ME571/Geol571 Geology and Economics of Strategic and Critical Minerals

Commodities: Tellurium

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- Safety moment
- NMGS presentations

Schedule

- April 17 Sustainable Development
- April 24 Misc. commodities; give out take home final
- May 1 Present project/research in class (last class)
- May 12 Final and written project/research reports due

ASSIGNMENT

- Barker, J. M., and McLemore, V. T., 2005, Sustainable development and Industrial minerals: Mining Engineering, December, p. 48-52, http://geoinfo.nmt.edu/staff/mclemore/documents/sustdevIM.pdf
- McLemore, V. T., and Dennis Turner, D., 2006, Sustainable development and exploration: Mining Engineering, February, p. 56-61, http://geoinfo.nmt.edu/staff/mclemore/documents/sustdev.pdf
- A GUIDE TO LEADING PRACTICE SUSTAINABLE DEVELOPMENT IN MINING, https://industry.gov.au/resource/Documents/LPSDP/guideLPSD.pdf

http://www.visualcapitalist.com/not-a-drop-to-drink-americas-water-crisis/?utm_source=Visual+Capitalist+Infographics+%28All%29&utm_campaign=9248b63fb1-Most_Valuable_Cash_Crop&utm_medium=email&utm_term=0_31b4d09e8a-9248b63fb1-43004761

AND THEN THERE'S THE "HIDDEN WATER" IN WHAT WE CONSUME AND ITEMS WE USE EVERY DAY.

A 60-WATT BULB
can use up to
5 GALLONS
OF WATER
for every hour it's left on.

A pound of beef, from farm to plate, uses
1,800 GALLONS
OF WATER.

WE USE PLENTY OF WATER EVERY DAY, BUT WE NEED TO FIND A WAY TO CONSERVE.

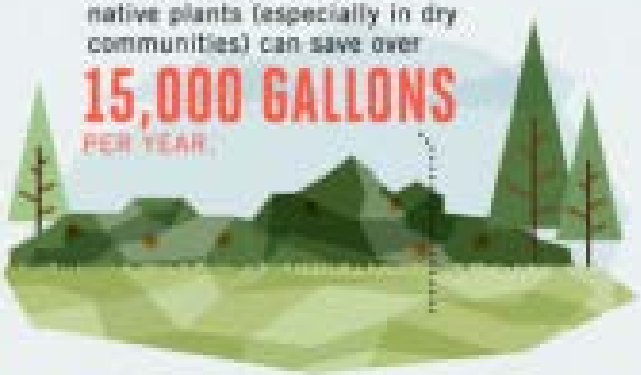
CONSERVATION

THERE ARE SMALL THINGS WE CAN ALL DO:

Old toilets use 7 GALLONS per flush.
New toilets can use as little as 1 GALLON.

INSTALLING WATER-EFFICIENT FIXTURES CAN REDUCE A HOUSEHOLD'S DAILY WATER USE BY
35 PERCENT.

Replacing grass lawns with native plants (especially in dry communities) can save over
15,000 GALLONS
PER YEAR.



AND BIG THINGS THAT INDUSTRIES CAN DO:

Farms that change to overhead or drip irrigation, from traditional surface irrigation, could significantly improve agricultural water efficiency, while preventing runoff and food waste.

INTRODUCTION

USGS
science for a changing world

USGS Mineral Resources Program

52
Te
[Kr]5s²4d¹⁰5p⁴
127.6

Tellurium—The Bright Future of Solar Energy

As part of a broad mission to conduct research and provide information on nonfuel mineral resources, the U.S. Geological Survey (USGS) supports science to understand

- *How and where tellurium resources form and concentrate in the Earth's crust*
- *How tellurium resources interact with the environment to affect human and ecosystem health*
- *Trends in the supply of and demand for tellurium in the domestic and international markets*
- *Where undiscovered sources of tellurium might be found*

Why is this information important? Read on to learn about tellurium and the important role it plays in the national economy, in national security, and in the lives of Americans every day.

Tellurium is one of the least common elements on Earth. Most rocks contain an average of about 3 parts per billion tellurium, making it rarer than the rare earth elements and eight times less abundant than gold. Grains of native tellurium appear in rocks as a brittle, silvery-white material, but tellurium more commonly occurs in telluride minerals that include varied quantities of gold, silver, or platinum. Tellurium is a metalloid, meaning it possesses the properties of both metals and nonmetals.

Tellurium was discovered within gold ores in the late 1780s in Transylvania, Romania. Fifteen years later, the element was isolated as a distinct substance and named tellurium, after the Latin word "tellus," which means "fruit of the Earth." Recovered tellurium has historically been used in metallurgy as an additive to stainless steel and in alloys made with copper, lead, and iron.

Because of its low abundance, little is known about environmental baseline concentrations for tellurium or its toxic effect on humans and ecosystems. Human exposure to tellurium can lead to a garlic odor on the breath, nausea, and eventual respiratory problems.

How Do We Use Tellurium?

Tellurium's primary use is for manufacturing films essential to photovoltaic solar cells. When alloyed with other elements—such as cadmium—tellurium forms a compound that exhibits enhanced electrical conductivity. Therefore, a thin film can efficiently absorb sunlight and convert it into electricity. As an additive to steel, copper, and lead alloys, tellurium improves machine efficiency, specifically in thermoelectric cooling applications where it improves ductility and tensile strength, and helps prevent sulfuric acid corrosion. Together, the photovoltaic and thermoelectric applications account for more than two-thirds of global tellurium consumption.

Tellurium is critical to efficient, thin-film photovoltaic cells that produce electricity from sunlight. A 2-megawatt, solar photovoltaic array occupies a former landfill at Fort Carson, Colo. Photograph from the U.S. Department of Energy Western Area Power Administration http://usarmy.vo.llnwd.net/e2/c/images/2013/12/05/323603/original.jpg.

Tellurium is used in copying machines and as a coloring agent in ceramics and glass, and as a vulcanizing agent in the chemical industry to make durable products, including an additive that improves rubber's heat resistance. Integrated circuits, laser diodes, and medical instrumentation, all of which have experienced robust manufacturing growth in recent years, contain tellurium. It can even be added to gasoline to prevent engine knocks in automobiles.

Cryogenic Underground Observatory for Rare Events (CUORE) experiment uses towers of cubic tellurium oxide crystals (pictured) to try and detect a Majorana neutrino.

http://12cnt1grpdfi.cl0hk1ia8ayerg.rocketdna-cdn.com/wp-content/uploads/sites/3/2105/04/CUORE_towers.jpg

Where Does Tellurium Come From?

Most tellurium used today is indirectly mined, as it is recovered as a byproduct of milled copper, iron, and other base-metal-rich ore bodies containing trace amounts of tellurium-bearing minerals. Globally, primary tellurium sources are large-tonnage, low-grade ores from copper and copper-gold porphyry-type deposits, as a byproduct of copper refining. Typically, concentrations of 1 to 4 percent tellurium are recovered from anode slimes at copper refineries. Seafloor volcanogenic massive sulfide (VMS) deposits can also yield significant amounts of byproduct tellurium; the large iron- and copper-rich ore bodies in the Ural Mountains of Russia are an important example.

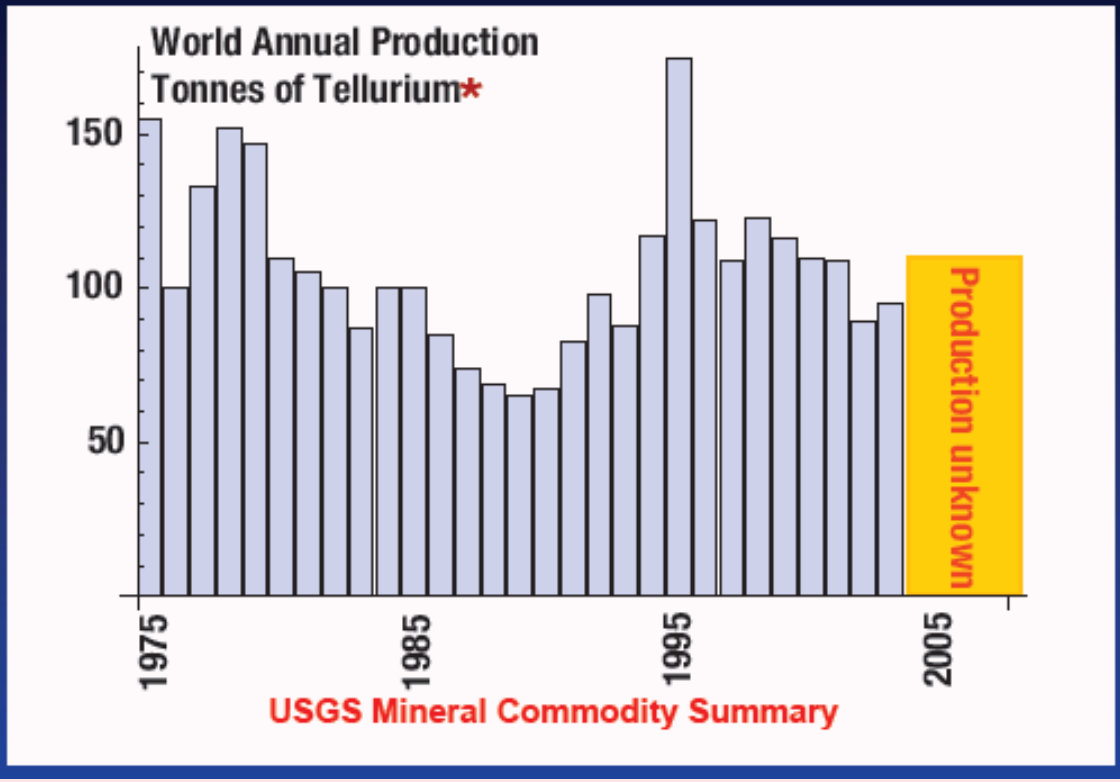
Tellurium is concentrated in discreet telluride minerals and the structures of sulfide minerals in most gold deposits. Telluride minerals are significant gold sources in many giant gold deposits, such as Cripple Creek in Colorado and the Golden Mile in Western Australia, Australia. However, the overall tonnage of tellurium in the gold deposits is low compared to anode sludge recoveries from the milling of large-tonnage base-metal deposits. Because of this fact, gold deposits, despite containing high grades of tellurium, are rarely viewed as potential tellurium resources. Significant tellurium quantities are recovered as a primary ore from only two mining districts in the world: the adjacent epithermal gold-tellurium vein deposits at Dashuigou and Majiagou in southwestern China and the epithermal-like mineralization at the Kankberg deposit, Skellefte VMS district, Sweden. The deposits in these districts account for about 15 percent of annual tellurium production worldwide. In addition, minor amounts of tellurium were recovered from a small, epithermal gold deposit in northern Sonora, Mexico.

https://pubs.usgs.gov/fs/2014/3077/pdf/fs2014-3077.pdf

INTRODUCTION

Tellurium – critical in use, possible supply risk

- 0.0000001% of earth's crust (compare gold -- 0.0000004%)
- Almost all comes from by-product of copper smelting
- Key in Cd-Te thin-film solar photovoltaics



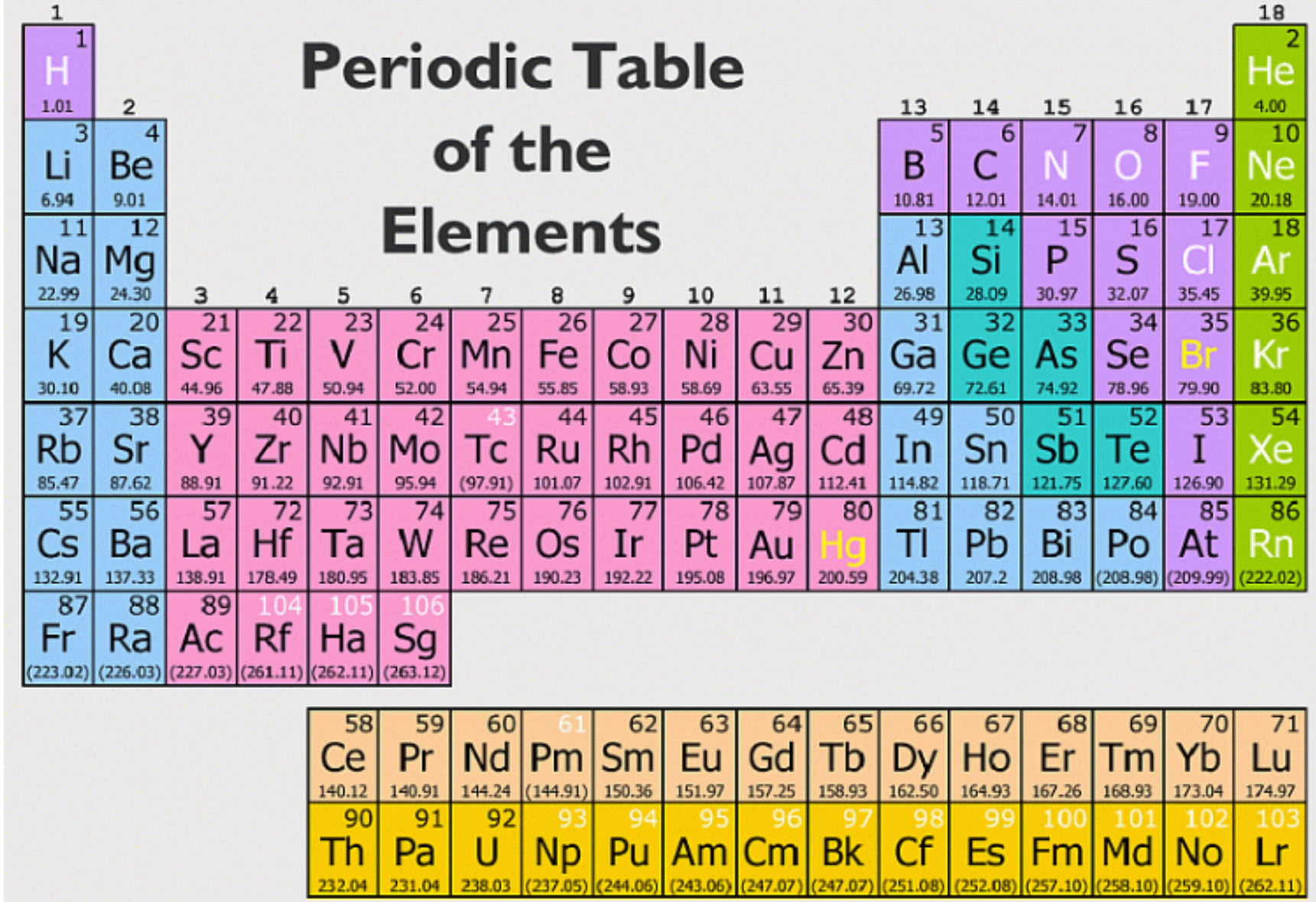


Figure 1. Periodic table of the elements. The rare earth elements comprise 15 elements, which range in atomic number from 57 to 71, including lanthanum (La) to lutetium (Lu). The elements are also commonly referred to as "lanthanides." Yttrium (Y, atomic number 39) is also typically included with the rare earth elements group because it shares chemical, physical, and application properties with the lanthanides.

http://pubs.usgs.gov/sir/2010/5220/

Tellurium

- Atomic number of 52
- Atomic weight of 127.6
- One of the least abundant in the crust, ~0.005 ppm
- Brittle, mildly toxic, rare, silver-white
- Tellurium was discovered in gold ores by Franz Joseph MδIler von Reichenstein, the chief inspector of mines in Trannsylvania in 1782
- Technically not a metal, but a metalloid

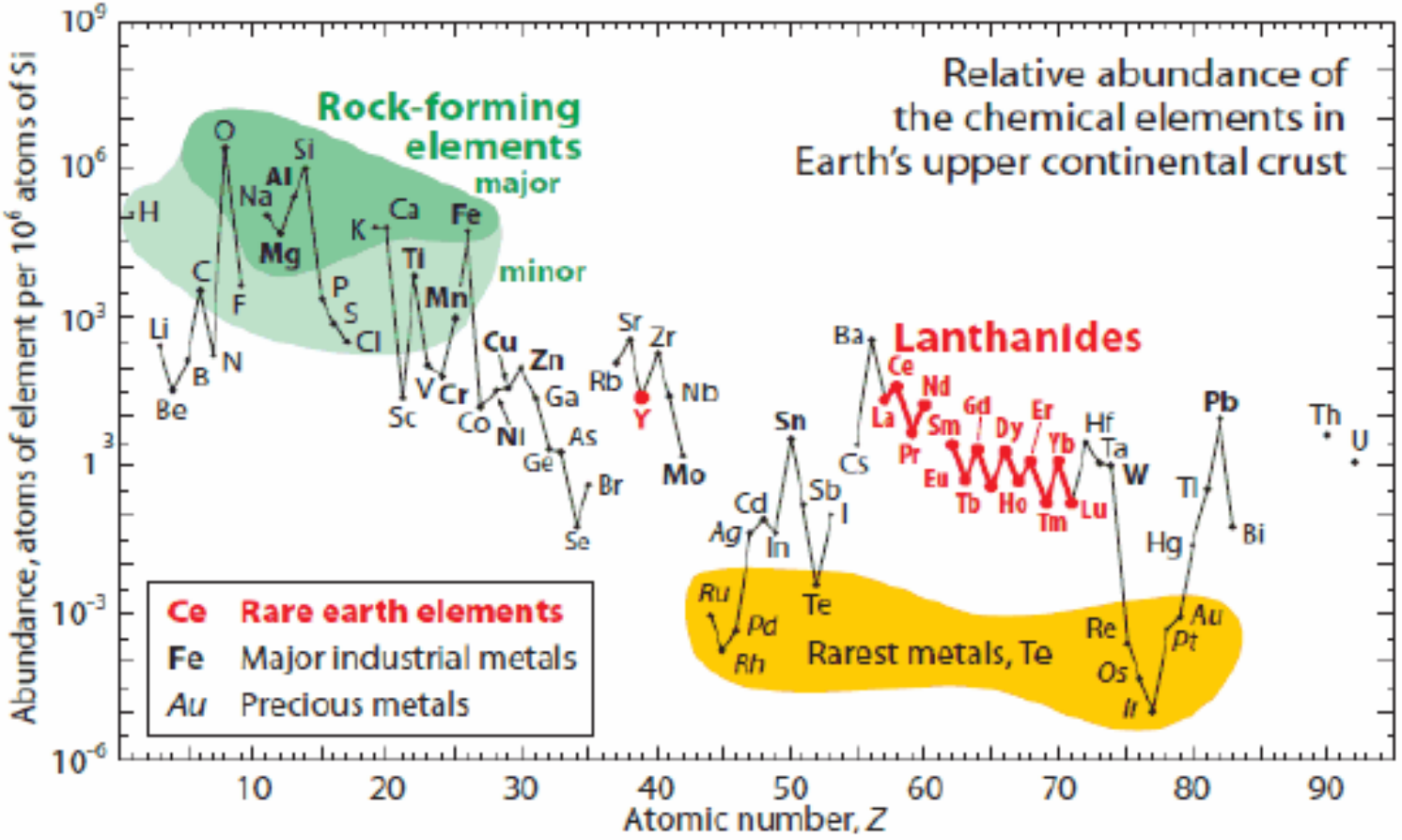
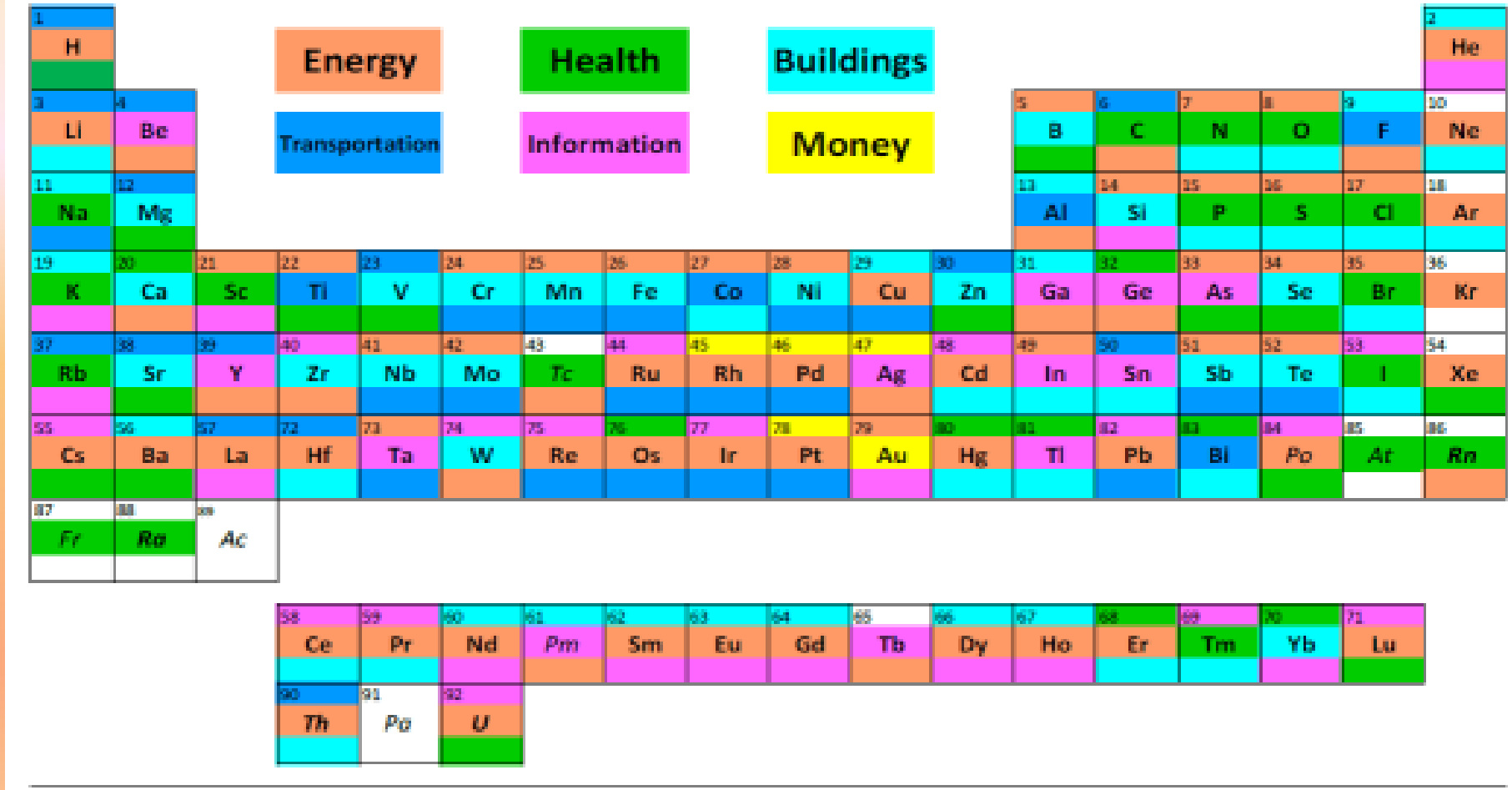


Figure 1 Relative abundance of rare earths (highlighted in red). Figure courtesy of Gordon Haxel, USGS.

Uses of Te



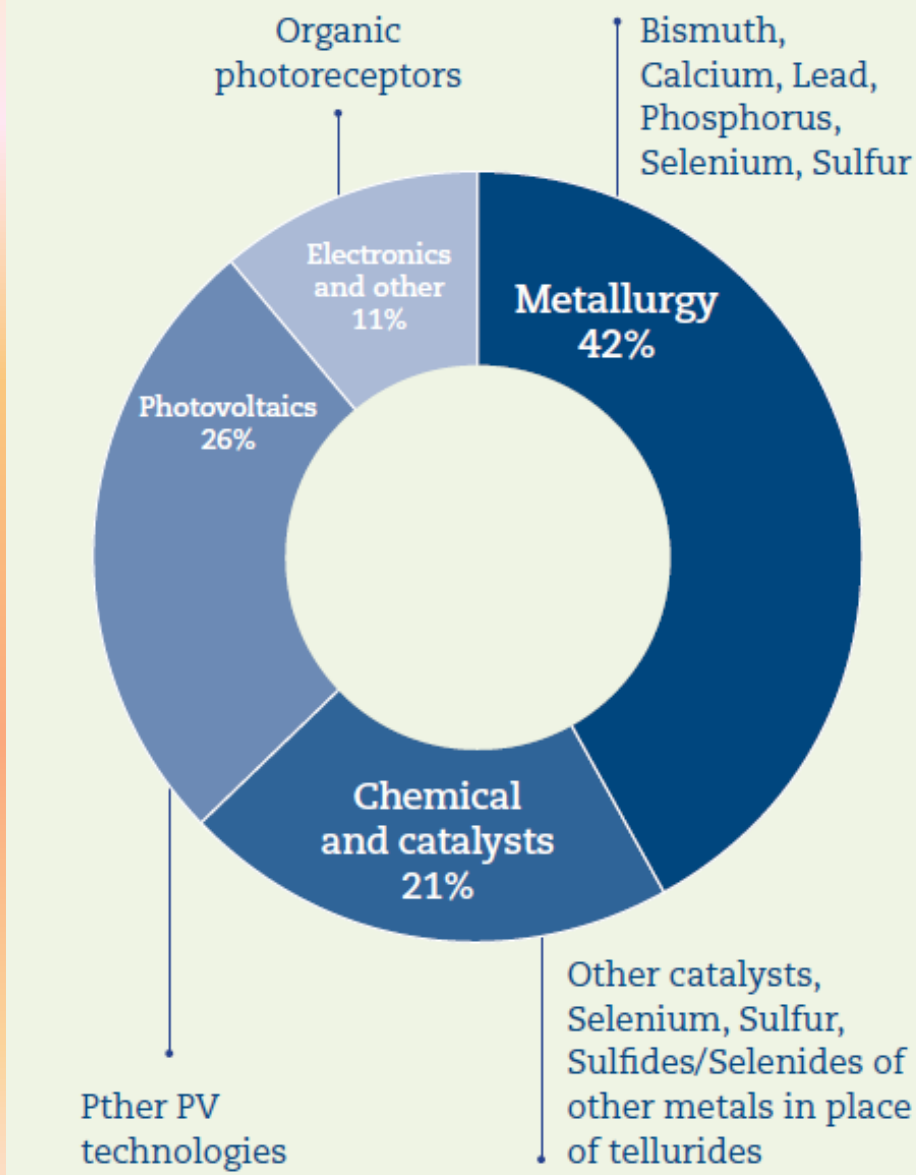
Energy includes the production, transmission , and storage of energy, as well as lighting. Health includes elements necessary for life (food & pharmaceuticals) and for the growing of crops (fertilizers and pesticides). Buildings include materials needed for structures and their general contents and the tools needed to construct them. Transportation includes vehicles and infrastructure, including moving water and wastewater. Information includes communication systems, electronics, and optics. Money includes items that are held as a backing of currencies or to substitute for money, plus jewelry and the arts. From Jon Price, 2015.

