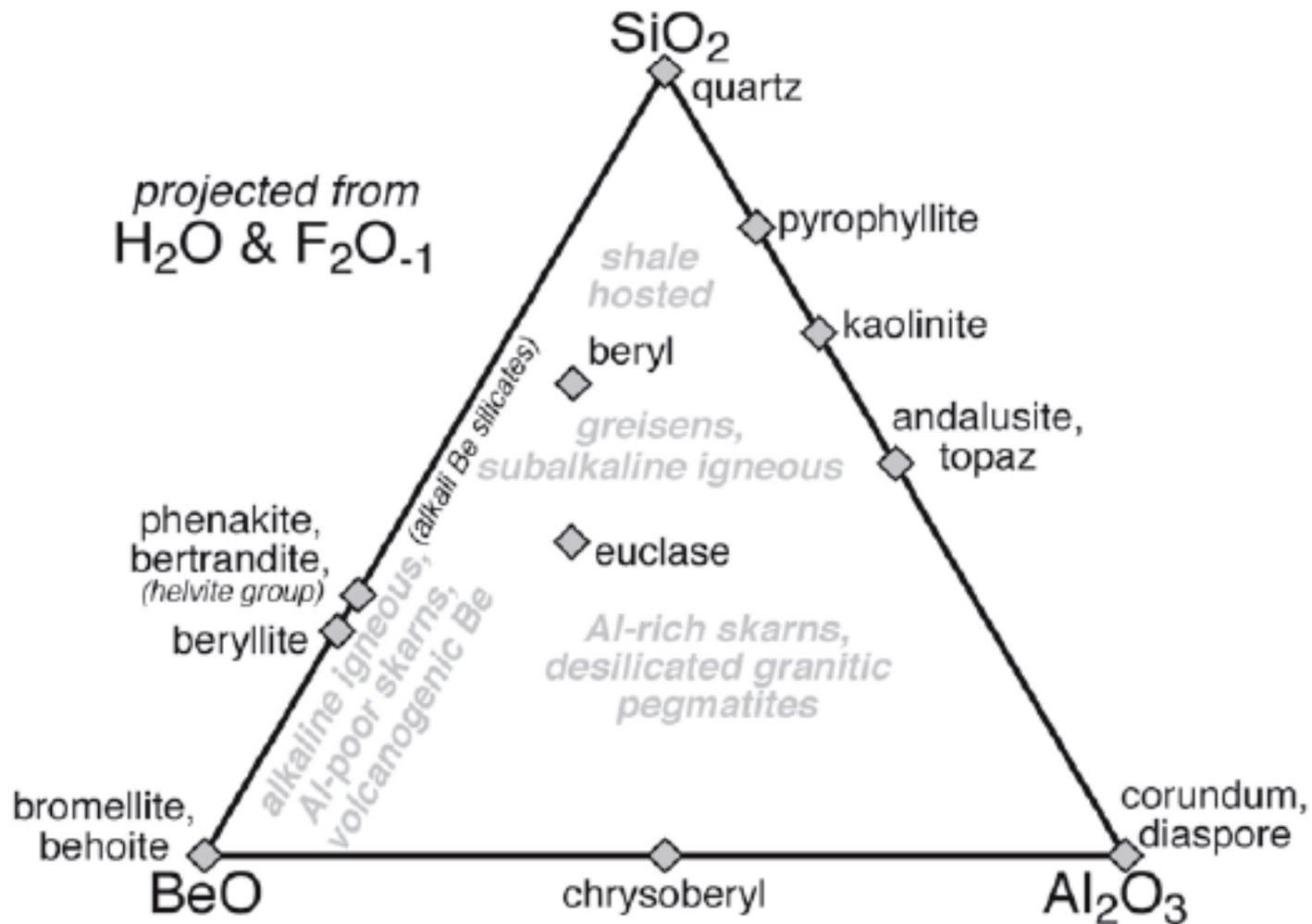
**Table 2. Comparison of some beryllium minerals**

<b>Mineral</b>	<b>Chemical Composition</b>	<b>% BeO</b>
Barylite	$\text{BaBe}_2\text{Si}_2\text{O}_7$	15.4–15.8
Bertrandite	$\text{Be}_4\text{Si}_2\text{O}_7(\text{OH})_2$	39.6–42.6
Beryl	$\text{Be}_3\text{Al}_2(\text{SiO}_3)_6$	10.0–14.0
Beryllonite	$\text{NaBePO}_4$	19.8
Chrysoberyl	$\text{BeAlO}_4$	16.9–19.7
Danalite	$\text{Fe}_4\text{Be}_3(\text{SiO}_4)_3\text{S}$	12.7–13.8
Eudidymite	$\text{HNaBeSi}_3\text{O}_8$	10.6–11.1
Helvite	$\text{Mn}_4\text{Be}_3(\text{SiO}_4)_3\text{S}$	10.5–15.0
Herderite	$\text{CaBePO}_4(\text{OH},\text{F})$	15.0–15.8
Phenakite	$\text{Be}_2\text{SiO}_4$	44.0–45.6

Adapted from Warner et al. 1959.

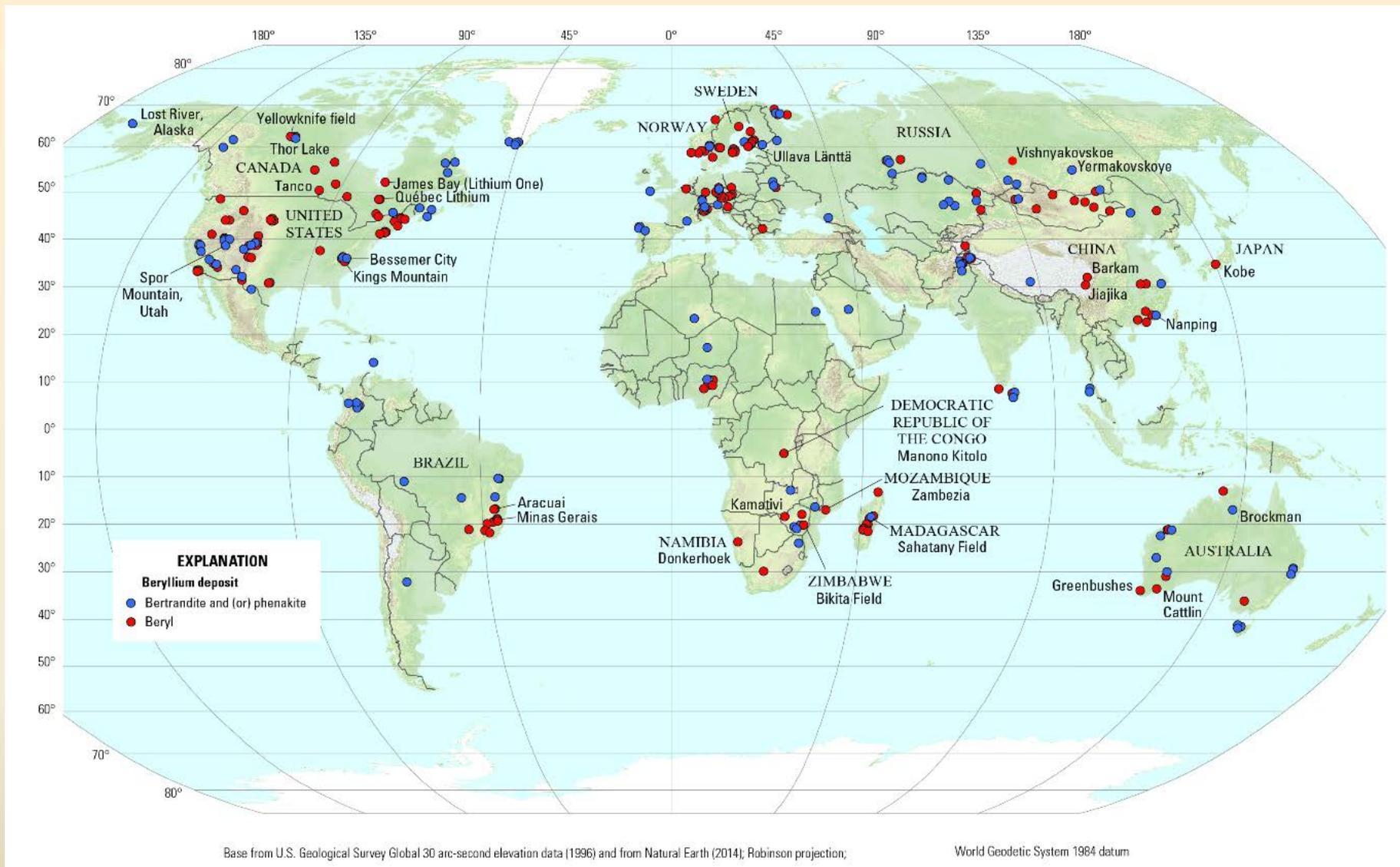
Name, Formula	Colour	Hardness	Specific gravity	Lustre	Crystal form	Transparency	Fracture
Barylite $\text{BaBe}_2\text{Si}_2\text{O}_7$	colourless, white, yellow	7	4	silky, greasy or vitreous	orthorhombic or monoclinic	transparent- translucent	brittle
Bertrandite $\text{Be}_4\text{Si}_2\text{O}_7(\text{OH})_2$	colourless, white, pale yellow	6-7	2.6	vitreous to pearly	orthorhombic	transparent	brittle
Beryl $\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$	white, pale- blue, green	7.5-8	2.6-2.9	vitreous	trigonal	transparent- translucent	uneven to conchoidal, brittle
Chrysoberyl $\text{BeAl}_2\text{O}_4$	green, yellow, red	8.5	3.5-3.8	vitreous	orthorhombic	transparent- translucent	conchoidal to uneven, brittle
Eudidymite $\text{NaBeSi}_3\text{O}_7(\text{OH})$	colourless, white, yellow, blue	6-7	2.55	vitreous	monoclinic	transparent- translucent	brittle
Helvite $(\text{Mn,Fe,Zn})_4\text{Be}_3\text{Si}_3\text{O}_{12}\text{S}$	brown, yellow, grey	5.5-6.5	3.2-3.4	vitreous to resinous	cubic	transparent- translucent	conchoidal to uneven, brittle
Phenakite/ Phenacite $\text{Be}_2\text{SiO}_4$	colourless, white	7.5-8	2.9-3.0	vitreous	trigonal	transparent	conchoidal, brittle

Table 1: Properties of some beryllium minerals.



**Figure 1.** Chemography of the principal solid phases in the BeO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-H<sub>2</sub>O(-F<sub>2</sub>O<sub>.1</sub>) “BASH” system with the projected positions of helvite group and alkali Be silicates. Also shown are generalized fields for some of the major types natural of occurrences (cf. Table 1, Fig. 4; see text for discussion).

# **GEOLOGY**



<https://minerals.usgs.gov/science/beryllium/images/world-Map-Of-Be-Deposits.jpg>

# TYPES OF BERYLLIUM DEPOSITS

TABLE 5. Types of beryllium deposits (Beus, 1966; Barton and Young, 2002; Sabey, 2006). USGS Classification after Cox and Singer (1986), Ludington and Plumlee (2009), and Foley et al. (2010).

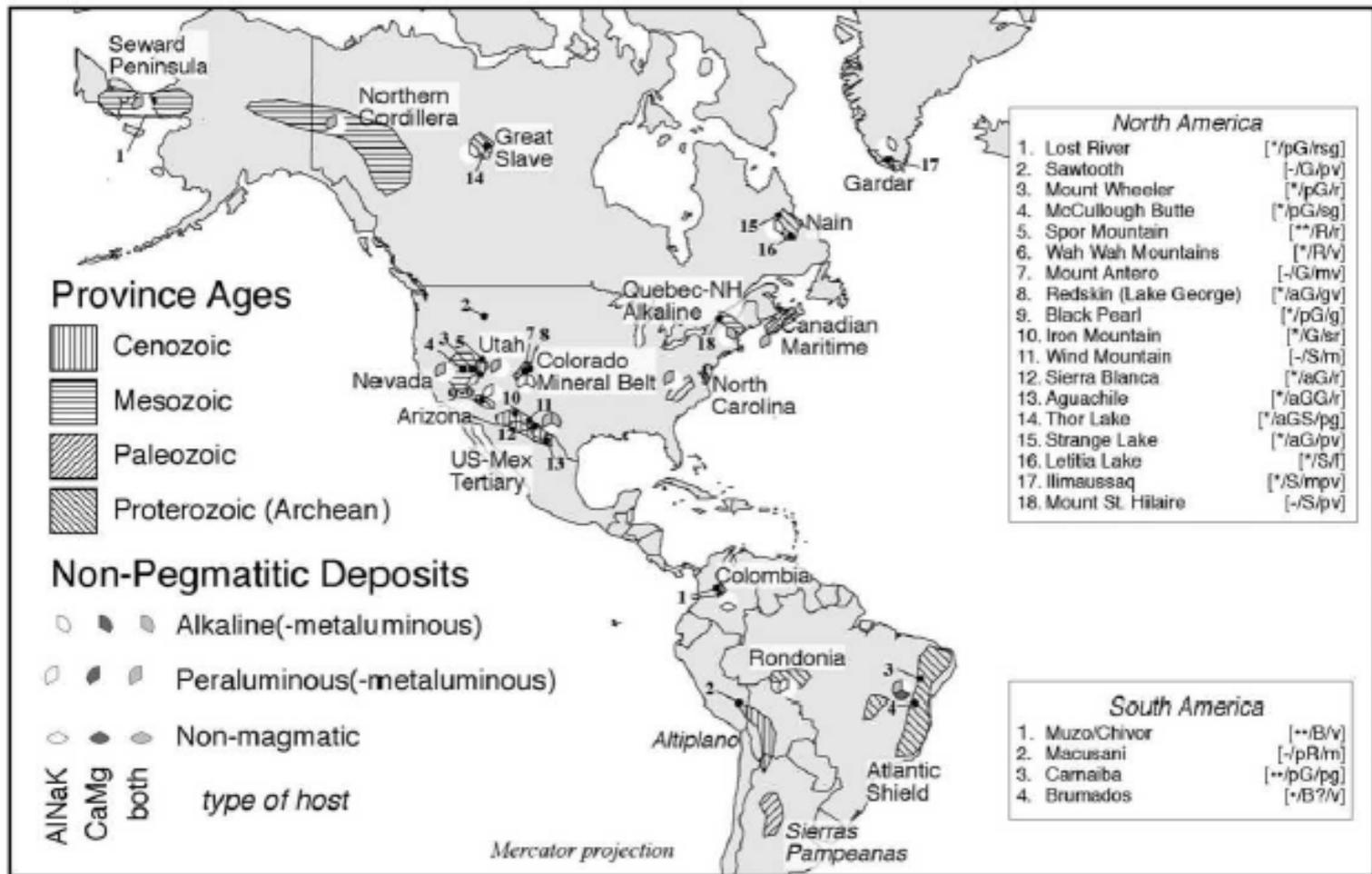
Type of Be deposit	USGS Classification	Example
Pegmatites	13	Tanco, Canada
Volcanogenic Be (volcanic-hosted replacement, volcanic-epithermal, Spor Mountain Be-F-U deposits)	Volcanogenic Be deposits	Spor Mountain, Utah
Carbonate-hosted replacement and skarn (Mo-W-Be, F-Be, Fe-Mn)	14a	Ermakovskoe, Russia
Alkaline igneous rocks (disseminations and veins in peralkaline rocks and fenites)	11	Strange Lake, Canada
Granite/rhyolites (topaz rhyolites)	25h	Taylor Creek, NM
Tin skarns	15c, 14b, 14c	Lost River, Ak
Greisens	Mo-W greisens, 15c	Boomer, Colorado
Veins	–	Columbia black shale
Porphyry molybdenum ( $\pm$ copper, tungsten)	16, 21a, 21b	Questa, NM
Metamorphic (schist)	31c	Regal Ridge, Yukon, Canada
Placer (mostly beryl and babefphite)	–	–
Coal	–	–

**Table 3. Significant beryllium deposits and resources**

Deposit(s)	Location	Resource, tons BeO	Grade, % BeO	Source
<b>Volcanic rock-hosted</b>				
Spor Mountain	Utah, United States	72,315*	0.71	This volume
<b>Pegmatite</b>				
Various	North Carolina, United States	122,800	0.05	Griffitts 1954
Various	Brazil	42,000	0.04	Soja and Sabin 1986
Various, Black Hills	South Dakota, United States	13,300	na†	Runke, Mullen, and Cunningham 1952
Tanco	Canada	1,800	0.20	Cerný 1982
Hellroaring Creek	Canada	<1,000	0.10	Barton and Young 2002
<b>Replacement and skarn</b>				
McCullough Butte	Nevada, United States	47,000	0.027	Barton and Young 2002
Sierra Blanca	Texas, United States	11,300	>2.0	Anon. 1986
Ermakovskoe	Russia	>10,000	1.3	Barton and Young 2002
Lost River	Alaska, United States	>10,000	0.3–1.75	Sainsbury 1963
Iron Mountain	New Mexico, United States	<1,000	0.2–0.7	Jahns 1944
<b>Peralkaline rock-hosted</b>				
Strange Lake	Canada	42,000	0.08	Richardson and Birkett 1996
Ilimaussaq	Greenland	>20,000	na	Barton and Young 2002
Thor Lake	Canada	13,300	0.76	Richardson and Birkett 1996
Seal Lake	Canada	6,800	0.35–0.40	Richardson and Birkett 1996
<b>Greisen</b>				
Aqshatau	Kazakhstan	16,000	0.03–0.07	Barton and Young 2002
Boomer	Colorado, United States	<1,000	2.0–11.2	Hawley 1969
<b>Vein</b>				
Gold Hill	Utah, United States	>5,000	0.5	Shawe 1966
Mount Wheeler	Nevada, United States	<1,000	0.75	Shawe 1966

\* Remaining reserves 2004.

† na = not available.

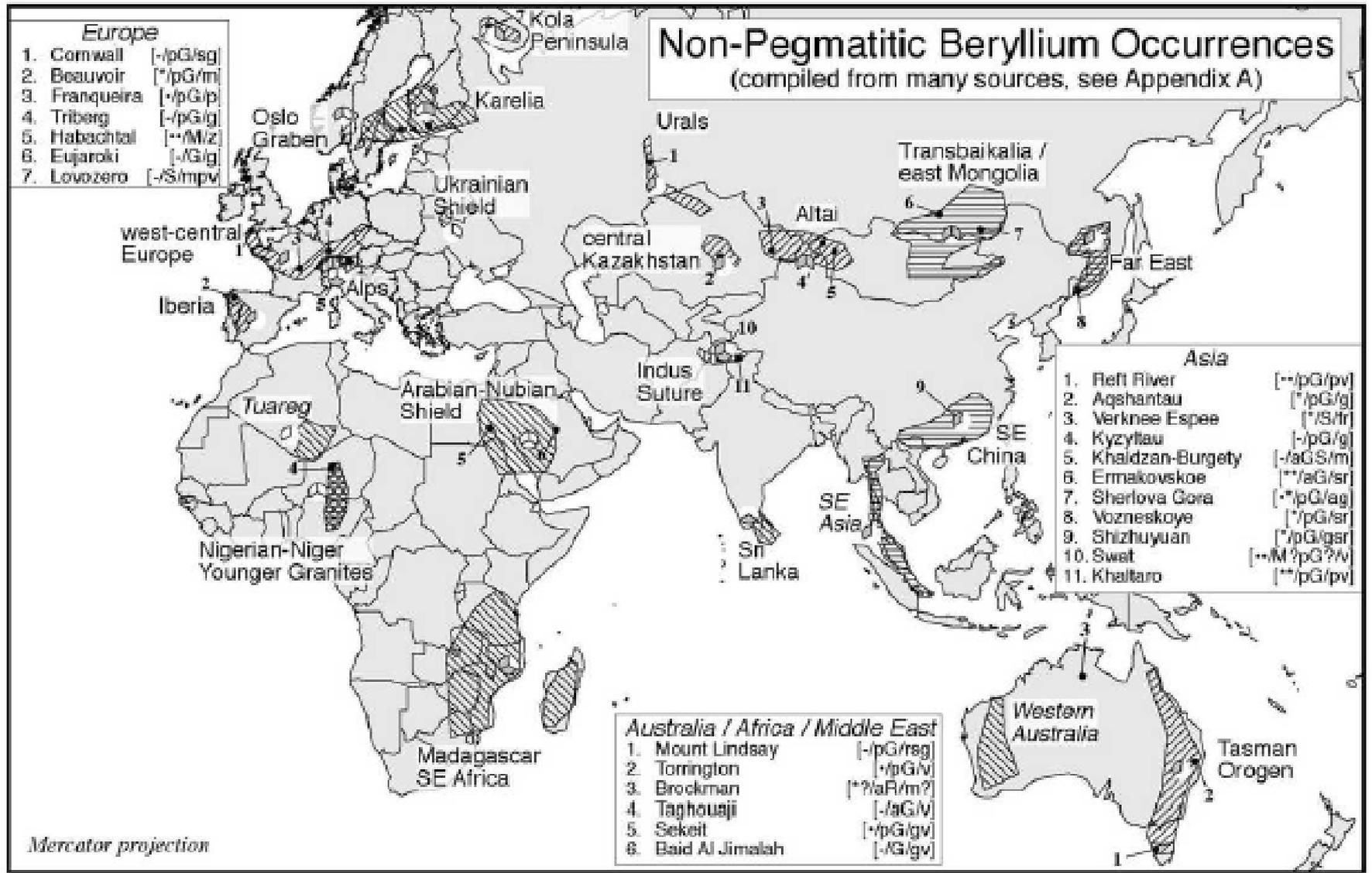


**Figure 2.** Map showing the location of non-pegmatitic Be occurrences and the Be-bearing belts that are mentioned in this paper. Deposit-type assignments can be uncertain or generalized depending on available information and the complexity of the region. The Symbolism for the key deposits is: significance (0-2 stars) / petrologic association (figure and caption continued next page >>>)

Barton and Young

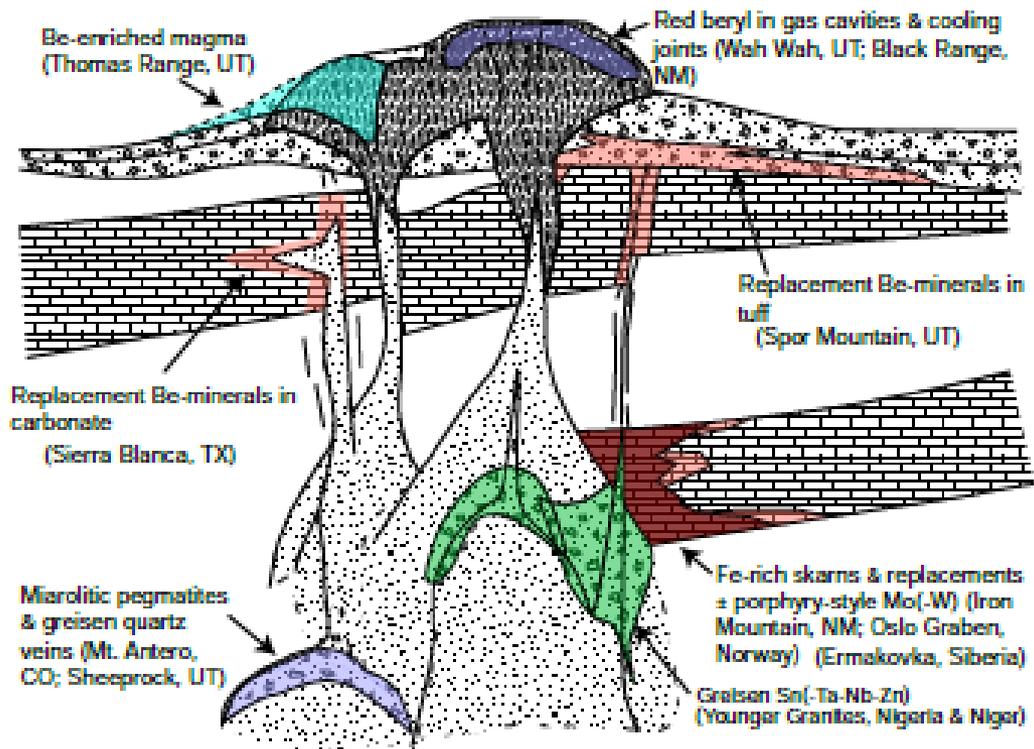


MERCATOR PROJECTION



Barton and Young

## Be environments associated with metaluminous and weakly peraluminous systems



### Rock Types

-  Rhyolite lavas and pyroclastic tuff deposits
-  Subvolcanic intrusions, domes, caldera structures
-  Granites, syenites, porphyry-style intrusives
-  Paleozoic sedimentary sequences, platform carbonates,

### Mineralization styles

-  Magmatic enrichments (dispersed in minerals or volcanic glass)
-  Miarolitic & pegmatitic zones (Alpine type clefts or pegmatites in metamorphic rocks)
-  High-temperature (>300°C) veins, individual, sheeted & stockwork
-  Low-temperature (<300°C) veins, mostly individual or sheeted
-  Skarns, typically F-rich with variable Al-Fe-metal contents
-  Carbonate replacement deposits, typically F-rich

A generalized cross-section showing geologic setting for the major types of Be deposits associated with metaluminous and weakly peraluminous magma systems and the relationship of volcanogenic Be deposits such as Spor Mountain to other type of Be deposits that are associated with magmas of this general composition. Modified from Barton and Young (2002).

# **Volcanic-hosted replacement deposits**

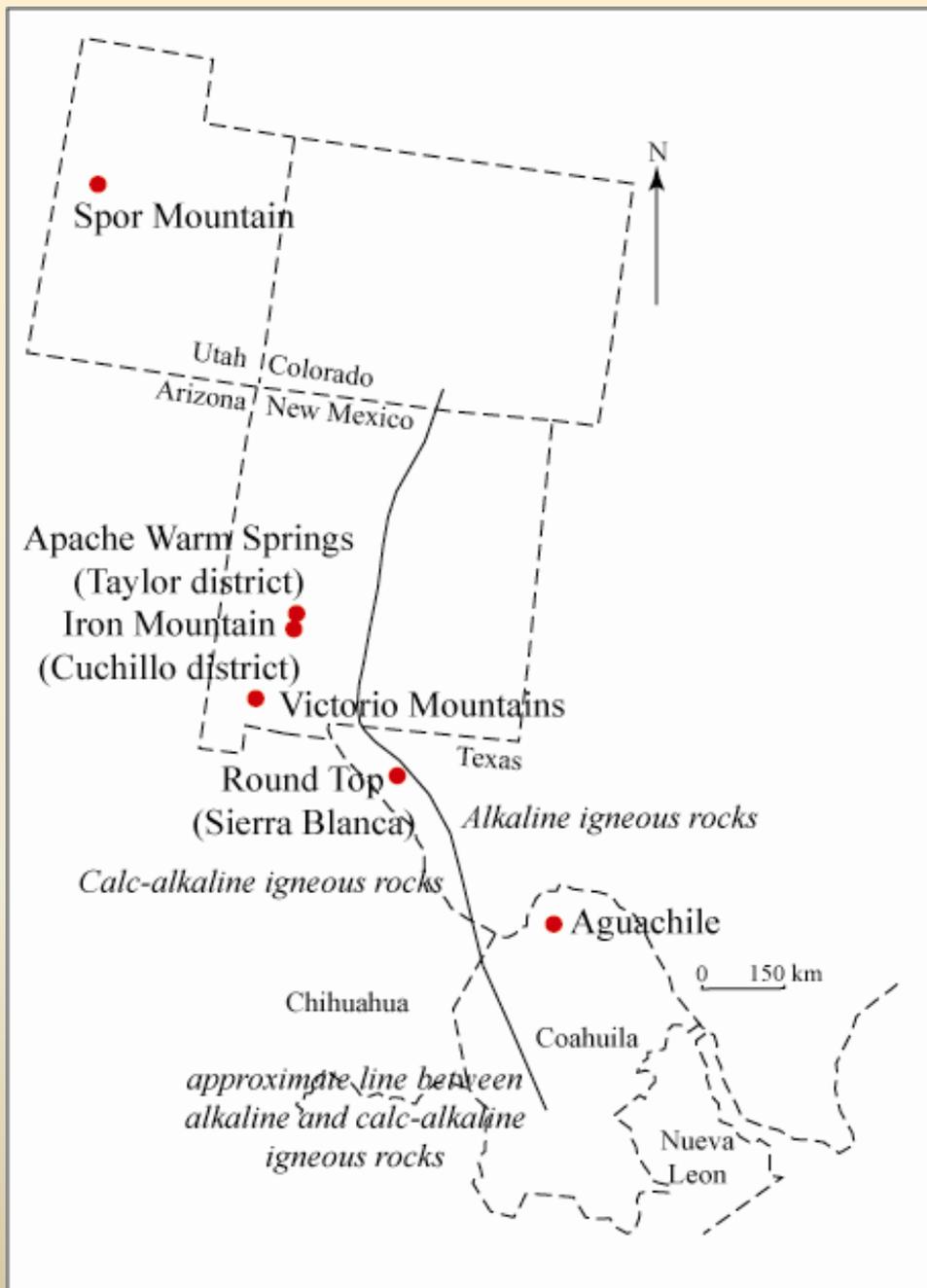
**Table 1.** Deposits and occurrences considered in developing the volcanogenic epithermal beryllium (Be) deposit model.