Uses of Te

- Alloying additive in steel to improve machining characteristics
- Processing of rubber
- As a component of catalysts for synthetic fiber production
- As pigments to produce various colors in glass and ceramics
- **Thermal imaging devices**
- Thermoelectric cooling devices, such as summertime beverage coolers
- **Thermoelectronics**
- **Solar panels/cells**

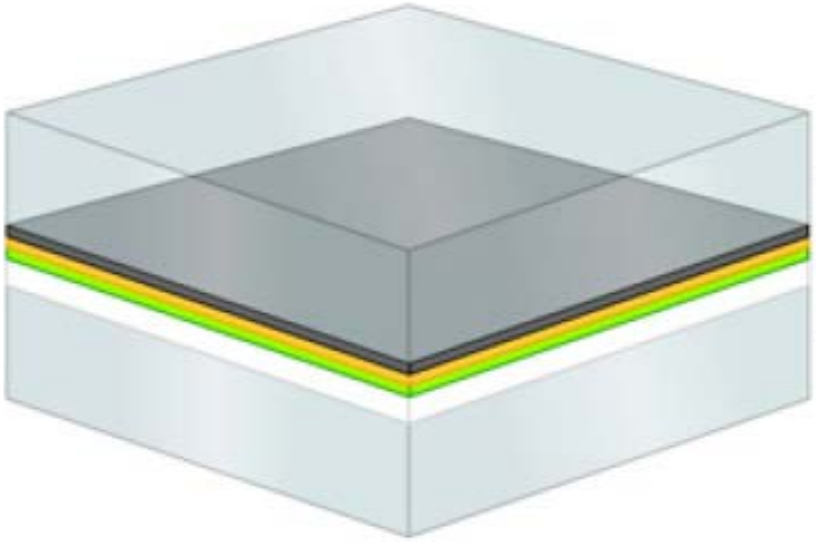
Tellurium is critical to efficient, thin-film photovoltaic cells that produce electricity from sunlight. A 2-megawatt, solar photovoltaic array occupies a former landfill at Fort Carson, Colo. Photograph from the U.S. Department of Energy Western Area Power Administration http://usarmy.vo.llnwd.net/e2/c/images/2013/12/05/323603/original.jpg.

End uses and substitutes



Source: USGS (2012)

Uses—TF solar panels



Front (Substrate) Glass
Soda Lime Glass – common window glass

Front Contact
TCO (transparent conducting oxide) – a thin layer of Tin Oxide is applied to the front glass. This is the same material used in low E-coating (insulator) for common insulating glass.

Semiconductor
CdS (Cadmium Sulfide) – window layer
CdTe (Cadmium Telluride) – absorber layer

Metal Conductor
Thin stack of metals that create the back contact

EVA
EVA (Ethyl Vinyl Acetate) – an adhesive, encapsulant material

Back (Cover) Glass
Soda Lime Glass – common window glass

Fig. 1 The First Solar module (www.firstsolar.com)

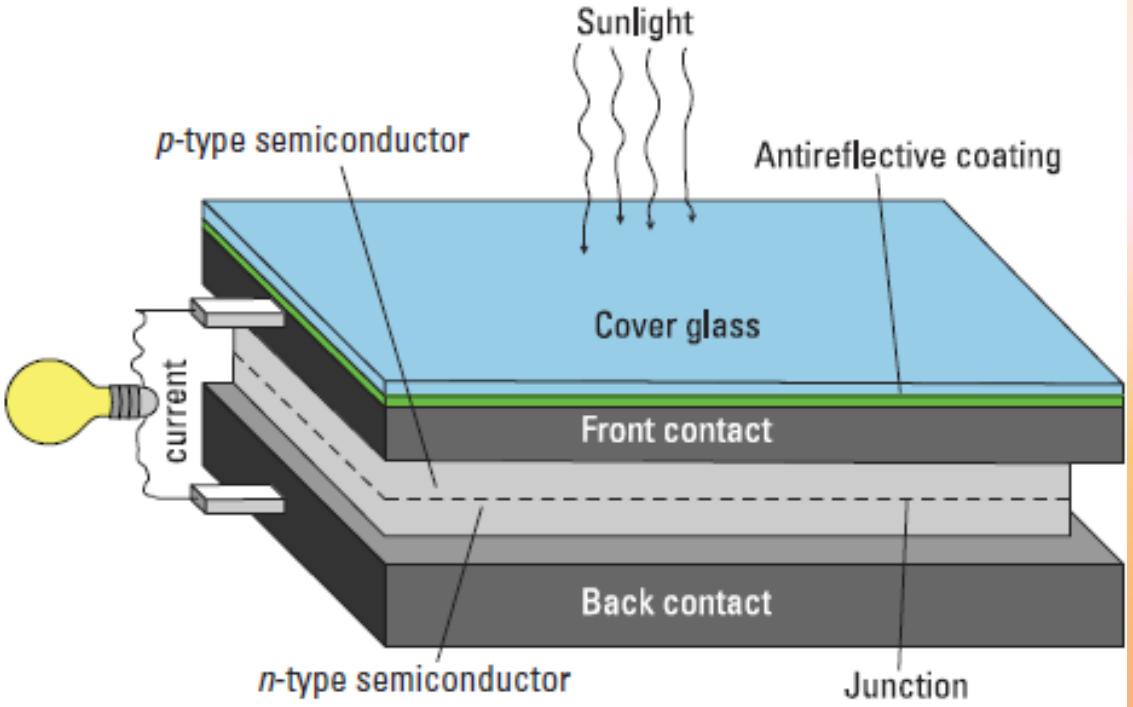


Figure 1. A generalized diagram showing the structure of an electricity-generating solar (photovoltaic) cell. Semiconductor films contain such metals as cadmium, gallium, germanium, indium, selenium, and tellurium. The *p* layer generates a positive charge and the *n* layer generates a negative charge. Front and back contacts made up of conductive metals and alloys containing aluminum, copper, gold, molybdenum, and silver. Diagram courtesy of California Energy Commission, used with permission.

http://pubs.usgs.gov/circ/1365/Circ1365.pdf

Table 2. Metals required[1] to produce thin-film photovoltaic cells with effective annual capacity of 8,760 gigawatthours.

[CIGS, copper-indium-gallium-selenide alloy; e, estimated; XX, not applicable]

Type of photovoltaic technology	Metals required			
	Metal	Quantity[e,2] (metric tons)	Percentage of 2008 estimated world refinery production from primary sources[3]	Value of contained metal[e,4] (in millions of dollars)
Thin-film CIGS	Gallium	30	27	17
	Indium	90	16	62
	Selenium	180	6	13
	Total	XX	XX	92
Thin-film cadmium telluride	Cadmium	340	2	2
	Tellurium	390	82	82
	Total	XX	XX	84

[1]Metals required to produce photovoltaic cells that can generate 4 gigawatts (GW) of peak power or 8,760 gigawatthours per year (GWh/yr) of effective capacity. One GW is equivalent to 1 billion watts, 1,000 megawatts, and 1 million kilowatts of effective capacity of electricity production. Applying a 25 percent capacity factor, an installed peak capacity of approximately 4 GW would be required to produce 1 GW of electricity on an average daily basis or 8,760 GWh/yr, electricity sufficient to meet the average annual need of 11,000 kilowatthours for 800,000 households in the United States (U.S. Department of Energy, Energy Information Administration, 2009a). No energy storage, such as batteries, was assumed.

Tellurium in Photovoltaics

- 9 gm/m^2 & 10% efficiency → 1/10 gm (Te)/W or 100 tonnes (Te)/GW
- ÷ 20 - 25% capacity factor → 400 tonnes (Te)/GW
- World electric consumption (2006) ~2000 GW (USEIA)
- Te "Reserve base" approx. 48,000 tonnes (USGS) → 120 GW

Bottom line — we don't know of enough Te in the world today to make solar as big a contributor to power generation as we would like.

Bismuth telluride heat pump.
This is a small bismuth telluride thermoelectric heat pump. Apply a DC voltage and one side gets cold while the other side gets hot. If you attach a good heat sink and fan to the hot side, you can pump heat out of something, cooling it down. This particular device was deployed inside a USB-powered mini-fridge designed to cool one can of soda using power from your computer.
Source: eBay seller goods_keeper
Contributor: Theodore Gray
Acquired: 28 March, 2009
Text Updated: 29 March, 2009
Price: $6
Size: 1.5"
Purity: <20%

http://periodictable.com/Elements/052/

PRODUCTION

Recent production

- byproduct of milled copper, iron, and other base-metal-rich ore bodies
- epithermal gold-tellurium vein deposits at Dashuigou and Majiagou in southwestern China
- mineralization at the Kankberg deposit, Skellefte VMS district, Sweden by Boliden
- A small, epithermal gold deposit in northern Sonora, Mexico

https://pubs.usgs.gov/fs/2014/3077/pdf/fs2014-3077.pdf

The Kankberg mine in Sweden produces ten percent of the world's tellurium from underground operations below this original pit and is one of the only deposits where tellurium is a direct product of mining activity. Photograph from http://www.boliden.com/Global/Press photos/Gruvor/Bolidenområdet/Kankberg_Foto_Erica_Nilsson_fri_hi.jpg.

PRODUCTION
(US est 50 tonnes)

Salient Statistics—United States:	2012	2013	2014	2015	2016[e]
Production, refinery	W	W	W	W	W
Imports for consumption	36	65	109	76	70
Exports	47	42	28	41	40
Consumption, apparent	W	W	W	W	W
Price, dollars per kilogram, 99.95% minimum[1]	150	112	119	77	34
Stocks, producer, refined, yearend	W	W	W	W	W
Net import reliance[2] as a percentage of apparent consumption	<50	>50	>75	>75	>75

	Refinery production 2015	Refinery production 2016[e]	Reserves[3]
United States	W	W	3,500
Canada	9	10	800
Japan	37	30	—
Peru	—	—	3,600
Russia	35	35	NA
Sweden	33	33	670
Other countries[4]	NA	NA	16,000
World total (rounded)	NA	NA	25,000

Specific international and domestic tellurium sources are not well-known

PRODUCTION

Domestic Production and Use: In 2016, one firm in Texas produced commercial-grade tellurium as a byproduct from domestic copper anode slimes and lead refinery skimmings. The primary producer and downstream producers further refined domestic and imported commercial-grade metal to produce tellurium dioxide, high-purity tellurium, and tellurium compounds for specialty applications. To avoid disclosing company proprietary data, U.S. tellurium production in 2016 was withheld.

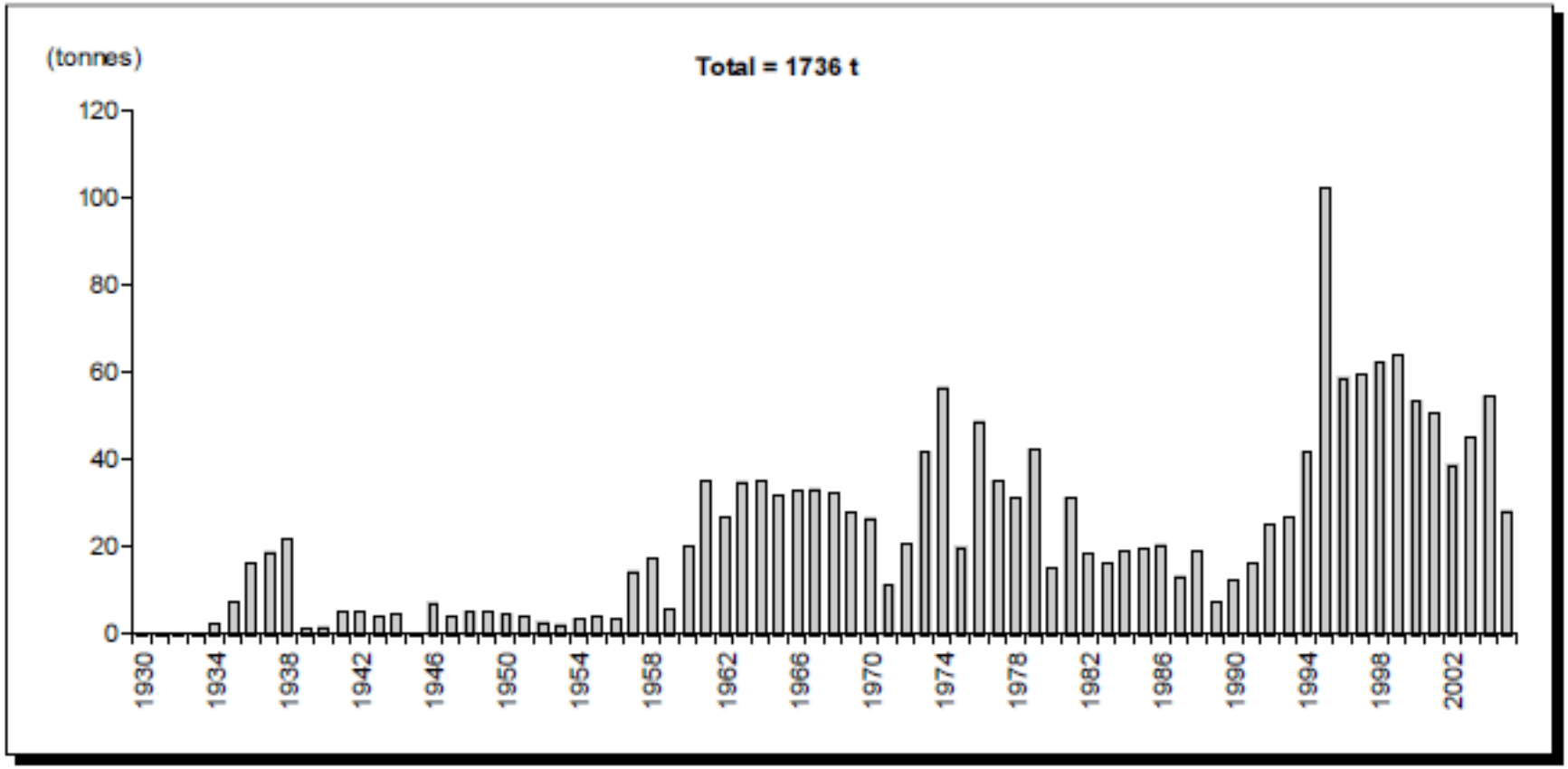
World Resources: Data on tellurium resources were not available. More than 90% of tellurium has been produced from anode slimes collected from electrolytic copper refining, and the remainder was derived from skimmings at lead refineries and from flue dusts and gases generated during the smelting of bismuth, copper, and lead-zinc ores. Other potential sources of tellurium include bismuth telluride and gold telluride ores.

Major sources of Te production

- There is no primary Te mine, but Au-Te mines
- Te is recovered as a byproduct of nonferrous metal mining
  - Copper porphyry deposits
  - Lead and zinc deposits

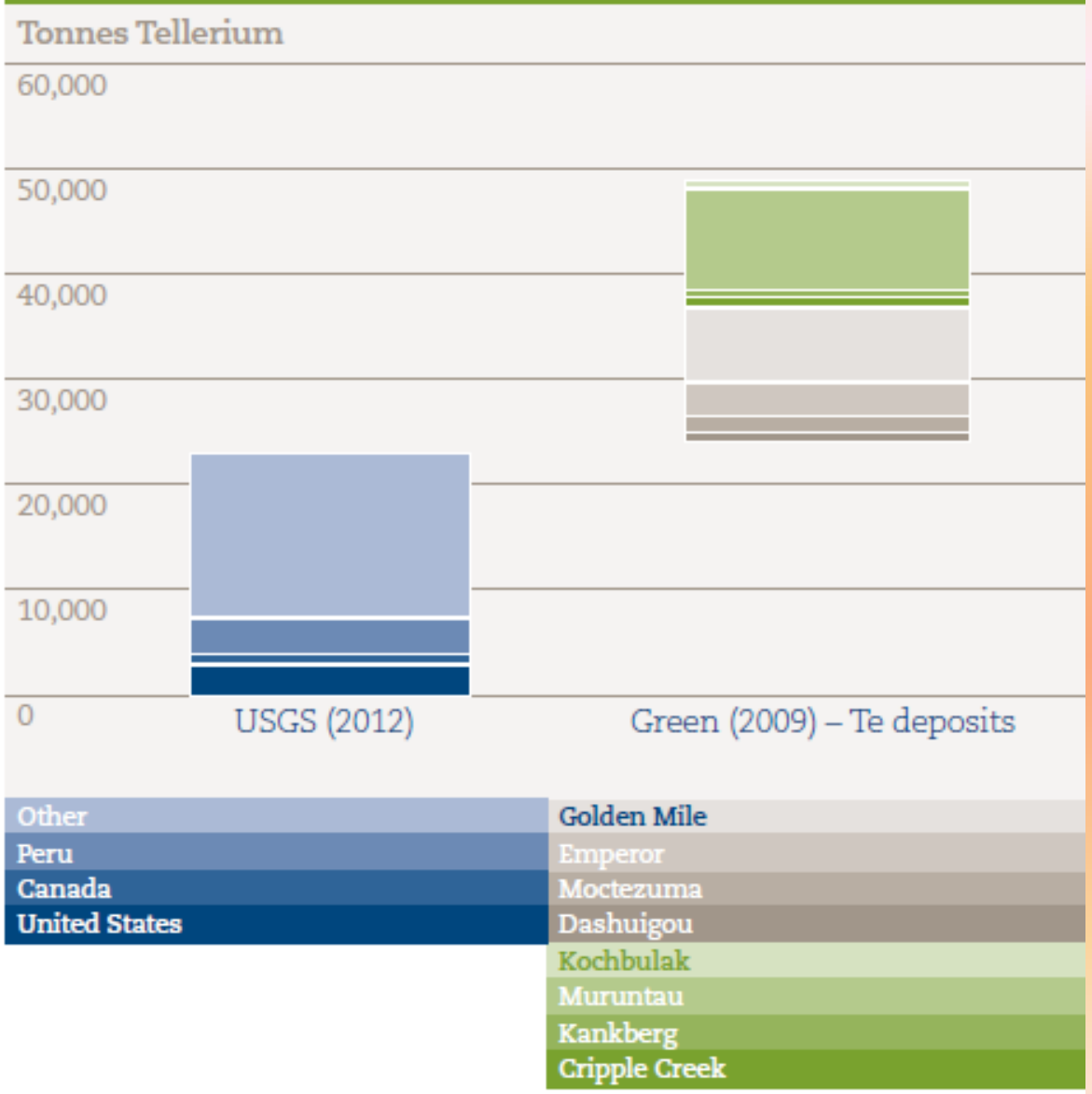
  - 2% Te in Te-bearing anode slimes (USGS)

Figure 4
Recoverable Tellurium in Concentrates Shipped From Canadian Mines, 1930-2005



Source: Natural Resources Canada.

Tellurium reserves and potential deposits for direct mining



Source: USGS (2012); Green (2009)

Demand

Economics will prevail (e.g., the ratio of the value of global copper production to that of tellurium in 2014 was approximately 2300 to 1, which means metallurgists won't risk lowering copper recovery to improve tellurium recovery).

Country	Reserves Contained Cu Metric Tons	Contained Te Metric Tons	Reserve Base[1] Contained Cu Metric Tons	Contained Te Metric Tons	Total Contained Te Metric Tons
United States	41,000,000	**8,200**	82,000,000	**16,000**	**24,200**
Australia	6,000,000	**1,300**	21,000,000	**4,200**	**5,500**
Canada	10,000,000	**2,000**	21,000,000	**4,200**	**6,200**
Chile	80,000,000	**16,000**	148,000,000	**30,000**	**46,000**
China	3,000,000	**500**	7,000,000	**1,500**	**2,000**
Indonesia	10,000,000	**2,000**	14,000,000	**2,700**	**4,700**
Kazakhstan	13,000,000	**2,500**	18,000,000	**3,600**	**6,100**
Peru	6,000,000	**700**	22,000,000	**2,200**	**2,900**
Philippines	6,000,000	**1,300**	10,000,000	**2,000**	**3,300**
Poland	18,000,000	**3,600**	33,000,000	**6,500**	**10,100**
Russia	18,000,000	**3,600**	27,000,000	**5,400**	**9,000**
Zaire	9,000,000	**1,800**	27,000,000	**5,400**	**7,200**
Zambia	11,000,000	**2,200**	34,000,000	**6,200**	**8,400**
Other Countries	50,000,000	**10,000**	91,000,000	**18,000**	**28,000**
Total	281,000,000	**55,700**	549,000,000	**107,900**	**163,600**

Note: All Figures Rounded

Country	Tons Production Electrolytic Copper	Contained Te (Pounds)	Contained Te Metric Tons	Total Possible Production/Yr. (50% Rec.) M/Tons
United States	1,730,000	548,000	249	124
Australia	490,000	196,000	89	44
Canada	654,700	261,880	118	59
Chile	2,511,000	1,004,400	455	227
China	414,000	165,600	75	37
Bulgaria	100,000	40,000	18	9
Indonesia	529,000	211,648	96	48
Iran	108,000	43,200	20	10
Kazakhstan	316,000	126,400	57	28
Mexico	342,319	136,928	62	31
Mongolia	125,300	50,120	23	11
Paupa New Guinea	111,700	44,680	20	10
Peru	391,265	78,253	35	17
Poland	414,000	165,600	75	37
Portugal	106,500	42,600	19	9
Russia	505,000	202,000	92	46
South Africa	186,000	74,400	34	17
Zambia	287,000	114,800	52	26
TOTAL	**9,321,784**		**1,589**	**795**

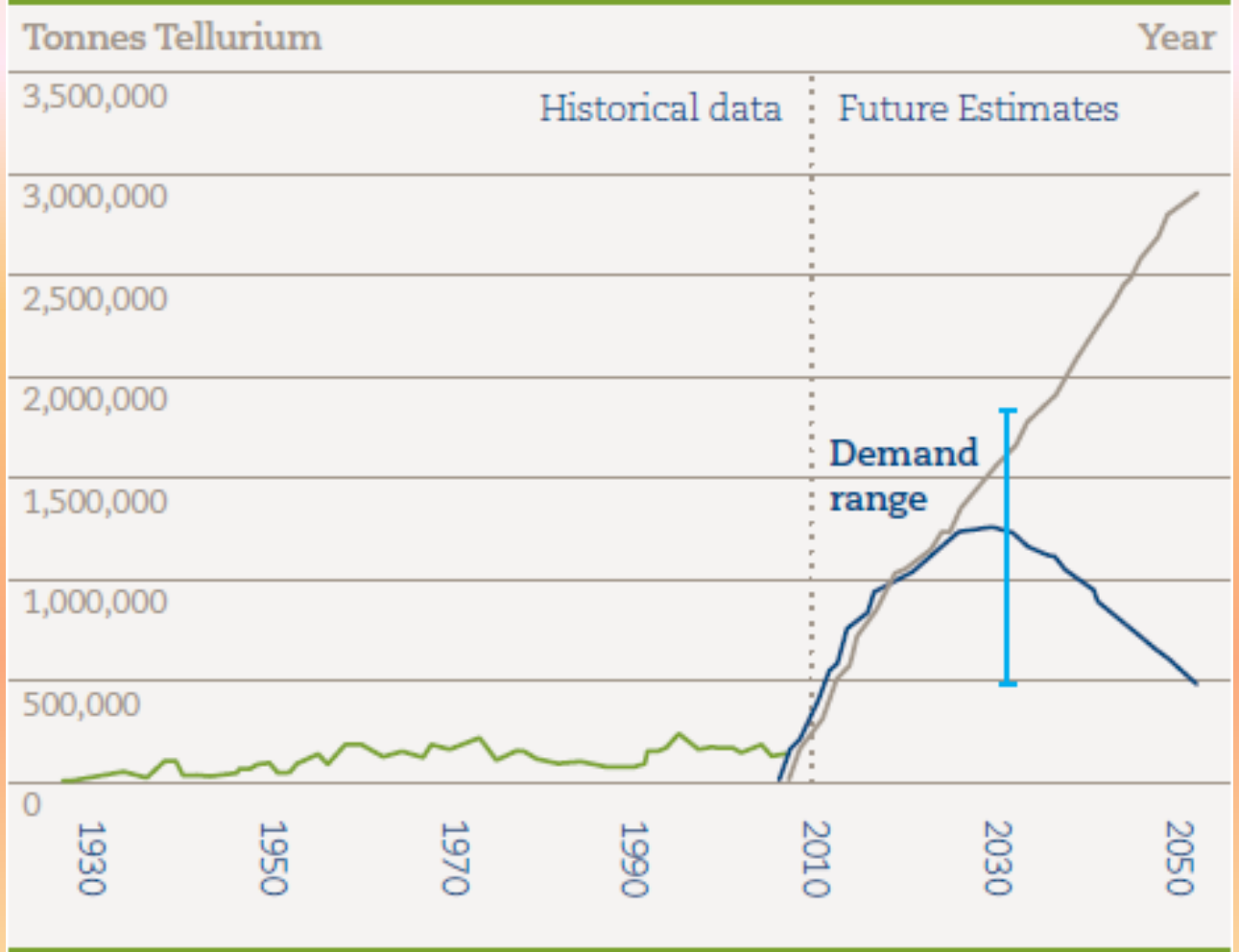
Note: Tellurium tonnage calculations rounded.

Country	Tons Production Refined Lead	Contained Te (Pounds)	Contained Te Metric Tons	Total Possible Production/Yr. (50% Rec.) M/Tons
United States	343,000	34,300	16	8
Australia	204,000	20,400	9	4.5
Belgium	84,400	8,440	4	2
Bulgaria	60,000	6,000	3	1.5
Canada	162,000	16,200	7	3.5
China	506,000	50,600	23	11.5
France	115,000	11,500	5	2.5
Germany	90,000	9,000	4	2
India	69.000	6,900	3	1.5
Italy	115,000	11,500	5	2.5
Japan	142,326	14,233	6	3
Kazakhstan	65,000	6,500	3	1.5
Korea(North)	75,000	7,500	3	1.5
Korea(Republic)	121,296	12,130	6	3
Mexico	168,164	16,816	8	4
Morocco	64,200	6,420	3	1.5
Peru	86,105	8,611	4	2
Poland	50,000	5,000	2	1
Sweden	50,000	5,000	2	1
United Kingdom	215,000	21,524	11	5.5
TOTAL	**2,785,491**		**127**	**64**

Year	Item	Development Rate Slow	Medium	Fast
2000				
	Mw PV Generated Power	1	5	10
	Consumption of Te (Kg/Mw)	130	130	130
	% Manufacturing Loss	40	40	40
	Consumption of Te in Metric Tons	**0.2**	**1**	**2**
2005	Mw PV Generated Power	5	25	100
	Consumption of Te (Kg/Mw)	130	130	130
	% Manufacturing Loss	30	30	30
	Consumption of Te in Metric Tons	**1**	**5**	**19**
2010	Mw PV Generated Power	25	100	1,000
	Consumption of Te (Kg/Mw)	90	90	90
	% Manufacturing Loss	20	20	20
	Consumption of Te in Metric Tons	**3**	**11**	**112**
2020	Mw PV Generated Power	100	500	10,000
	Consumption of Te (Kg/Mw)	90	90	90
	% Manufacturing Loss	10	10	10
	Consumption of Te in Metric Tons	**10**	**50**	**1,000**
2030	Mw Pv Generated Power	500	2,000	30,000
	Consumption of Te (Kg/Mw)	90	90	90
	% Manufacturing Loss	10	10	10
	Consumption of Te in Metric Tons	**50**	**200**	**3,000**

Note: Tellurium Tonnage calculations rounded

Tellurium: Historical production forecast supply and future demand

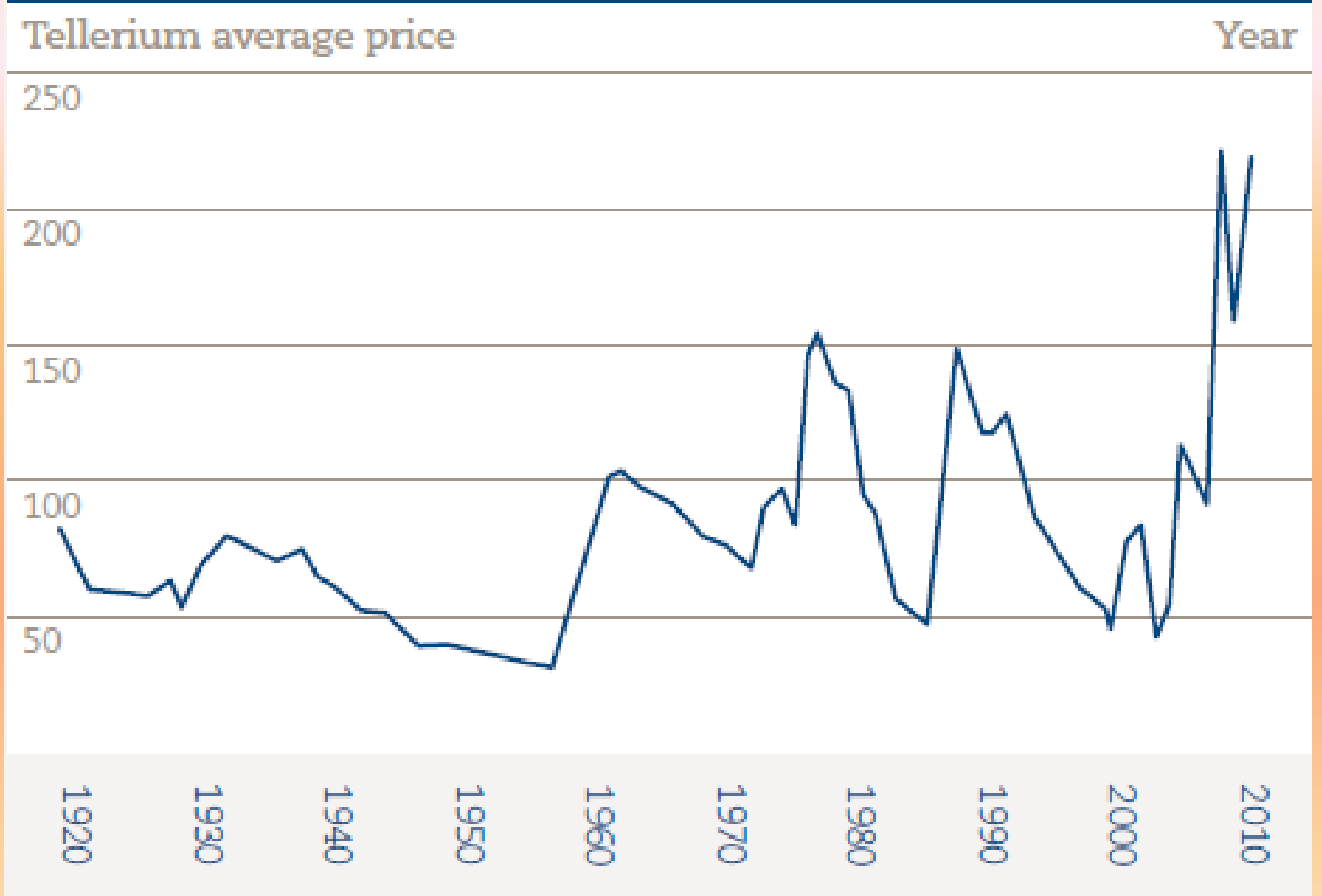


Historical production (USGS & BGS)

High supply scenario | Low supply scenario

Source: USGS (2012); Speirs et al (2011)

Tellerium average yearly price



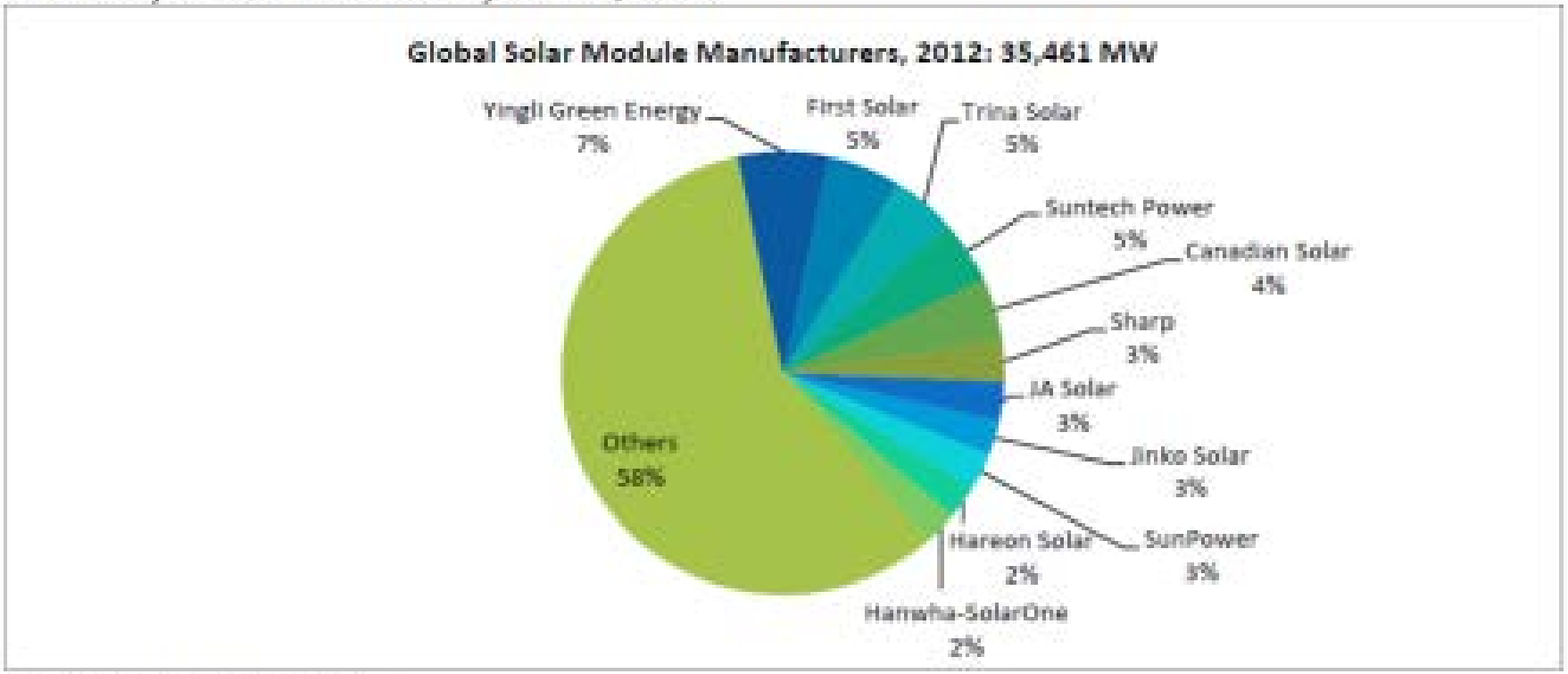
Source: USGS (2011)

Solar energy metals requirements

Technology	Elements	Annual EU Demand (tonnes)		Annual EU Demand / World Supply	
		2020	2030	2020	2030
Solar PV	Te	150	126	12.0%	6.9%
	In	145	121	7.6%	4.9%
	Sn	14,913	12,505	3.6%	2.6%
	Ag	619	519	1.7%	1.2%
	Ga	4	3	0.8%	0.5%
	Se	15	13	0.4%	0.3%
	Cd	109	91	0.3%	0.2%
	Cu	70,650	59,241	0.3%	0.2%
	Pb	8,672	7,272	0.1%	<0.1%

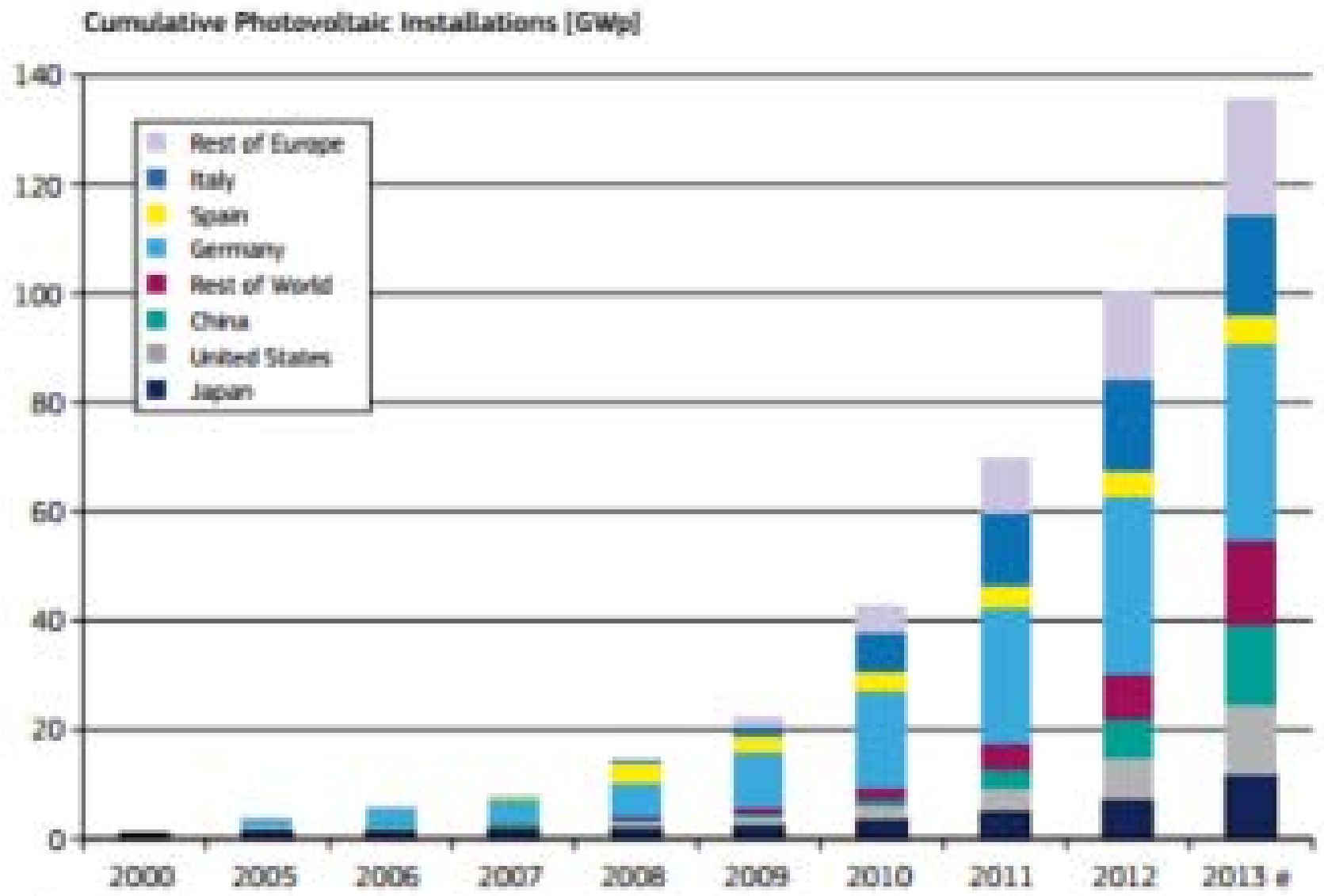
EC JRC/SETIS (2013), Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector

Global major solar module manufacturers, 2012



Source: GTM PV News, May 2013

Cumulative photovoltaic installations from 2000 to 2013 (GWp)



EC JRC/SETIS (2013), 2013 PV status report pg 12

Demand

- Currently 300 metric tons of Te per year are required
- By 2020 1,000 metric tons and non PV Te demand is estimated to be 600 metric tons
- By 2020 new sources of Te will have to be developed in order to meet any increasing demand by the PV industry

Mineralogy

Major Te minerals

- calaverite $AuTe_2$
- krennerite $(AuAg)Te_2$
- petzite Ag_3AuTe_2
- sylvanite $AgAuTe_4$
- hessite (Ag_2Te)
- tellurobismuthite ($BiTe_3$)
- tetradymite (Bi_2Te_2S)
- altaite (PbTe)

- native metal
- 40 minerals
- many of which are telluride minerals
- Few elements to bond with native Au
- Coal—2 ppm Te

Sylvanite, $AgAuTe_4$, Pyrite from Silver City, New Mexico

http://www.johnbetts-fineminerals.com/jhbnyc/mineralmuseum/picshow.php?id=20437

Altaite, PbTe, Hilltop Mine, Organ District, Dona Ana County, NM

http://www.johnbetts-fineminerals.com/jhbnyc/mineralmuseum/picshow.php?id=20437

TYPES OF TELLURIUM DEPOSITS

Te associated

- Any age
- Alkaline rocks
- Porphyry deposits
- Bismuth deposits
- Pyrrhotite-chalocpyrite-pentlandite-telluride deposits
- Palladium in PGM deposits

TYPES OF TELLURIUM DEPOSITS

- Au-Ag-Te alkaline-related veins
- Volcanic-epithermal veins
- Skarns/carbonate-hosted deposits
- Polymetallic veins
- Vein and replacement deposits in Proterozoic rocks
- Porphyry copper (±molybdenum, gold) deposits
- Polymetallic gold deposits
- Gold quartz-pebble conglomerate deposits
- Carlin-type deposits
- Lead-zinc ores
- Black shale hosted deposits
- Coal

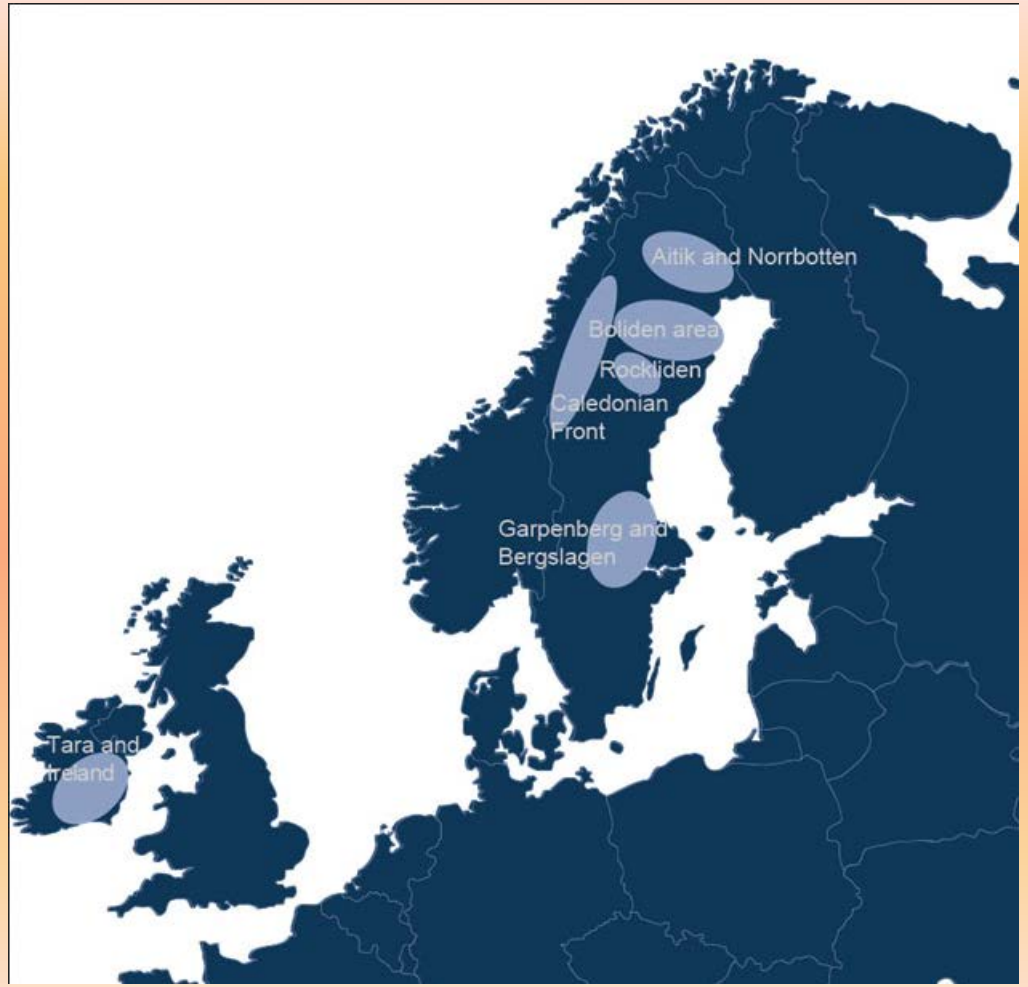
Type of deposit	Te (ppm)
Gold-quartz veins	0.2-2,200
Gold skarn deposits	0.2-0.5
Polymetallic gold deposits	0.2-10
Gold quartz-pebble conglomerate deposits	<0.2-0.7
Carlin-type deposits	<0.2-0.6
Porphyry copper deposits	<0.1-6,000
Lead-zinc ores	0.5-1.0

Ranges in concentration of tellurium in selected deposits (Everett, 1964; Boyle, 1979; Cox et al., 1995).

Deposit/Region	Tellurium Concentration Pounds Per Refined Ton Of Metal
U.S. Porphyry Copper Deposits	0.4
Sudbury Canada Massive Sulfide Deposits	0.06
World Wide Lead Ore Deposits	0.1
Peru Porphyry Copper Deposits	0.2
Chile Porphyry Copper Deposits	0.4
Congo Copper Deposits	0.4
Zambia Copper Deposits	0.4
Russian/CIS Copper Nickel-Copper, Massive Sulfide Deposits	0.4
Mexican Copper and Massive Sulfide Deposits	0.4
Australia/New Guinea Copper Deposits	0.4
Japan/Philippines/Chinese Copper and Massive Sulfide Deposits	0.4
European Copper and Massive Sulfide Deposits	0.4

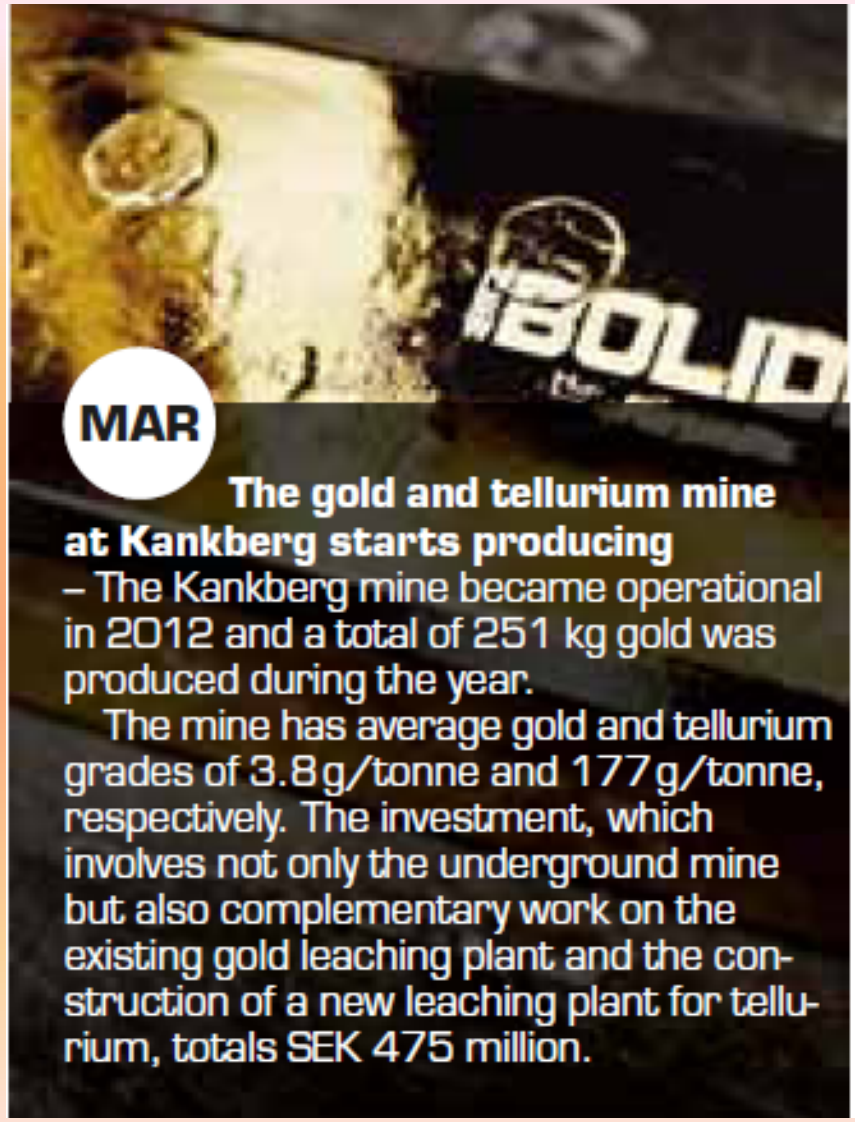
VMS (volcanic massive sulfide) deposits

Kankberg, Boliden in Sweden



Kankberg

- Skellefte district
- VMS deposit
- Previously operated for Cu-Zn in the 1990s
- Underground
- Concentrator and gold-recovery plant