[Data summarized primarily from Barton and Young (2002, their appendix A); Mt, million metric tons; kT, kiloton; Ma, million years ago; ppm, parts per million]

<b>Deposit/ occurrence</b>	<b>Age of complex/ volcanic unit/ mineralization</b>	<b>Brief description of occurrence and contained Be ore</b>	<b>Primary data references</b>
Spor Mountain/ Utah, U.S.A.	Middle Cenozoic/ ≈21 Ma/≈21 Ma and younger	Bertrandite in fluorite-silica replacement of carbonate clasts in lithic tuff (7 Mt at 0.72% BeO), extensive Li-Zn-bearing K-feldspar and clay alteration; overlying 6–7 Ma topaz rhyolites have red beryl	Griffitts, 1964; Shawe, 1966, 1968; Lindsey and others, 1973; Lindsey, 1977; Ludwig and others, 1980; Burt and Sheridan, 1981; Baker and others, 1998
Honey Comb Hills/ Utah, U.S.A.	Middle Cenozoic	Be in fluorite-silica replacements, stringers, veins in tuff	Montoya and others, 1964; McAnulty and Levinson, 1962
Wah Wah Mountains/ Utah, U.S.A.	Middle Cenozoic/ ≈23 Ma	Topaz rhyolite with late red beryl + kaolinite in fractures with early Mn-Fe oxides; main gem red beryl source	Keith and others, 1994; Thompson and others, 1996
Apache Warm Springs/Socorro County, New Mexico, U.S.A.	Middle Cenozoic/ ≈28 Ma/≈<28– >24.4 Ma, bracketed by stratigraphy	Bertrandite in small quartz veins and stringers in fractures and disseminations in rhyolite and rhyolite ash-flow tuff, intense acid-sulfate alteration	McLemore, 2010a,b and references therein; Shawe, 1966; Hillard, 1969; Be Resources, Inc. at <a href="http://www.beresources.com">http://www.beresources.com</a> ; accessed December 10, 2011
Aguachile/ Coahuila, Mexico	Middle Cenozoic/ ≈28 Ma	Bertrandite-adularia-bearing fluorite replacement (17 Mt at 0.1% BeO) adjacent to alkaline rhyolite and riebeckite quartz syenite	Levinson, 1962; McAnulty and others, 1963; Griffitts and Cooley, 1978; Simpkins, 1983

Sierra Blanca/ Texas, U.S.A.	Middle Cenozoic/ 36.2 Ma/coeval with intrusion	Fluorite-rich replacement bodies in limestone adjacent to Li-Be-Zn-Rb-Y-Nb-REE-Th-rich alkaline cryolite-bearing rhyolites; 850 kT at 1.5% BeO as bertrandite, phenakite (behoite, berborite, chrysoberyl); minor grossularitic skarn; clays + analcime	McAnulty and others, 1963; Price and others, 1990; Rubin and others, 1987, 1988, 1990; Henry, 1992
Northern Basin and Range Province/ Oregon, Idaho, Nevada, Utah, and California, U.S.A.	Middle Cenozoic/ Miocene	Mainly western Utah Be belt; most occurrences in volcanic rocks, but also skarn (helvite-beryl) and granite-hosted occurrences—dominant Be producer; magmas up to 80 ppm Be	Warner and others, 1959; Shawe, 1966; Lindsey, 1977; Burt and Sheridan, 1986; Congdon and Nash, 1991
Andean Altiplano/ Macusani, Peru	Middle Cenozoic/ Miocene (4.2 Ma; 9.3 Ma)	Beryllium minerals apparently rare, but widespread. Miocene rare-metal-enriched felsic intrusive and volcanic centers, many with Sn-Ag-(±B) ores, fluorite is relatively uncommon; Macusani tuff	Pichavant and others, 1988a,b; Lehmann and others, 1990; Dietrich and others, 2000; Noble and others, 1984
Transbaikal/ eastern Mongolia Teg-Ula	Mesozoic	Many deposit types associated with mainly Mesozoic granitoids ranging from peraluminous to peralkaline; volcanic-hosted Be in Mongolia	Kovalenko and Yarmolyuk 1995; Kremenetsky and others, 2000; Reyf and Ishkov, 2006; Lykhin and others, 2010
Shixi/ Zhejiang, South China	Mesozoic?	Hypabyssal dikes of porphyritic sodic rhyolite, albitized and sercitized, high Be (as helvite, beryl, bertrandite, and euclase) and Nb, Ta, Zr, F	Lin, 1985
Brockman/Western Australia	Paleoproterozoic/ 1870 Ma	Hydrothermally altered fluorite-bearing alkali rhyolite with Nb-Zr-REE-Ta-Be enrichment (4.3 Mt at 0.08% BeO); predates orogenesis	Ramsden and others, 1993; Taylor and others, 1995a,b

USGS SIR-5070f



Location of selected beryllium deposits found in southwestern U.S. and Mexico. Approximate line separating the Tertiary alkaline and calc-alkaline igneous rocks is from Price et al. (1987) and McLemore (1996).

# SPOR MOUNTAIN, UTAH



## BRUSH WELLMAN BERYLLIUM PLANT

[show on map]



This large industrial plant in the remote Sevier Desert of western Utah is one of the only sources of concentrated beryllium in the world. The plant is a mill and finishing facility for beryllium, a high-strength, lightweight metal used in military, aerospace, and medical industries. The ore for the plant comes from Brush Wellman's mine, located in the Topaz-Spor Mountains, 50 miles west, which is North America's only developed source for the metal. The facility is located here due to the remoteness of the area, as beryllium dust is highly toxic, and the proximity of a large source of power: the Intermountain Power Project, a massive coal-fired power plant located a few miles away.

**Visitation:** Located next to the road, at the intersection of Highway 6 and 174, 10 miles north of Delta.

**Coordinates:** 39.467606, -112.436913

**General Location:** Ten miles N of Delta

**State:** Utah

TABLE 3. Production and reserves from the Spor Mountain mine owned by Brush Wellman (metric tons Be content, McNeil, 2004; Brush Engineered Materials, Inc., 2004, 2008, 2009).

Year	Bertrandite processed tons	Grade % Be	Proven bertrandite reserves	Grade % Be	Probable bertrandite reserves	Grade % Be
Total 1969-2009	3,000,000	~0.2	–	–	–	–
2009	39,000	0.330	6,425,000	0.266	3,519,000	0.232
2008	64,000	0.321	6,454,000	0.266	3,519,000	0.232
2007	52,000	0.321	6,531,000	0.266	3,519,000	0.232
2006	48,000	0.352	6,550,000	0.267	3,519,000	0.232
2005	38,000	0.316	6,601,000	0.268	3,519,000	0.232
2004	39,000	0.248	6,640,000	0.268	3,519,000	0.232
2003	41,000	0.224	6,687,000	0.267	3,519,000	0.232
2002	40,000	0.217	6,730,000	0.267	3,519,000	0.232
2001	48,000	0.224	7,270,000	0.268	3,081,000	0.219
2000	84,000	0.235	7,690,000	0.263	3,166,000	0.217
1999	93,000	0.215	–	–	–	–

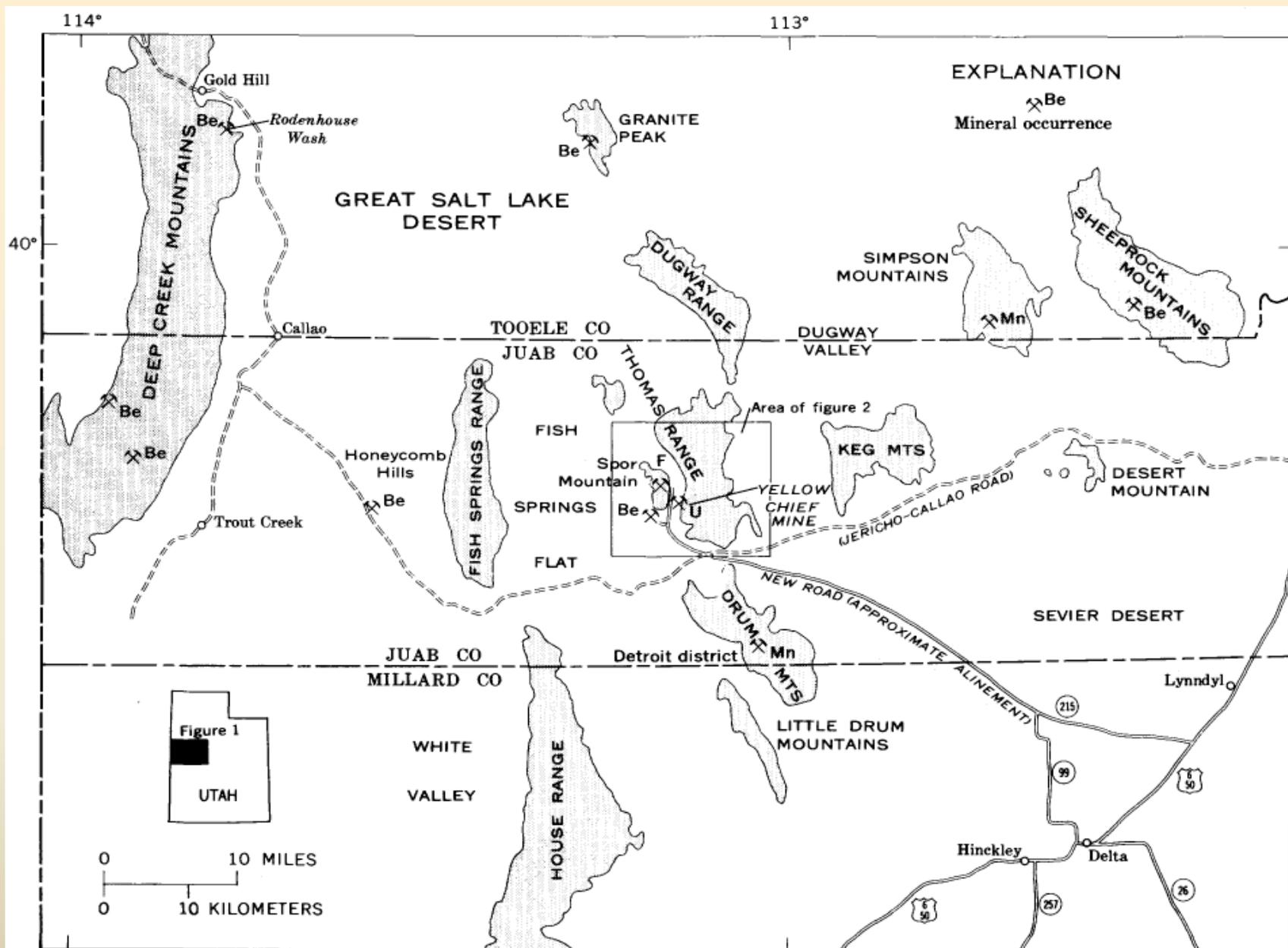
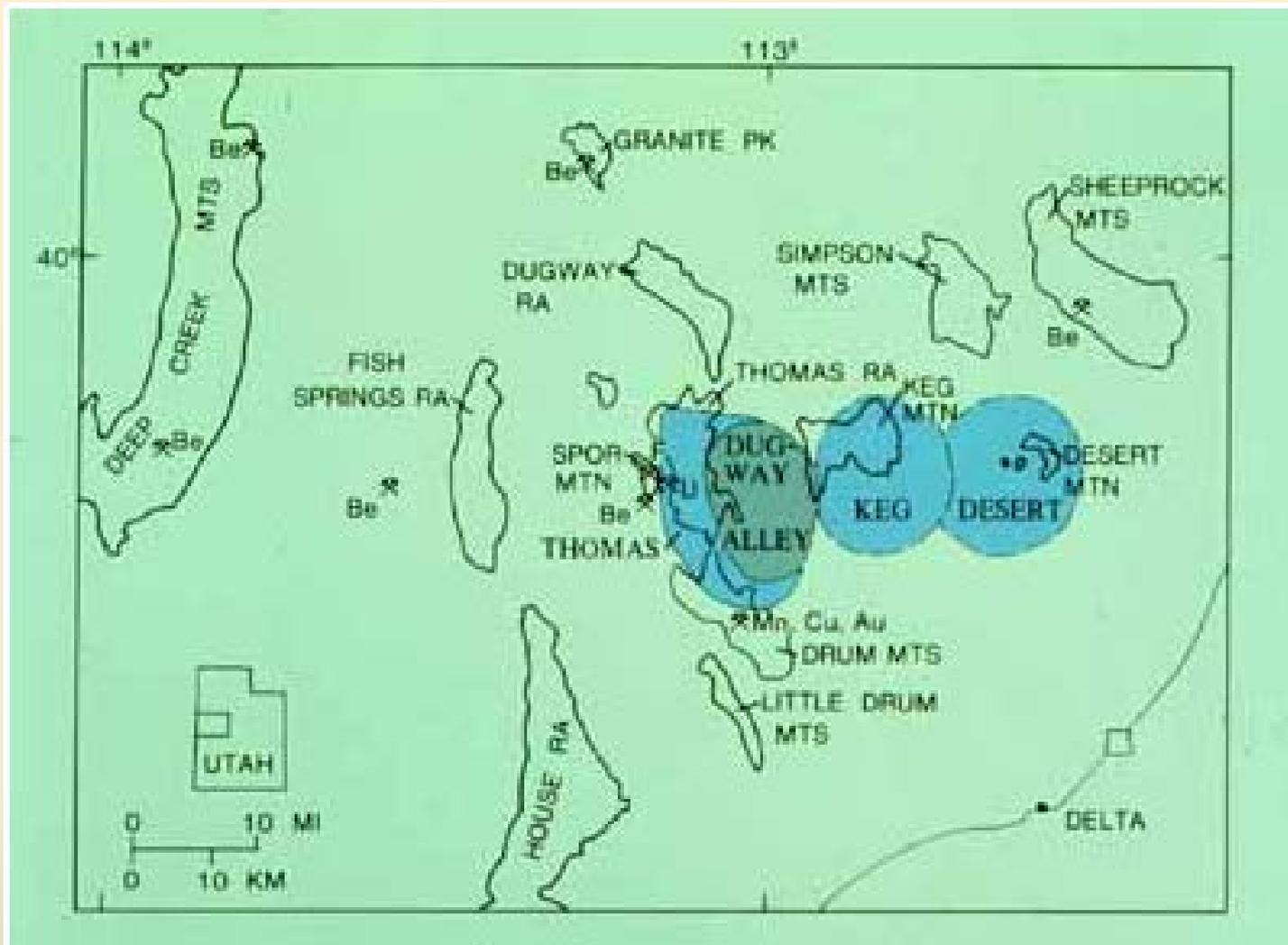
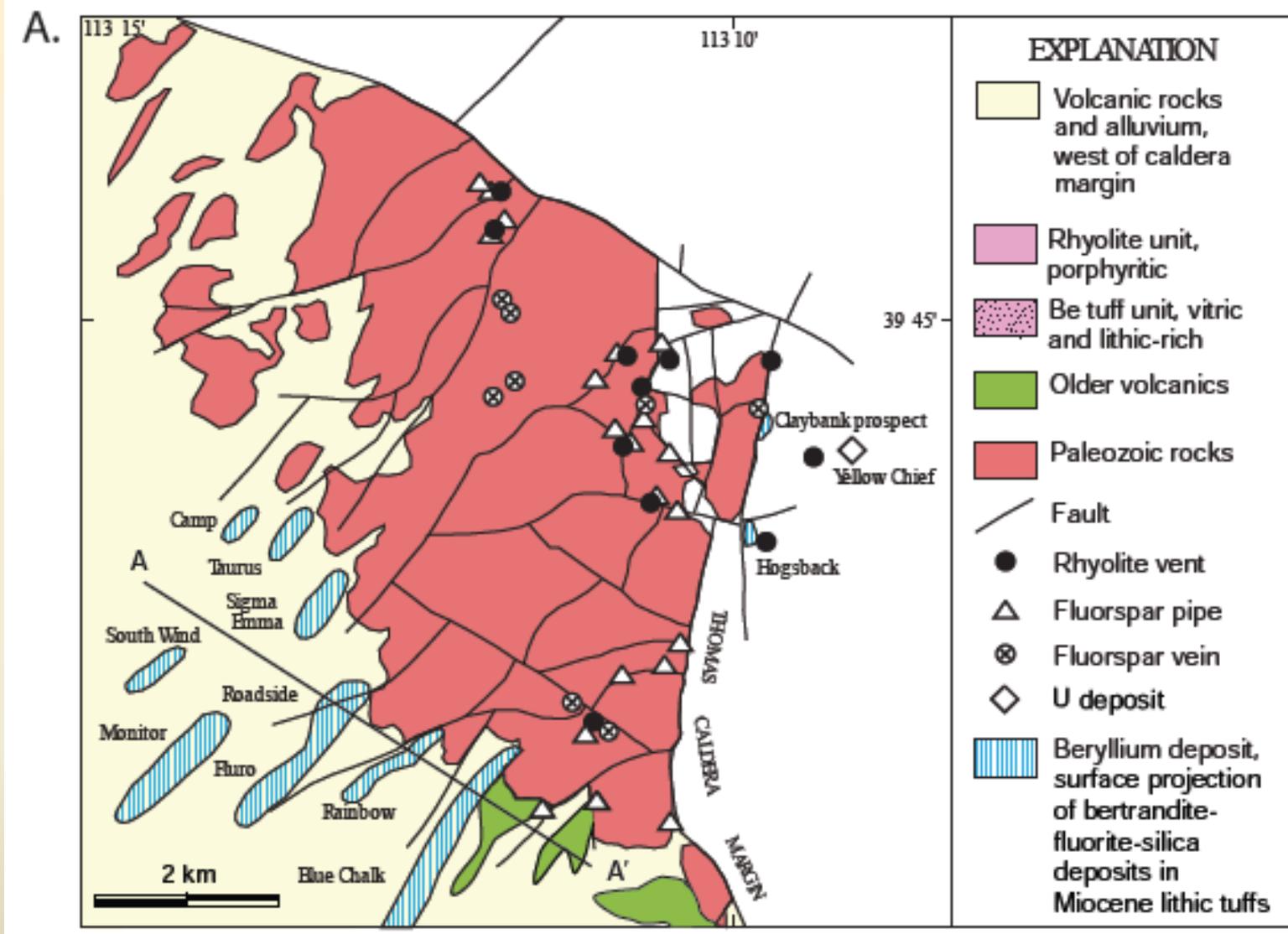


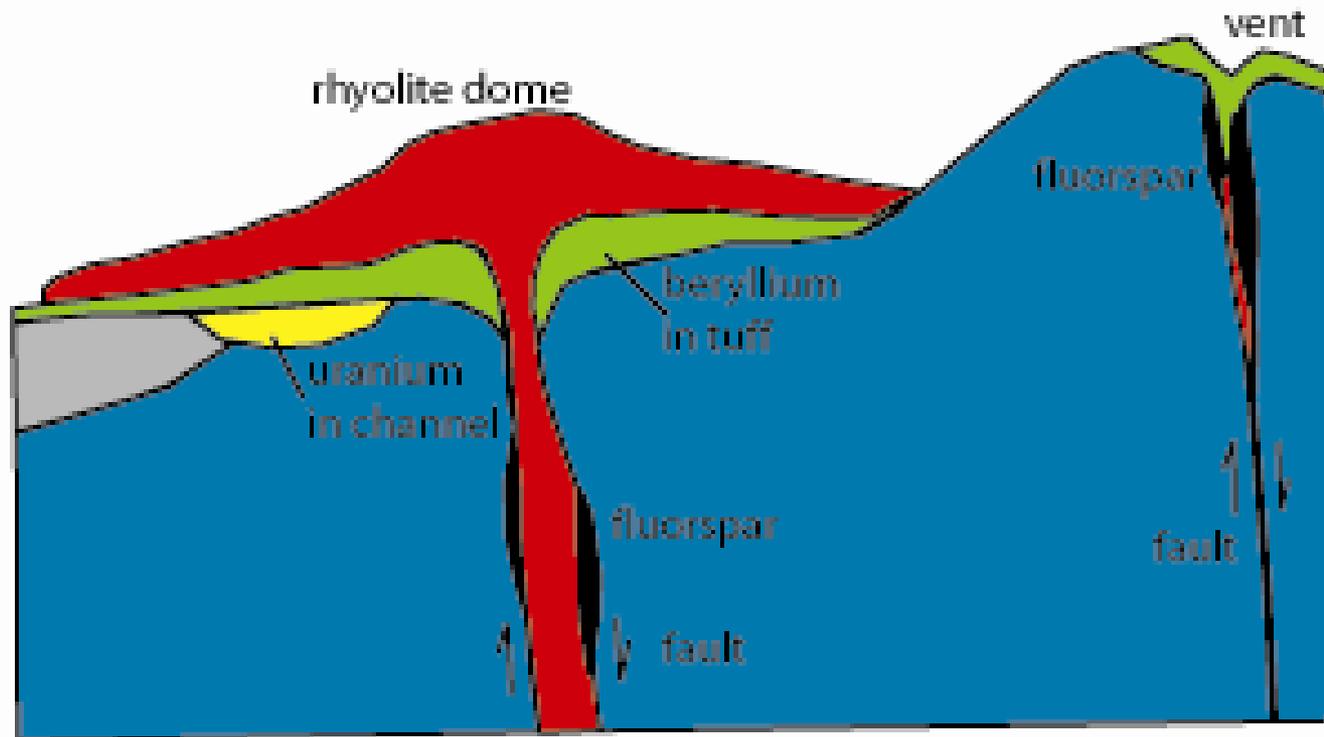
FIGURE 1. — Map showing location of Spor Mountain, other geographic features, and mineral occurrences mentioned in text.



Beryllium belt of western Utah," also the "Deep Creek-Tintic belt. Be, F, U, Li, Cu, Au, base metals (USGS OF 98-524)



Generalized geologic map of the Spor Mountain and Thomas Range area, Utah, showing the locations and distribution of Be deposits and fluorite pipes. Modified from Lindsey, 2001.



Miocene Spor Mountain Formation

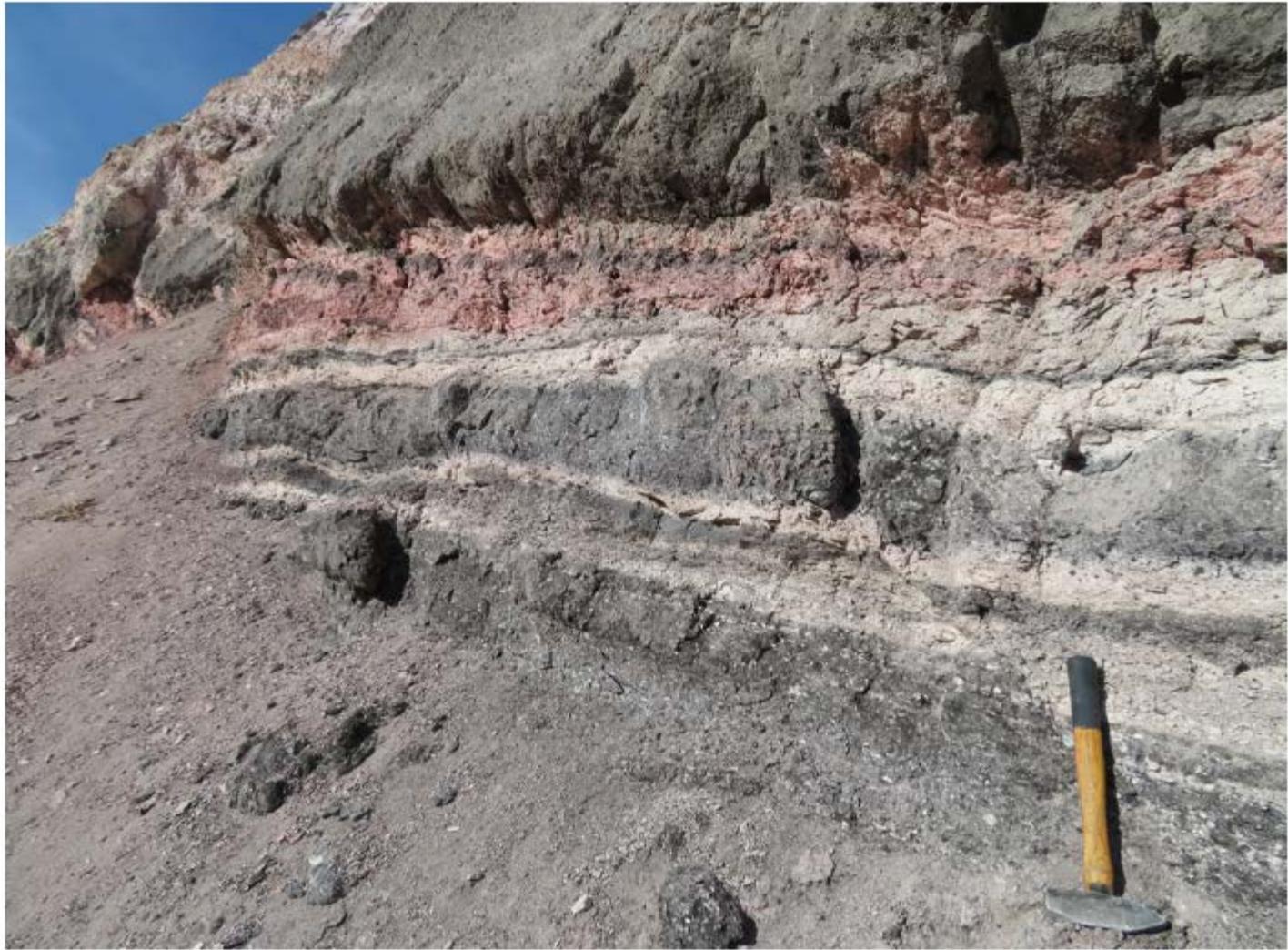
- porphyritic rhyolite
- vent breccia
- tuff
- tuffaceous sandstone and conglomerate

- Eocene Drum Mountains rhyodacite
- Paleozoic sedimentary rocks

# Spor Mountain—Cross section

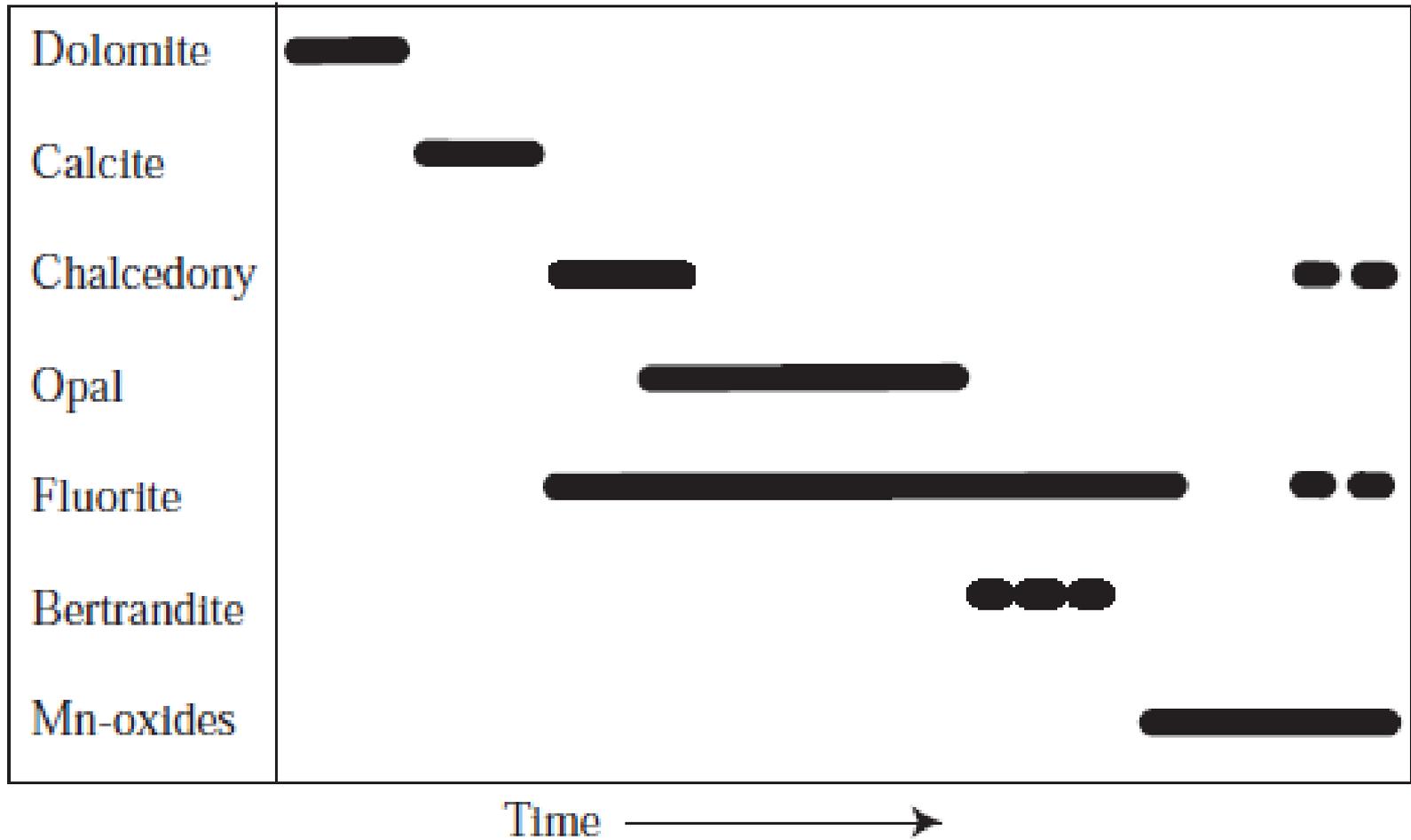


Overlying Spor Mountain rhyolite caprock and underlying Beryllium Tuff member. Photograph by Nora Foley, USGS.

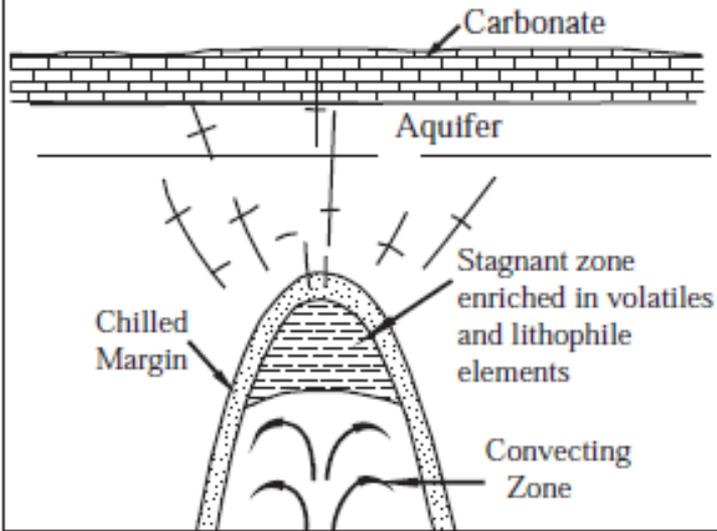


Closeup of the Beryllium Tuff member, Spor Mountain, Utah. Photograph by Nora Foley, USGS.

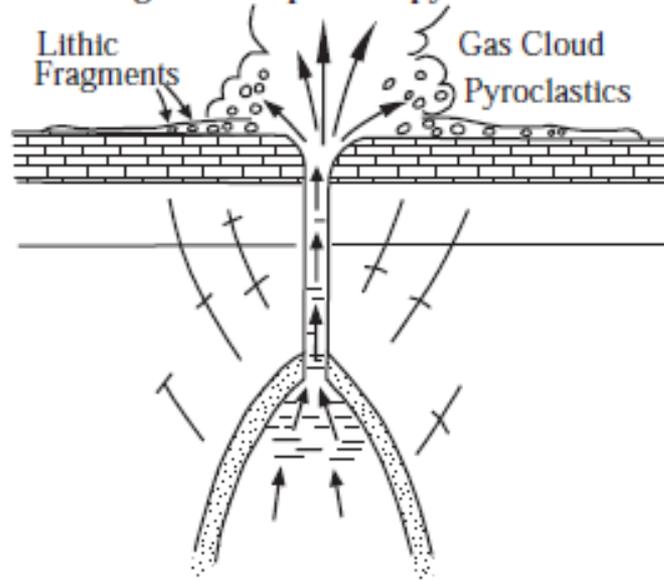
# Paragenesis Spor Mountain



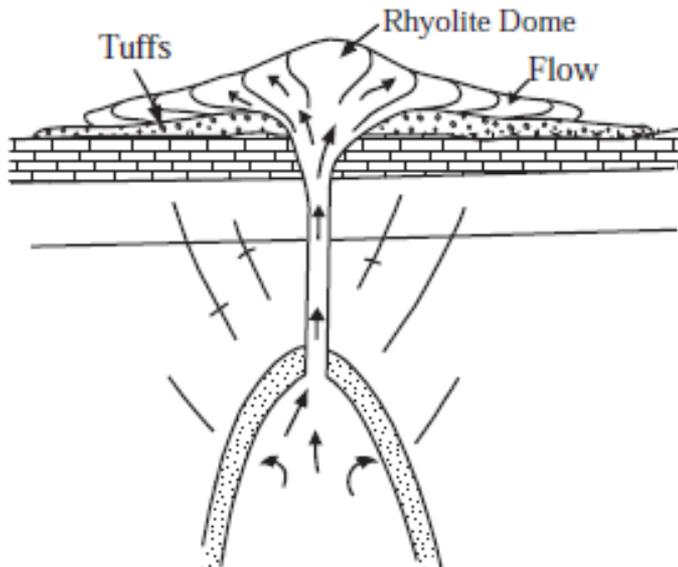
**Stage 1: Intrusion of magma**



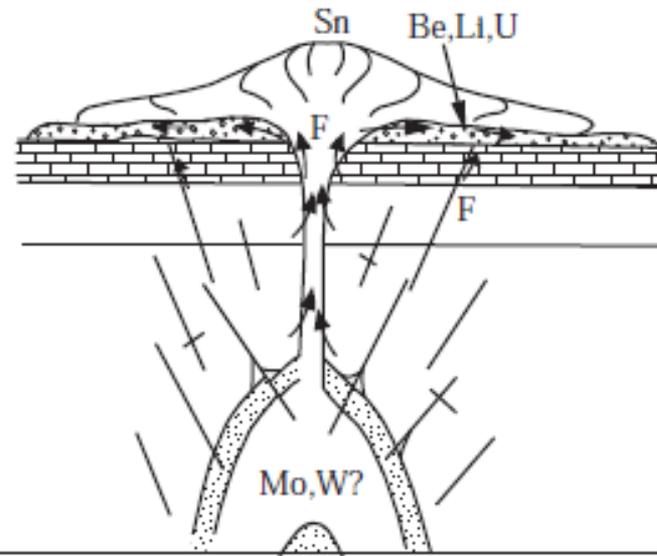
**Stage 2a: Eruption of pyroclastics**



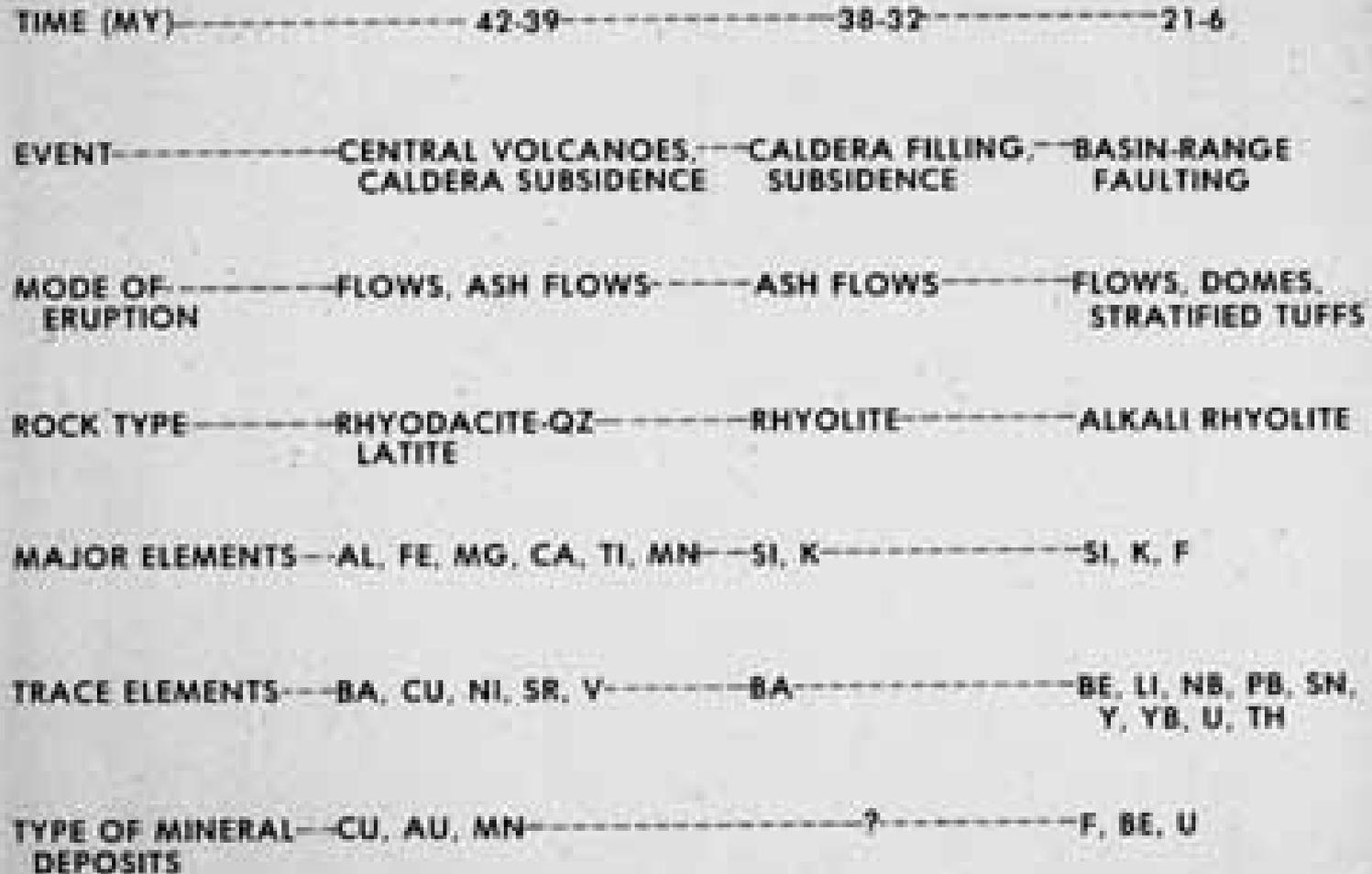
**Stage 2b: Eruption of dome-flow complex**



**Stage 3: Mineralization resulting from near-surface convection**



General model for formation of volcanogenic deposits of U and other lithophile elements, including Be, as proposed by Burt and Sheridan (1981).



USGS OF 98-524



Be at Spor Mountain has been mined  
by Brush Wellman since about 1970,  
Roadslide pit in 1970 (USGS OF 98-  
524)



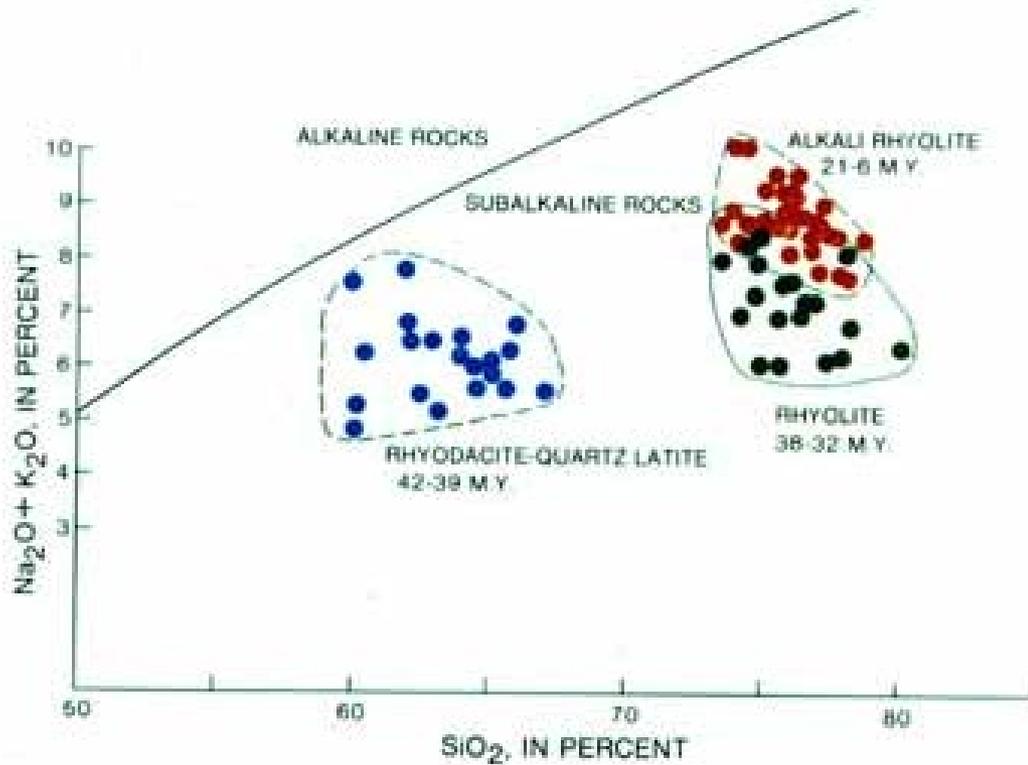
Monitor pit as it appeared in 1979,  
also Brush-Wellman (USGS OF 98-  
524)

# Controls of mineralization

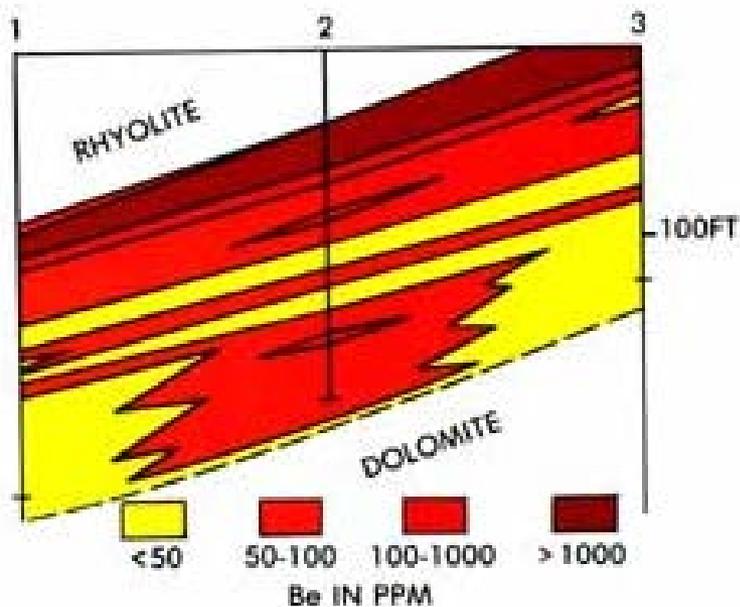
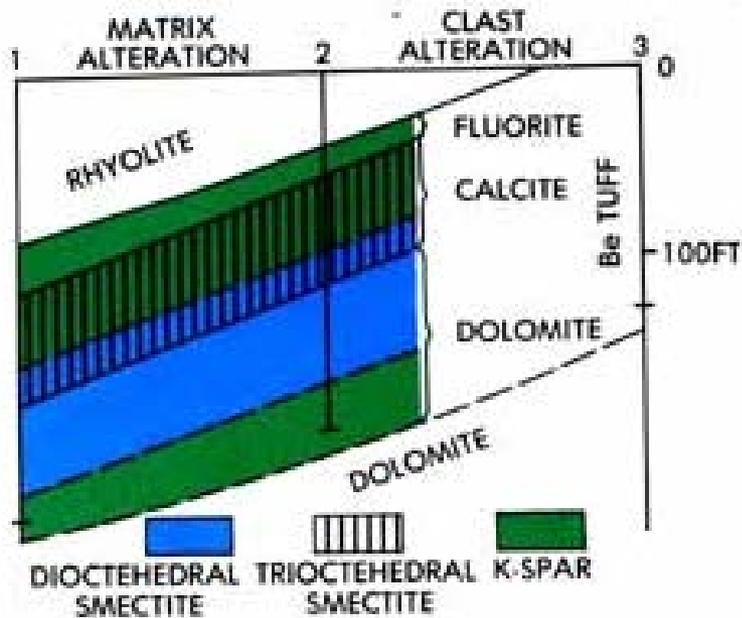
- magma chemistry
- favorable host rocks
- structure
- extension tectonics (F, U, Be, Li, alkaline rocks)



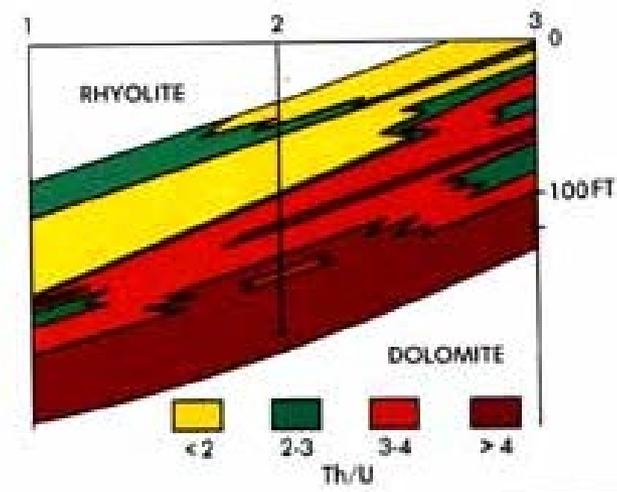
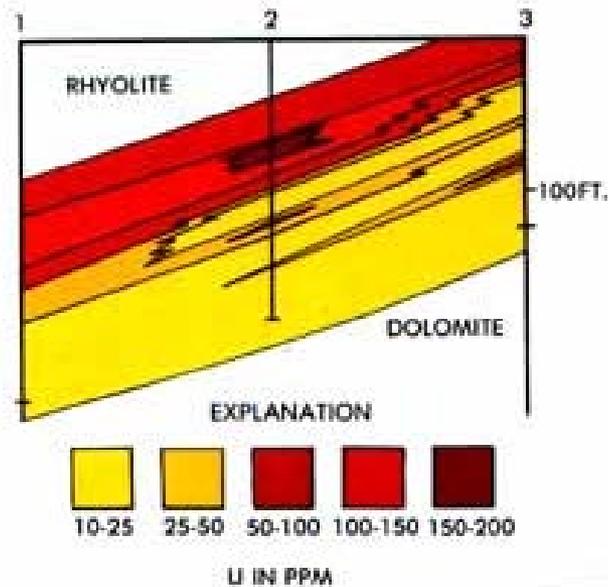
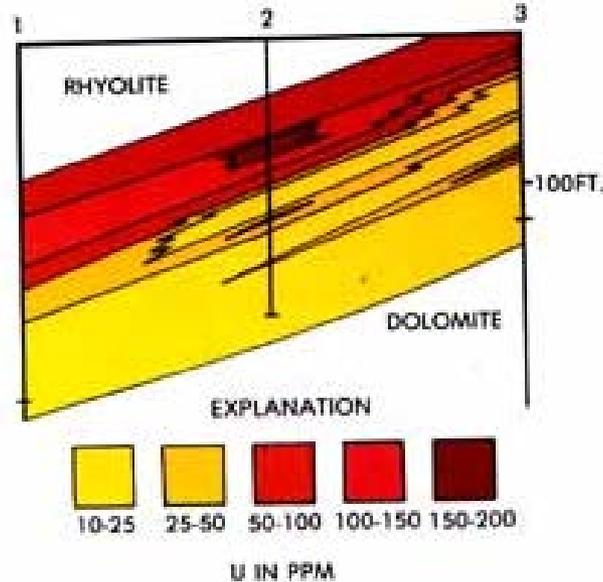
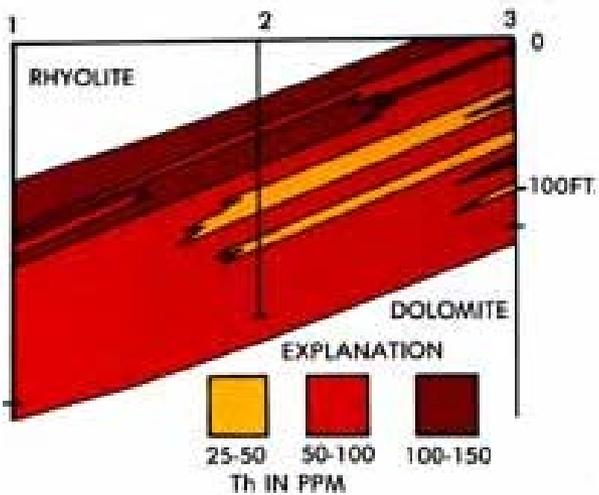
beryllium tuff (USGS OF 98-524)



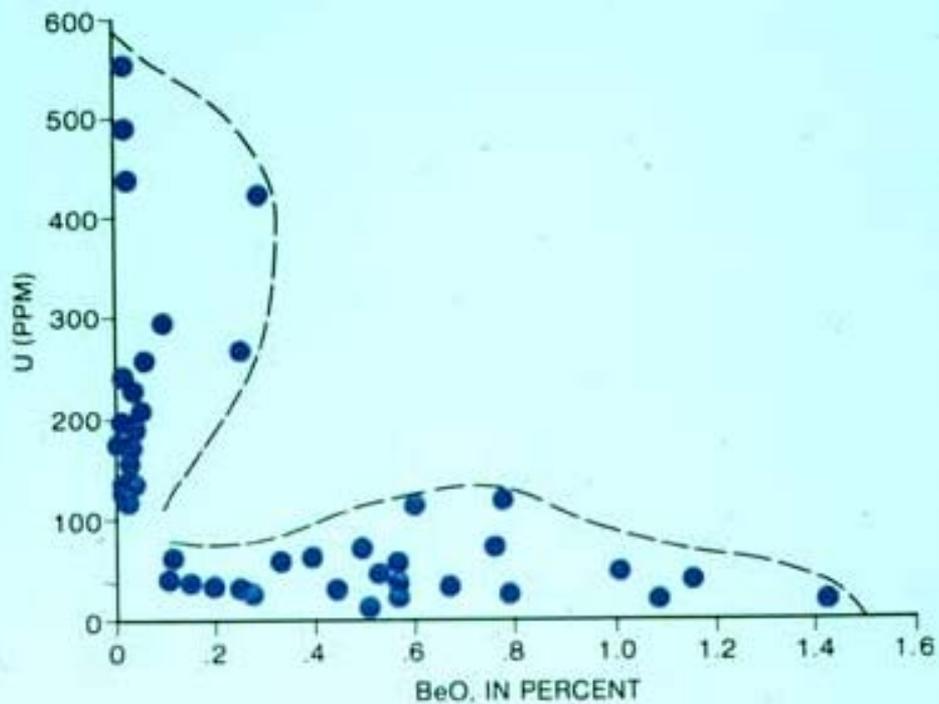
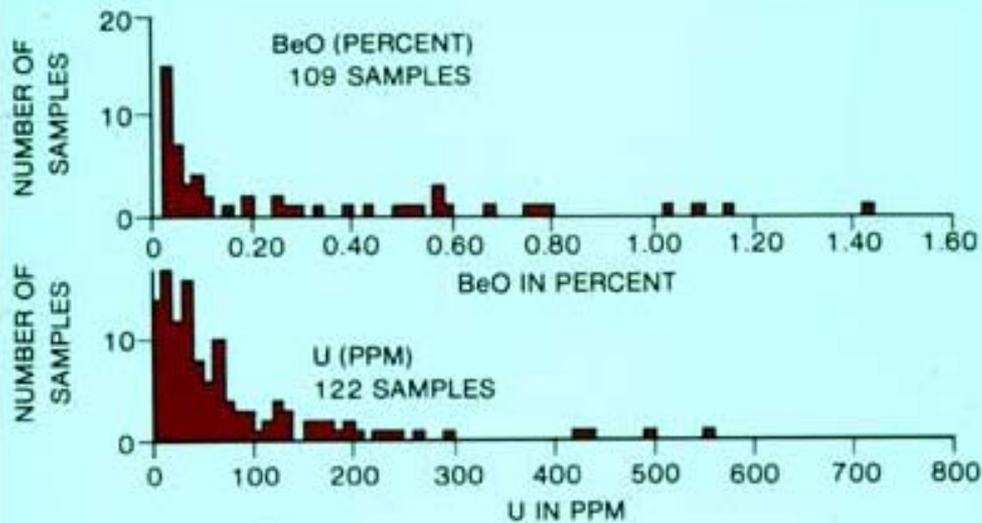
- First stage=rhyodacitic and quartz latitic composition, contain the largest trace concentrations of base metals such as Pb, Zn, and Cu
- Middle stage=mostly rhyolite, contain the smallest concentrations of all trace
- Third stage=Alkali rhyolite, post-caldera stage, contains the largest trace concentrations of lithophile elements such as Be, Li, thorium, and U (USGS OF 98-524)



Be ore is concentrated in the upper part of the Be tuff member, as typified by the Roadside ore body (USGS OF 98-524)



Th follows  
Be, but U  
does not



Summarizes analyses of drill cuttings from many mineralized zones in the Be tuff member (USGS OF 98-524)

**Table 6.** A model hydrothermal fluid composition for Spor Mountain.

[Modified based on thermodynamic estimates and other data from Wood (1992)<sup>1</sup> and Murphy (1980)<sup>2</sup>. Mg/kg, milligrams per kilogram; ppb, parts per billion, ppm; parts per million; --, no unit]

Parameter	Unit	Fluid characteristic
Temperature	°C	200–100 <sup>1</sup> ; (160–140 <sup>2</sup> )
pH	--	4–6 (no alunite, K-feldspar alteration); near-neutral <sup>1</sup>
SiO <sub>2</sub> (aq)	--	Activity fixed by cristobalite
Ca, Al, K	--	Estimated by alteration assemblage of K-feldspar, Ca-clinoptilolite, beidellite-Ca (montmorillonite), rare sericite (muscovite)
HCO <sub>3</sub>	mg/kg	100
Cl	mg/kg	1,000
F		>0.01 molal <sup>1</sup> or fixed by fluorite <sup>1</sup>
Mn	mg/kg	1
Be	mg/kg	1 <sup>1</sup> ; (500 ppb–5 ppm)
Saturated phases	--	Bertrandite, quartz, fluorite, pyrolusite

# ROUND TOP MOUNTAIN, SIERRA BLANCA, TEXAS





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# ILLUMINATE

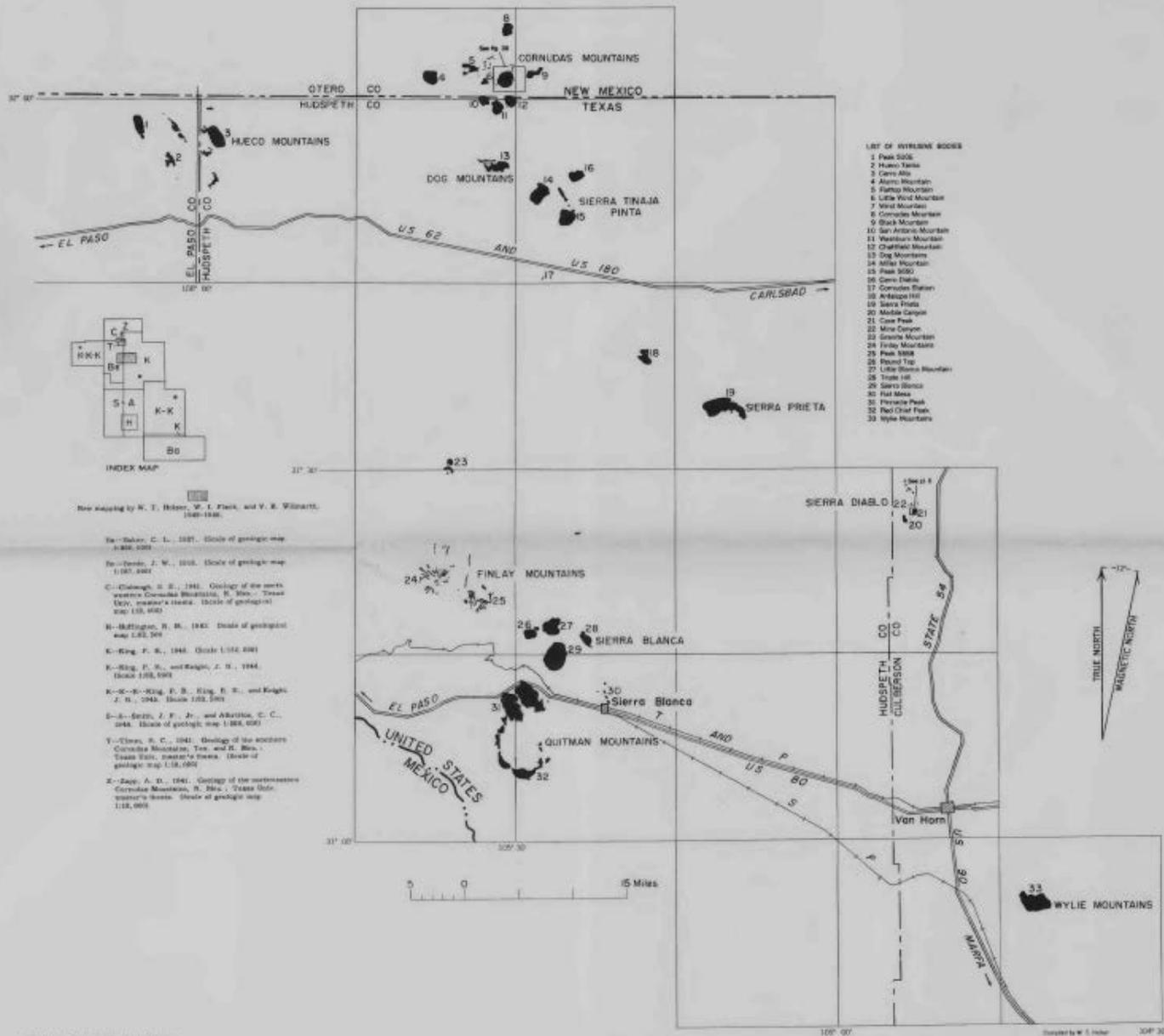
## Welcome to Texas Rare Earth Resources