Kankberg mine

- 2.78 million tonnes
- 4.1 grams per tonne Au
- 186 grams per tonne Te

http://www.businesswire.com/news/home/20110224005755/en/Boliden-Starting-Gold

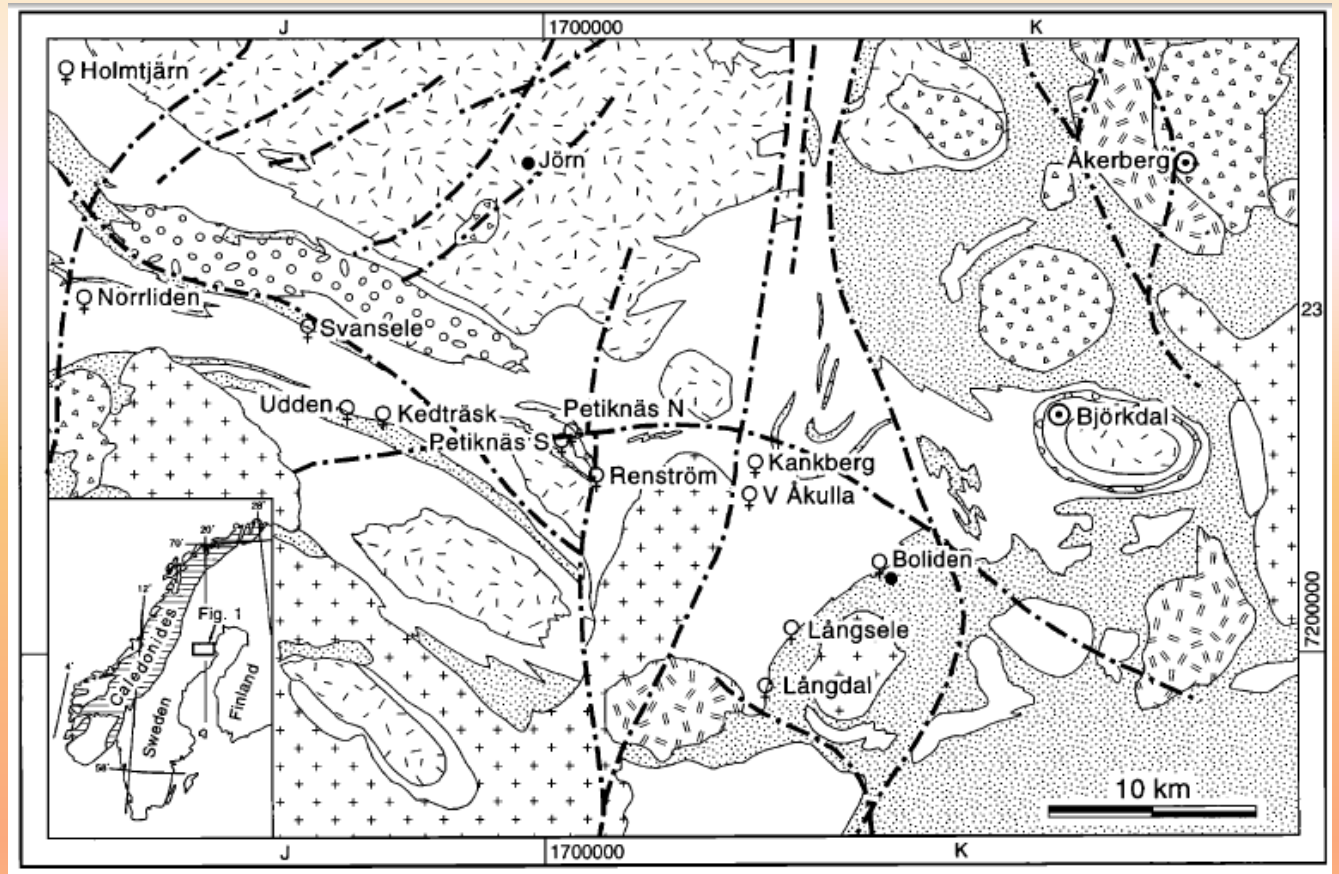


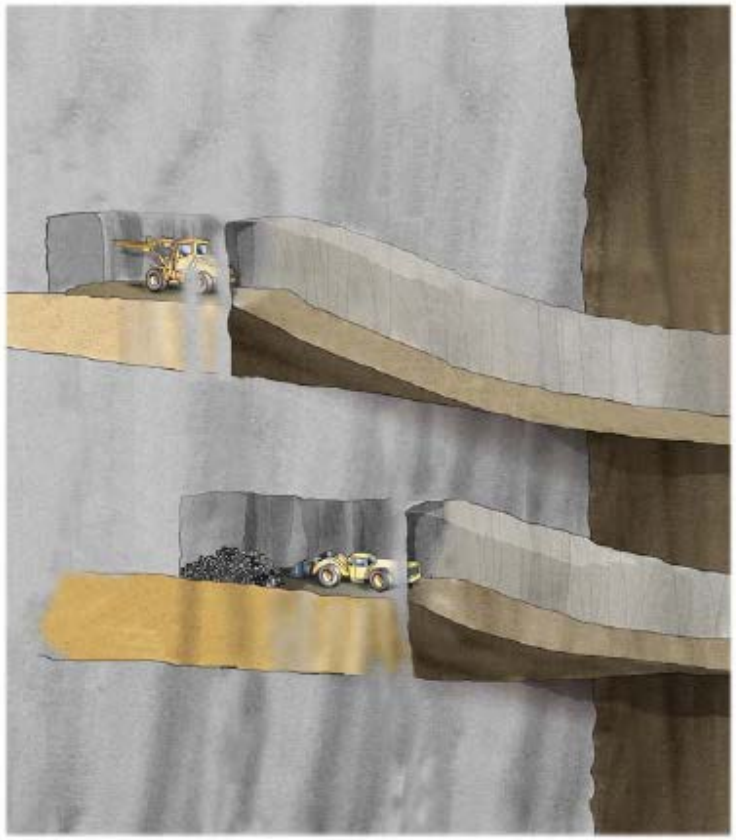
FIG. 1. Simplified geology of the Skellefte district with the location of the Boliden deposit. Modified from Allen et al. (1996). Coordinates in national grid.

Weihed et al., Econ Geol, v. 91, 1996

The project

- Project includes
  - Mine facilities
  - Underground development
  - Leaching plant rebuilding
- Production until 2020
  - Gold 1,150 kg average annual volume
  - Tellurium 41 tonnes average annual volume
- Start of production mid 2012

- Ore reserve 2,880 ktonnes
- Average grades
  - Gold 4.1 g/tonne
  - Tellurium 186 g/tonne



BOLIDEN

http://www.boliden.com/Documents/Press/Presentations/Kankberg.pdf

Kankberg – a new gold mine

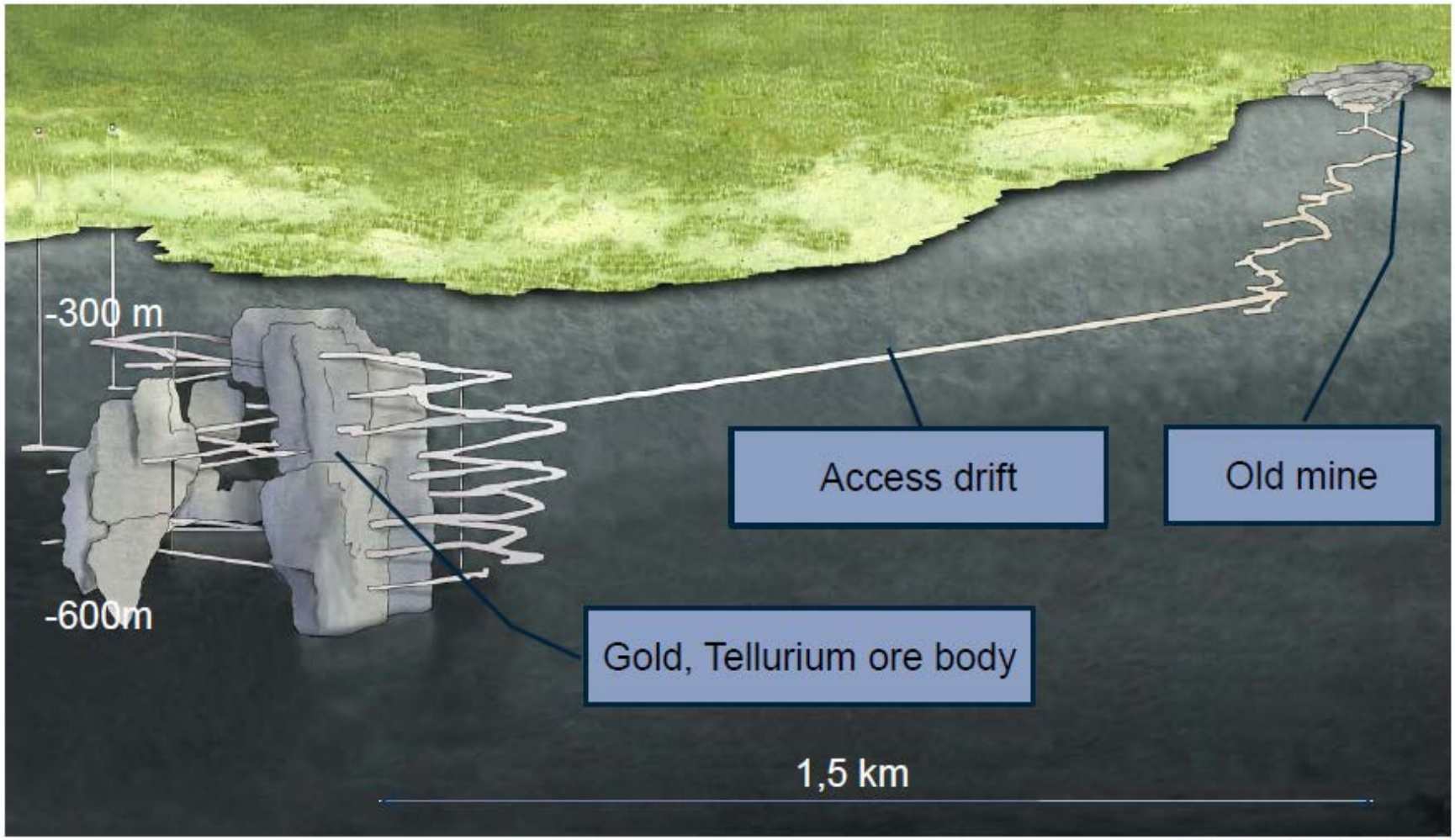
- Mineral reserve: 3,100 ktonnes
- Average grades
  - Gold 4.1 g/tonne
  - Tellurium 186 g/tonne
- Production between 2012-2020
  - Ore 320,000 tonnes
  - Gold 1,150 kg[1)]
  - Tellurium 41 tonnes[1)]
- The SEK 475 million investment includes:
  - Mine infrastructure
  - A new leaching plant
- Production starts in mid-2012

1) Metal content

NEW BOLIDEN

http://www.boliden.com/Documents/Press/Presentations/Group_Presentation_Boliden.pdf

The Kankberg mine – side view



BOLIDEN

Boliden concentrator
– leaching plant to be rebuilt

BOLIDEN

Boliden Mineral, Mineral Reserves as of December 31, 2012

		2012 Kton	2011 Kton	Au g/t	Ag g/t	Cu %	Zn %	Pb %	Mo g/t	Te g/t
Boliden Area										
Polymetallic Mineralizations										
Kristineberg	Proven	1,000	*1,020*	1.3	24	1.4	1.8	0.1		
	Probable	3,600	*3,800*	0.5	42	0.4	7.1	0.4		
Renström	Proven	140	*140*	3.0	137	0.6	7.5	1.5		
	Probable	2,840	*2,180*	2.1	121	0.9	5.6	1.1		
Maurliden	Proven	1,300	*1,300*	1.3	51	0.2	3.6	0.4		
	Probable									
Maurliden Östra	Proven									
	Probable	190	*520*	0.5	14	1.0	0.2			
Total	**Proven**	**2,430**	***2,460***	**1.4**	**45**	**0.7**	**3.1**	**0.3**		
Polymetallic Min.	**Probable**	**6,680**	***6,500***	**1.2**	**74**	**0.6**	**6.2**	**0.7**		
Gold Mineralizations										
Kankberg	Proven	1,050	*500*	2.7	10					161
	Probable	2,530	*2,600*	4.3	16					184
Aitik	**Proven**	**476,000**	***486,000***	**0.14**	**1.5**	**0.24**			**26**	
	Probable	**226,000**	***224,000***	**0.15**	**1.7**	**0.26**			**30**	
Garpenberg	**Proven**	**15,400**	***17,400***	**0.3**	**117**	**0.06**	**5.5**	**2.2**		
	Probable	**10,200**	***6,200***	**0.3**	**151**	**0.05**	**4.6**	**1.9**		
Tara	**Proven**	**2,300**	***3,300***				**7.5**	**1.8**		
	Probable	**11,700**	***12,400***				**7.1**	**1.7**		

Roundings may occur

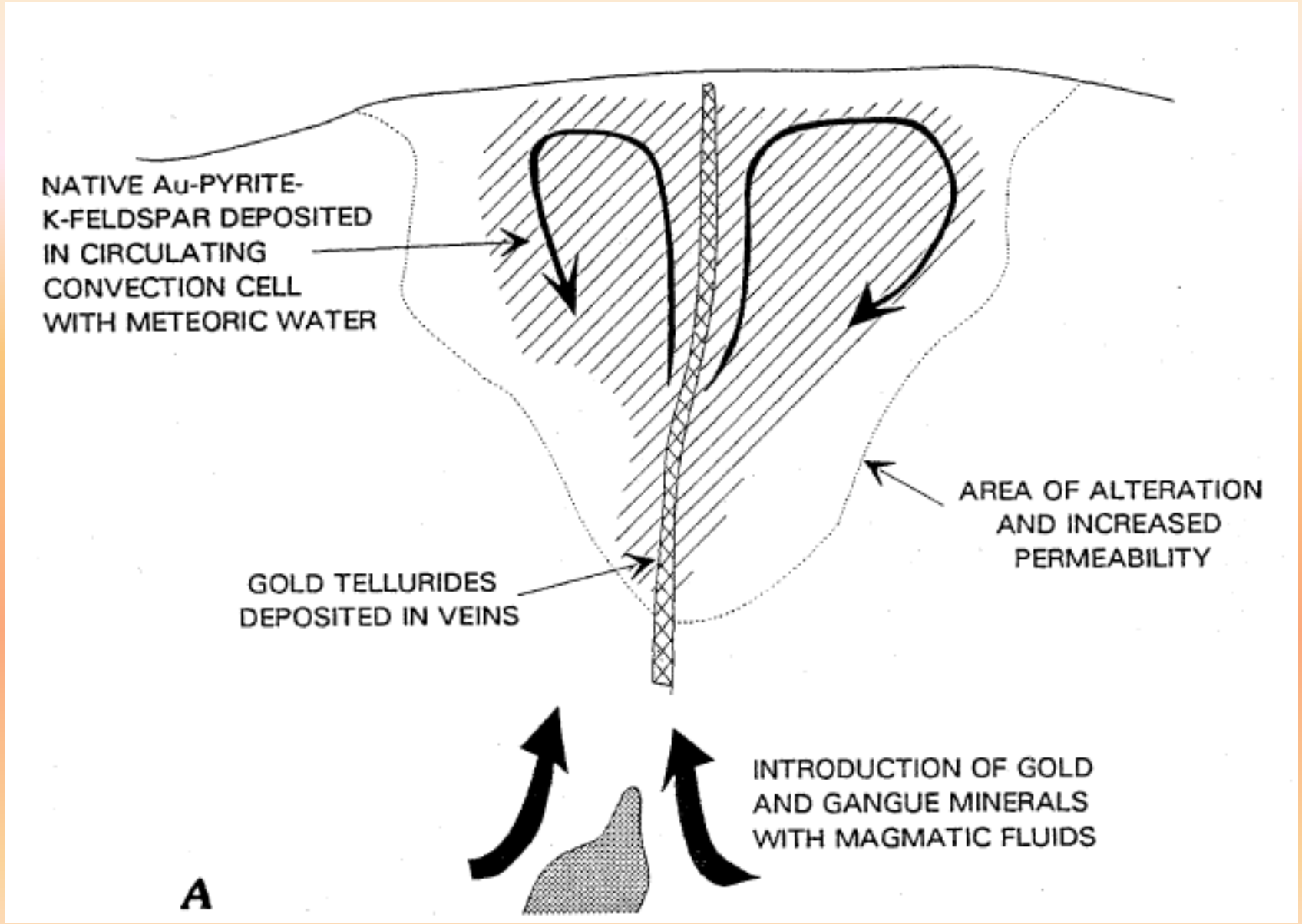
Au-Ag-Te alkaline-related veins

Table 1 Traditional gold and copper deposit types related to alkaline rocks

Deposit type	Example	Metals	Related alkaline rocks	Selected reference
Porphyry Cu–Au	Cadia, NSW, Australia	Au–Cu	Monzodiorite-quartz monzonite porphyry stock	Holliday et al. (2001), this volume
Skarn	Lukas Canyon, New Mexico	Au–Cu	Monzonite and latite porphyry stocks	Maynard et al. (1990)
Sediment-hosted (Carlin-style)	Foley Ridge and Annie Creek, South Dakota	Au	Monzonite porphyry, quartz monzonite porphyry and phonolite dykes and sills	Lessard and Loomis (1990)
Breccia pipe	Golden Sunlight, Montana	Au	Latite porphyry intrusions	Spry et al. (1996)
Low-sulphidation epithermal vein	Emperor, Fiji	Au	Absarokite-shoshonite shield volcano and monzonite stocks	Eaton and Setterfield (1993)
Pluton-related (mesothermal or orogenic) vein	Dongpin, China	Au	Syenite pluton, latite porphyry and lamprophyre dykes	Zhang and Mao (1985)
Volcanogenic massive sulphide (VMS)	Rea, British Columbia	Cu–Zn–Pb–Ag–Au	Alkaline basalt tuffs	Höy (1991)

Au-Ag-Te alkaline-related veins

- Cripple Creek
- Zortman-Landusky
- Golden Sunlight
- White Oaks and Ortiz



http://pubs.usgs.gov/of/1995/ofr-95-0831/CHAP15.pdf

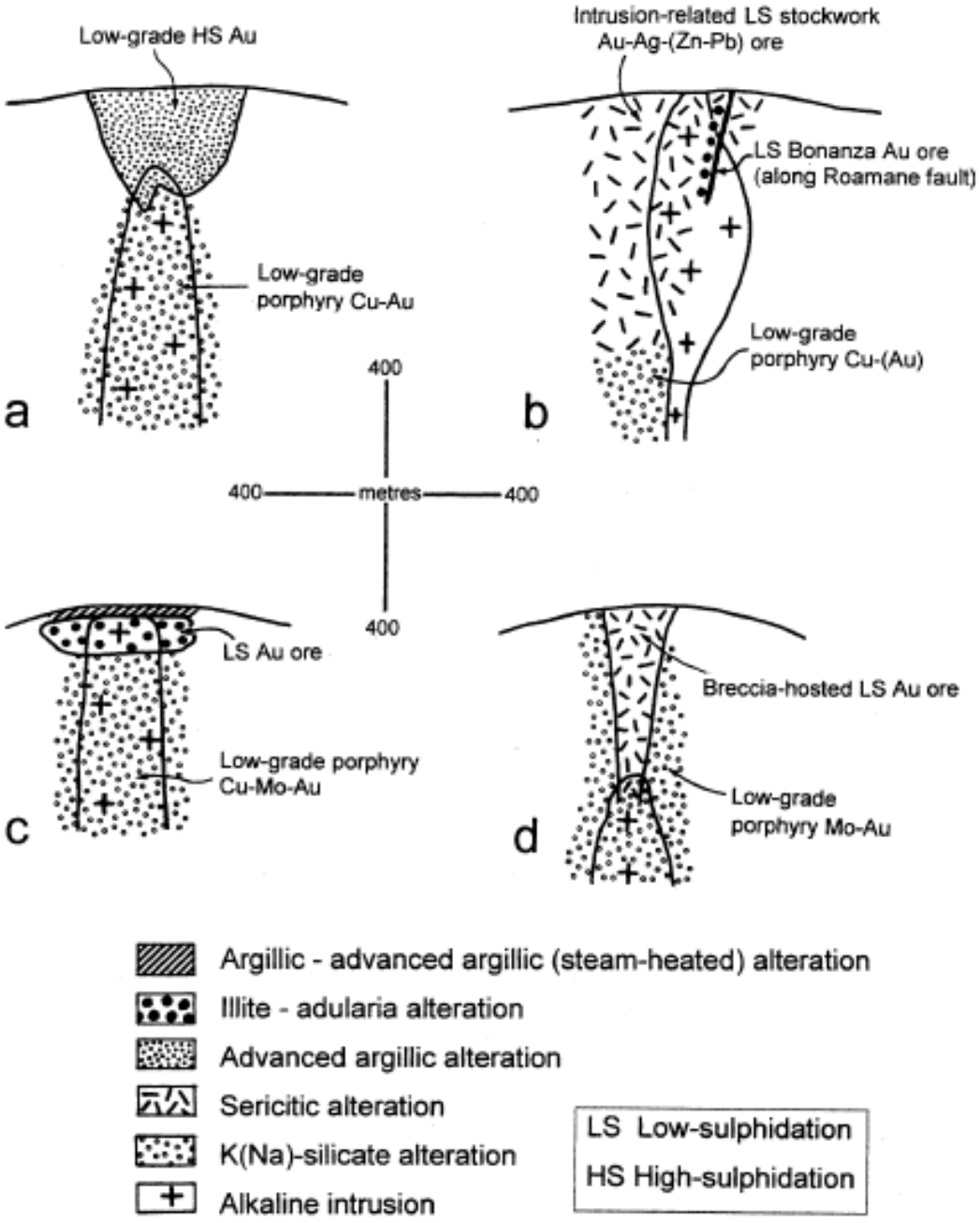


Fig. 1a–d Cartoons to show the generalised nature of the porphyry-epithermal transition in four gold ± copper systems related to alkaline rocks. **a** Navisi 3, Fiji (inspired by Eaton and Setterfield 1993). **b** Porgera, Papua New Guinea (inspired by Richards and Kerrich 1993, and Ronacher et al. 1999). **c** Ladolam, Papua New Guinea (inspired by Moyle et al. 1990). **d** Golden Sunlight, Montana, United States (inspired by Spry et al. 1996; personal observations, 1980). Existence of the high-sulphidation epithermal environment at Navisi 3 is unusual in alkaline igneous centres, which appear to be typified by low-sulphidation epithermal mineralisation above or overprinting the porphyry environment

Au-Ag-Te alkaline-related veins

- calaverite and sylvanite
  - Au:Te ratio is 1:1
- petzite and krennerite
  - Au:Te ratio is 2:1
- Emperor mine (Fiji) the Au-Te is 10 ppm for Au and 10 ppm for Te
- Bambola ore deposit, the Au-Te is 1:176
- Lone Pine ore deposit (NM), the ratio of Au (4.5 ppm) to Te (4500 ppm) becomes 1:1000

Table 1: Representative Au-Te deposits. Supplementary data from Jensen and Barton (2000); Sillitoe (2002)

Deposit	Province	Type	Tellurides			Au (t)	Age (Ma)	Reference(s)
			Au-Ag	Bi	Others			
Golden Mile, Kalgoorlie, Western Australia	Yilgarn Craton	Transitional epi-mesozonal	X		X	1,457	2675-2660	Hagemann & Cassidy 2000; Shackleton et al. 2003
Cripple Creek, CO, USA	Colorado alk. prov.	Epithermal LS	X			834	31-28	Kelley et al. 1998
Golden Sunlight, MT, USA	Montana alk. prov.	Epithermal LS	X			112	70-80	Spry et al. 1997
Emperor, Fiji	Pacific Rim	Epithermal LS	X		X	120	5-4	Pals & Spry 2003
Porgera, Papua New Guinea	Pacific Rim	Epithermal LS	X			660	6	Richards & Kerrich 1993
Ladolam, Papua New Guinea	Pacific Rim	Epithermal LS	X			1,190	<1	Müller et al. 2002
Acupan, Baguio, Philippines	Pacific Rim	Epithermal LS	X			200+	0.6	Cooke & McPhail 2001
Sacarîmb, Romania	'GQ', Apuseni Mts.	Epithermal LS	X		X	32	12-10	Ciobanu et al. 2004a
Kochbulak, Uzbekistan	Kurama Belt, Middle Tien Shan	Epithermal LS/HS	X	X	X	33.5	280-270	Kovalenker et al. 1997

Table 2 Aberrant gold and copper deposits related to alkaline rocks

Deposit	Metal content	Related alkaline rocks	Age (Ma)	Tectonic setting	Selected reference
Cripple Creek, Colorado	834 t Au	Phonotite to alkali basalt (lamprophyre) diatreme complex	31–28	Extensional back arc, preparatory to Rio Grande intracontinental rift	Kelley et al. (1998)
Ladolam, New Papua Guinea	1,190 t Au	Trachyandesite-latite stratovolcano, monzodiorite stocks	< 1	Post-subduction extension	Moyle et al. (1990)
Porgera, Papua New Gunea	660 t Au	Minor alkaline gabbro and mafic porphyry stocks	6	Fold-thrust belt linked to continent-island arc collision	Richards and Kerrich (1993)
Olympic Dam, Australia	20 Mt Cu, 1,200 t Au, 1 Mt U	Syenogranite pluton, felsic and alkaline mafic-ultramafic dykes	~1590	Intracontinental rift	Reeve et al. (1990)
Phalaborwa, South Africa	4.25 Mt Cu + Au	Foskorite and carbonatite intrusions	~2060	Intracontinental extension	Verwoerd (1986)
Zortman-Landusky, Montana	120 t Au	Quartz monzonite and syenite phases of laccolith, tinguaite dykes	~62	Extensional back-arc above flat slab	Russell (1991)

North American Alkaline Gold Belt

Tellurium in Igneous-related Epithermal Precious Metal Deposits in Co

Overview | Project Activities | Partners

Overview

Why are we doing this research?

Tellurium, which is used in metal alloys, semiconductors, and in the rapidly growing solar energy field, is recovered as a primary resource from only two locations in the world: the adjacent Dashigou and Majiagou deposits in southwestern China and the Kankberg deposit in Sweden. Currently, about 85% of global production of tellurium comes as a byproduct of copper mining through a process called electrolytic refining.