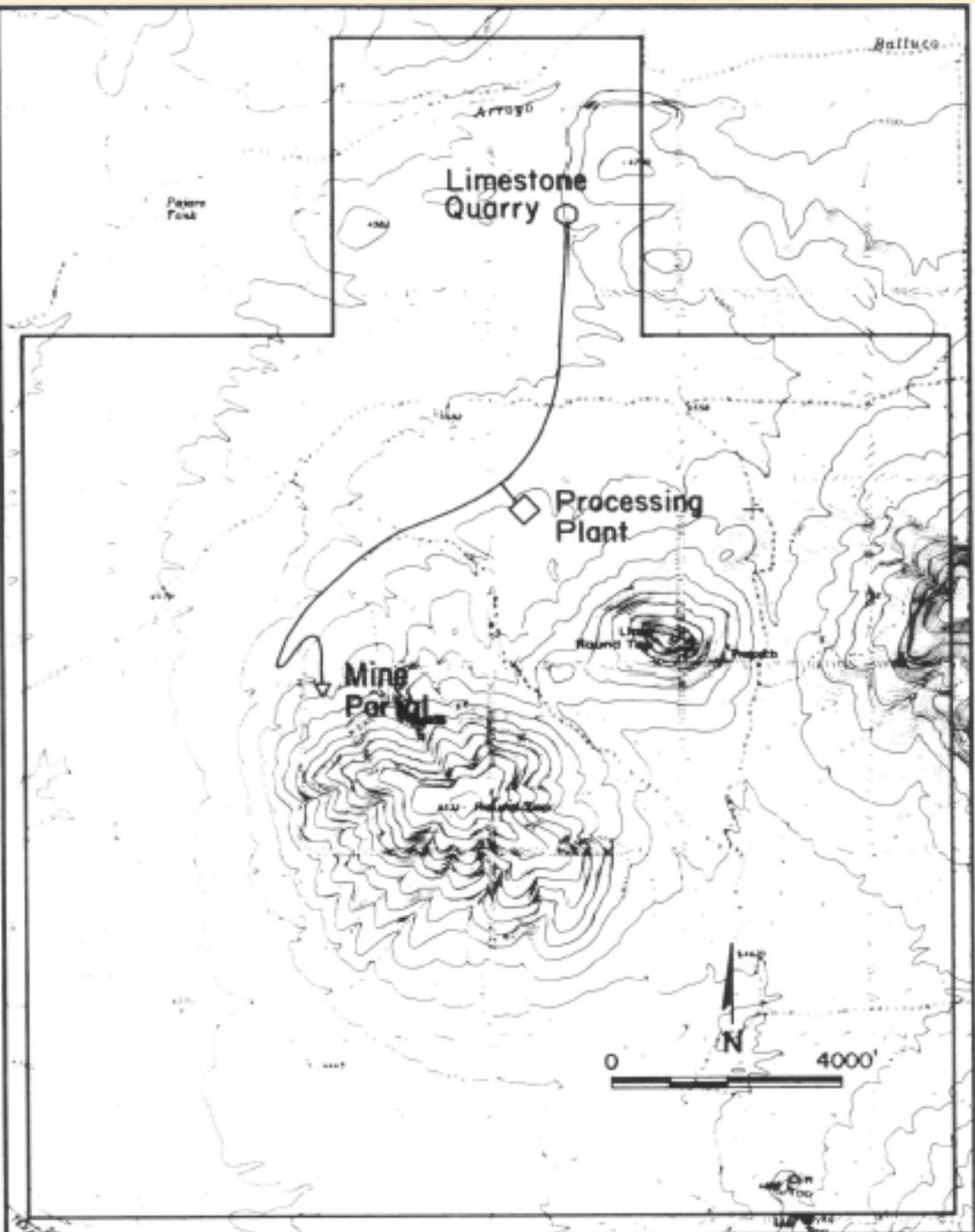
Texas Rare Earth Resources Corp. (TRER) is a U.S.-based minerals company engaged in the exploration and development of critical rare earth elements and in the pursuit of precious metals opportunities.

## Recent News

JANUARY 24, 2013

Texas Rare Earth Resources Engages Representative in Order to Explore





Cyprus' Exploration Decline

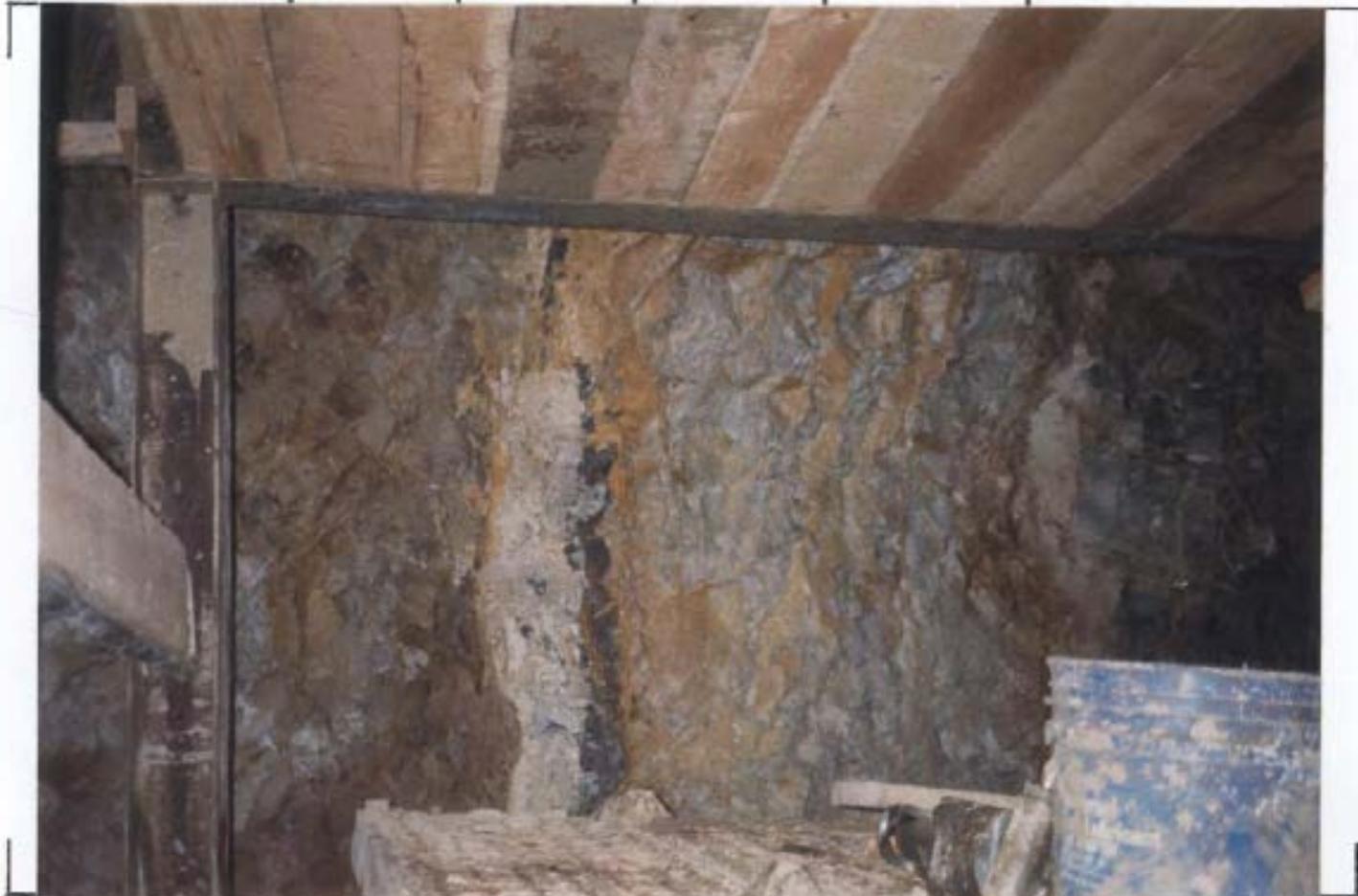
# Round Top

Round Top Measured + Indicated Mineral Resources						
Metric Tonnage 359,150 kt						
	Element Symbol	gpt	Conversion Factor	Element Oxide	Oxide kg	Oxide %
Lanthanum	La	20.3	1.173	La <sub>2</sub> O <sub>3</sub>	8,550,000	0.002%
Cerium	Ce	81.0	1.171	Ce <sub>2</sub> O <sub>3</sub>	34,064,000	0.009%
Praseodymium	Pr	10.4	1.17	Pr <sub>2</sub> O <sub>3</sub>	4,369,000	0.001%
Neodymium	Nd	28.8	1.166	Nd <sub>2</sub> O <sub>3</sub>	12,051,000	0.003%
Samarium	Sm	10.5	1.16	Sm <sub>2</sub> O <sub>3</sub>	4,391,000	0.001%
<b>Total LREO'</b>					<b>63,425,000</b>	<b>0.018%</b>
Europium	Eu	0.20	1.158	Eu <sub>2</sub> O <sub>3</sub>	82,000	0.000%
Gadolinium	Gd	10.6	1.153	Gd <sub>2</sub> O <sub>3</sub>	4,375,000	0.001%
Terbium	Tb	3.6	1.151	Tb <sub>2</sub> O <sub>3</sub>	1,487,000	0.000%
Dysprosium	Dy	31.7	1.148	Dy <sub>2</sub> O <sub>3</sub>	13,057,000	0.004%
Holmium	Ho	8.0	1.146	Ho <sub>2</sub> O <sub>3</sub>	3,307,000	0.001%
Erbium	Er	32.8	1.143	Er <sub>2</sub> O <sub>3</sub>	13,464,000	0.004%
Thulium	Tm	7.1	1.142	Tm <sub>2</sub> O <sub>3</sub>	2,903,000	0.001%
Ytterbium	Yb	56.5	1.139	Yb <sub>2</sub> O <sub>3</sub>	23,114,000	0.006%
Lutetium	Lu	8.9	1.137	Lu <sub>2</sub> O <sub>3</sub>	3,626,000	0.001%
Yttrium	Y	220.9	1.269	Y <sub>2</sub> O <sub>3</sub>	100,660,000	0.028%
<b>Total HREOs</b>					<b>166,075,000</b>	<b>0.046%</b>
<b>Total REOs</b>					<b>229,500,000</b>	<b>0.064%</b>

- 44.6 ppm or g/t U content in the Round Top rhyolites
- 298,000 tons of 1.9% Be (historic resource)

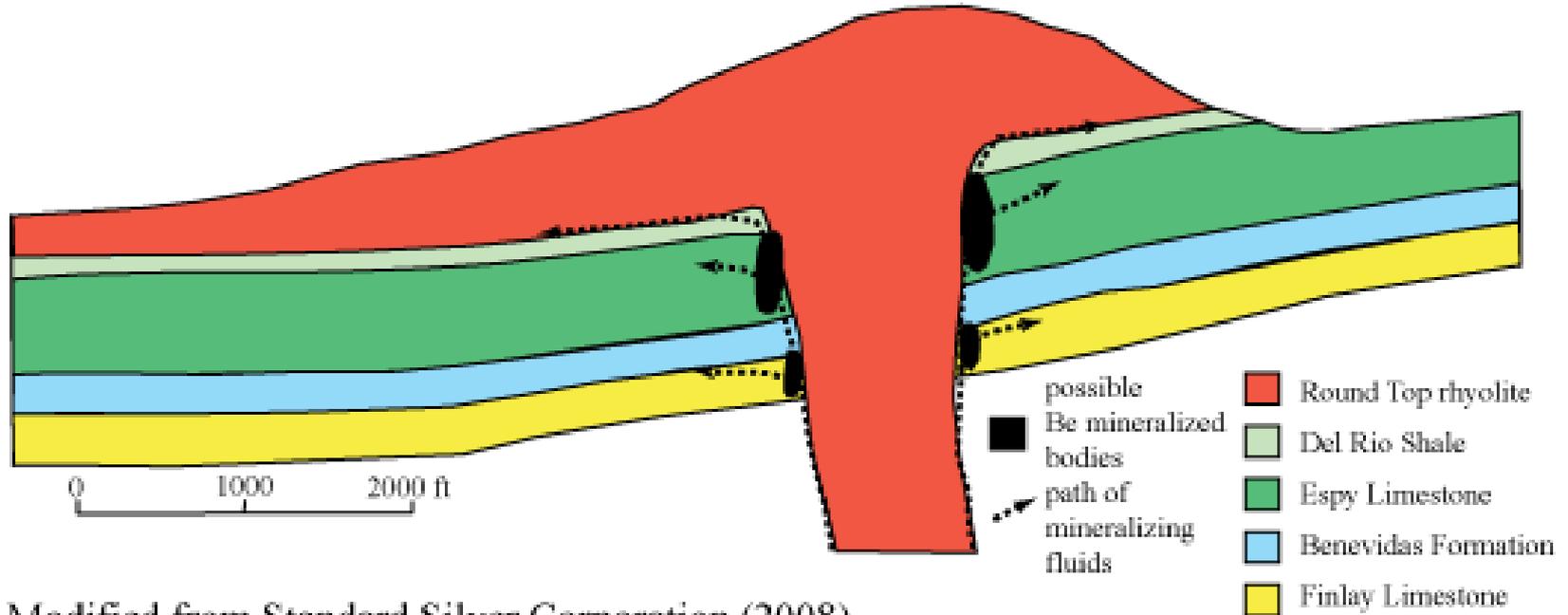
# Ore Body - BeO Assay Values

**0.1   0.77   5.95   3.7   0.21**



# ROUND TOP MOUNTAIN, SIERRA BLANCA, TEXAS

Schematic cross section showing Be-fluorite deposition



Modified from Standard Silver Corporation (2008)



**Red Rhyolite containing Rare Earth Minerals, Round Top, North Side**

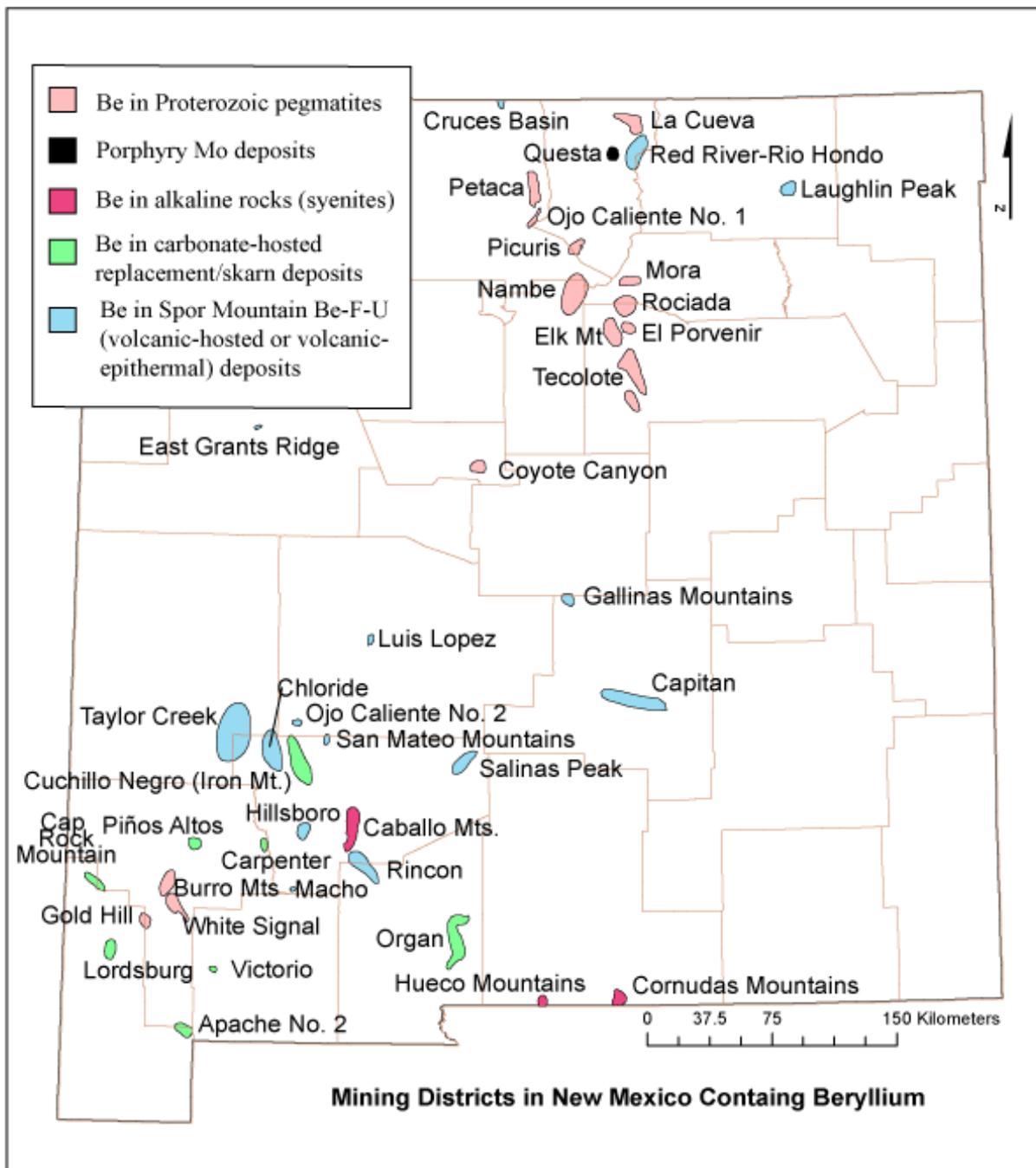
Image 27 of 36

CLOSE X



**Mineralized Contact between Sedimentary Rock & Rhyolite, Round Top, North Side**  
Image 9 of 12

CLOSE X



Mining districts in New Mexico that contain beryllium (Be). More details are in McLemore (2010).

**Apache Warm Springs deposit,  
Socorro County, New Mexico**

# BE Resources Inc.

"continues to search for a suitable new project for the Company and to review its options for its New Mexico beryllium project which has been placed on care and maintenance."

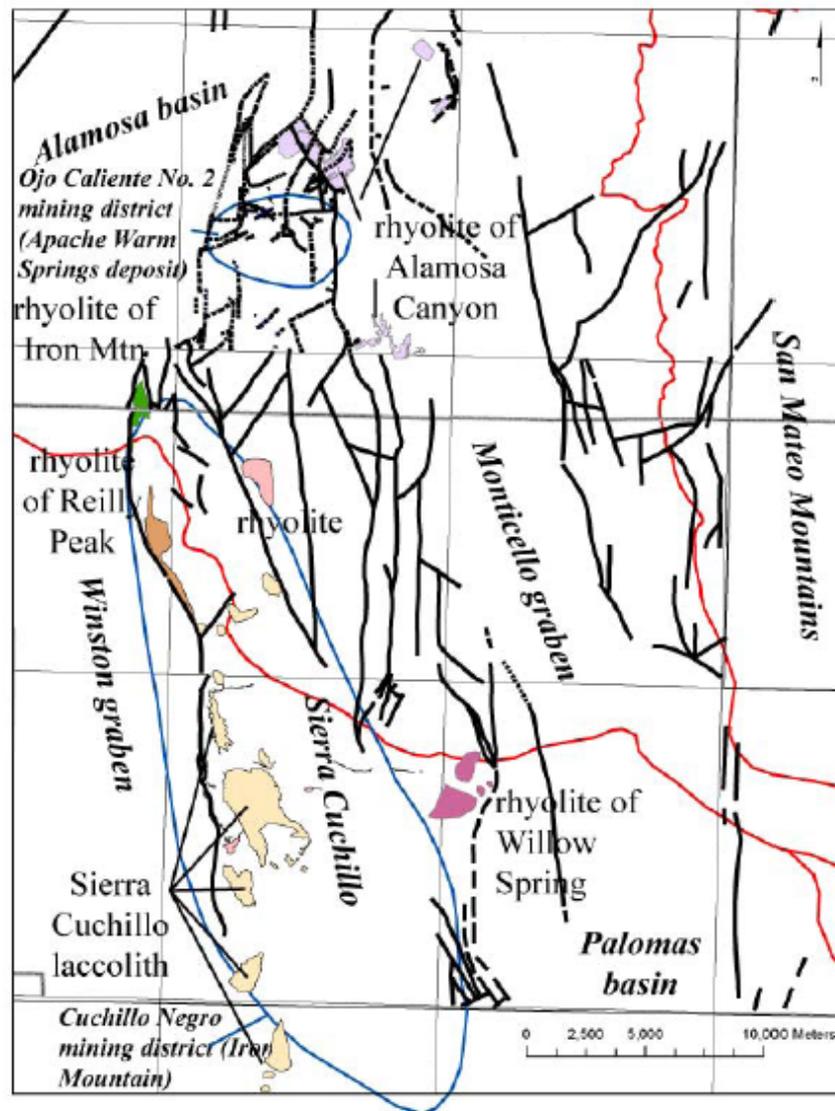
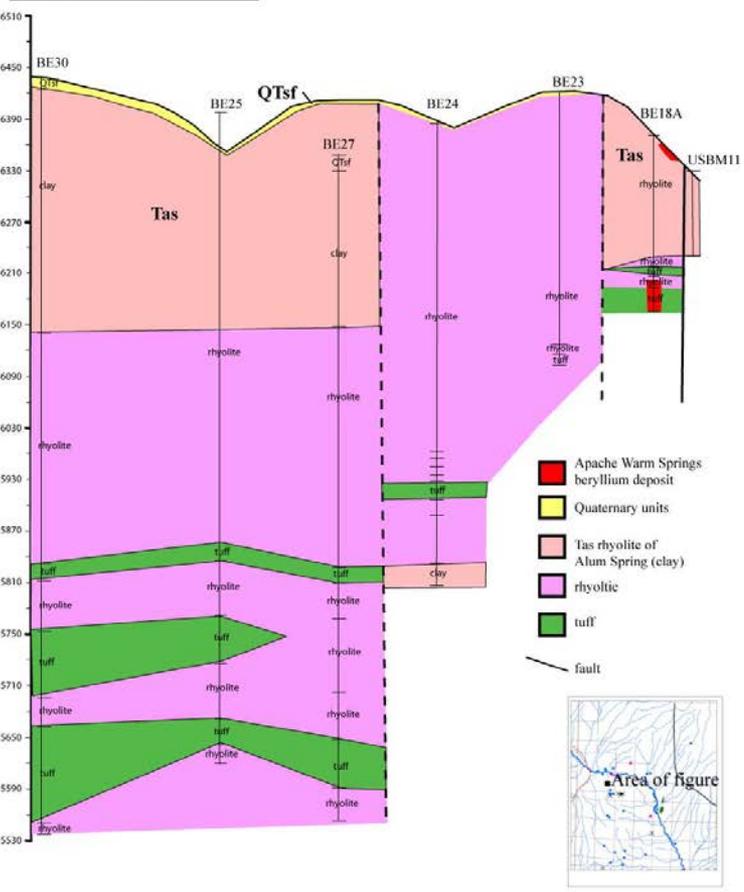
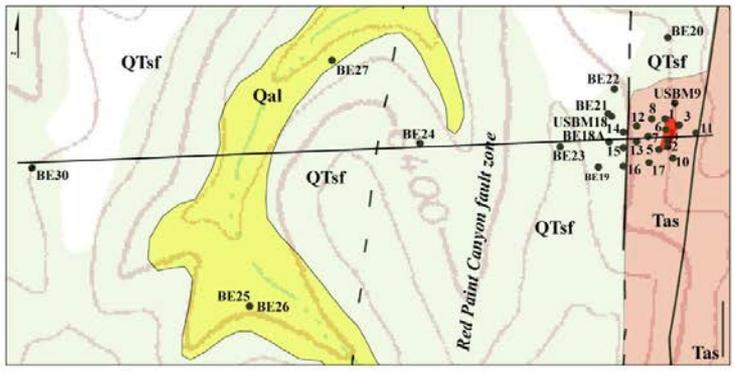


FIGURE 10. Regional structure map of the Sierra Cuchillo-San Mateo area showing the mining districts (blue) in the area (defined by McLemore, 2010a). Red line is boundary of Alamosa basin. Major granitic-rhyolite intrusions are shown in colored polygons and discussed in text. Not all rhyolite intrusions in the San Mateo Mountains are shown. Black lines are faults from Osburn (1984), Harrison (1992), Jahns et al. (2006), Ferguson et al. (2007), and McLemore (2010a).

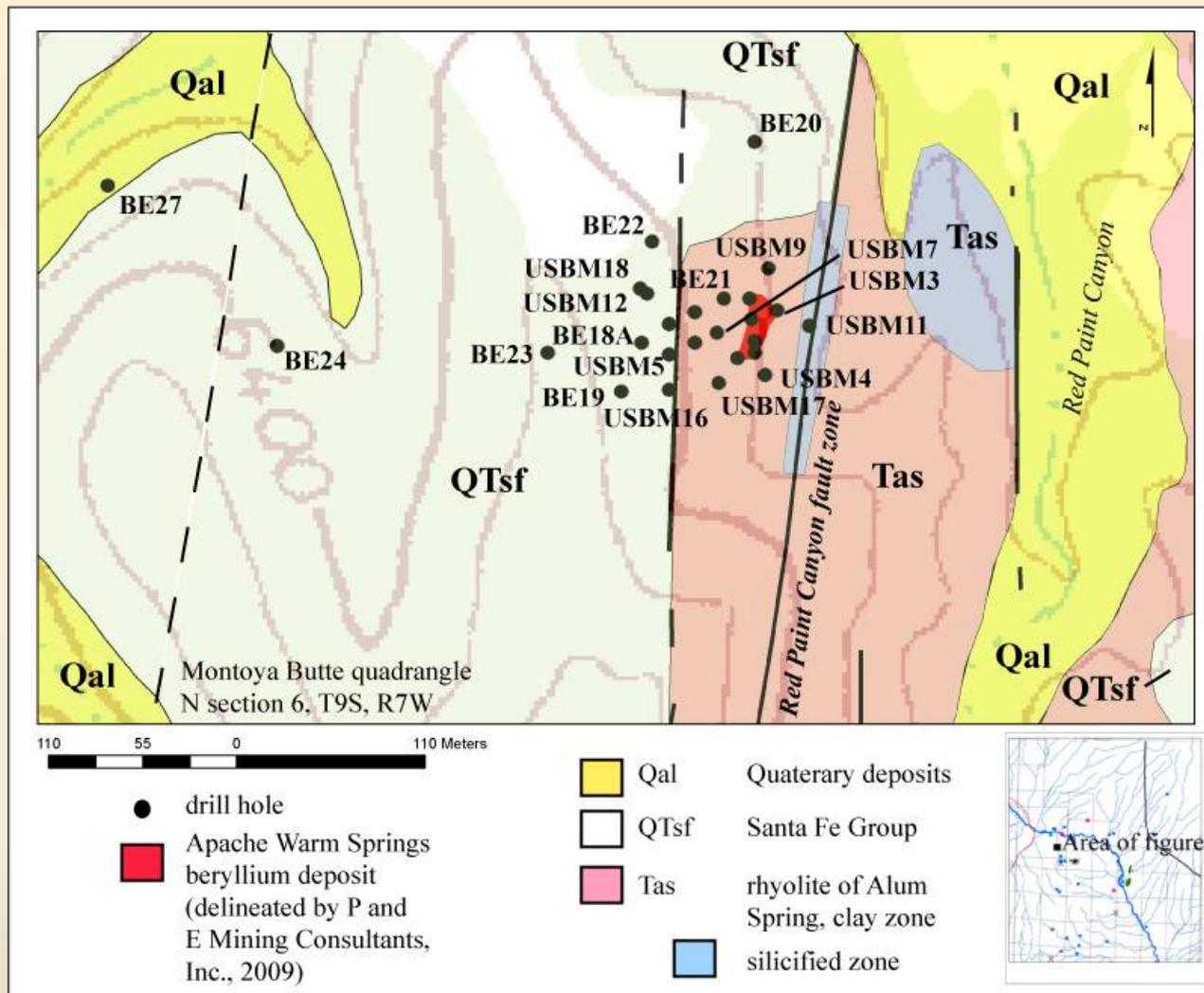


Geologic map and cross section of the Apache Warm Springs beryllium deposit and adjacent area (N section 6, T9S, R7W).

Interpretations are by the author from examination of drill cuttings, using available drill data (McLemore, 2010a), and surface mapping.

Apache Warm Springs beryllium deposit (Be), as delineated by P and E Mining Consultants, Inc. (2009) as determined from trenching and drilling, looking northeast (N section 6, T9S, R7W).





Alteration map of the Apache Warm Springs beryllium deposit. The western fault (between BE27 and BE 24) is identified from drilling data (McLemore, 2010a).