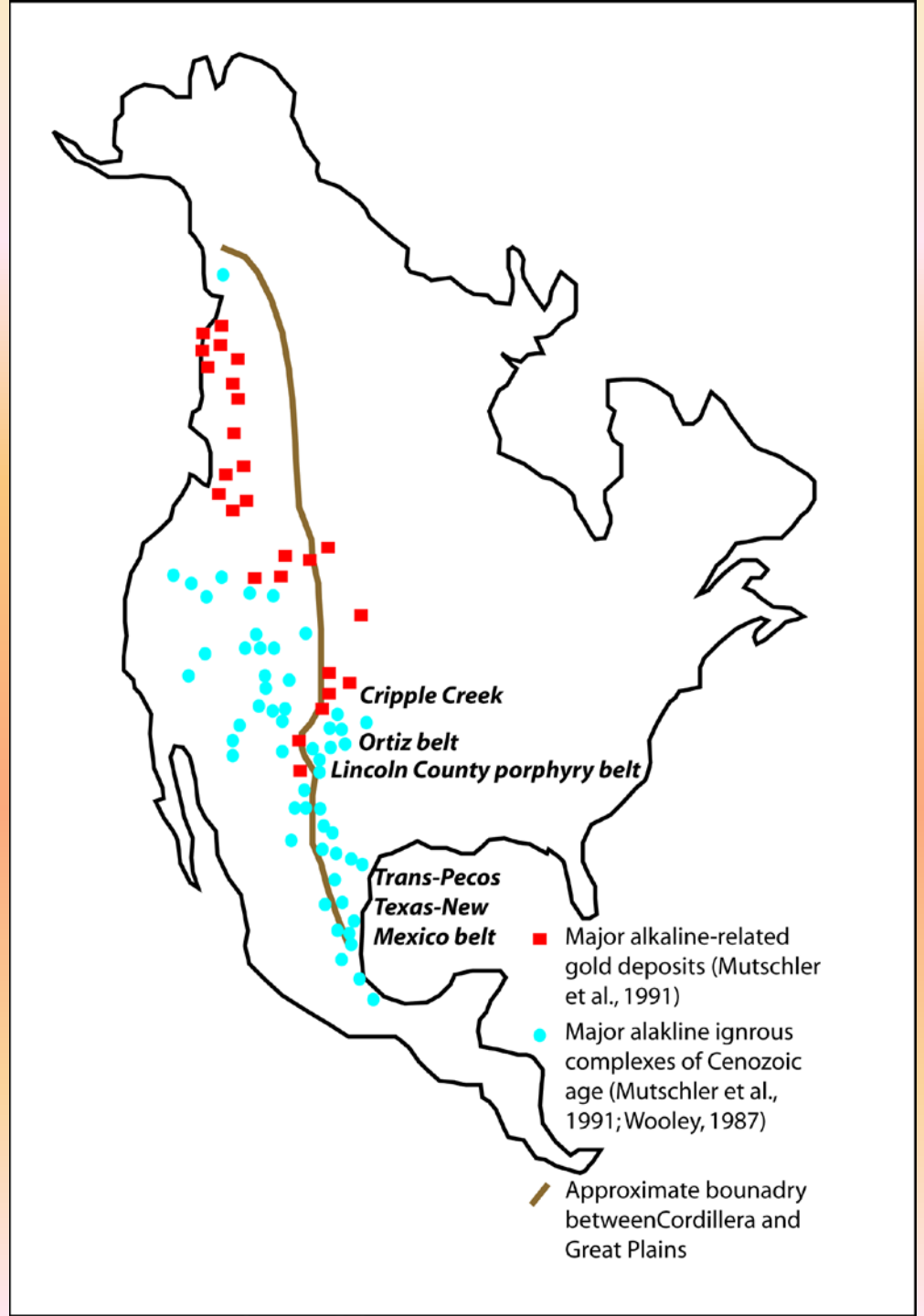
Alamosa Solar Generating Project was the largest high concentrating solar photovoltaic power station in the world when it was completed in 2012. It is located on 225 acres in the San Luis Valley near Alamosa, CO. Photograph by Dennis Schroeder, NREL.

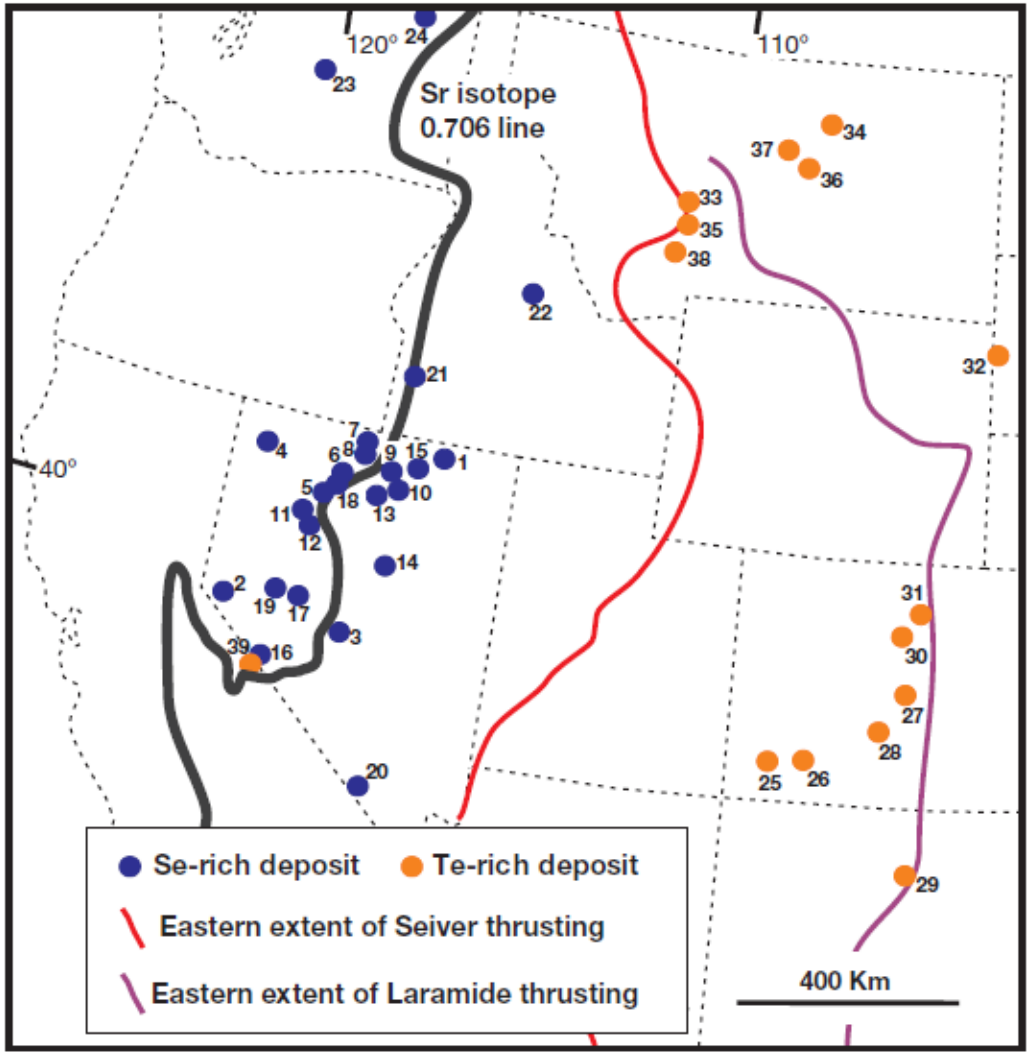
However, there is currently a shift in the mode of production of copper (to increase recovery of copper) from electrolytic refining to solvent extraction-electrowinning (SX-EW) and recycling. Recycling and solvent extraction-electrowinning do not produce tellurium as a byproduct, and therefore, the future supply of tellurium will be greatly reduced. Meanwhile, more tellurium will be required as more solar fields are built. In light of this, it is imperative that we understand the enrichment processes of potential alternative sources of tellurium, such as epithermal gold deposits. From a national security viewpoint, it is a great benefit that there are known domestic occurrences of these deposits.

Tellurium in Colorado and New Mexico Deposits

It is commonly assumed that most epithermal gold deposits associated with alkaline igneous rocks (deficient in silica with respect to alkalis) are enriched in tellurium, and within Colorado and New Mexico, many deposits are indeed tellurium-rich. However, many known alkalic-related deposits contain low tellurium concentrations. Alternatively, significant tellurium concentrations are associated with some calc-alkaline epithermal gold deposits. Cripple Creek and deposits in the Jamestown district in Boulder County are alkaline-related gold deposits in which gold resides primarily within gold-tellurium minerals. Whole rock ore samples from Cripple Creek and Boulder County contain tens of parts per million to over 0.1% tellurium. However, very few of the alkaline-related epithermal deposits in New Mexico contain significant concentrations of tellurium. The Lone Pine calc-alkaline epithermal gold deposit, which contains gold-tellurium minerals and native tellurium, has been the only producer of tellurium in New Mexico.

https://minerals.usgs.gov/science/tellurium-igneous-related-epi-deposits-co-nm/index.html#overview


Cripple Creek
Ortiz belt
Lincoln County porphyry belt
Trans-Pecos
Texas-New
Mexico belt
Major alkaline-related gold deposits (Mutschler et al., 1991)
Major alakline ignrous complexes of Cenozoic age (Mutschler et al., 1991; Wooley, 1987)
Approximate bounadry betweenCordillera and Great Plains

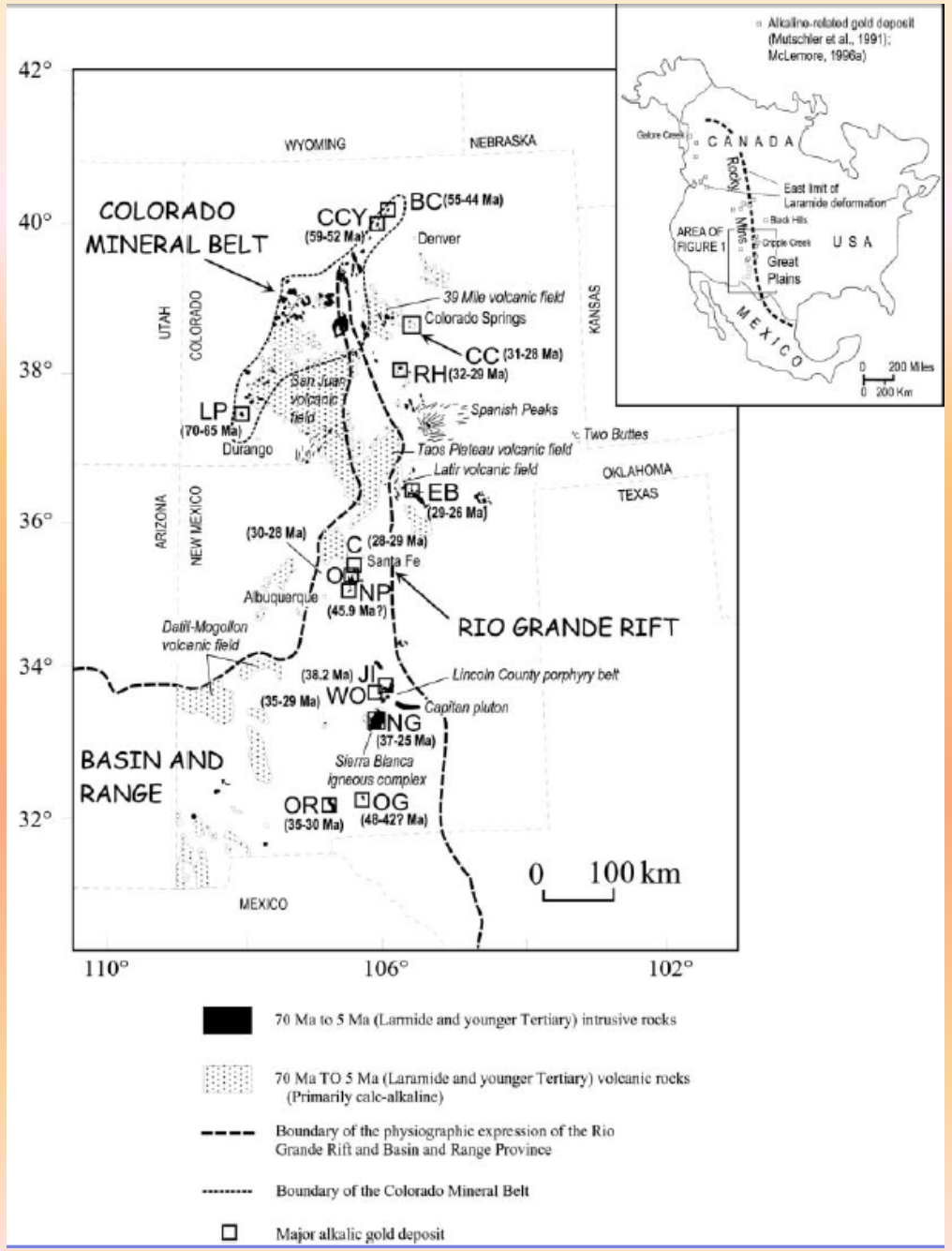


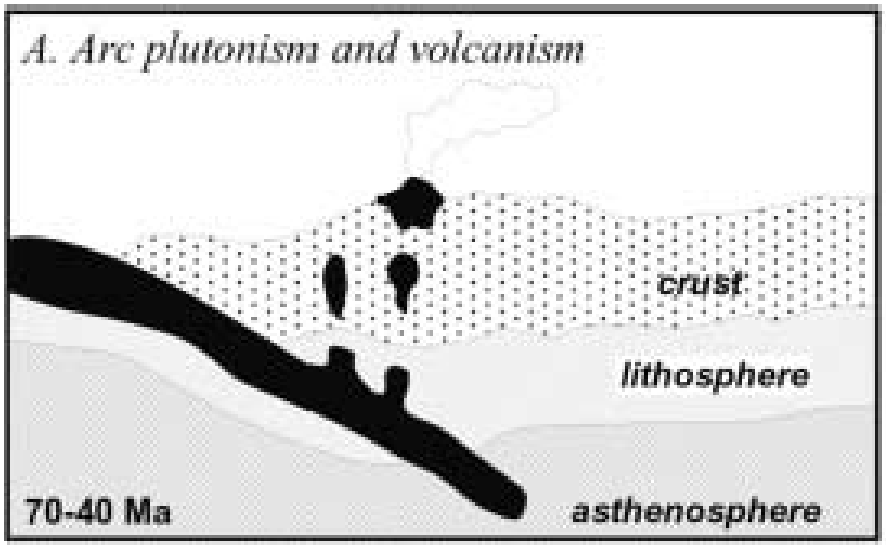
hypothesis that Laramide subduction prepared the mantle underlying the western United States for subsequent ore genesis

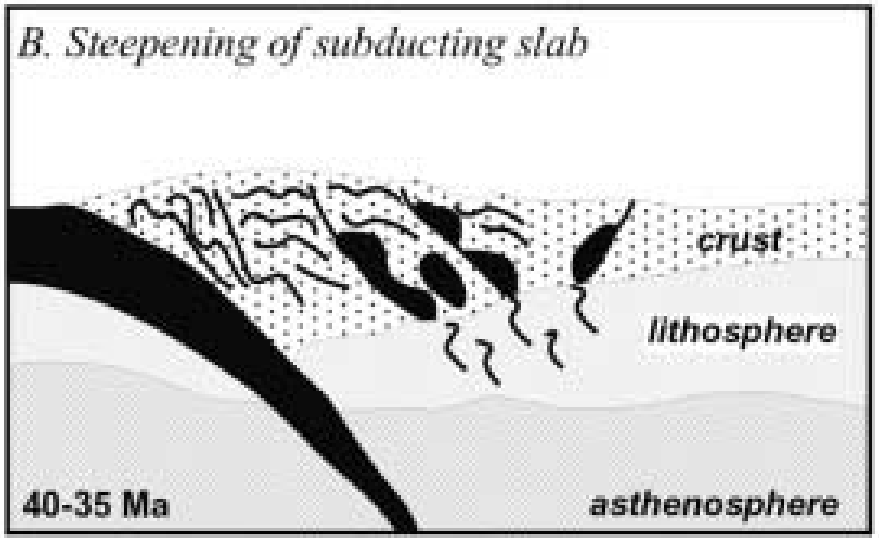
devolatilization reactions in a subducted slab can cause the overlying mantle to be enriched in volatile ore-forming constituents

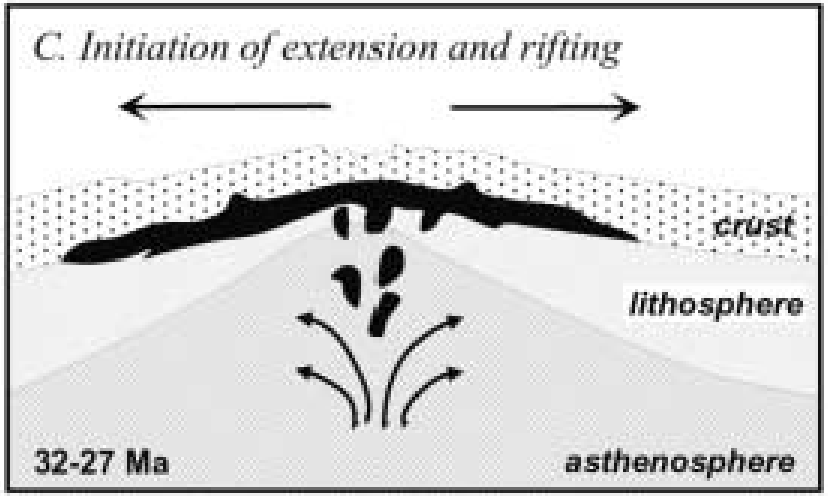
FIG. 2. Map showing localities of Laramide and younger epithermal ores of the western United States where data on Te and Se exists. See Table 1 for deposit names, data sources.

Saunders and Brueseke, 2012, Econ Geol


Alkaline-related gold deposit (Mutschler et al., 1991; McLemore, 1996a)
CANADA
Galore Creek
Rocky Mts.
East limit of Laramide deformation
Black Hills
AREA OF FIGURE 1
Cripple Creek
U S A
Great Plains
MEXICO
0 200 Miles
0 200 Km
42°
40°
38°
36°
34°
32°
110°
106°
102°
WYOMING
NEBRASKA
COLORADO MINERAL BELT
BC (55-44 Ma)
CCY (59-52 Ma)
Denver
39 Mile volcanic field
Colorado Springs
CC (31-28 Ma)
RH (32-29 Ma)
UTAH
COLORADO
KANSAS
San Juan volcanic field
LP (70-65 Ma)
Durango
Spanish Peaks
Two Buttes
Taos Plateau volcanic field
Latir volcanic field
OKLAHOMA
TEXAS
EB (29-26 Ma)
ARIZONA
NEW MEXICO
(30-28 Ma)
C (28-29 Ma)
Santa Fe
Albuquerque
NP (45.9 Ma?)
RIO GRANDE RIFT
Datil-Mogollon volcanic field
(38.2 Ma) JI
(35-29 Ma) WO
Lincoln County porphyry belt
Capitan pluton
NG (37-25 Ma)
BASIN AND RANGE
Sierra Blanca igneous complex
OR (35-30 Ma)
OG (48-427 Ma)
0 100 km
MEXICO
70 Ma to 5 Ma (Larmide and younger Tertiary) intrusive rocks
70 Ma TO 5 Ma (Laramide and younger Tertiary) volcanic rocks (Primarily calc-alkaline)
Boundary of the physiographic expression of the Rio Grande Rift and Basin and Range Province
Boundary of the Colorado Mineral Belt
Major alkalic gold deposit

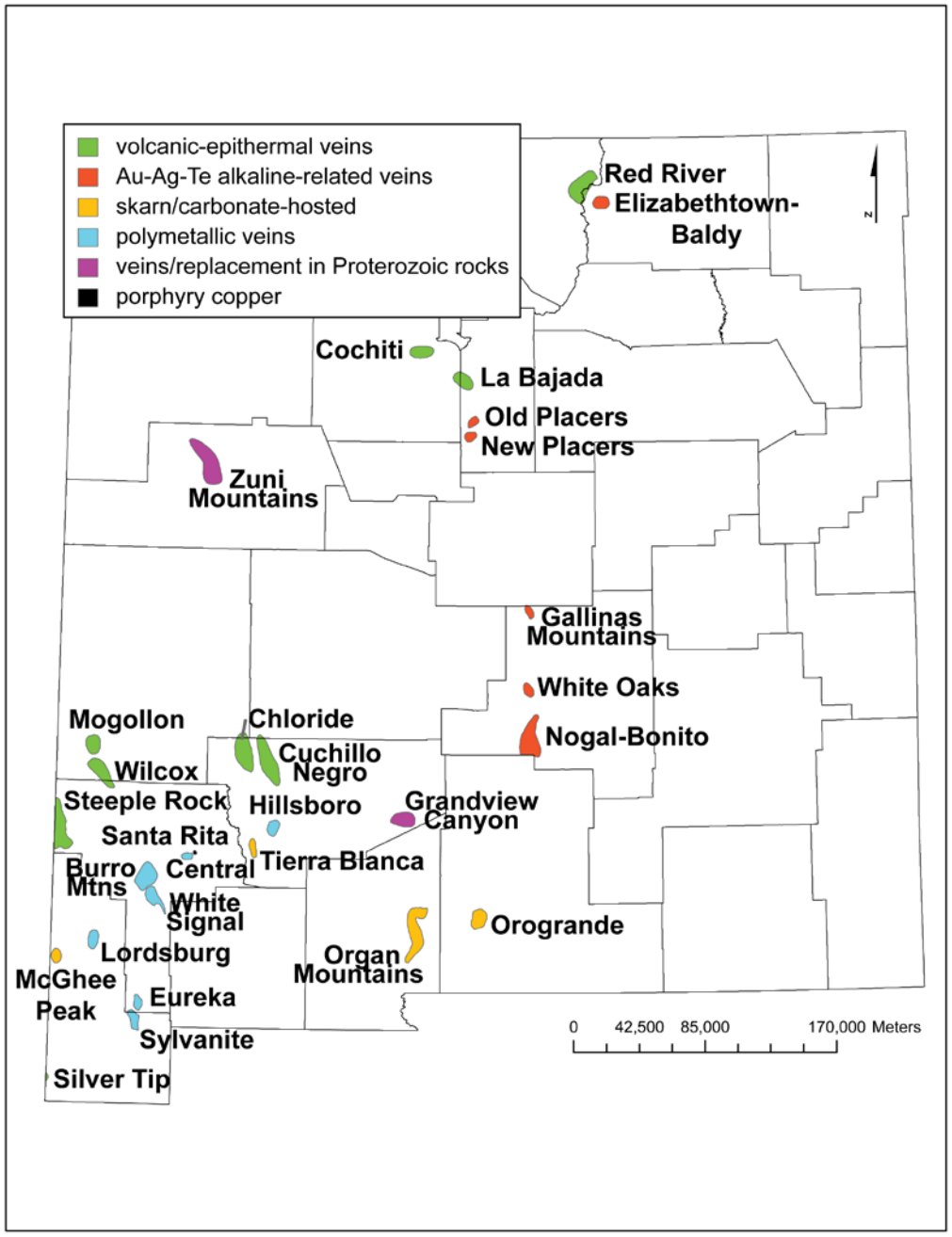

A. Arc plutonism and volcanism
crust
lithosphere
70-40 Ma
asthenosphere


B. Steepening of subducting slab
crust
lithosphere
40-35 Ma
asthenosphere


C. Initiation of extension and rifting
crust
lithosphere
32-27 Ma
asthenosphere

New Mexico Deposits

- Elizabethtown-Baldy district
  - 471,400 oz Au produced
- Old Placers district
  - 450,000 oz produced
- New Placers district
- Jicarilla district
- White Oakes district
- Nogal-Bonito district
- Orogrande district
  - 305,000 metric tons of ore grading 1.7 ppm Au
- Great Western deposit – 3.275 million metric tons of ore containing less than 2 ppm Au
- Vera Cruz deposit – 188,590 metric tons of ore grading 4.8 ppm Au
- Carache Canyon breccia deposit—4.5 million metric tons of ore grading 3.2 ppm Au
- Lukas Canyon—5.4 million metric tons of ore grading 1 ppm Au



Mining districts in New Mexico with tellurium minerals or chemical assays >20 ppm Te

Te in NM deposits

- Laughlin Peak-Chico Hills—210 ppm Te (Schreiner, 1991)
- Mudpuppy-Waterdog deposit—7.1 ppm Te
- Te minerals reported in Elizabethtown-Baldy

Types of deposits

- polymetallic epithermal to mesothermal veins
- gold-bearing breccia deposits and quartz veins
- copper-gold and/or gold porphyries
- iron skarns and replacements
- copper, lead-zinc, and gold skarns or carbonate-hosted replacements
- gold placers
- Th-U-REE-fluorite epithermal veins and breccias

Polymetallic epithermal to mesothermal veins

- thin, less than a meter wide, have steep dips, and occur along faults
- weak propylitic to argillic
- Ag/Au ratios less than 5
- Te spotty, with pyrite and gold

Gold-bearing breccia deposits and quartz veins

- Breccia deposits occur as pipes or conical bodies and vary in size
  - Vera Cruz deposit is approximately 200 m long and 60 m wide
  - Cunningham Hill deposit was approximately 210 m long and 120 m wide
- Quartz, pyrite, electrum, and native gold with little or no additional sulfides
- Breccia fragments are typically highly altered and vary in size
- multiple banding, hydrothermal brecciation, bladed calcite and/or quartz, vuggy textures, and druzzy quartz
- Te unknown but reported

Copper-gold and/or gold porphyries

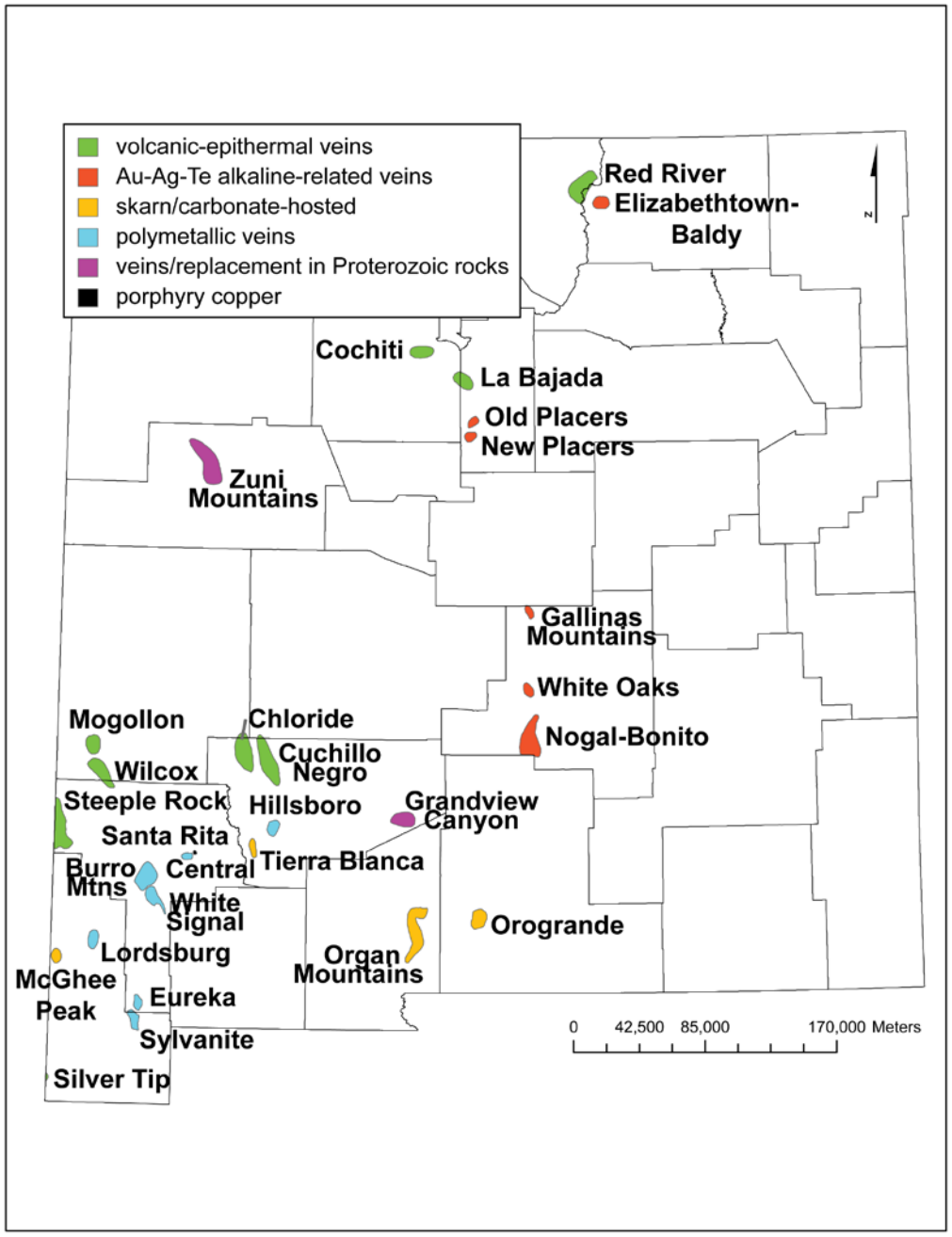
- Cu minerals and locally Au and Mo occur as disseminations and stockwork veinlets
- Mudpuppy-Waterdog– zoned outer propylitic to argillic to inner phyllic alteration to a core of silicified and oxidized breccia
- Ag/Au ratios >1
- Te???