Clay zone with red hematite-kaolinite and white kaolinite surrounding the Apache Warm Springs beryllium deposit (N section 6, T9S, R7W). A sample collected from the site shown on the left contains kaolinite, quartz, and hematite (Mont-35, McLemore, 2010a).



A sample collected from the white clay shown in the photograph on the right contains quartz, kaolinite, illite, smectite and mixed layered clays (Mont-61, McLemore, 2010a).

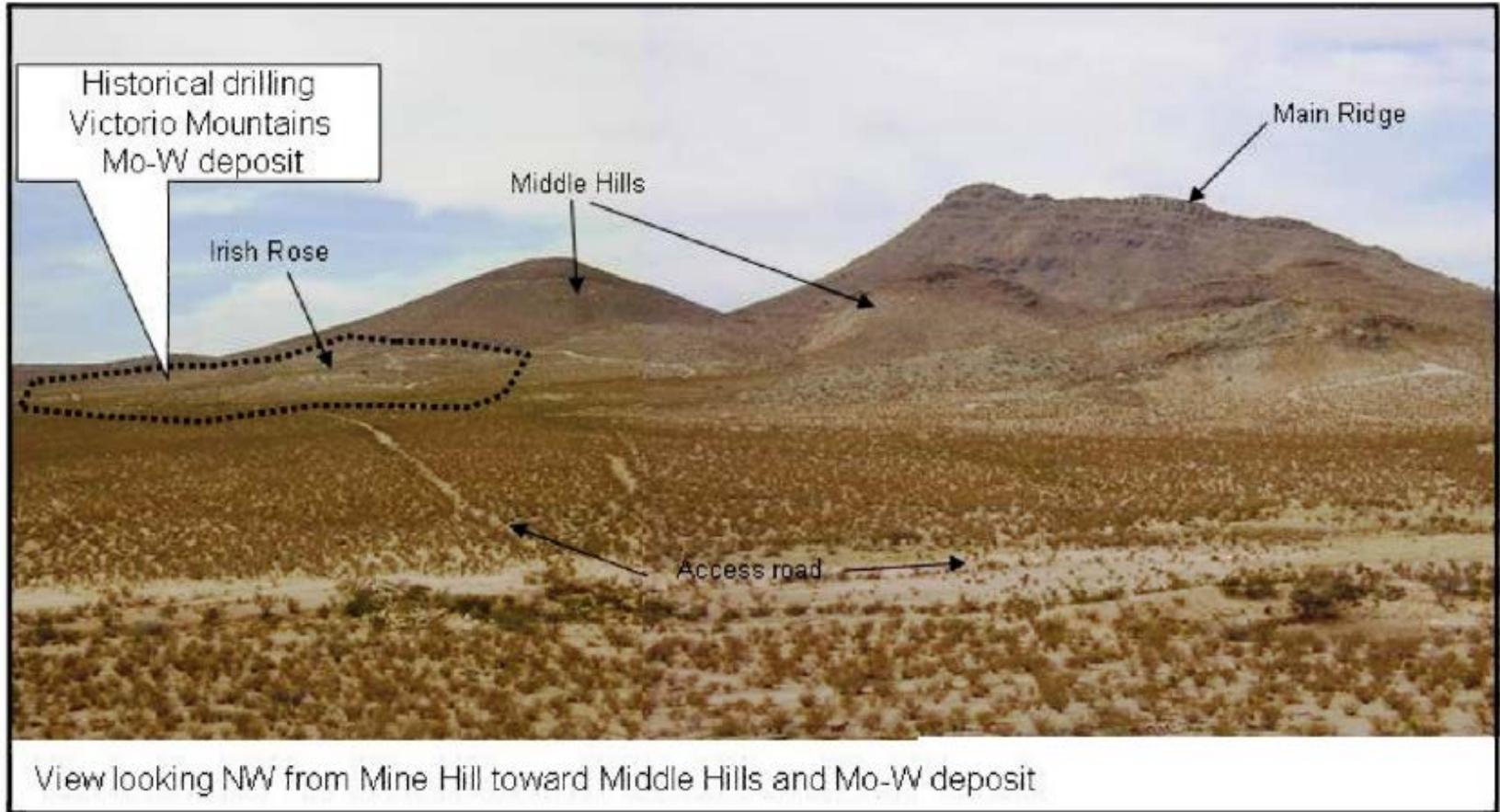


Silicified zone, looking southwest. The Apache Warm Springs beryllium deposit is to the right (N section 6, T9S, R7W).



**Porphyry molybdenum  
(±tungsten) deposits and  
Carbonate-hosted replacement and  
skarn deposits**

# Victorio Mountains, New Mexico



# Galway Metals



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TSX-V:GWM

## PROJECTS

### Victorio

Click on thumbnail to  
Enlarge



Property Location Map



Claim Location Map

## VICTORIO

The Victorio Molybdenum-Tungsten Project is an advanced-stage exploration property in which Galway Metals has an option to acquire a 100% interest. Significant activity at Victorio has been inactive since the early 1980's due to depressed metal pricing. The property has favorable infrastructure such as access by paved road to within a few miles of the site, a nearby railway and a gas pipeline. Victorio is located approximately 20 miles west of Deming, New Mexico, in Luna County.

In 2008, Galway completed a 12-hole, 25,000 foot, phase 2 infill drilling program. The purpose of the infill drilling program was to upgrade the resources with the next step being a pre-feasibility study. The first phase of drilling included 6 holes totaling 13,000 feet. This project was acquired in June 2006, and was worked on extensively by Gulf Minerals in the early eighties as they drilled 165,000 feet.

The current Technical Report on Victorio's Resources by Dr. H. Peter Knudsen and Peter H. Hahn dated November 15, 2012, was derived from 217,000 feet of drilling using an \$8.00 Tungsten and \$15.00 per pound molybdenum long term price.

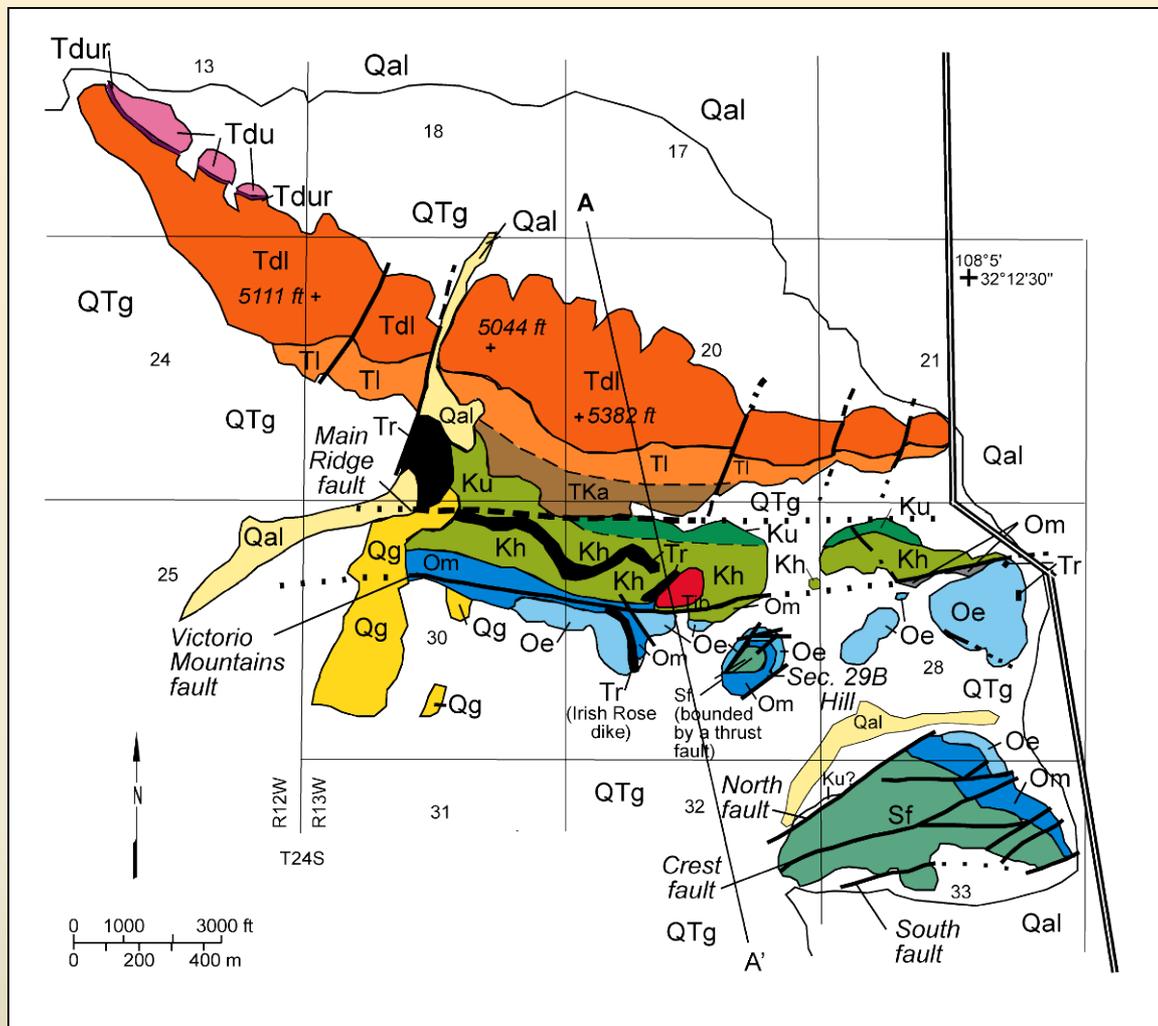
### Video for the Victorio Project



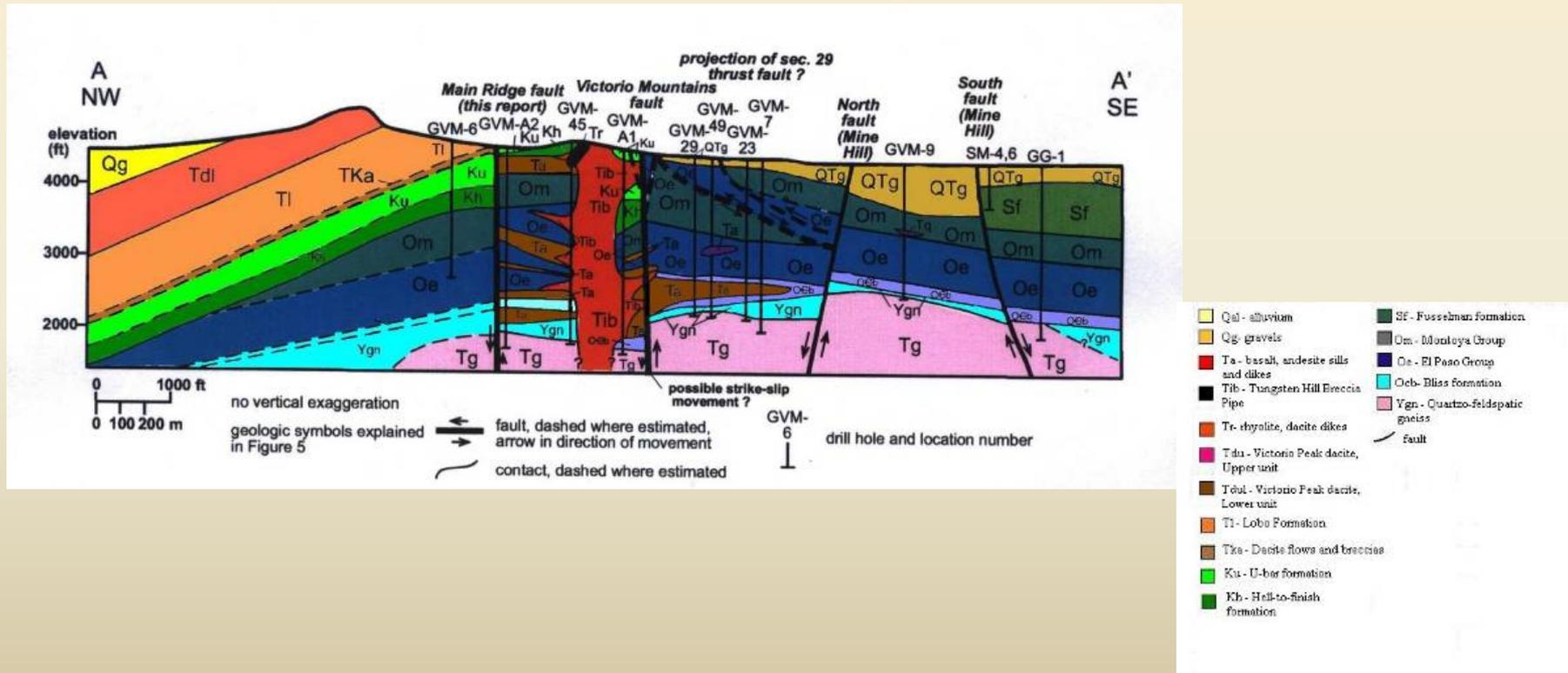
NI 43-101 Technical  
Report on Resources  
November 15, 2012



Simplified geologic map of the Victorio Mountains (modified from Kottowski, 1960; Thorman and Drewes, 1980; unpublished mapping by Gulf Resources, Inc.; unpublished mapping by V. T. McLemore).

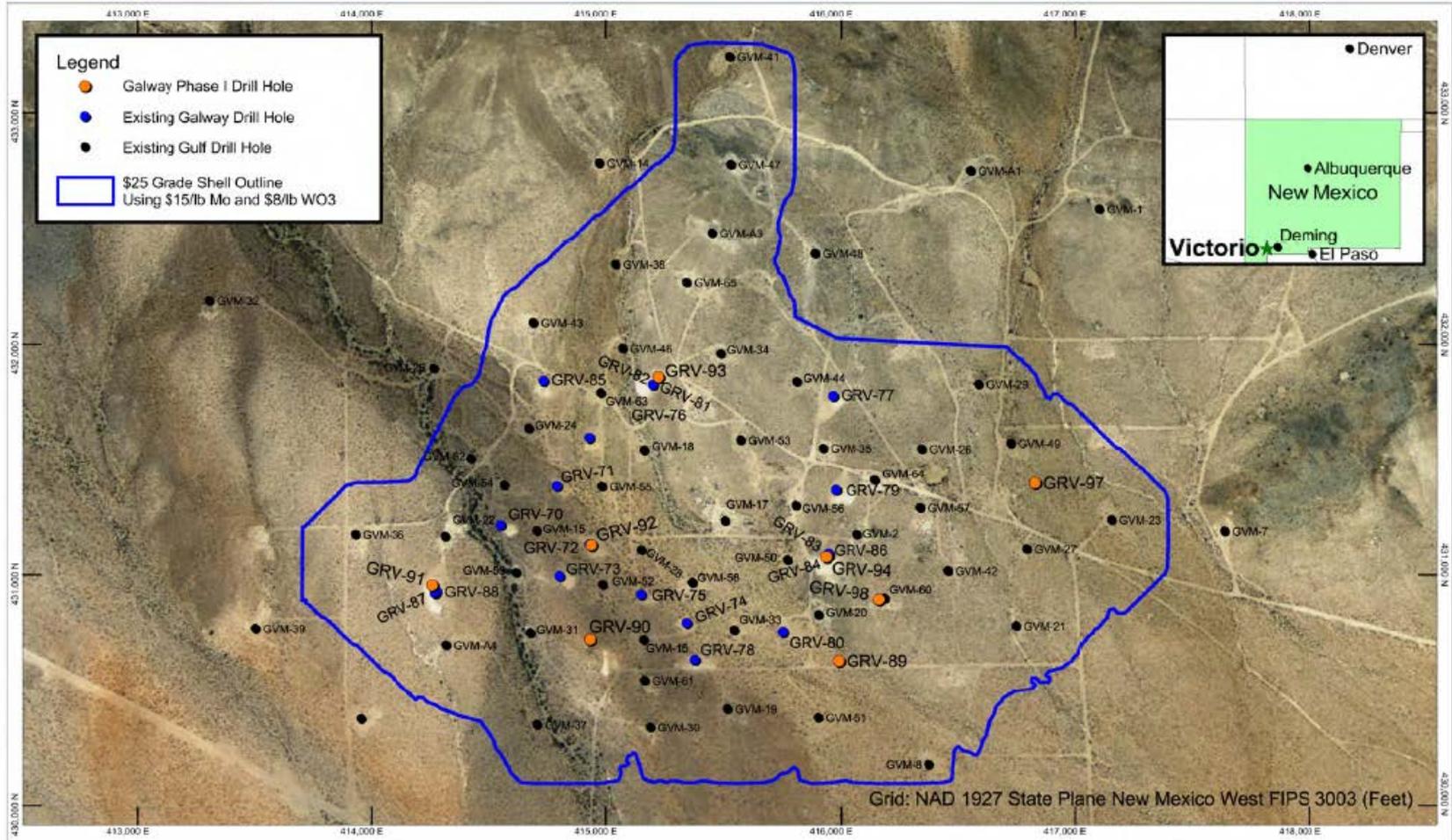


Simplified cross section of the Victorio Mountains (modified from company drill data and unpublished mapping by K. Donahue and V.T. McLemore). Some of the drill holes are projected onto the cross section.

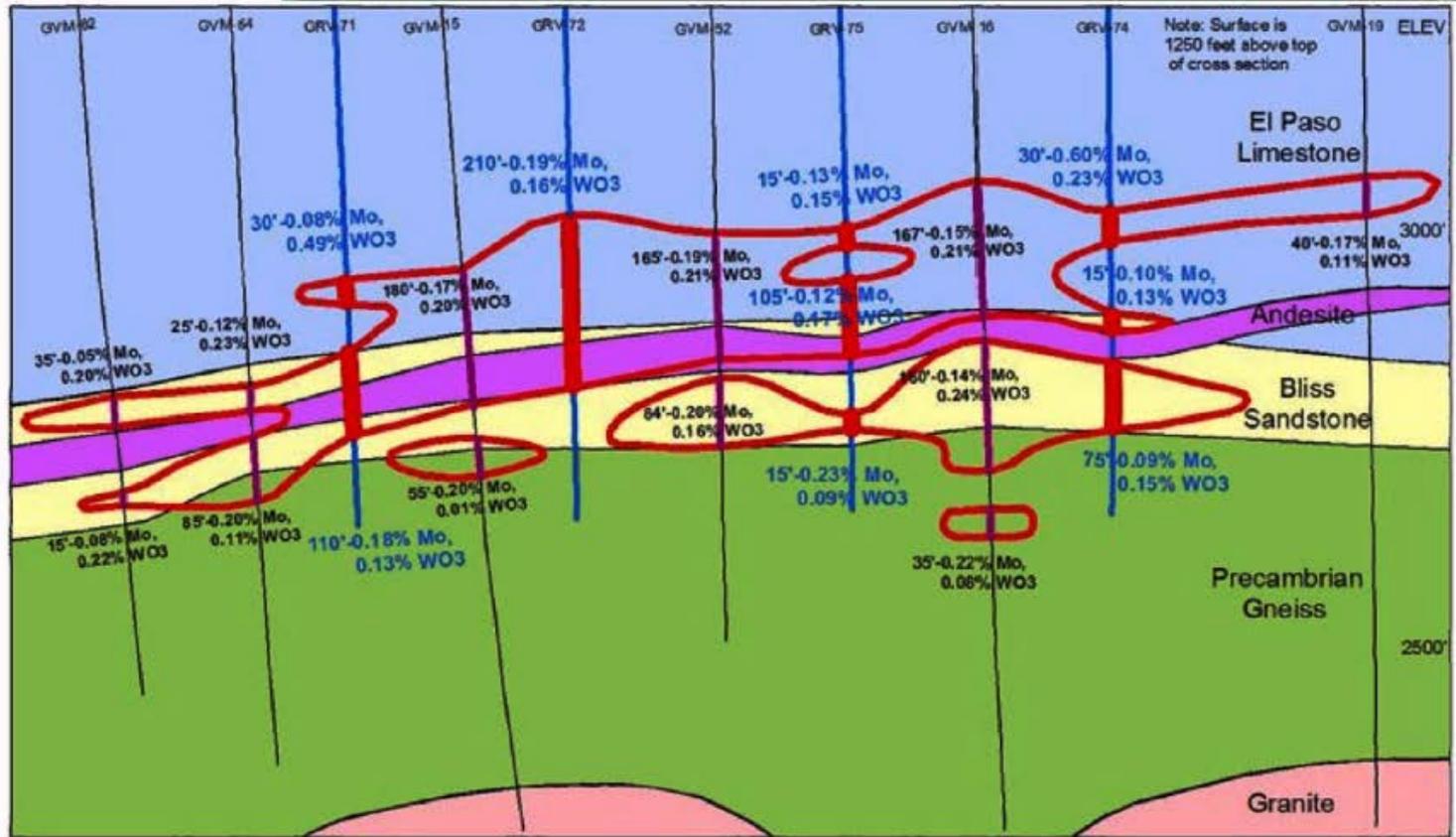




# Victorio Project Drill Hole Location Map



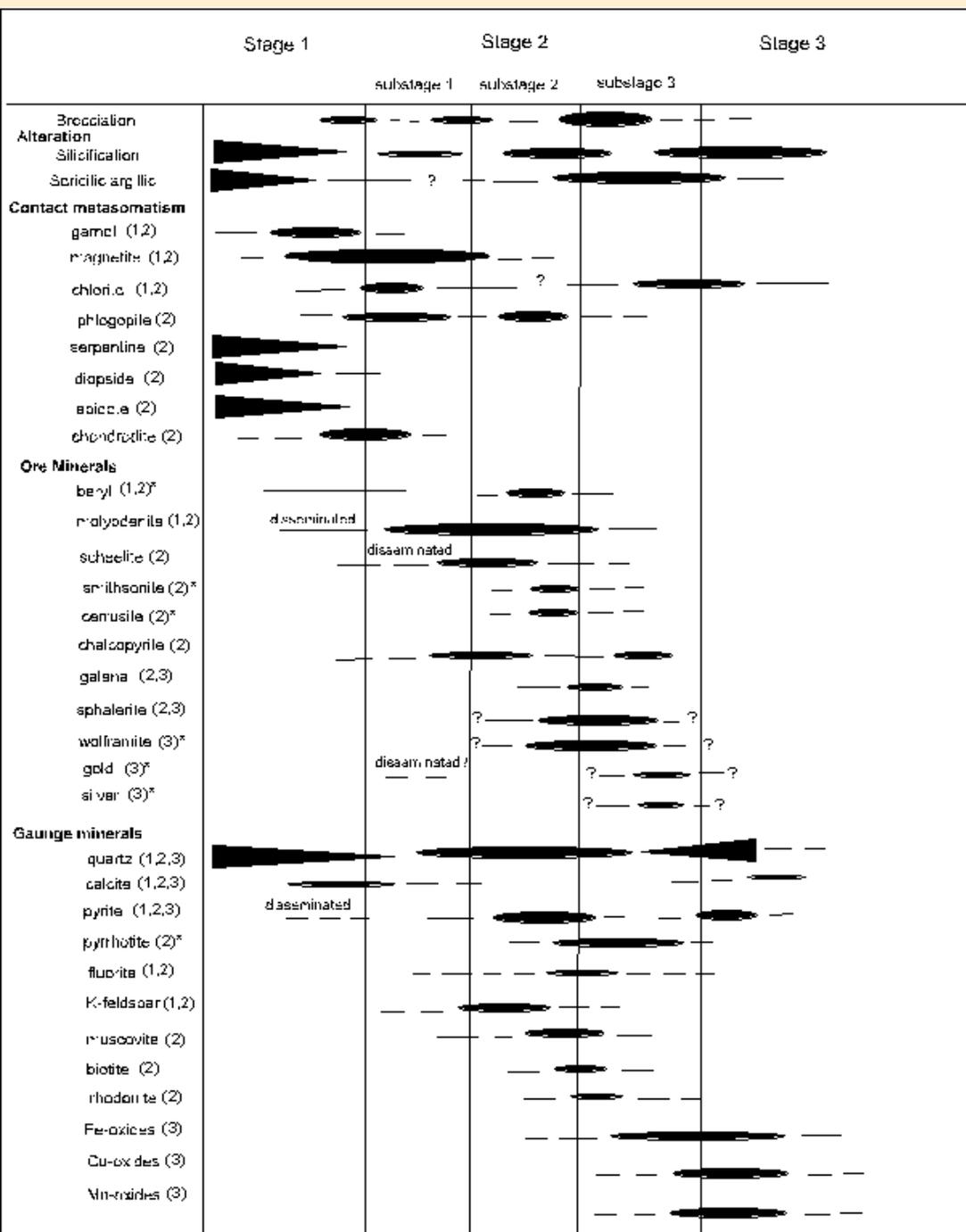
# Victorio - Thick Ore Intercep



- Gulf Drill Hole
- Galway 2006-07 Drill Hole
- Mo/WO3 Resource-greater than \$40/ton at \$12/lbs Mo, \$8/lbs WO3

200 feet

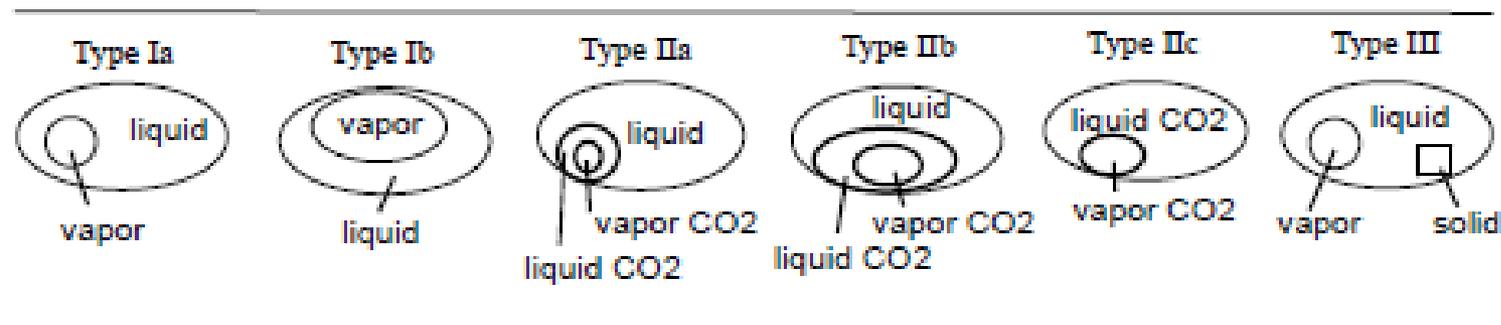
Horiz = Vert



Relative paragenetic sequence for the Victorio mining district showing the mineral relationships and alteration events (from Donahue, 2002). The paragenetic sequence is for all three types of deposits. 1 = porphyry Mo, 2 = skarn, 3 = carbonate-hosted replacement deposit,

TABLE 9. Summary of all fluid inclusion results. Figure below illustrates the classification used to identify the fluid inclusion type (From Donahue, 2002).

Deposit	Type	Size Range micron ( $\mu$ )	Th range degrees	Th ave degrees	Salinity range eq. wt% NaCl	Salinity ave eq. wt% NaCl
Carbonate-hosted replacement	Ia, IIa, IIb, IIc	<2-15	109 - 350	213	0.8 - 19.3	8.8
Mine Hill siliceous veins	Ia, IIa, IIb, IIc	<2-10	109 - 350	217	0.8 - 4.1	2.1
E109 non-oxidized	Ia	<2-5	151 - 257	209	10.2 - 19.3	12.9
Skarn	Ia, Ib, IIa, IIb, III	<2-40	171 - 360	242	0.02 - 25.6	6.6
Barren qtz veins	Ia, Ib, IIa, IIb	<2-40	199 - 340	278	3.1 - 10.9	5.9
Porphyry	Ia, Ib, IIa, IIb	<2-10	179 - 325	255	2.0 - 11.2	6.1



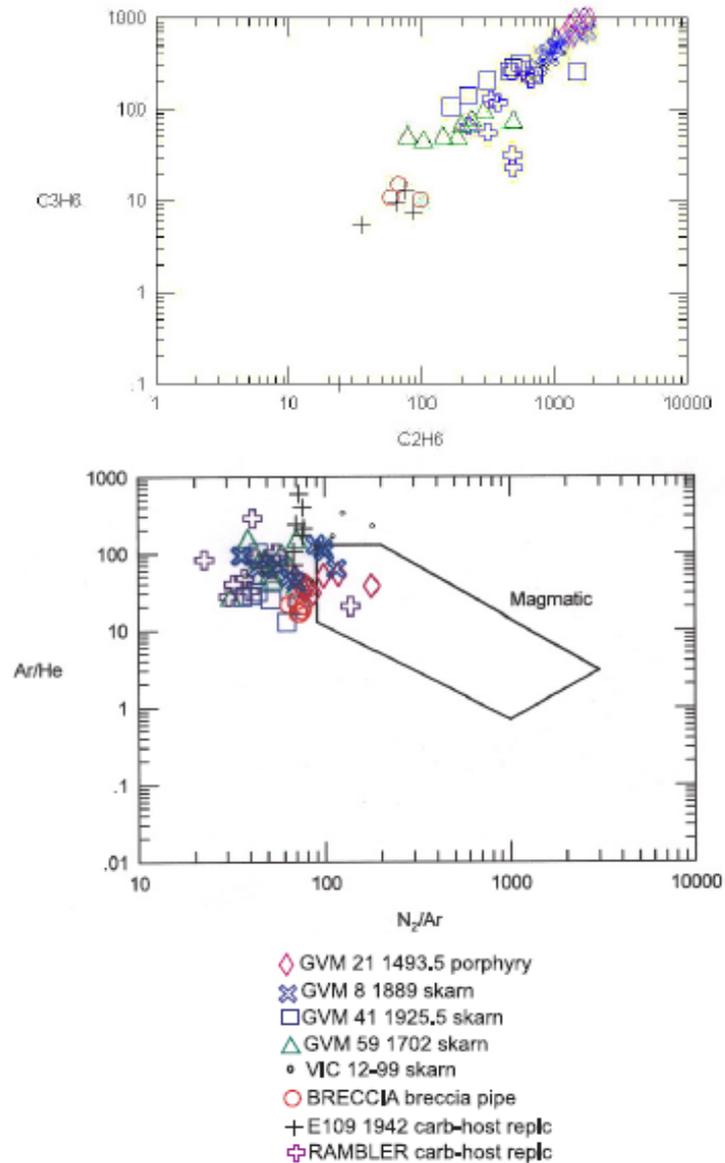
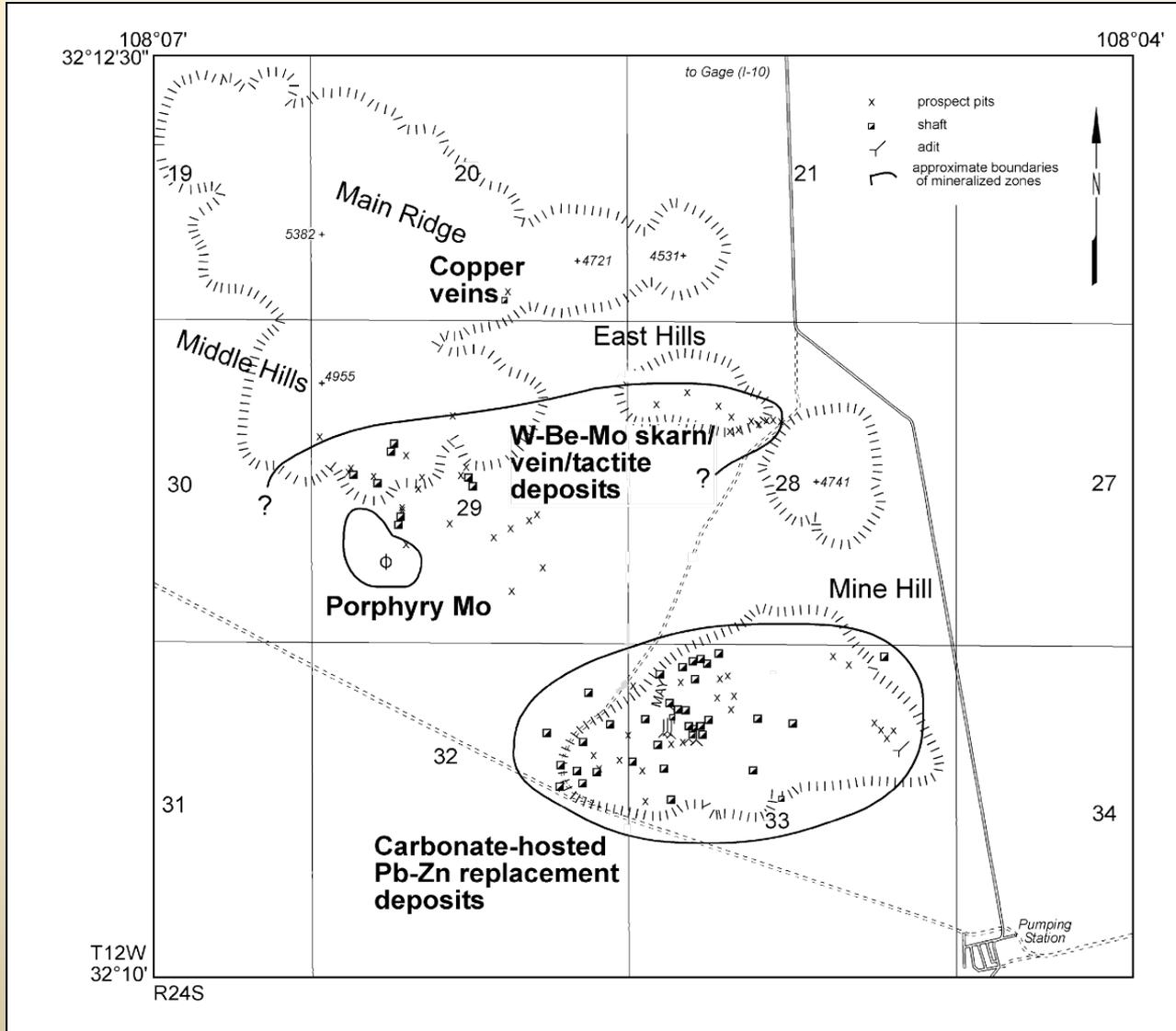


FIGURE 19. Fluid inclusion gas analysis results showing the possible origins of the fluids, the majority of the Victorio samples fall on the boundary and just outside the

# Mineral zonation in the Victorio Mountains mining district.



Victorio Resource Estimate using \$15/lb molybdenum and \$8/lb Tungsten

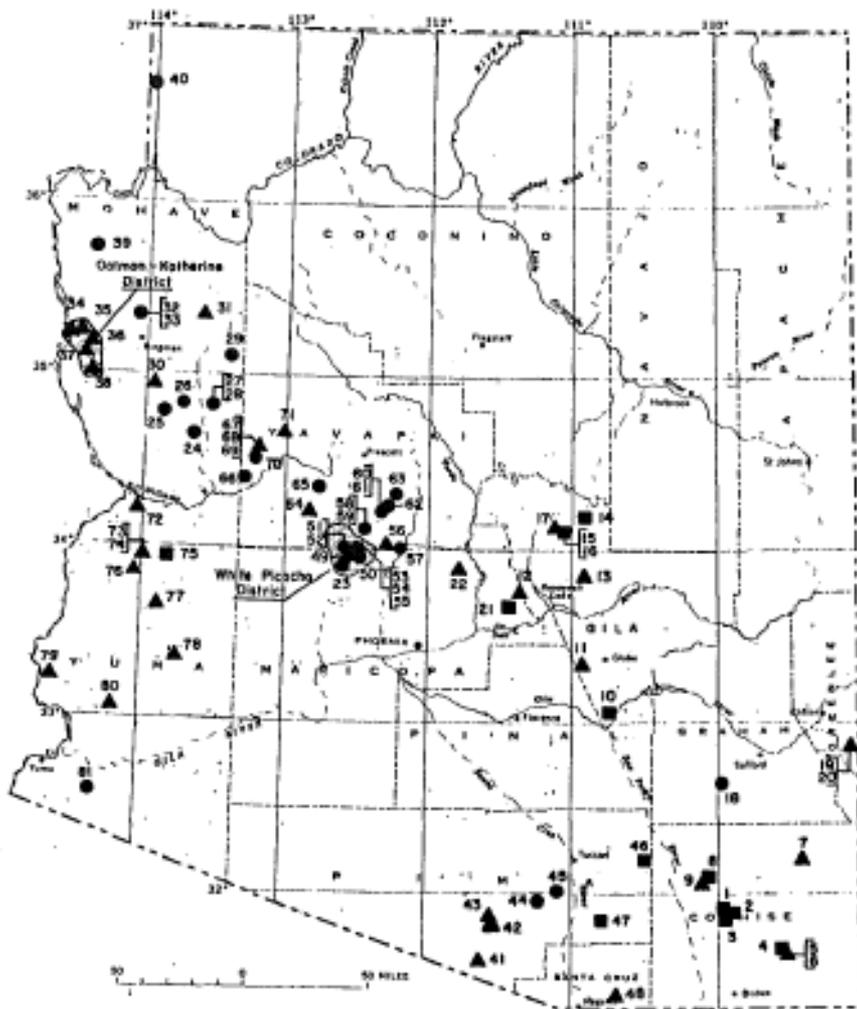
Category	Cutoff/ Ton	Tons	Mo %	Tungsten %	Contained Metal (pounds)	
					Molybdenum	Tungsten
Measured	\$25	37,737,913	0.10	0.08	71,702,035	61,890,177
Indicated	\$25	39,499,463	0.08	0.09	64,779,119	72,679,012
<b>M+I</b>	<b>\$25</b>	<b>77,237,376</b>	<b>0.09</b>	<b>0.09</b>	<b>136,481,154</b>	134,569,189
Inferred	\$25	77,222,232	0.07	0.09	114,288,903	143,633,352
Measured	\$35	20,275,366	0.12	0.11	47,444,356	42,983,776
Indicated	\$35	19,125,184	0.10	0.12	39,397,879	45,517,938
<b>M+I</b>	<b>\$35</b>	<b>39,400,550</b>	<b>0.11</b>	<b>0.11</b>	<b>86,842,235</b>	88,501,714
Inferred	\$35	34,728,550	0.10	0.11	66,678,816	78,486,523

Also Be

# Arizona

- Be along fractures in granite mined from Beryl Hill and Live Oak mines in 1950s in the Dos Cabezas Mountains
- Tungsten veins in Yuma and Graham Counties
- Pegmatites
  - Kingman, Mohave County
  - Bradshaw Mountains, Yavapai County

# AGS Bull 180

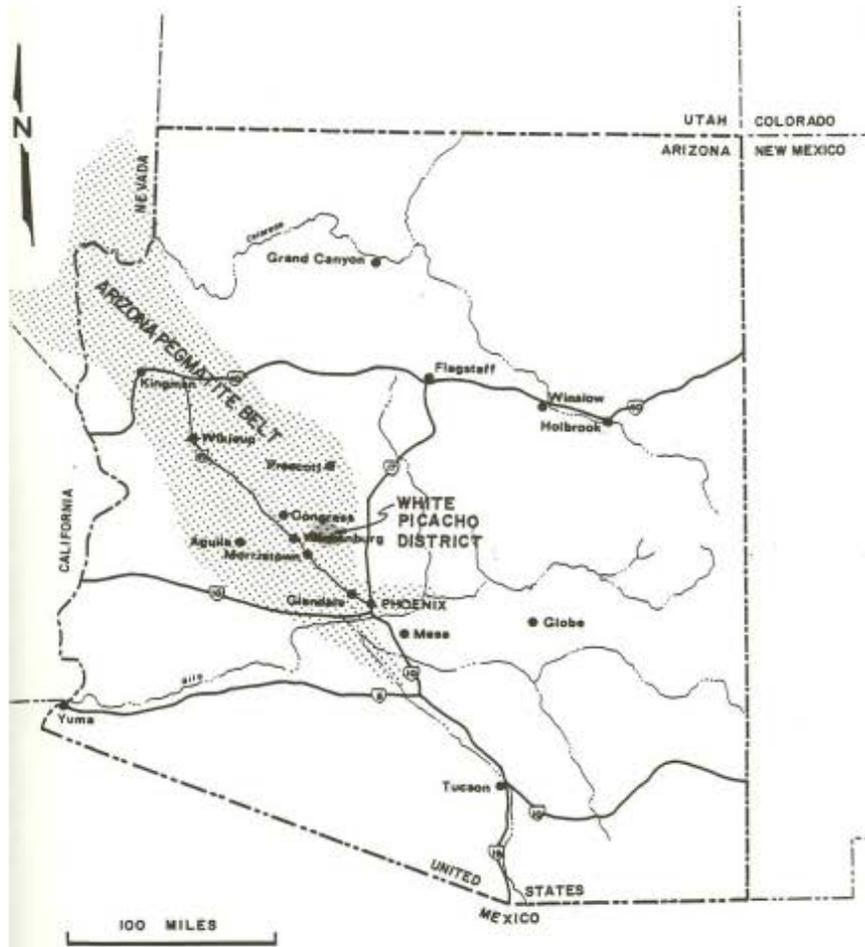


## EXPLANATION

-  Mining district
-  Pegmatites and apatites
-  Veins
-  Tactites, replacements, and dissections in granitic rocks

(Numbers refer to localities mentioned in text and in table 11.)

FIGURE 16.—Beryllium in Arizona.

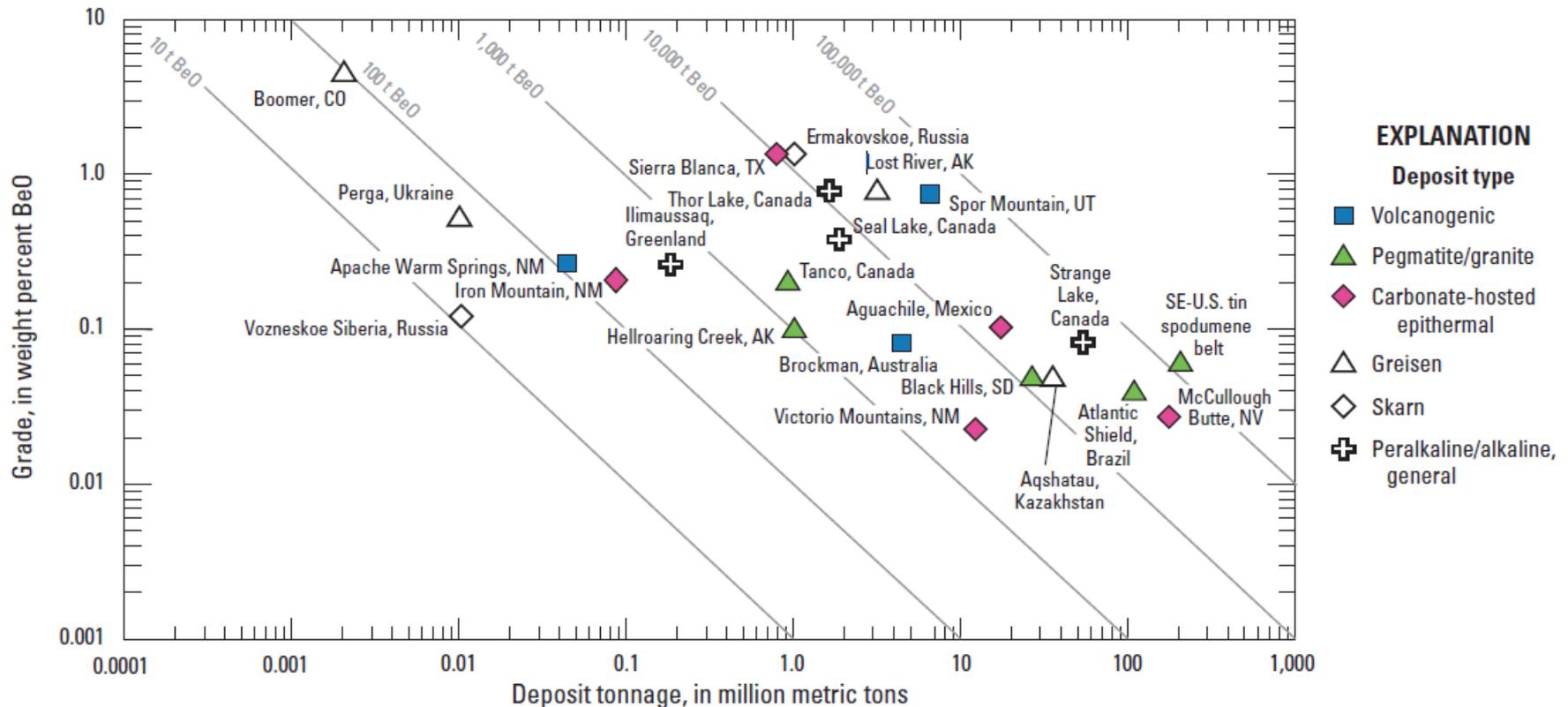


	Be PPM	Bi PPM	Cs PPM	Ga PPM	Li PPM	Rb PPM	Ta PPM
5.26.10.1 Morning Star*	1.21	0.27	1.22	2.27	7.5	21.4	<0.01
5.26.10.2 Do.*	0.96	3.53	2.43	1.46	3.3	18.7	<0.01
5.26.10.3 Do.	2.35	0.21	35.5	8.29	113.5	610	1.92
5.26.10.4 Do.	1.69	0.32	78.9	14.5	75	1840	2.55
5.26.10.5 Sunset	26.7	0.64	99	36.6	24.5	890	17.3
5.26.10.6 Do.	4.08	0.81	4.98	7.67	150	88.6	1.66
5.26.10.7 Do.	13.6	1.52	19.95	30.6	74.3	510	1.89
Lower							
5.26.10.8A Jumbo	30	1.23	457	71.9	156	3000	3000
5.26.10.8B Do.	3.05	0.53	76.9	137	21100	560	200
5.26.10.8C Do.	2.99	1.58	214	87.1	7680	1350	4200
5.26.10.8D Do.	3.21	0.19	369	74.1	5100	2850	300
5.26.10.8E Do.	2.26	0.68	468	60.1	5630	3220	1400
5.26.10.8F Do.	2.67	4.72	4.75	33.9	223	70.2	4.74
5.26.10.9 Sunrise	67.9	442	26.2	20.8	33	244	11.4
5.26.10.10 Do.	43.7	1.51 ?		79.4	11900	6990	500
5.26.10.11 Do.	67.8	29.5	9.86	32	122	88.2	61
5.26.10.12 Do.	5.18	0.6	75.6	17.65	134.5	790	12.35
5.26.10.13 Unnamed	203	84.9	63	55	232	500	34.6
5.26.10.14 Do.	2.29	0.38	2.72	14.2	38.8	169.5	1.52
5.27.10.8 Buckhorn	1.44	0.08	5.72	18.4	17.3	206	3.59



6 INCHES

# GRADE-TONNAGE



**Figure 3.** Estimates of grade and tonnage for a variety of beryllium deposits, districts, and belts in the United States and worldwide that have potential for minable beryllium resources. Diagonal lines show equal value of contained metal in metric tons. Available data for deposits of these types are sparse; some deposit information was compiled using incompletely documented past-production, reserve, and resource information. (For additional information, see Trueman and Sabey [2014]; Foley and others [in press], and references therein.)

# 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 loses suddenly the volatiles and only small crystals grow
- mostly due to large volumes of gases (volatiles =H<sub>2</sub>O, 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

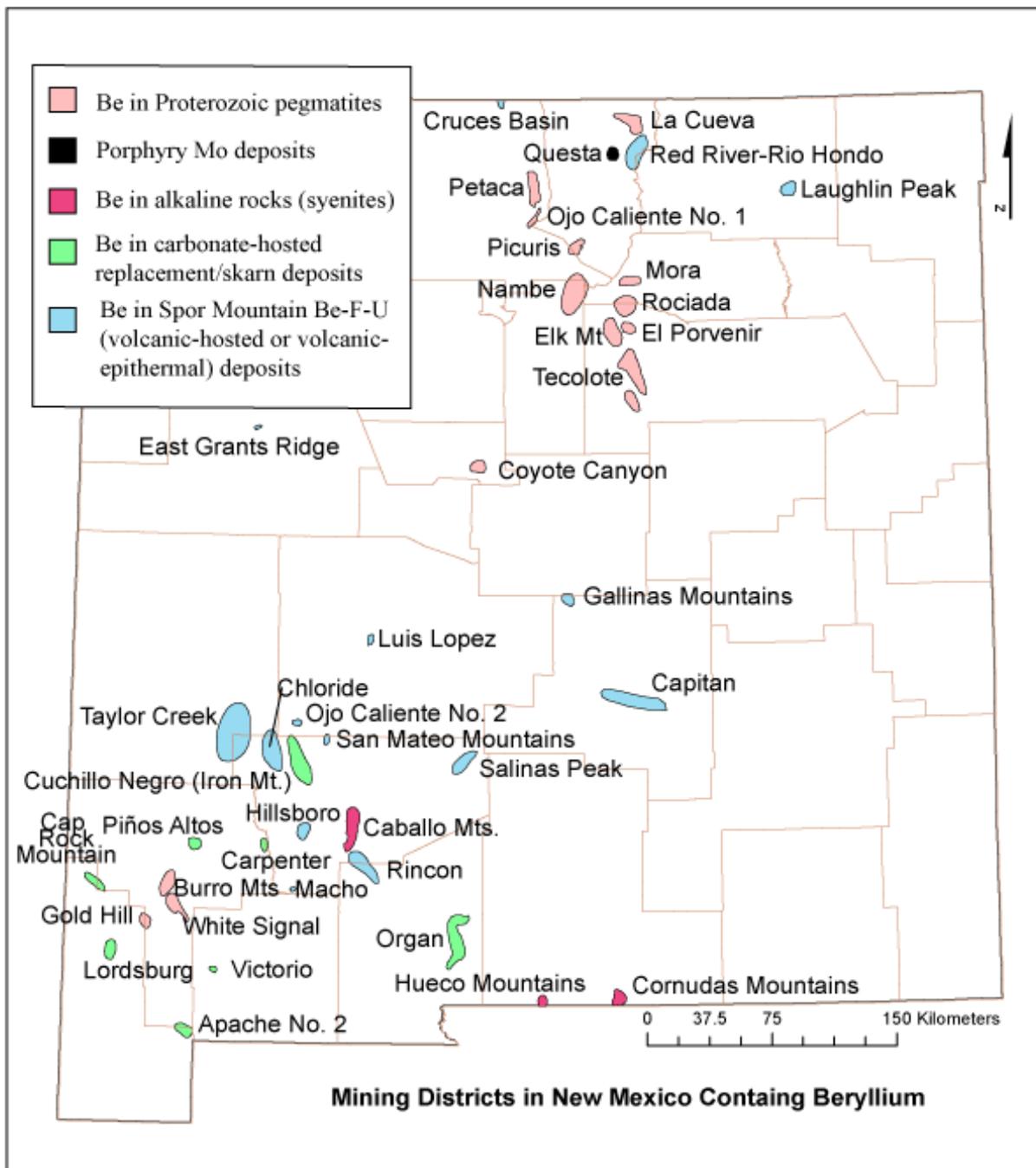
# Types

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



**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

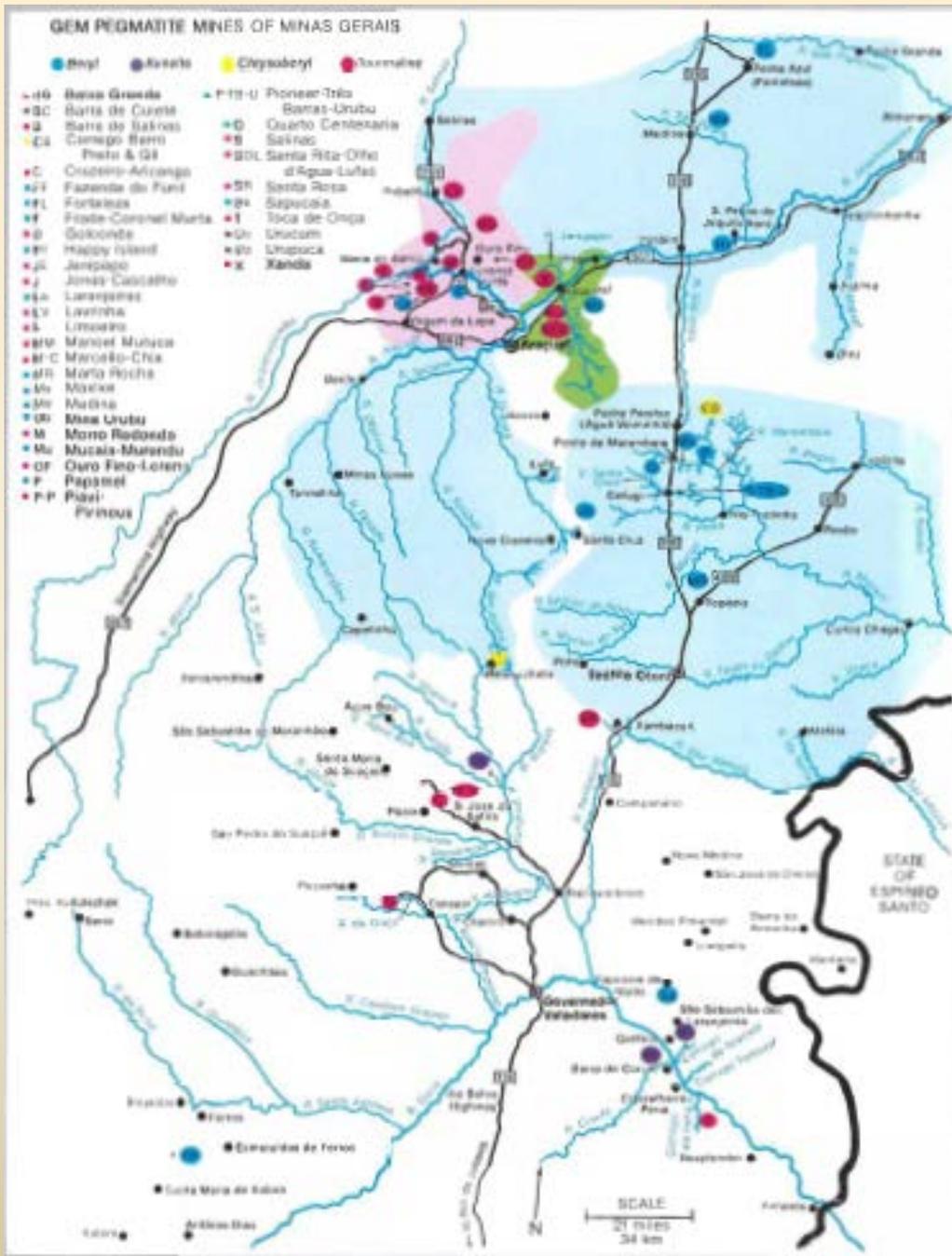


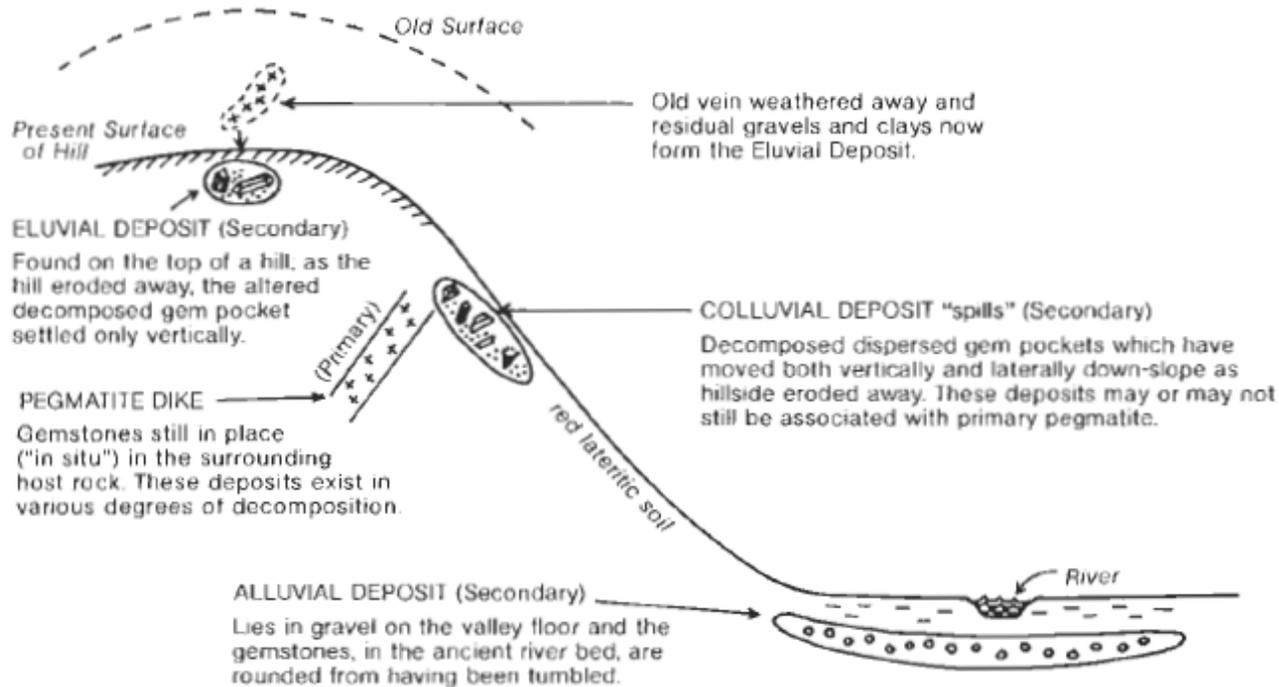
Mining districts in New Mexico that contain beryllium (Be). More details are in McLemore (2010).