Iron skarns and replacements

- Capitan, contained >1 million tons of Fe ore grading 45.64% Fe
- hematite and magnetite
- lenses or irregular bodies in limestone and as veins filling fractures, faults, and along bedding planes
- Te??

Copper, lead-zinc, and gold skarns or carbonate-hosted replacements

Organ Mountains, Doña Ana County—carbonate-hosted Pb-Zn



Mining districts in New Mexico with tellurium minerals or chemical assays >20 ppm Te

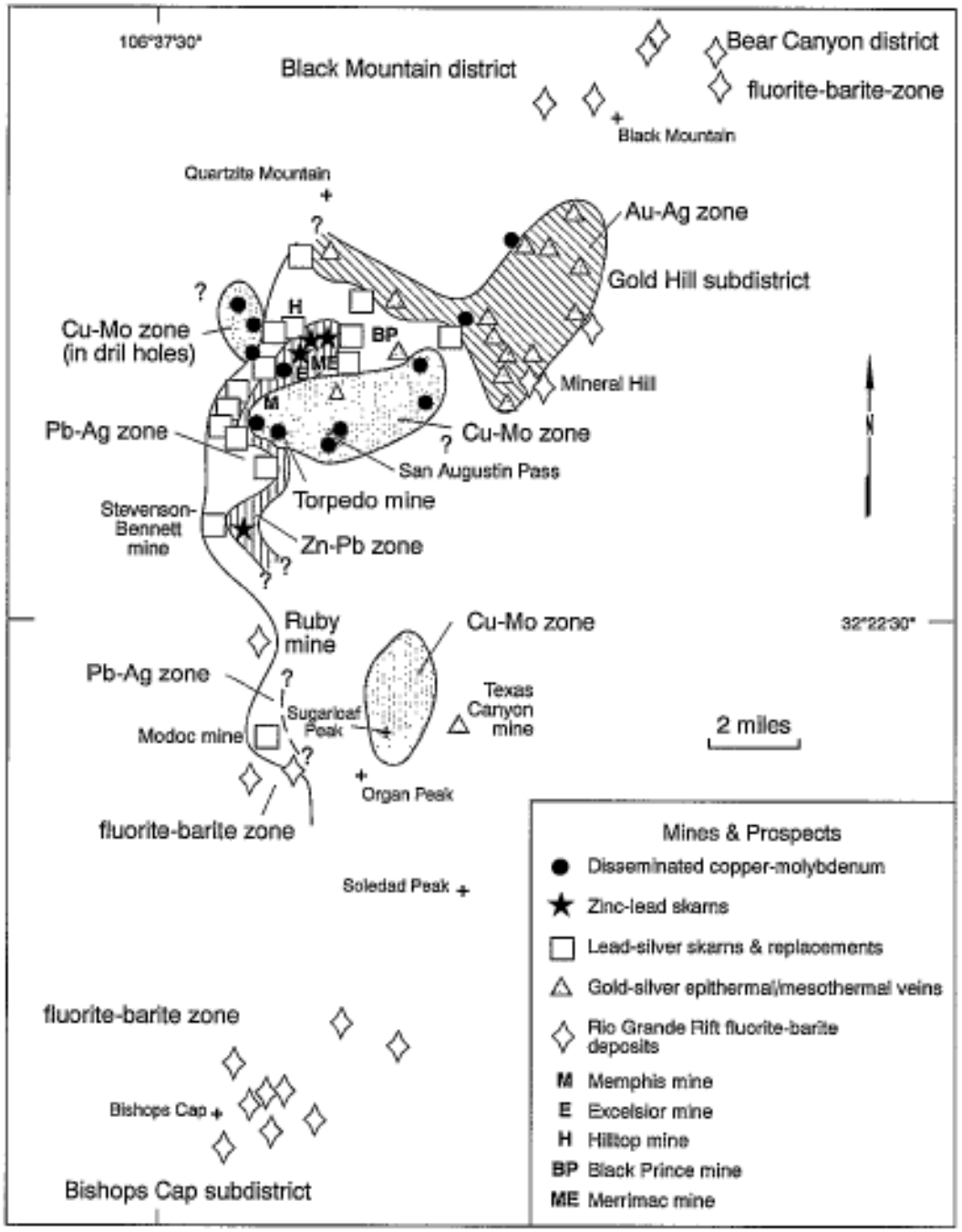
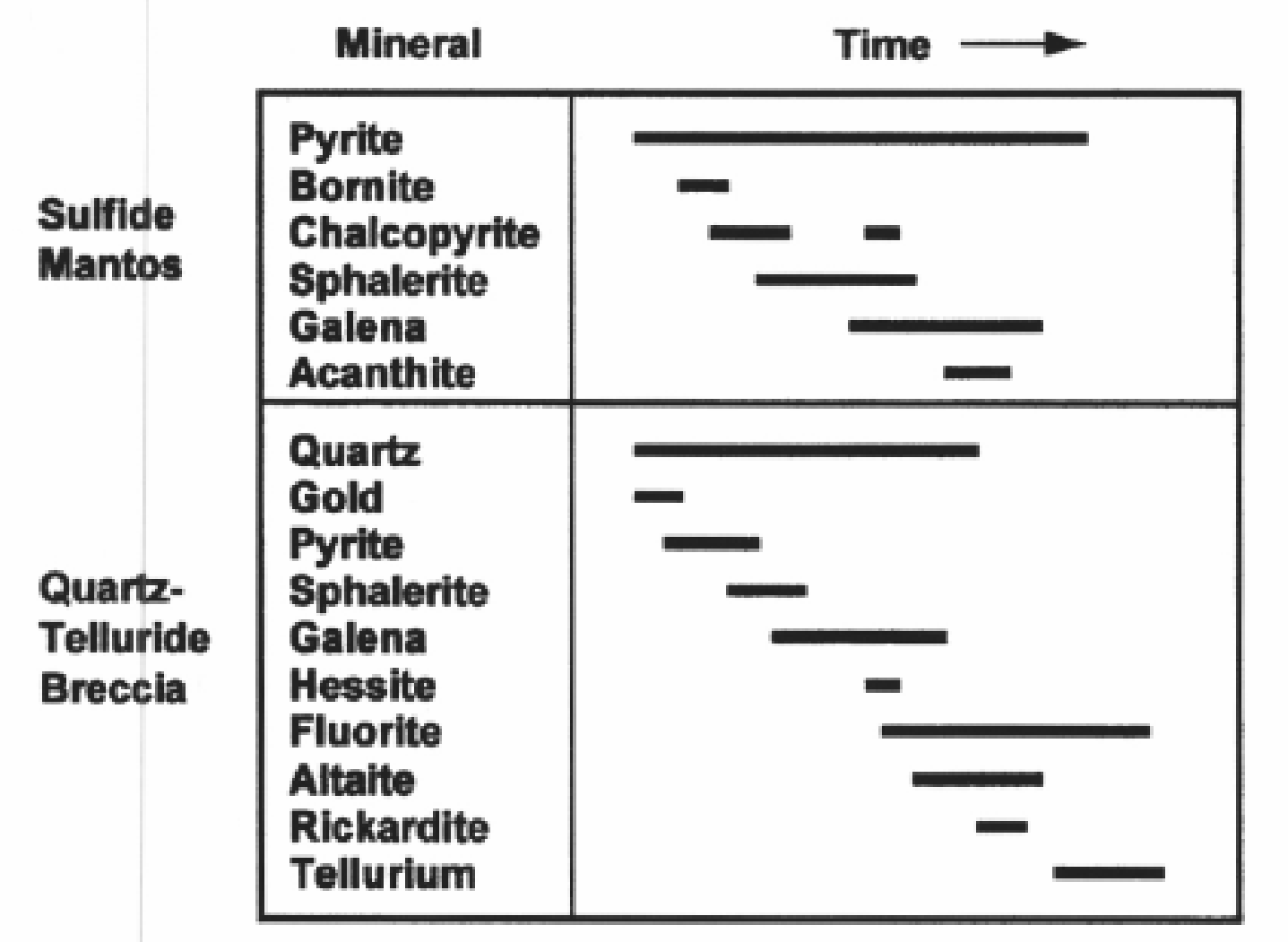


Figure 8—District zoning in the Organ Mountains, Doña Ana County, New Mexico (modified from Dunham, 1935; Seager, 1981).

Lueth and McLemore (1998) and McLemore et al. (1996)

Minerals

- ALTAITE (PbTe)
- RICKARDITE (Cu_3Te_2)
- TETRADYMITE (Bi_2Te_2S)



Paragenesis (Lueth, 1998)

Origin of Te mineralization

- Part of the porphyry copper system

OR

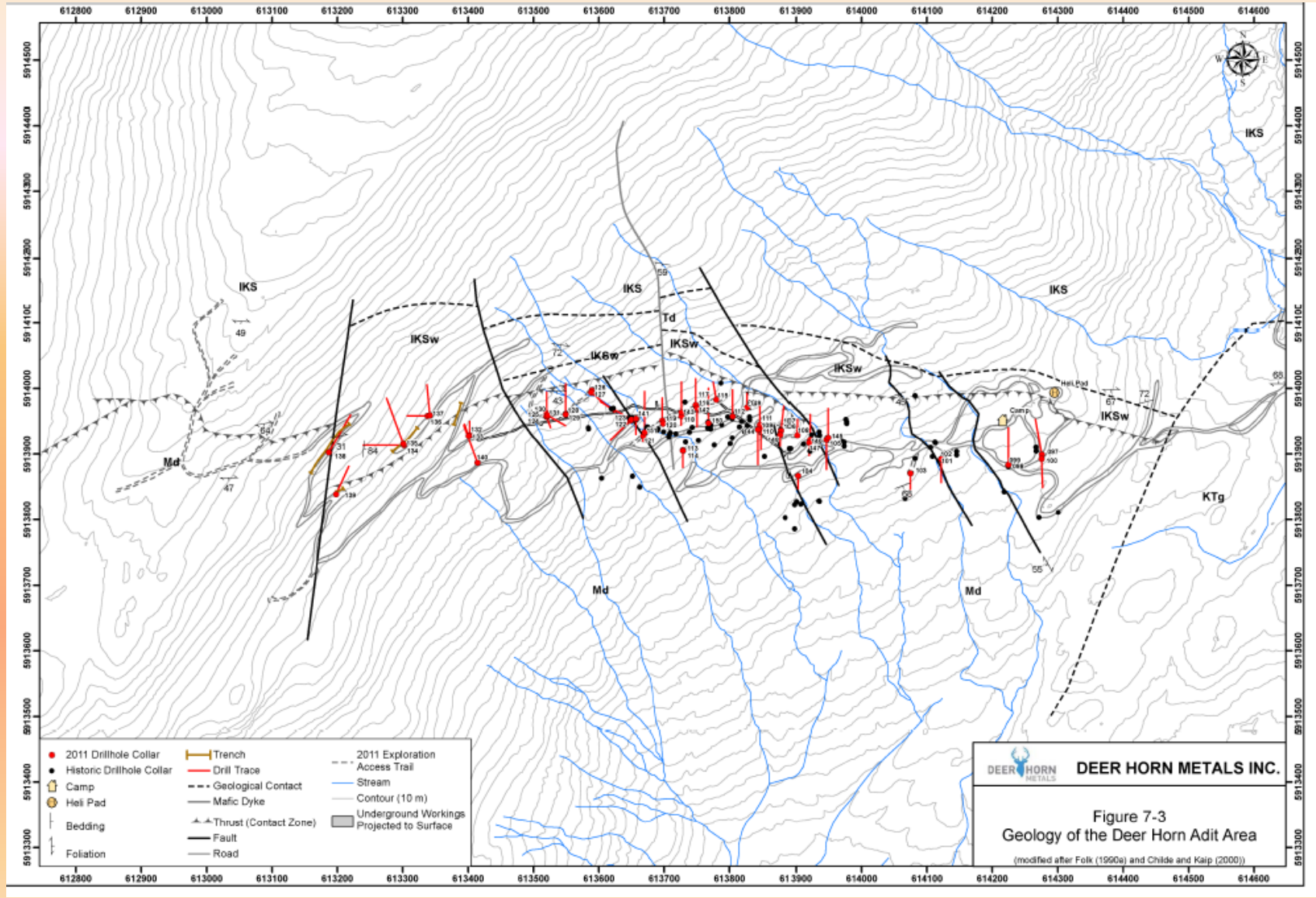
- Superimposed on the porphyry system as a retrograde phase

OR

- Separate event

Deer Horn, British Columbia

- Au-Ag-Te deposit (some Mo, W)
- 1.5 km long
- May be the only NI 43-101 resources for Te



http://www.deerhornmetals.com/i/pdf/reports/2013-03-12_PEA-NI43-101.pdf

Figure 7-4 Common geometric arrangements of fault-filled and extensional veins in shear zones

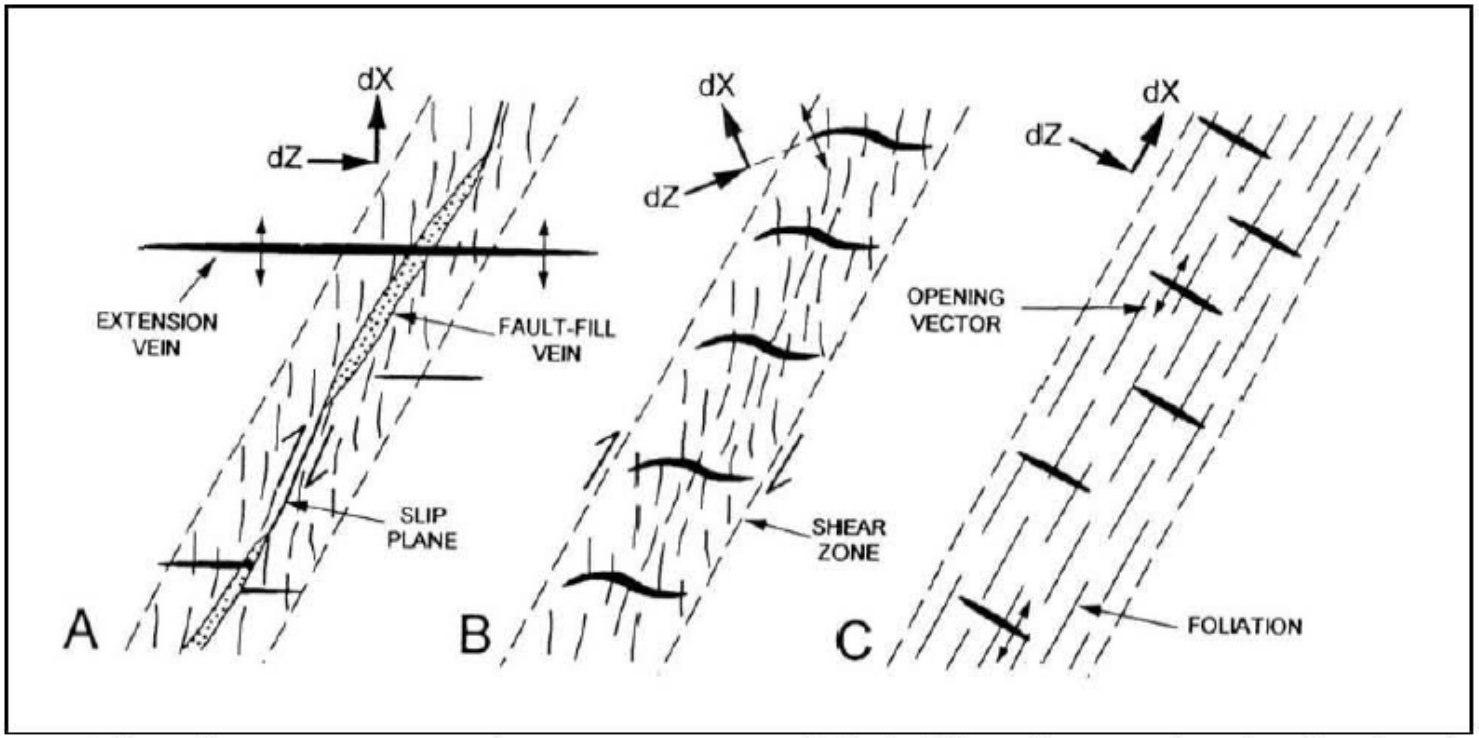
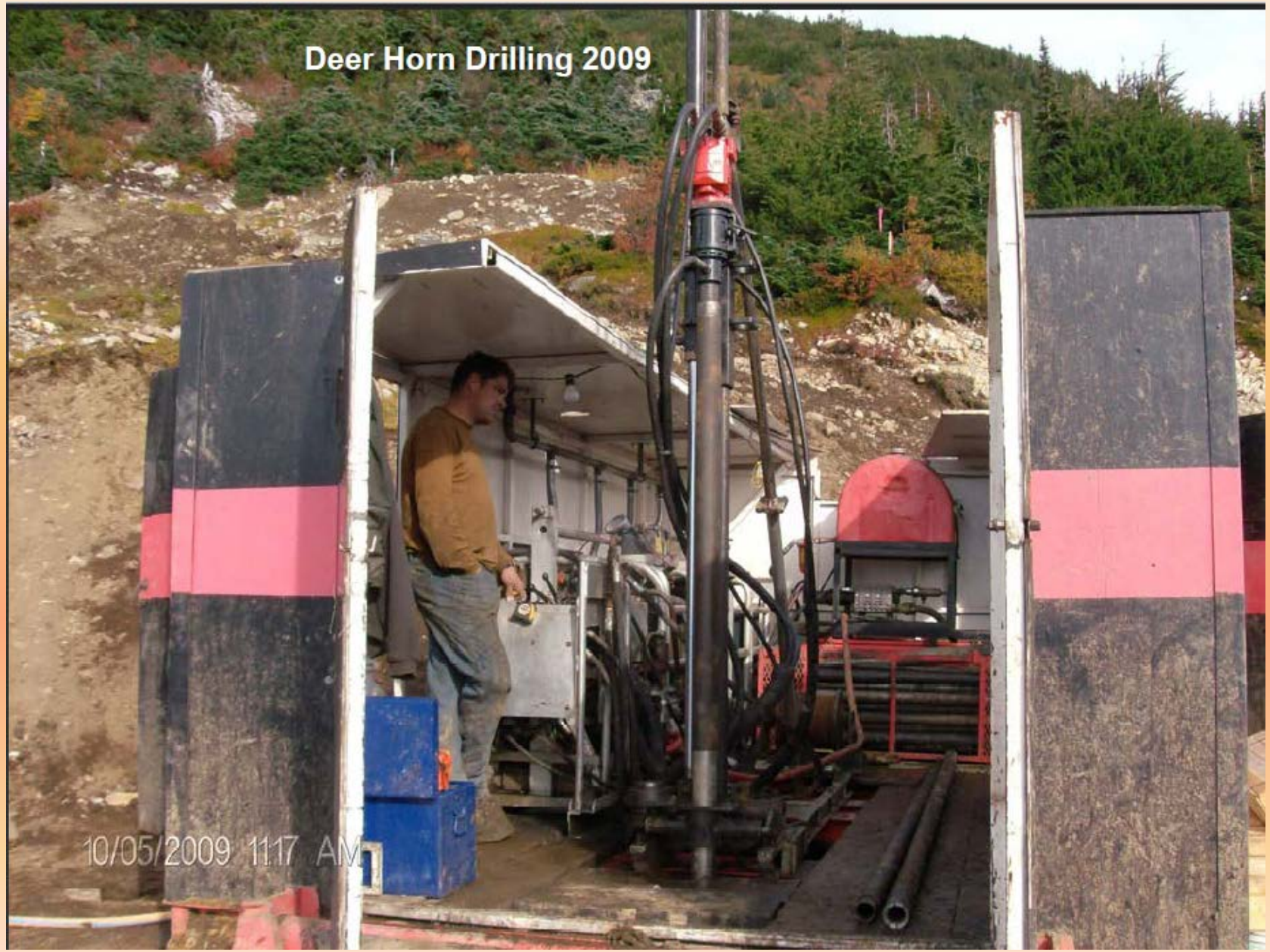
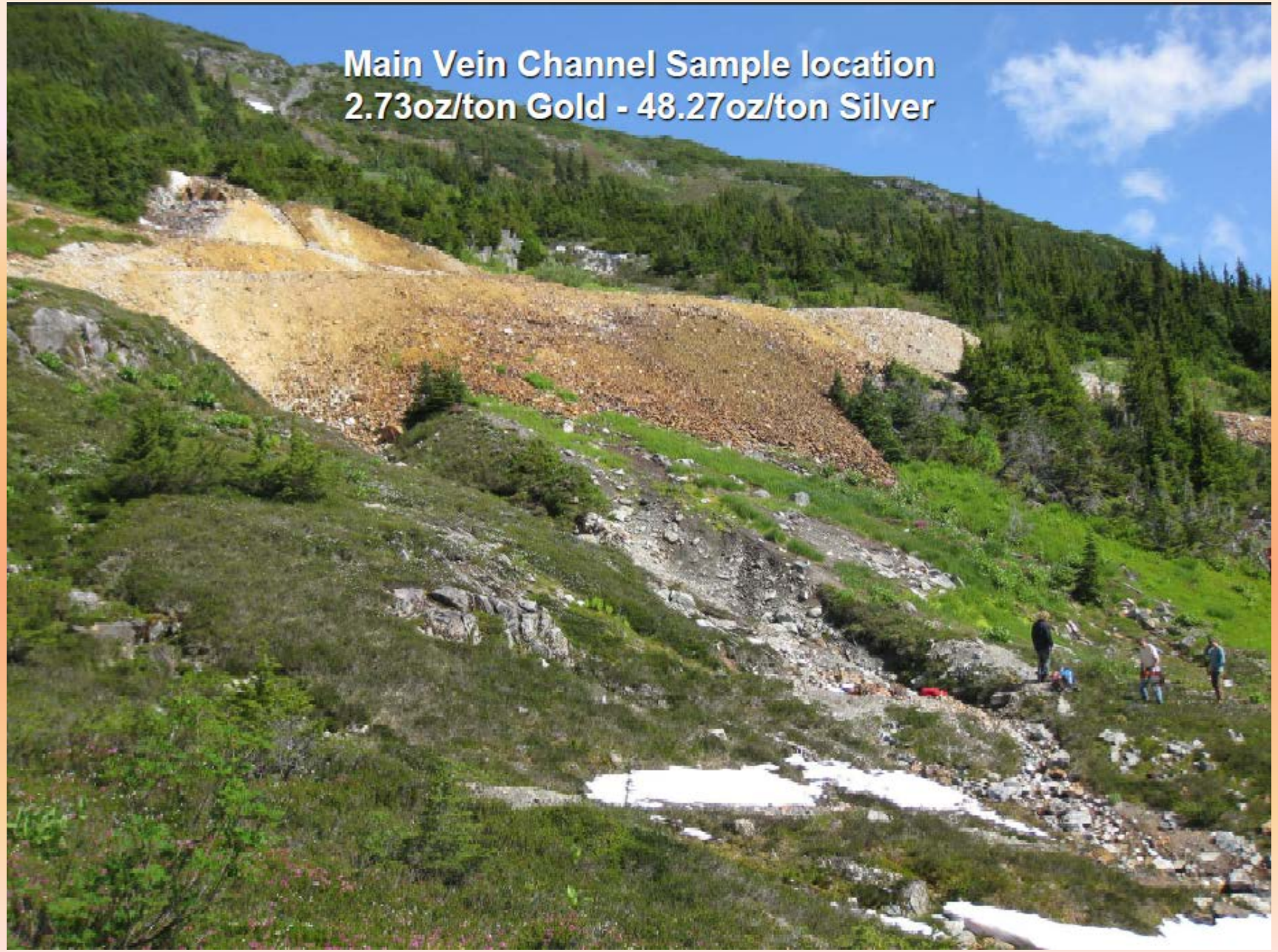


Figure 7-4 shows common geometric arrangements of fault-filled and extensional veins in shear zones and their relationship to incremental axes of shortening (dZ) and elongation (dX). A) Fault-filled veins in the central part of a reverse shear zone showing conflicting crosscutting relationships with planar extensional veins extending outside the shear zone; B) Arrays of en echelon sigmoidal extensional veins within shear zones; C) Arrays of stacked planar extensional veins within shear zones (Robert and Poulsen, 2001).