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

# Minas Gerais, Brazil (Proctor, 1984)





*Figure 4. Diagram of primary (pegmatite dike) and secondary (eluvial, colluvial, and alluvial) deposits. All three secondary deposits have traveled some distance from their original primary pegmatite.*

Minas Gerais, Brazil (Proctor, 1984)



Brazilian Aquamarine

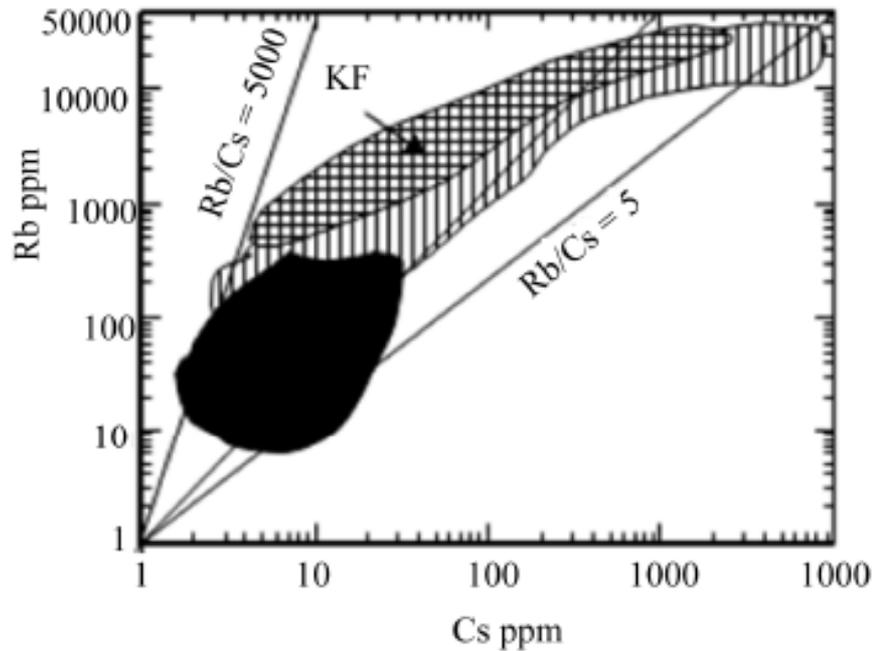
**Table 1. Main characteristics of the first group Pegmatites [3].**

Zone	Mineralogy
Beryl pegmatite	Quartz, K-feldspar, biotite, muscovite, tourmaline, albite, garnet, beryl, columbite-tantalite (Nb > Ta).
Beryl Spodumene Pegmatite	Quartz, K-feldspar, muscovite, Li - mica, albite, tourmaline gem quality ( <b>Figure 2</b> ), behierit, mica, beryl, spodumene, amblygonite, columbite-tantalite (Nb = Ta), cassiterite and the apatite.
Spodumene Pegmatite	Quartz, K-feldspar, muscovite, Li-mica, albite, Elbaite, Behierit, garnet, (blue and pink) beryl, spodumene, amblygonite, columbite-tantalite (Nb < Ta), triphylite, ferrisiklerite, heterosite, cassiterite and the apatite.

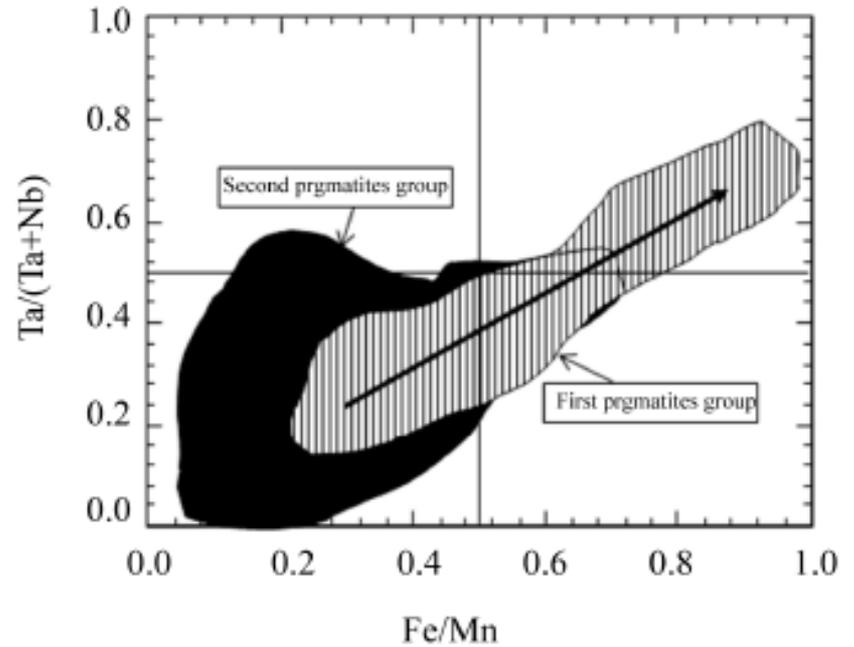
**Table 2. Main characteristics of the second group [3].**

Zone	Mineralogy
Contact	Quartz, biotite, K-feldspar, muscovite, albite, fluorite, garnet (almandine-spessartine)
Wall	Graphics Quartz, K-feldspar, muscovite, beryl, apatite, monazite (Ce), columbite-tantalite
Intermediary zone	K-Feldspar, Muscovite, Quartz.
core	Quartz
Metasomatic zone	Amazonite, beryl (construction or pink), cleavelandite (albite), apatite, phosphates (25 minerals), fluorite, columbite-tantalite ((Fe, Mn) Nb <sub>2</sub> O <sub>6</sub> ), euxenite (Y) ((Y, Ca, Ce, U, Th) (Nb, Ta, Ti) <sub>2</sub> O <sub>6</sub> ), Topaz, samarskite ((Fe, Y, U, REE) (Nb, Ta)O <sub>4</sub> ), autunite ((Ca (UO <sub>2</sub> ) <sub>2</sub> (PO <sub>4</sub> ) <sub>2</sub> ) Microlite ((Ca, Na) <sub>2</sub> Ta <sub>2</sub> O <sub>6</sub> (O, OH, F)), Wulfenite (PbMoO <sub>4</sub> ), bismuthinite (Bi <sub>2</sub> S <sub>3</sub> ), huttonite (ThSiO <sub>4</sub> ) and Kerala ((Ca, Ce, Th) (P, Si)O <sub>4</sub> )

Bilal et al. (2012)



(a)



(b)

A systematic compositional trend seems to suggest a petrogenetic link between the pegmatites of the region.

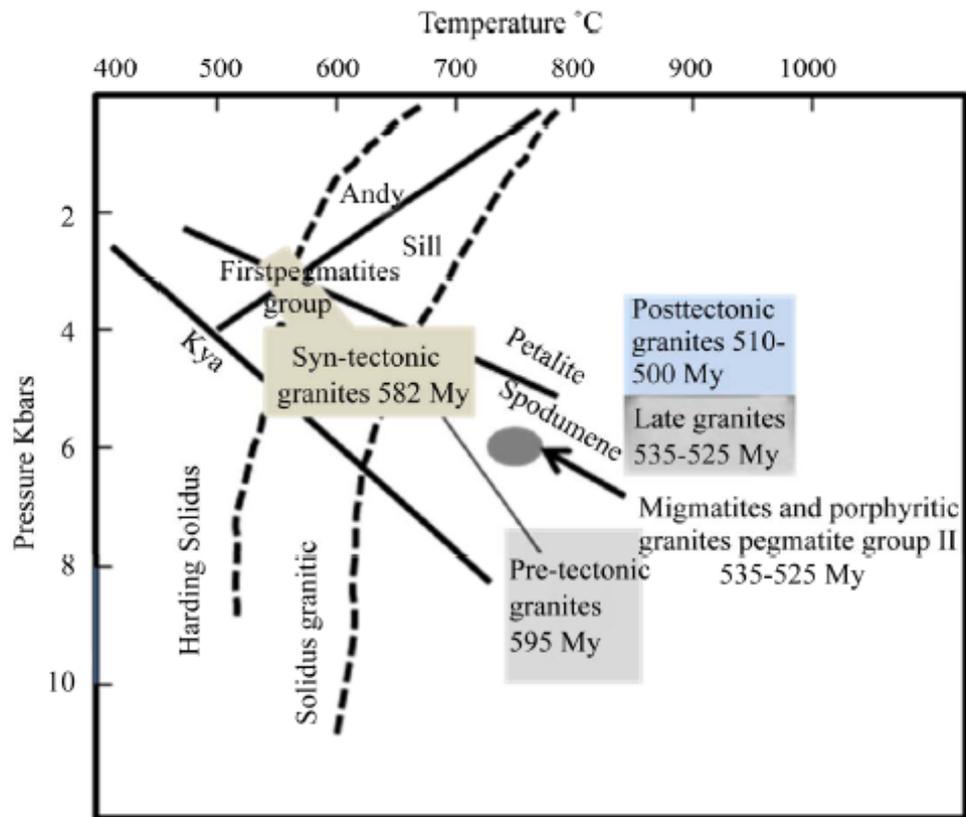


Figure 8. Compilation of the P-T-t Neoproterozoic granites of the Minas Gerais [2,5]. The pre-tectonic granites (595 My) are exhumed during a main deformation phase D1 (590 - 565 My) corresponding to a collisional event. The syn-tectonic and the P-Li-Be bearing pegmatites have an age of 582 My. The late and post-tectonic granitoids and the 2<sup>nd</sup> pegmatites group (537 - 520 My) are contemporaneous with the second phase of deformation D2 that corresponds to extensional movements. The post-tectonic granitoids were emplaced in the upper crust, 511 to 500 My.



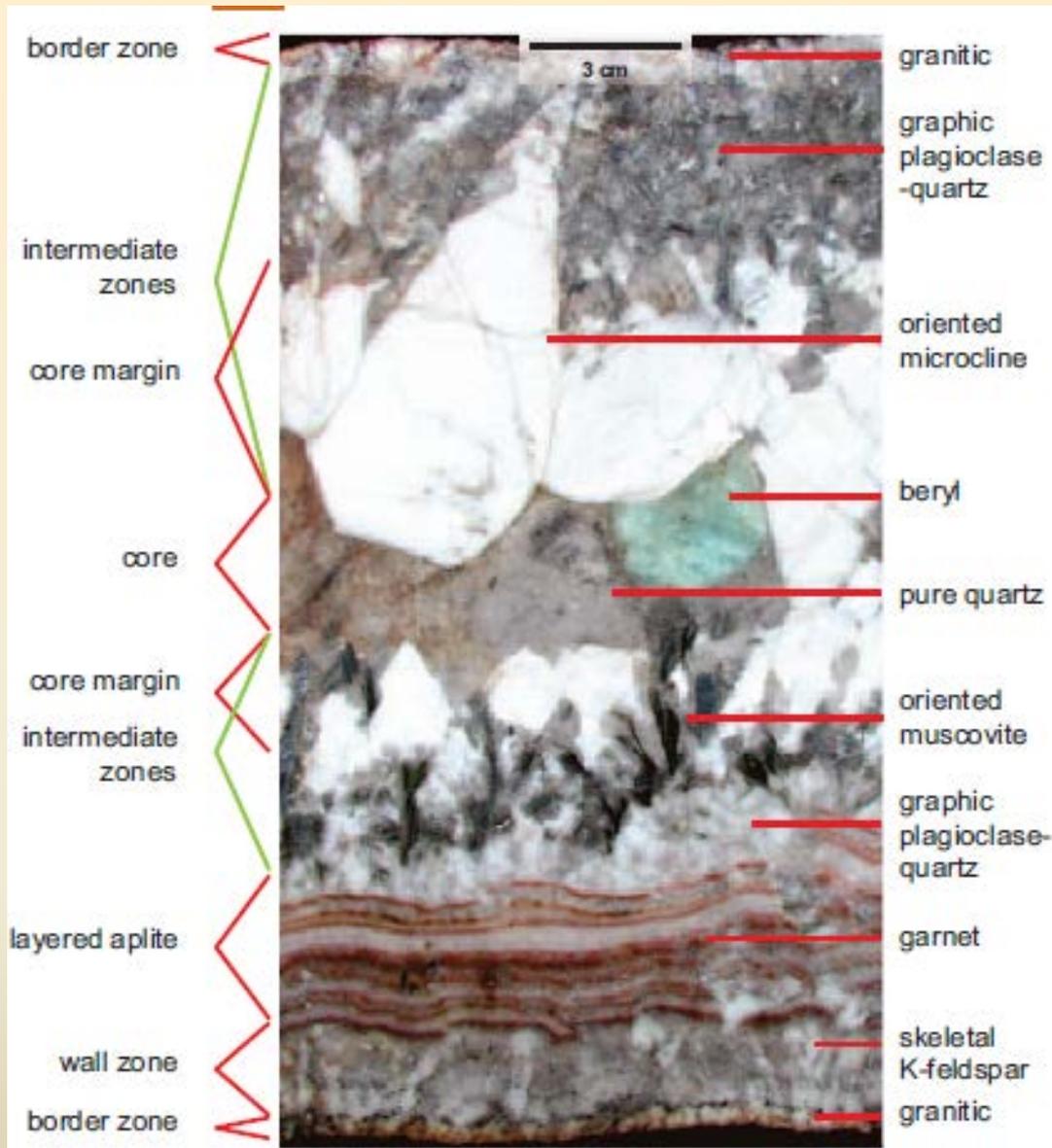
*Figure 5. Heavy machinery is often required for hard-rock mining in Brazil. At the Golconda tourmaline mine, bulldozers are used to move the overburden and waste from the mine entrance.*

Minas Gerais, Brazil (Proctor, 1984)

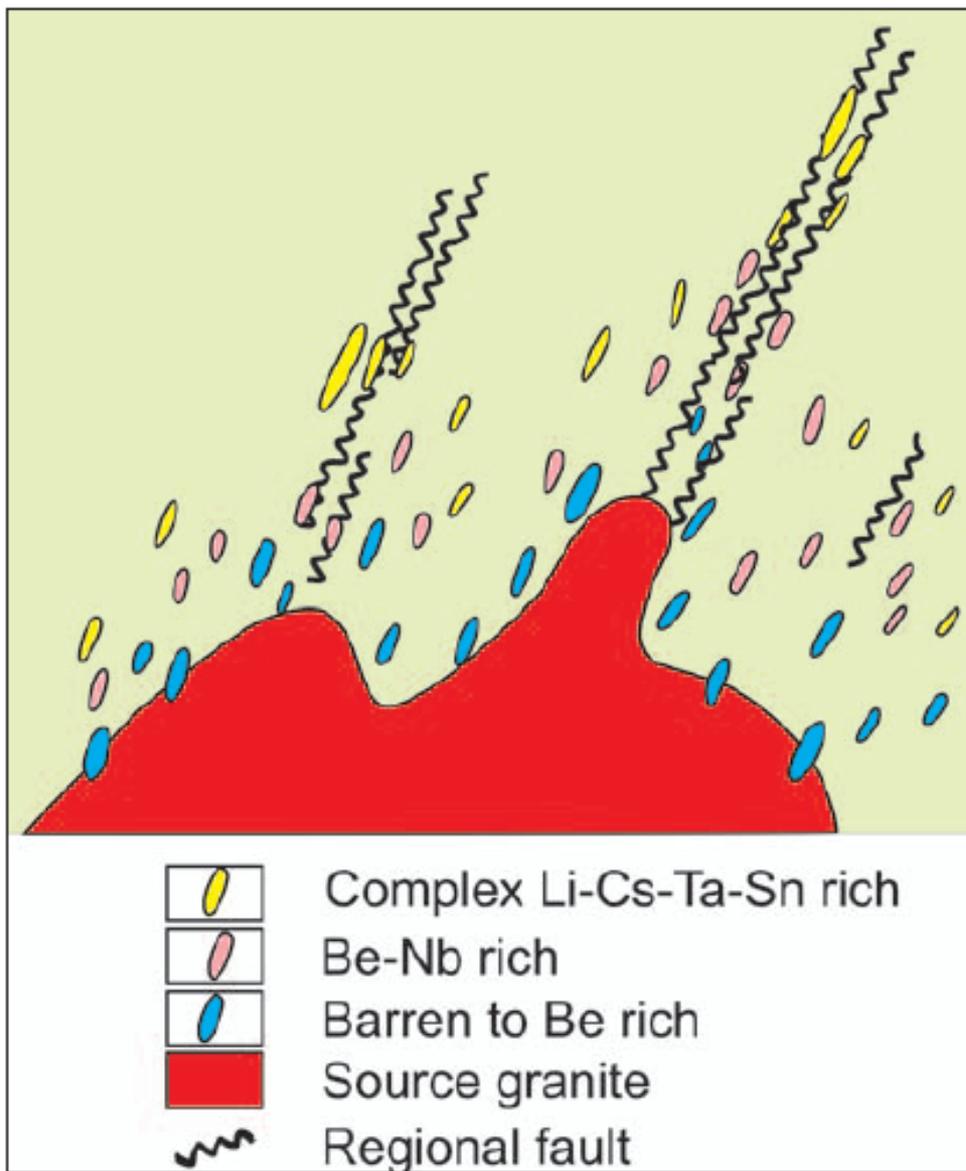
Class	Subclass	Type	Subtype	Family
Abysal	HREE			NYF
	LREE			
	U			NYF
	BBe			LCT
Muscovite				
Muscovite-rare element	REE			NYF
	Li			LCT
Rare element	REE	allanite-monazite euxenite gadolinite		NYF
	Li	beryl	beryl-columbite beryl-columbite-phosphate	
		complex	spodumene petalite lepidolite elbaite amblygonite	LCT
		albite-spodumene albite		
Mirolitic	REE	topaz-beryl gadolinite-fergusonite		NYF
	Li	beryl-topaz spodumene petalite lepidolite		LCT

**TABLE 1** The pegmatite classification scheme of Černý and Ercit (2005), modified to show the correlation between pegmatite classes and families. NYF = niobium-yttrium-fluorine family (green); LCT = lithium-caesium-tantalum family (yellow); HREE = heavy rare earth elements; LREE = light rare earth elements

# London and Kontak (2012)



**FIGURE 4** Textural and zonal attributes of pegmatites. The image shows a complete section of a pegmatite dike, about 28 cm thick, located near Palomar Mountain, San Diego County, California (USA).



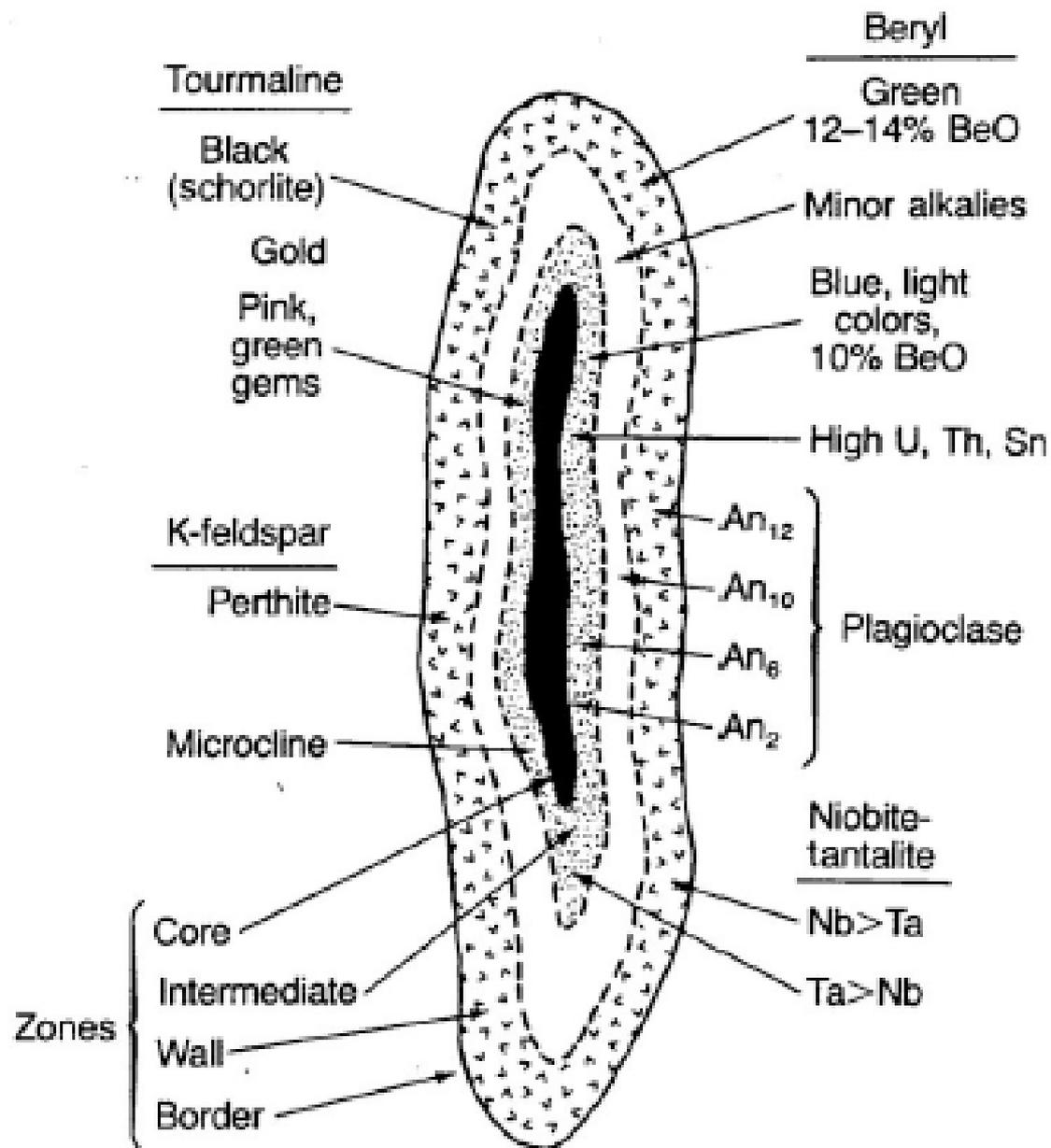
**FIGURE 1** Idealized zoned pegmatite field around a source granite. The maximum distance of pegmatites from the source granite is on the order of kilometers or, at most, tens of kilometers. MODIFIED FROM ČERNÝ (1989)

# Stages

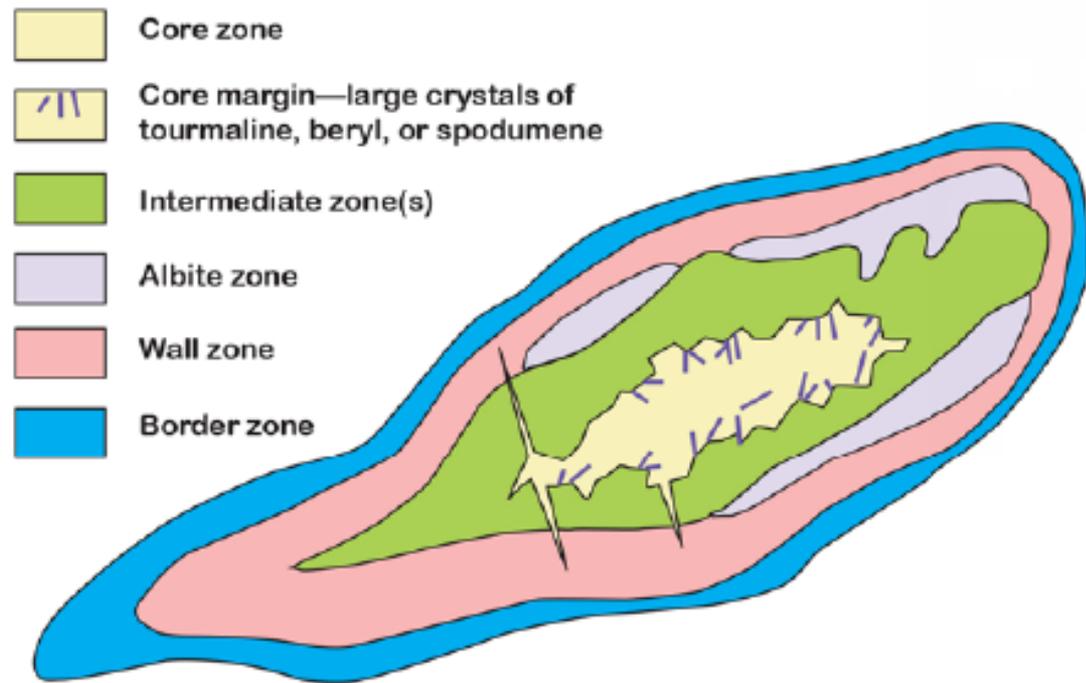
- Magmatic
  - Precipitation of feldspar and quartz, followed by other minerals
  - Formation of aqueous fluids
- Hydrothermal
  - Fluids ascend from the magma (decrease temperature, pressure)
  - Boiling
  - Volatiles enter vapor phase
  - Metals precipitate

# Zoning

- Unzoned or simple (quartz, feldspar, mica)
- Zoned or complex
  - Core (massive quartz, spodumene)
  - Intermediate (giant feldspar)
  - Wall (graphic texture, beryl, quartz, feldspar, mica, tourmalene)
  - Border (albite)



Jahns



**Figure 2.** Deposit-scale zoning patterns in an idealized pegmatite, redrafted from Fetherston (2004) and Černý (1991).



Porphyritic monzogranite

core margin wall zone  
Hanging-wall aplite (albite-rich  $\pm$  biotite) (gray-blue)

Perthite-quartz micrographic intergrowth (green)

Coarse graphic perthite-quartz (light gray)

Quartz crystals (gray) and beryl crystal (orange)

Core-zone miarolitic cavity

Elbaite tourmaline crystals projecting into cavity  
(black with gray terminations)

Hydrothermal clay filling (bottom of cavity)

Schorl and quartz intergrowths (black and gray)

Petalite crystals (yellow) and pollucite crystals (rounded yellow)

Albite (blue) and lepidolite (purple)

Sekaninaite (brown)

core margin  
Perthite-quartz micrographic intergrowth (green)

wall zone  
Footwall aplite (albite-rich  $\pm$  biotite) (gray-blue)

Footwall contact

Porphyritic monzogranite

FIGURE 3

Idealized Elba pegmatite. DRAWING BY FEDERICO PEZZOTTA

Table 2 The four classes of granitic pegmatites.

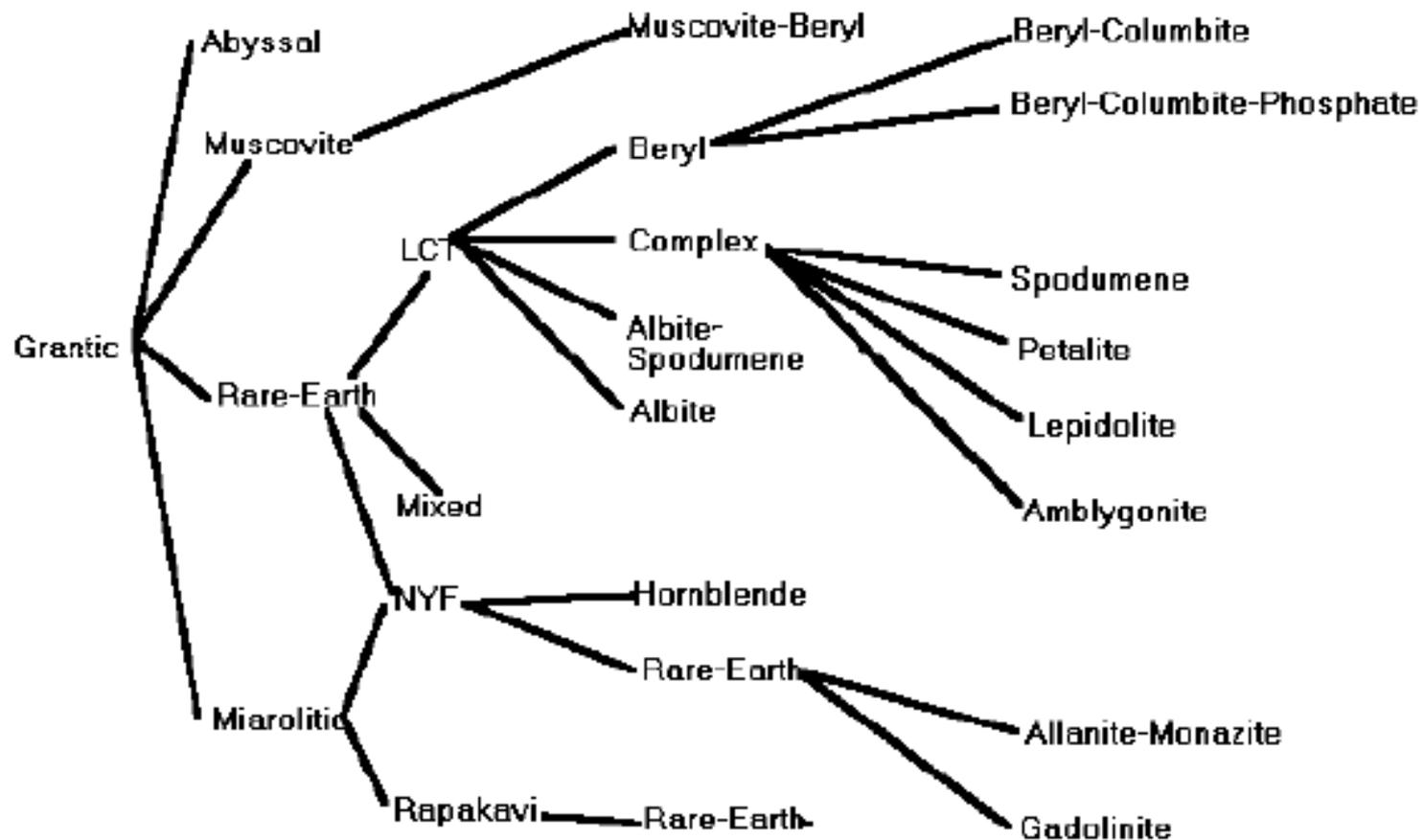
Class	Family*	Typical Minor Elements	Metamorphic Environment	Relation to Granites	Structural Features	Examples
Abyssal	—	U,Th,Zr,Nb,Ti,Y, REE,Mo poor (to moderate) mineralization	(upper amphibolite to) low- to high-P granulite facies; ~4-9 kb, ~700-800°C	none (segregations of anatectic leucosome)	conformable to mobilized cross-cutting veins	Rae and Hearne Provinces, Sask. (Tremblay, 1978); Aldan and Anabar Shields, Siberia (Bushev and Koplus, 1960); Eastern Baltic Shield (Kalita, 1965)
Muscovite	—	Li,Be,Y,REE,Ti, U,Th,Nb>Ta poor (to moderate)** mineralization; micas and ceramic minerals	high-P, Barrovian amphibolite facies (kyanite-sillimanite); ~5-8 kb, ~650-580°C	none (anatectic bodies) to marginal and exterior	quasi- conformable to cross- cutting	White Sea region, USSR (Gorlov, 1975); Appalachian Province (Jahns <i>et al.</i> , 1952); Rajasthan, India (Shmakin, 1976)
Rare- element	LCT	Li,Rb,Cs,Be,Ga,Sn, Hf,Nb>Ta,B,P,F poor to abundant mineralization; gemstock; industrial minerals	low-P, Abukuma amphibolite (to upper greenschist) facies (andalusite- sillimanite); ~2-4 kb, ~650-500°C	(interior to marginal to) exterior	quasi- conformable to cross- cutting	Yellowknife field, NWT (Meintzer, 1987); Black Hills, South Dakota (Shearer <i>et al.</i> , 1987); Cat Lake-Winnipeg River field, Manitoba (Černý <i>et al.</i> , 1981)
	NYF	Y,REE,Ti,U,Th,Zr, Nb>Ta,F; poor to abundant mineralization; ceramic minerals	variable	interior to marginal	interior pods, conformable to cross- cutting exterior bodies	Llano Co., Texas (Landes, 1932); South Platte district, Colorado (Simmons <i>et al.</i> , 1987); Western Kevy, Kola, USSR (Beus, 1960)
Miarolitic	NYF	Be,Y,REE,Ti,U,Th, Zr,Nb>Ta,F; poor mineralization; gemstock	shallow to sub- volcanic; ~1-2 kb	interior to marginal	interior pods and cross- cutting dykes	Pikes Peak, Colorado (Foord, 1982); Idaho (Boggs, 1986); Korosten pluton, Ukraine (Lazarenko <i>et al.</i> , 1973)

**Notes**

\* See Table 4 for explanation;

\*\* Some Soviet authors distinguish a rare-element-muscovite class, in all respects intermediate between the muscovite and rare-element classes proper

# Pegmatite Classes



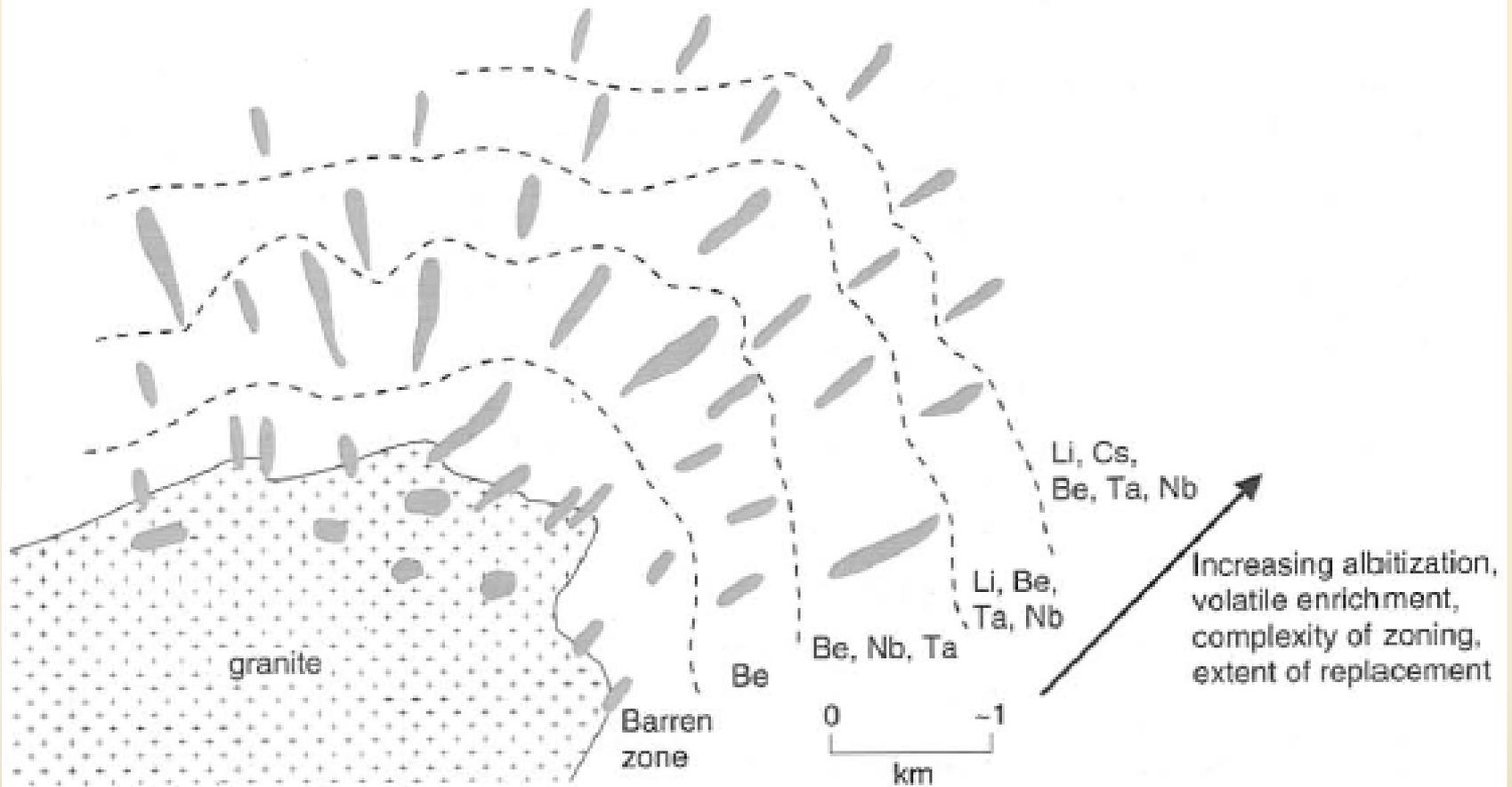
(Cerny 1992)

Table 21-2. Production/reserves of selected Canadian and foreign pegmatite deposits.

Deposit	Production/reserves	Comments/references
<i>Canadian deposits</i>		
Tanco mine, Manitoba	a) 1.9 Mt; 0.216% Ta <sub>2</sub> O <sub>5</sub> b) 6.6 Mt; 2.76% Li <sub>2</sub> O (in spodumene + petalite) c) 0.3 Mt; 23.3% Cs <sub>2</sub> O d) 0.8 Mt; 0.20% BeO	Reserves (Crouse et al., 1964)
Preissac-Lacorne area, Quebec	19 Mt; 1.25% Li <sub>2</sub> O	Production plus reserves from the (former) Quebec Lithium property (Flanagan, 1976)
Fl (J.M.-Lit), Yellowknife district, N.W.T.	13.9 Mt; 1.19% Li <sub>2</sub> O	*Identified paramarginal resources* (Lasmanis, 1978)
Thor (Echo), Yellowknife district, N.W.T.	8.4 Mt; 1.5% Li <sub>2</sub> O	*Identified paramarginal resources* (Lasmanis, 1978)
Violet, Herb Lake area, Manitoba	5.9 Mt; 1.2% Li <sub>2</sub> O	Reserves (Williams and Trueman, 1976)
Nama Creek, Georgia Lake area, Ontario	3.9 Mt; 1.06% Li <sub>2</sub> O	Reserves, North and South zones (Pye, 1965)
Lac la Croix, Ontario	1.4 Mt; 1.3% Li <sub>2</sub> O	Reserves (Mulligan, 1965)
Madawaska mine, (formerly Faraday mine), Bancroft district, Ontario	4.5 Mt; 0.09% U <sub>3</sub> O <sub>8</sub>	Production 1957-1964 and 1976-1982 (Carter and Colvine, 1985)
<i>Foreign deposits</i>		
Tin-spodumene Belt, North Carolina	a) 26 Mt; 1.5% Li <sub>2</sub> O	Measured and indicated reserves, Kings Mountain, Foote Mineral Co. (Kunasz, 1982)
	b) 30.5 Mt; 1.5% Li <sub>2</sub> O	Reserves, Bessemer City, Lithium Corporation of America (Company news release, 1976)
Bikita, Zimbabwe	10.8 Mt; 3.0% Li <sub>2</sub> O	Reserves (Wegener, 1961)
Kamativi, Zimbabwe	100 Mt; 0.114% Sn, 0.603% Li <sub>2</sub> O	*Maximum inerrable reserves of a single pegmatite* (Bellasis and van der Heyde, 1962)
Uis, Namibia	87 Mt; 0.134% Sn	Mineable plus possible reserves (Mining Magazine, November, 1983, p. 291)
Greenbushes, Australia	a) 28 Mt; 0.114% Sn, 0.043% Ta <sub>2</sub> O <sub>5</sub> , 0.031% Nb <sub>2</sub> O <sub>5</sub>	Underground reserves (Knight and Wallace, 1982)
	b) 33.5 Mt; 2.55% Li <sub>2</sub> O	Proven and probable reserves (Knight, 1986)
Manono-Kitotolo, Zaire	35 Mt; 1.3% Li <sub>2</sub> O	Reserves proved by systematic exploration (Evans, 1978)
Minas Gerais and Ceara states, Brazil	106 Mt; 0.04% BeO	Estimated in situ ore (Soja and Sabin, 1986)

Sinclair, 1996

TYPE 21



GSC

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

Sinclair, 1996

**Table 21-2. Production/reserves of selected Canadian and foreign pegmatite deposits.**

Deposit	Production/reserves	Comments/references
<i>Canadian deposits</i>		
Tanco mine, Manitoba	a) 1.9 Mt; 0.216% Ta <sub>2</sub> O <sub>5</sub> b) 6.6 Mt; 2.76% Li <sub>2</sub> O (in spodumene + petalite) c) 0.3 Mt; 23.3% Cs <sub>2</sub> O d) 0.8 Mt; 0.20% BeO	Reserves (Crouse et al., 1984)
Minas Gerais and Ceara states, Brazil	106 Mt; 0.04% BeO	Estimated in situ ore (Soja and Sabin, 1986)

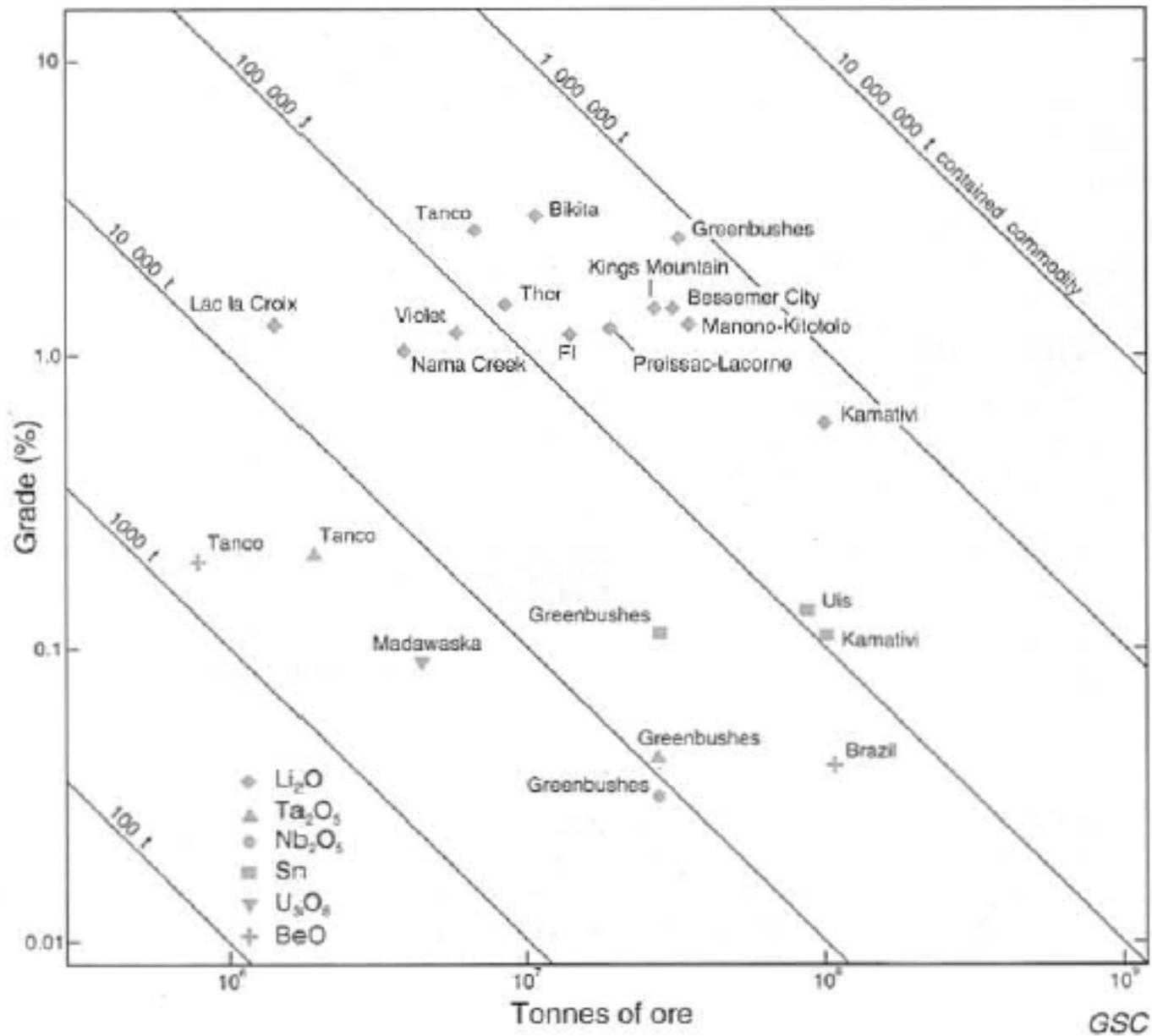
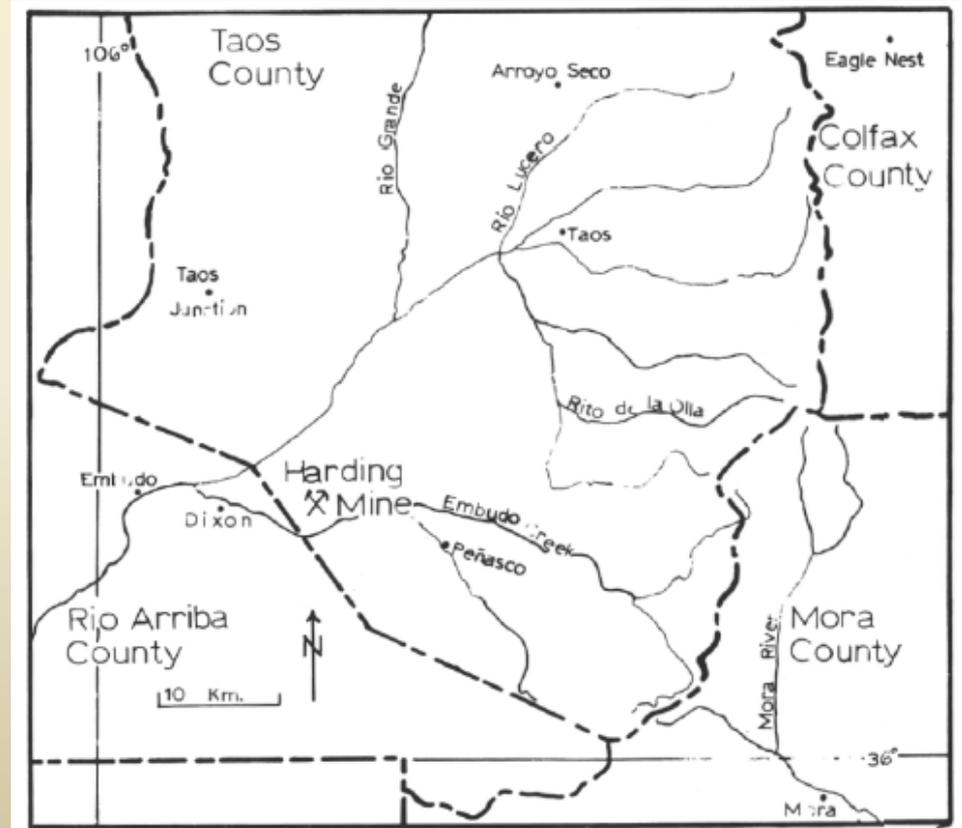


Figure 21-2. Grade versus tonnage diagram for pegmatite deposits (data are from Table 21-2).

Sinclair, 1996

# Harding Mine, New Mexico

- Discovered 1910
- Lepidolite mining 1919-1930
  - 12,000 tons of lepidolite-spodumene ore, averaging 3.5%  $\text{LiO}_2$
- Microlite 1942-1947
  - 12,000 tons of lepidolite-spodumene ore, averaging 3.5%  $\text{LiO}_2$
- Beryl 1950-1959
  - 12,000 tons of lepidolite-spodumene ore, averaging 3.5%  $\text{LiO}_2$



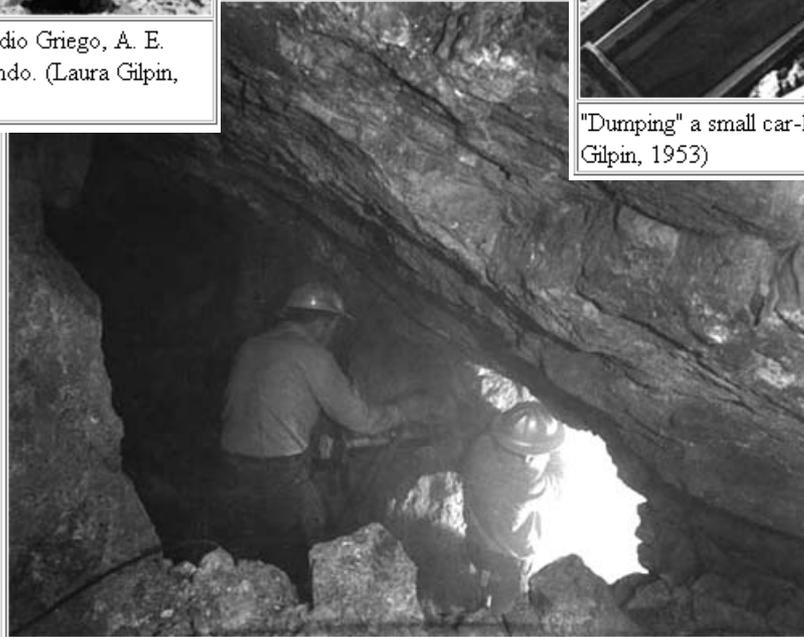
# Harding mine, New Mexico



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



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



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

# Harding Mine

- BIOTITE + MUSCOVITE + QUARTZ ± GARNET ± MARGARITE ± SCHORL
- QUARTZ + ALBITE + MUSCOVITE ± PERTHITE
- QUARTZ ± ALBITE ± MUSCOVITE
- QUARTZ + LATH SPODUMENE
- MICROCLINE + SPODUMENE + LEPIDOLITE + ALBITE + MUSCOVITE + QUARTZ
- CLEVELANDITE + ROSE MUSCOVITE ± QUARTZ
- CLEVELANDITE + QUARTZ ± MUSCOVITE
- BLOCKY PERTHITE ± QUARTZ ± ALBITE
- QUARTZ + APLITIC ALBITE ± MUSCOVITE

# Be in Coal in NM

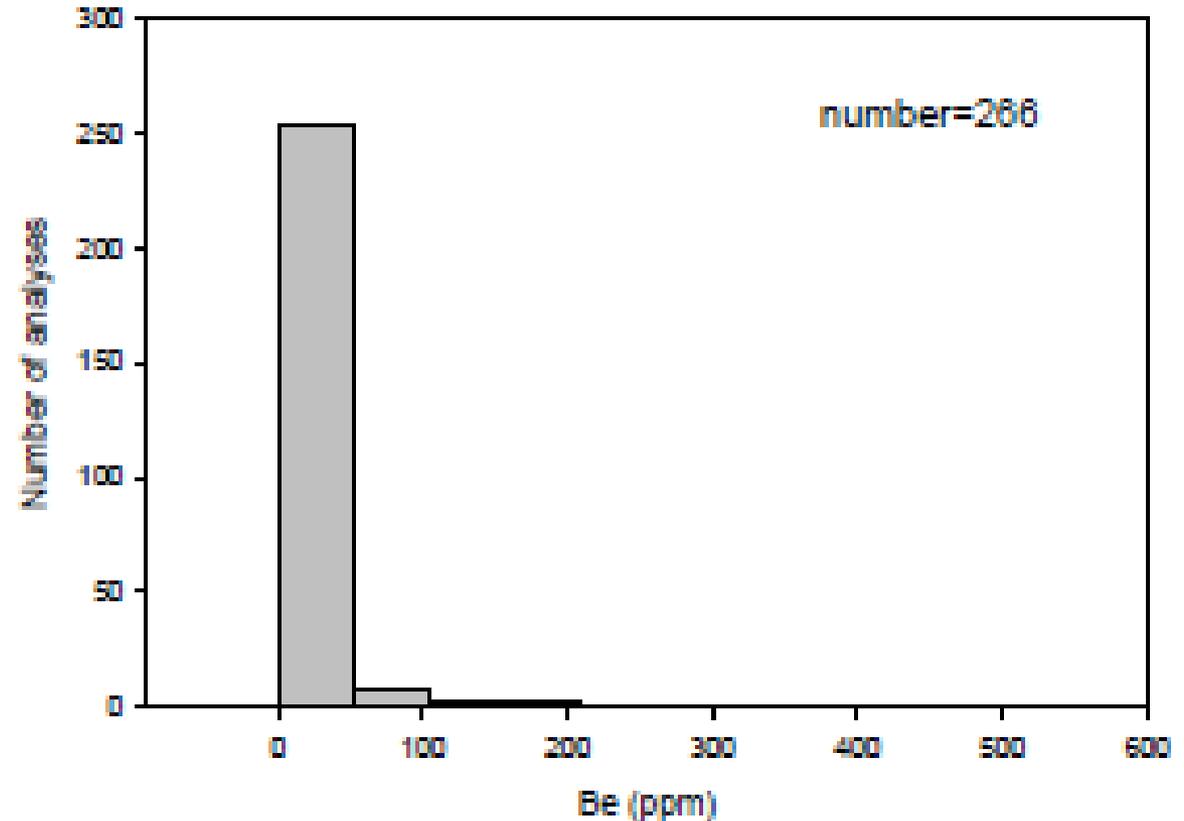


FIGURE 32. Beryllium analyses in coal samples (Hoffman, 1991).

# Materion Brush Resources Inc. of the USA, wholly-owned subsidiary of Materion Corporation, is the only known fully-integrated beryllium company in world

- Mines Utah to plant in Delta, Utah to form Be hydroxide
- Elmore plant, Ohio produces beryllium metal and alloys
- Lorain plant, Ohio produces ceramic grade powder
- Reading plant, Pennsylvania produces produces strip and wire products

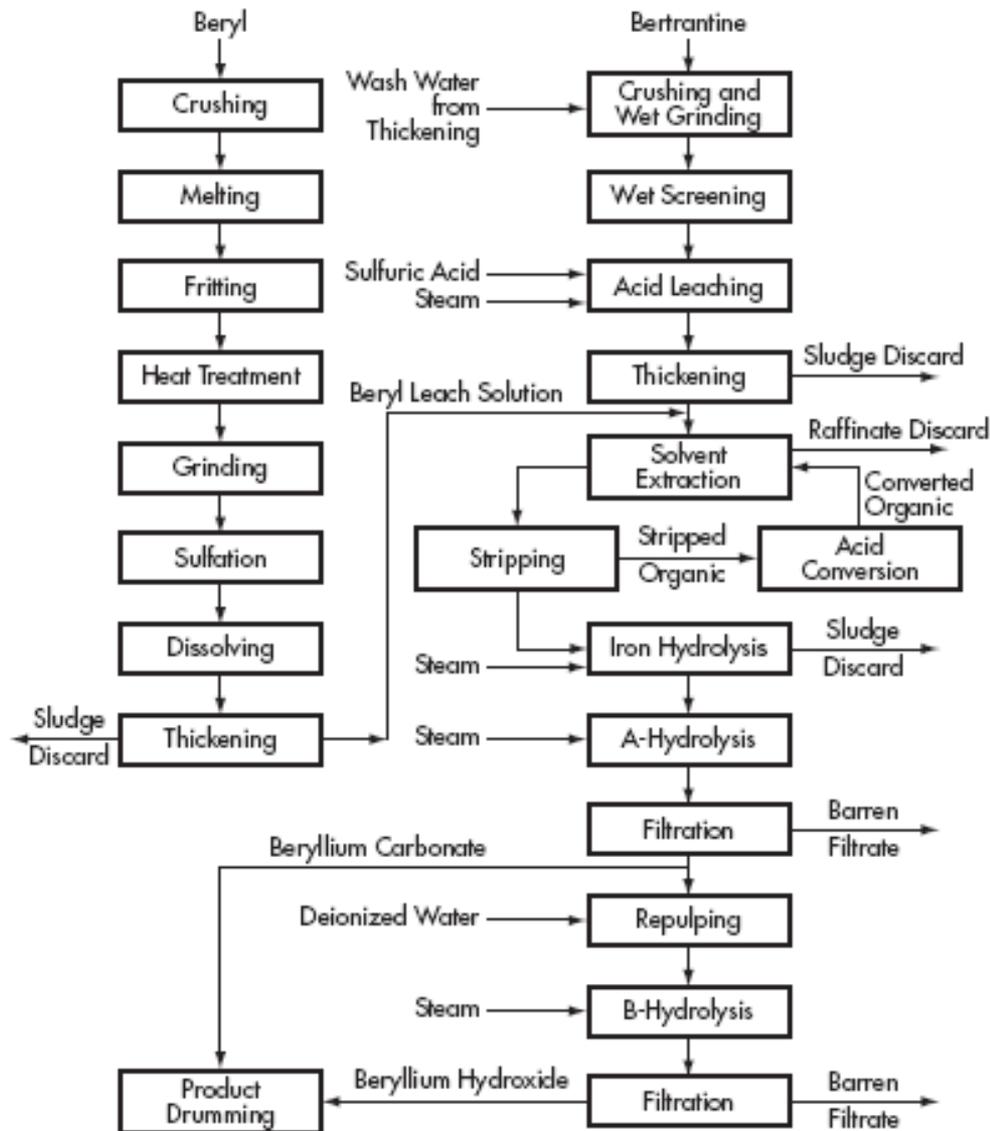
# Other companies

- NGK Metals Corp, part of NGK Insulators of Japan
- NGK Metals Corporation, Starmet and Advanced Industries International in USA
- Ulba Metallurgical Plant (UMP) in Kazakhstan

# Beryllium—Processing

- Similar to Al, therefore it is not simple to separate
- maintain careful control over the quantity of beryllium dust and fumes in the workplace
- Mined, crushed, melted, solidified, treated with sulfuric acid to form a sulfate
- Be sulfate undergoes a series of chemical extraction steps resulting in pure Be hydroxide

# Processing



Courtesy of Brush Resources Inc.

**Figure 1. Beryllium hydroxide production from bertrandite and beryl**

# Beryllium—Health risks

- Toxic metal
  - Chronic beryllium disease, or CBD, is an inflammation in the lungs
- Radioactive

# ASSIGNMENT

- **NEXT WEEK (Feb 13, 20) no class, REE Feb 27, March 6**
- Castor, S.B., 2008, The Mountain Pass rare-earth carbonatite and associated ultrapotassic rocks, California: The Canadian Mineralogist, v. 46, p. 779-806,  
<http://canmin.geoscienceworld.org/content/46/4/779.full.pdf+html?sid=180ae325-acd5-4226-9a02-175f7a865e17>
- Long, K.R., van Gosen, B.S., Foley, N.K. and Cordier, D., 2010, The principle rare earth elements deposits of the United States—A summary of domestic deposits and a global perspective: U.S. Geological Survey, Scientific Investigations Report 2010-5220, 104 p., <http://pubs.usgs.gov/sir/2010/5220/> (accessed 5/1/12).
- Mariano and Mariano, 2012, Rare earth mining and exploration in North America: Elements, v. 8, 369-376,  
<http://elements.geoscienceworld.org/content/8/5/369.full.pdf+html?sid=605ebd04-9070-4994-9bce-b1cdd79f349d>