Deer Horn Drilling 2009
10/05/2009 11:17 AM

Quartz – Sulphide Vein Mineralization, Contact Zone (DH09-072 @ 36.58 m)


Main Vein Channel Sample location
2.73oz/ton Gold - 48.27oz/ton Silver

Deer Horn, British Columbia

Indicated Resource
(1.00 g/t Au cut-off)

Tonnes	Au (g/t)	Ag (g/t)	Te (ppm)	Contained Ounces Au	Contained Ounces Ag	Contained Kg Te
414,000	5.12	157.50	160	68,000	2,120,000	66,000

Inferred Resource
(1.00 g/t Au cut-off)

Tonnes	Au (g/t)	Ag (g/t)	Te (ppm)	Contained Ounces Au	Contained Ounces Ag	Contained Kg Te
197,000	5.04	146.50	137	32,000	930,000	27,000

http://www.deerhornmetals.com/i/pdf/nr/2012-04-17_NR.pdf

Production highlights for the 14 year mine life are as follows:

Total Tonnes to Mill	949,000
Annual Tonnes to Mill	74,000
Average Grades:	
Gold (grams per tonne)	2.45
Silver (grams per tonne)	77
Tellurium (ppm)	74
Total Production:	
Gold (ounces)	67,000
Silver (ounces)	2,112,000
Tellurium (kg)	63,000

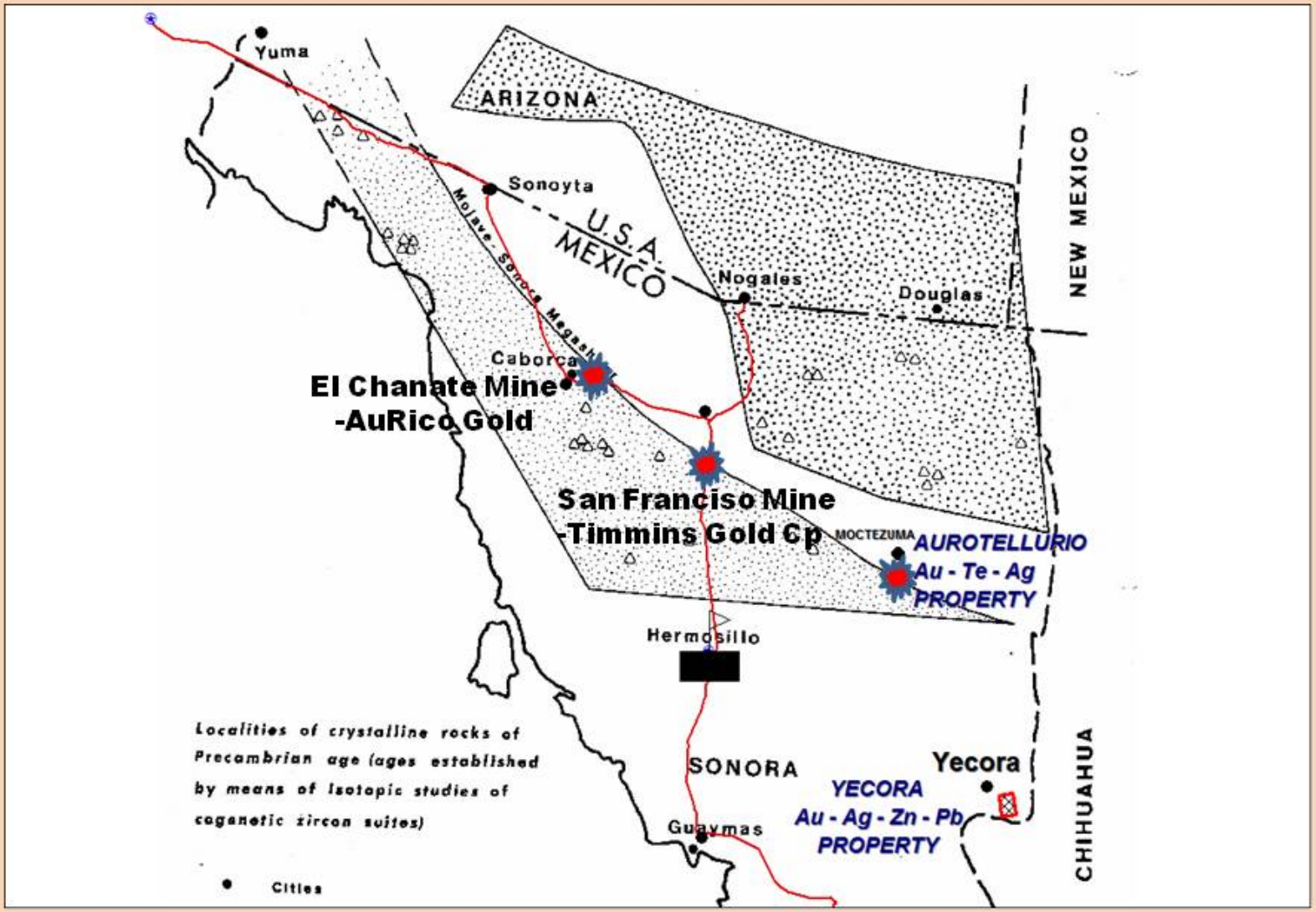
http://www.deerhornmetals.com/s/news.asp?ReportID=576227

Moctezuma district, Mexico

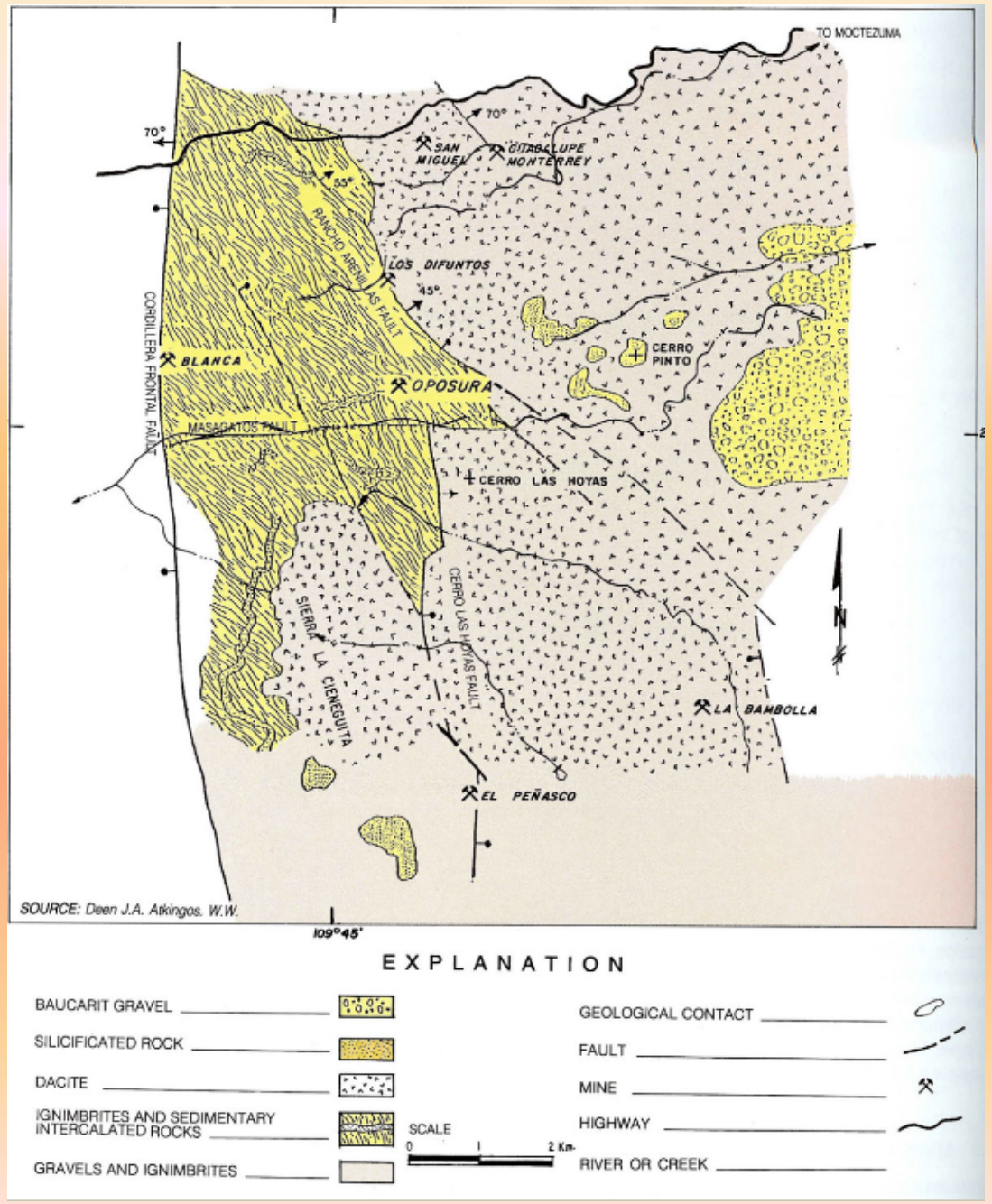
Moctezuma district, Mexico

- replacement-style zinc-lead base metal deposits in mantos (Oposura)
- Structure-controlled veins
- Quartz and quartz-carbonate (San Miguel and La Bambolla, Blanca Norte)

AUROTELLURIO Regional Map



http://www.mexivada.com/i/maps/mx/AuroTellurio-Regional-Map.jpg



http://www.mexivada.com/i/maps/mx/Moctezuma_Geology.jpg

SAMPLE	Au-AA24	ME-MS61 Ag	ME-MS61 Te
51401	<0.005	357	0.07
51402	<0.005	220	0.05
51403	<0.005	17.2	<0.05
51404	<0.005	6.88	12.95
51405	<0.005	0.33	0.47
51406	0.008	16.85	0.28
51407	0.011	13.85	0.25
51408	0.005	32.1	0.57
51409	<0.005	0.63	0.08
51410	0.007	0.17	3.96
51411	0.183	20.1	5.4
51412	0.059	0.72	16.55
51413	0.015	0.49	2.07

Table 3. Surface Sampling in the Moctezuma Mining District.

http://www.mexivada.com/i/pdf/AuroTellurio_techreport_4-09.pdf

Pb-Zn veins

- Romania, Bulgaria and Russia
- veins, lens-shaped and metasomatic bodies within granites, volcanic-sedimentary, acid granites and alkaline derivatives
- Altaite
- Zyryanovsk, Russia with galena containing 150ppm Te in the oxidation zone, as altaite
- Baia de Aries, Romania, where the Te field occurs in the western part of the metallogenic area, as vein bodies

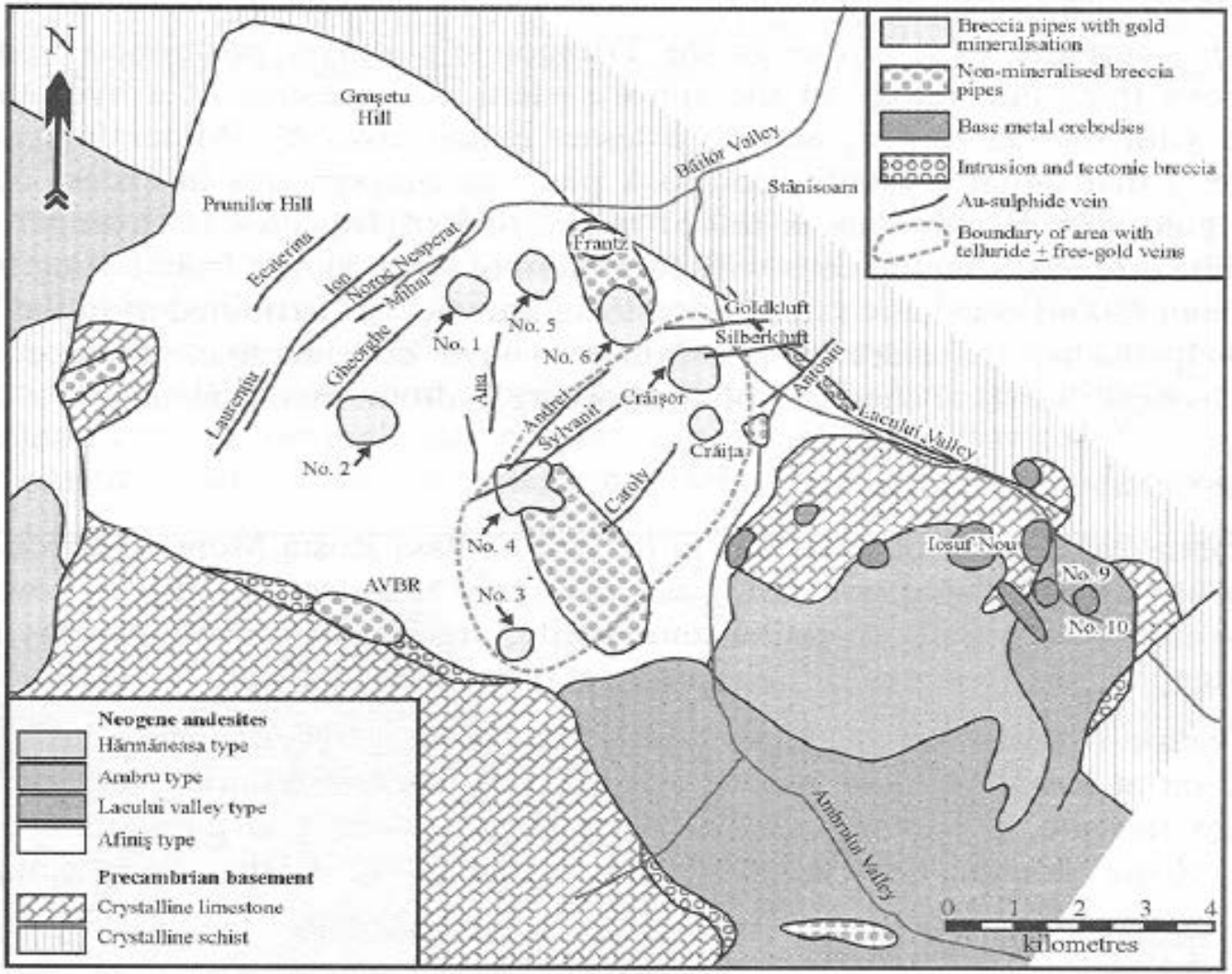
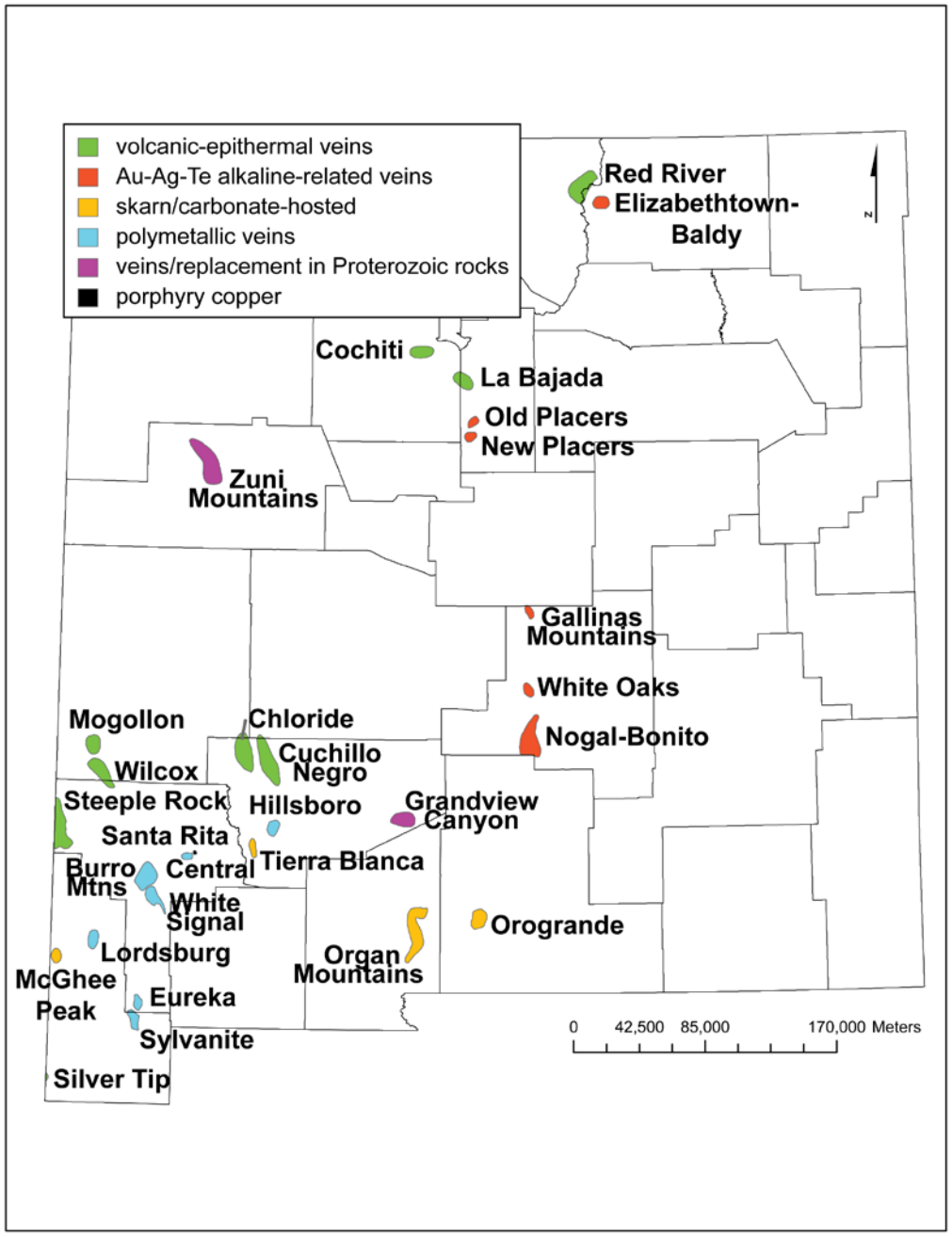


Fig. 3 Simplified geological map of the Baia de Aries deposit (Ciofica et al., 1999)

Lone Pine, Wilcox district, Catron County—volcanic epithermal vein



Mining districts in New Mexico with tellurium minerals or chemical assays >20 ppm Te

Production

- Discovered about 1889

- 5 tons of Te 1961-1962
- 1.23 oz Au
- 19 oz Ag
- 10,603 tons of fluorite

Geology

- Hosted by volcanic rocks
- Fracture fillings and veinlets
- Along north- and northwest-trending fractures and faults that were intruded by rhyolite dikes
- Clay alteration, locally silicified, hematization
- Pyrite to pyrite-Te to fluorite-rich zones
- 400 to 500 feet long
- up to 1,800 feet long
- As much as 5000 ppm Te, 6 oz/ton Au

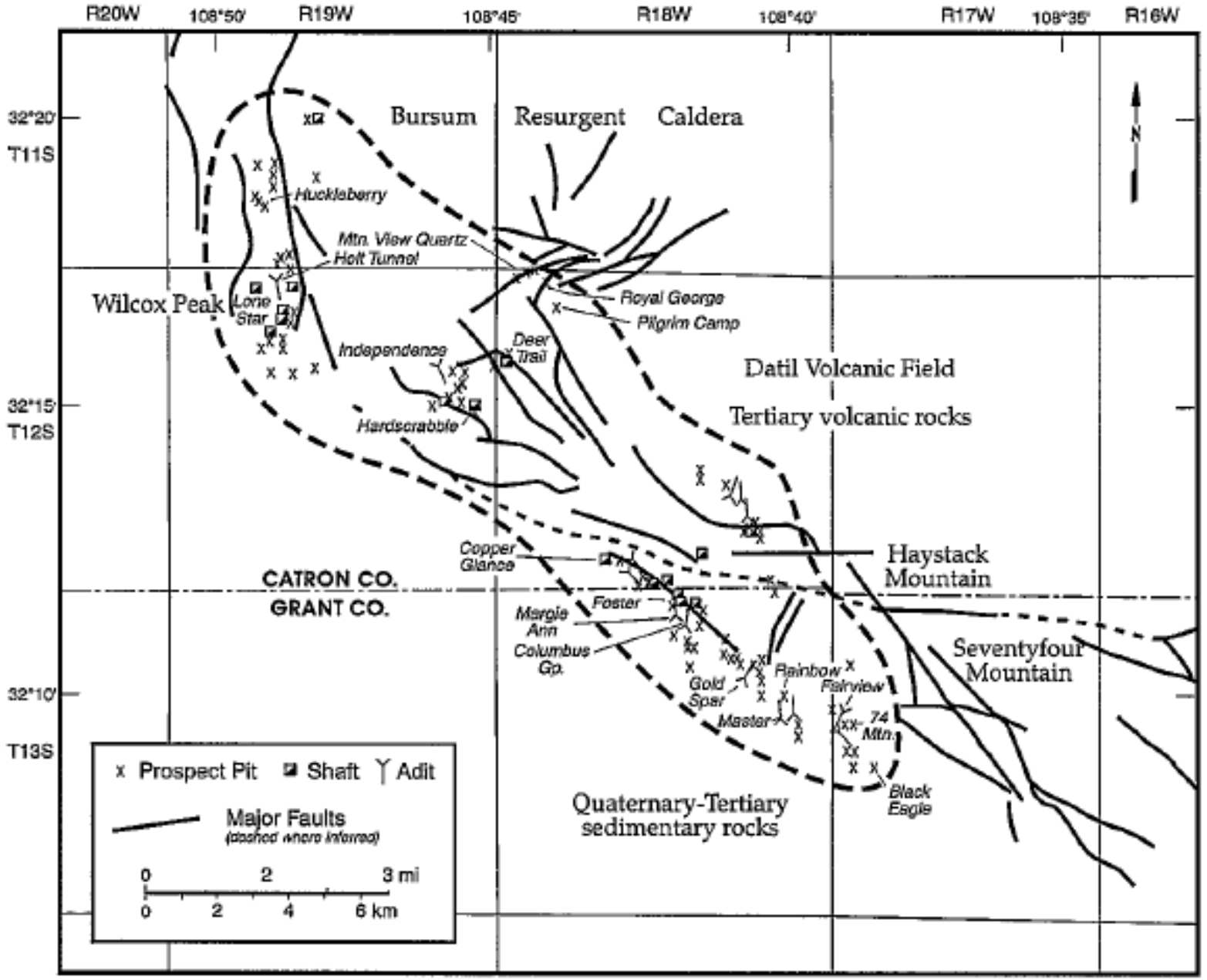
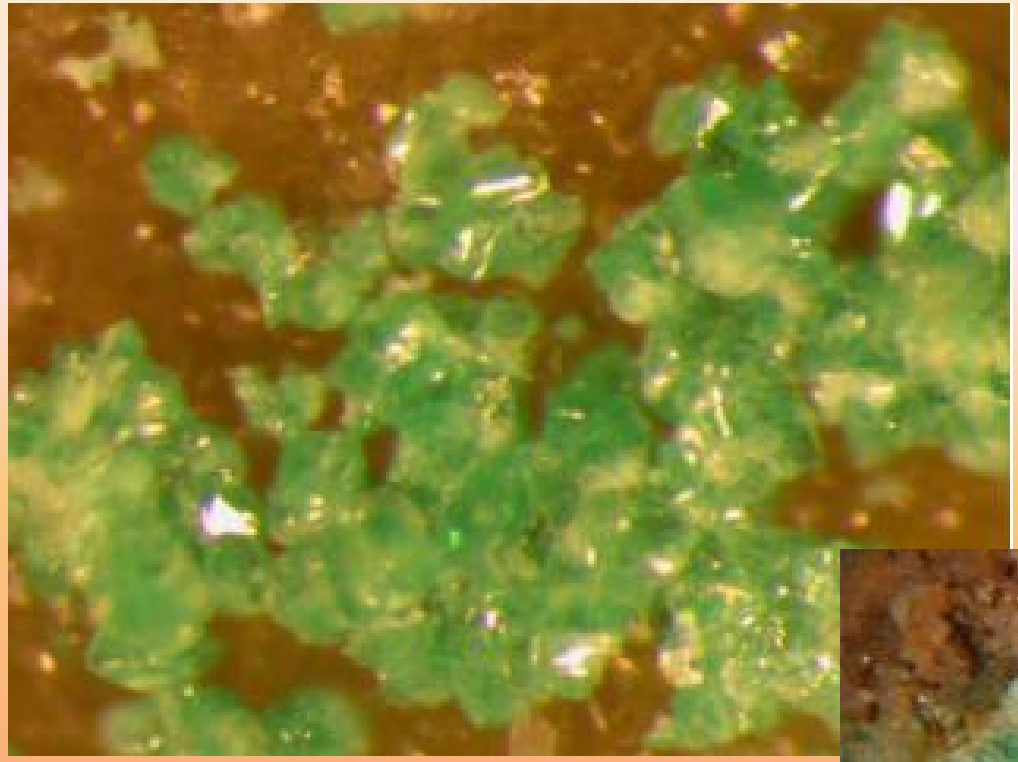


Figure 61—Mines and prospects in the Wilcox mining district, Grant and Catron Counties, New Mexico.

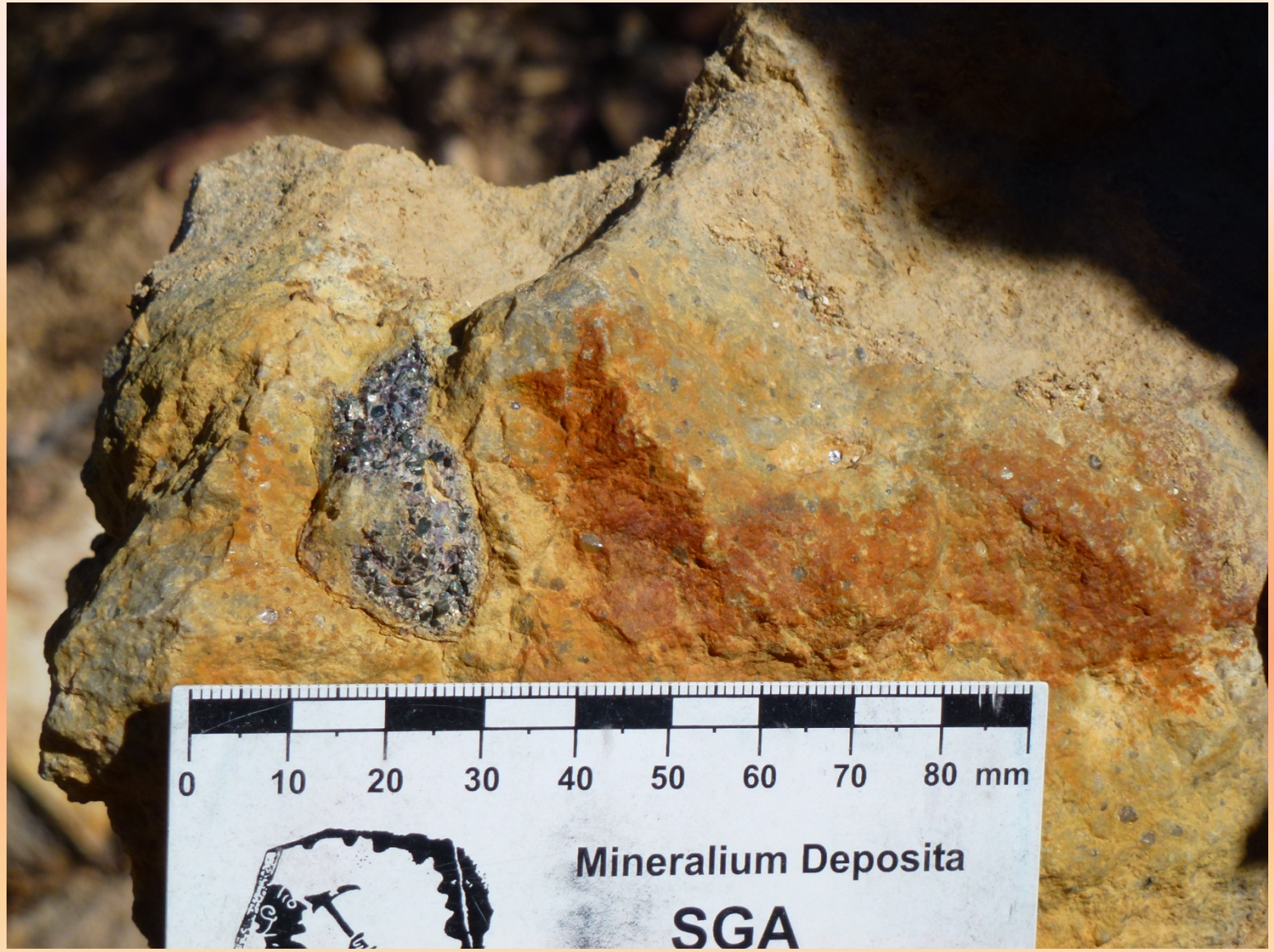
Minerals (Lueth et al., 1995)

- Quartz
- Pyrite
- Acanthite
- Bismuthinite
- Tellurite
- Paratellurite
- Teeurobismuthite
- Native tellurium
- Tetradymite?
- Krennerite(?)
- emmonsite ($Fe_2Te_3O_9 \bullet 2H_2O$)
- mackayite ($FeTe_2O_5(OH)$)
- sonoraite ($FeTeO_3(OH) \bullet H_2O$)
- blakeite ($Fe_2(TeO_3)_3$)
- poughite ($Fe_2(TeO_3)_2(SO_4) \bullet 3H_2O$)
- rajite ($CuTe_2O_5$)



rajite ($CuTe_2O_5$)

http://www.mindat.org/loc-3966.html

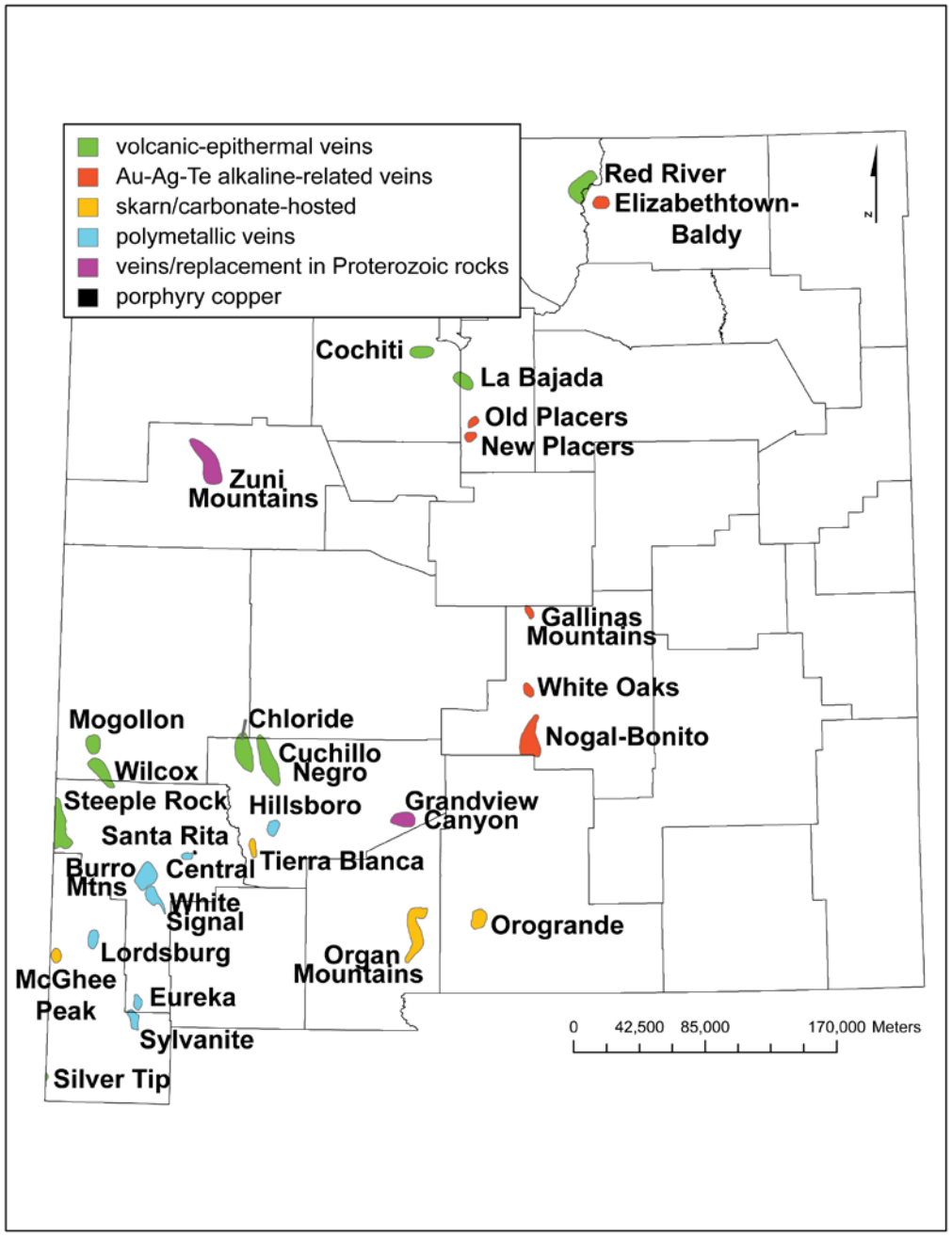


tetradymite (Bi_2Te_2S)

Sylvanite district, New Mexico

Sylvanite, $AgAuTe_4$

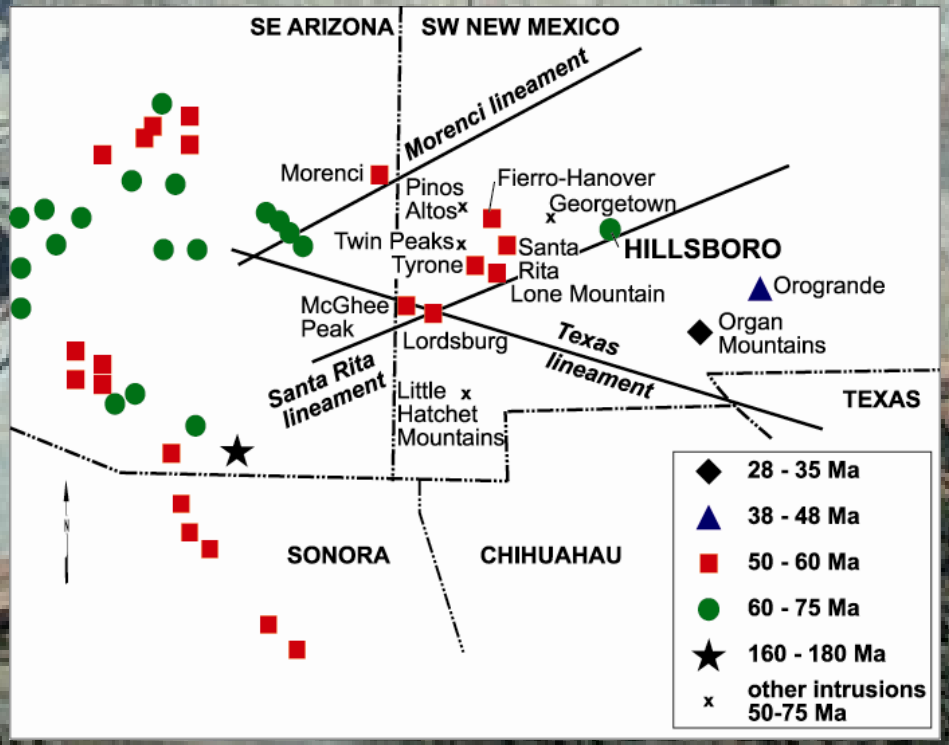
https://www.mineralauctions.com/auctions/weekly-collection-liquidation-auctions-end-march-31-478/sylvanite-old-rare-nm-locale-velte-coll-22476.html



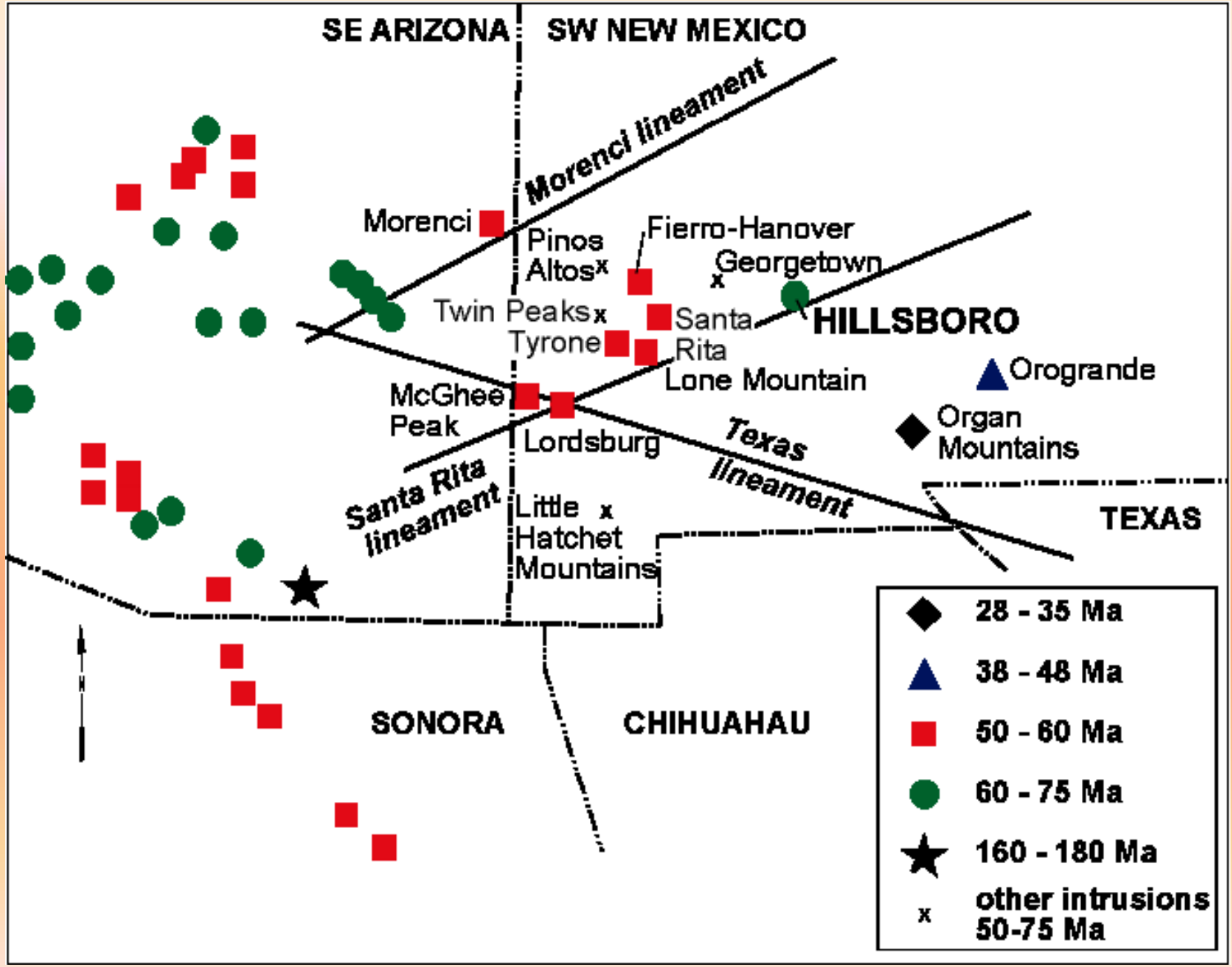
Mining districts in New Mexico with tellurium minerals or chemical assays >20 ppm Te

Laramide Porphyry copper deposits

- Current
  - Gold
  - Silver
  - Molybdenum
- Possible
  - Tellurium
  - Gallium
  - Germanium
  - Indium
  - Others

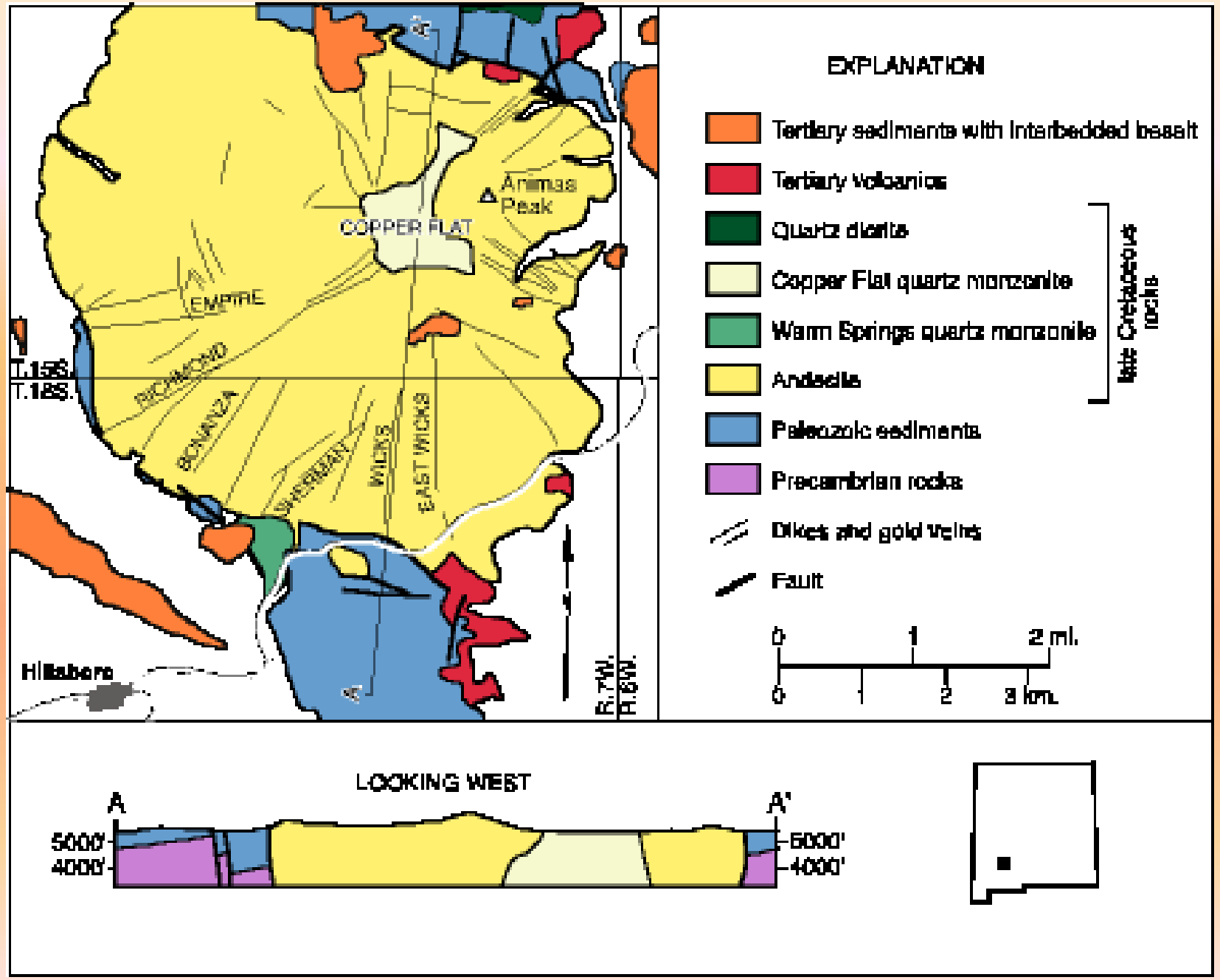


Copper Flat, Hillsboro, Sierra County, NM

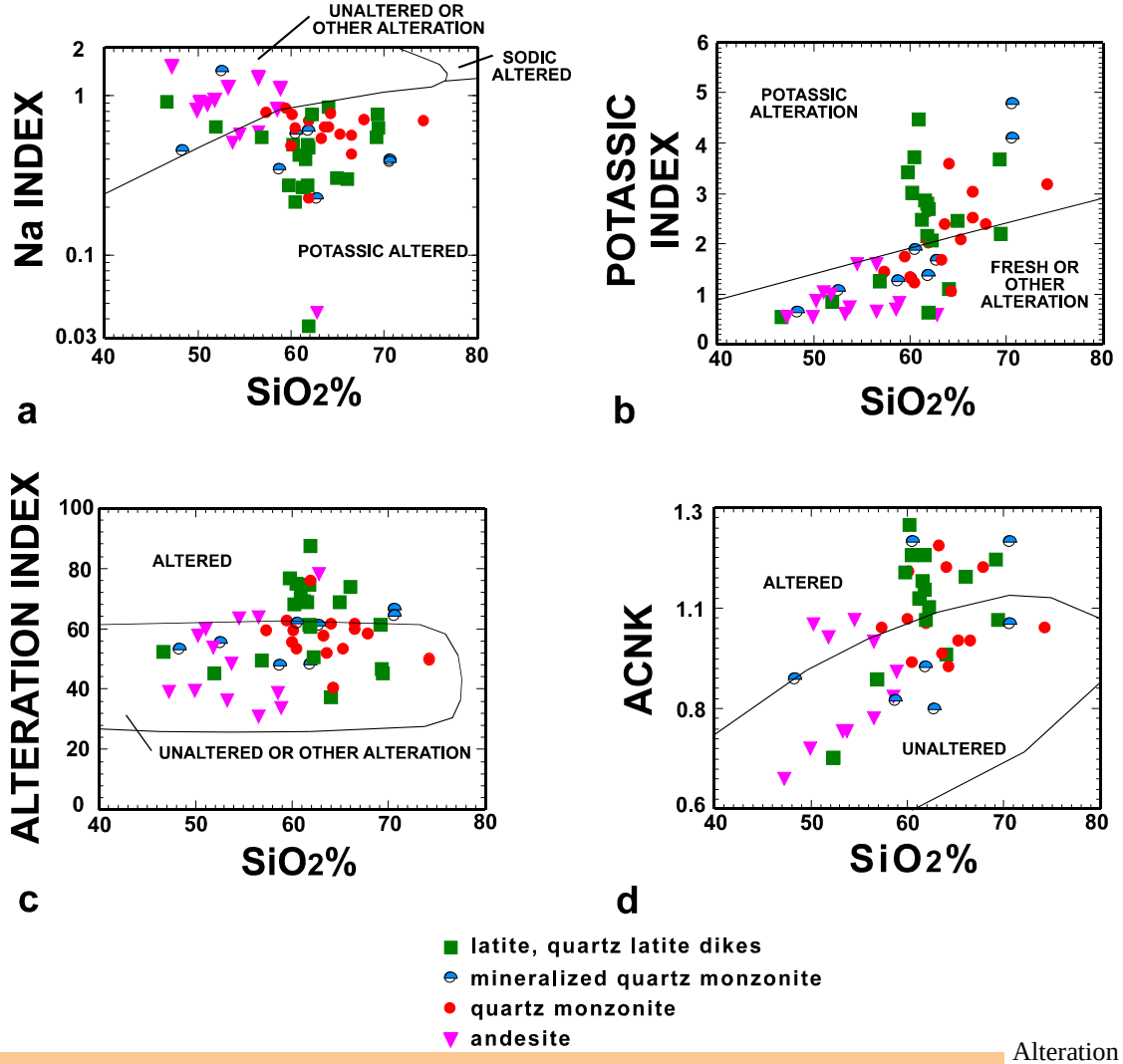

SE ARIZONA
SW NEW MEXICO
Morenci lineament
Morenci
Pinos Altos
Fierro-Hanover
Georgetown
Twin Peaks
Tyrone
Santa Rita
HILLSBORO
Lone Mountain
Orogrande
McGhee Peak
Lordsburg
Organ Mountains
Texas lineament
Santa Rita lineament
Little Hatchet Mountains
TEXAS
SONORA
CHIHUAHAU
28 - 35 Ma
38 - 48 Ma
50 - 60 Ma
60 - 75 Ma
160 - 180 Ma
other intrusions 50-75 Ma

Copper Flat

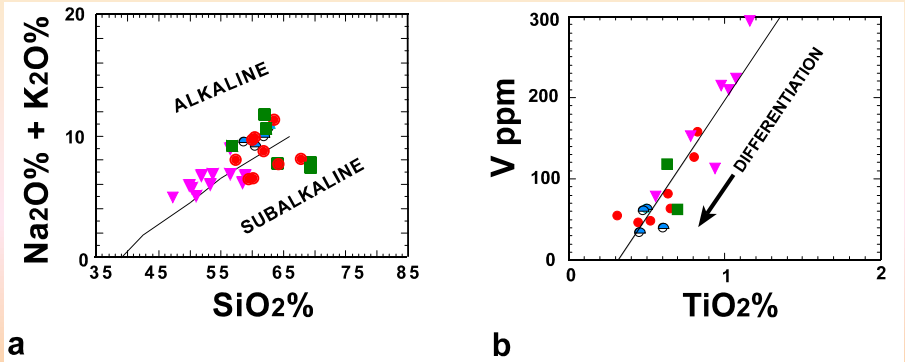
- proven and probable reserves of 45.5Mt of ore at a reported grade of 0.45% Cu, 0.14g/t Au, 2.3 g/t Ag and 0.0015% Mo
- quartz monzonite stock (CFQM; 74.93±0.66 Ma) with a breccia pipe is located in the center of the district
- Surrounded by Laramide veins and carbonate-hosted Pb-Zn and Ag-Mn deposits

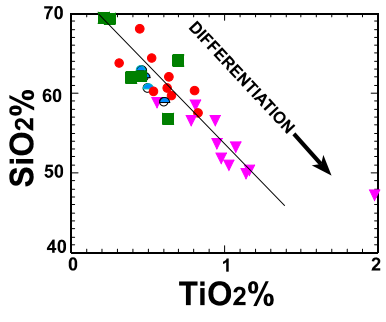

EXPLANATION
Tertiary sediments with interbedded basalt
Tertiary volcanics
Quartz diorite
Copper Flat quartz monzonite
Warm Springs quartz monzonite
Andesite
late Cretaceous rocks
Paleozoic sediments
Precambrian rocks
Dikes and gold veins
Fault
0 1 2 mi.
0 1 2 3 km.
Animas Peak
COPPER FLAT
EMPIRE
RICHMOND
BONANZA
SHERIDAN
WICKS
EAST WICKS
T.15S.
T.16S.
R.7W.
R.6W.
Hillsboro
LOOKING WEST
A
A'
5000'
4000'
5000'
4000'

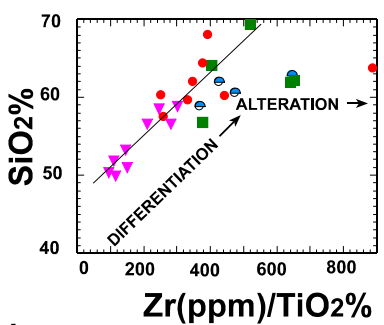
Chemistry



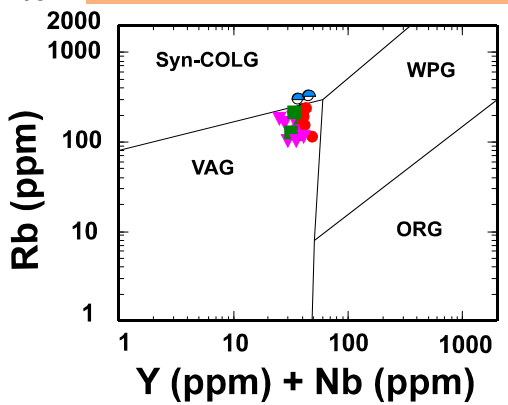
Alteration filter diagrams showing fresh and altered fields (after Wilt, 1995; Keith and Swan, 1996). Na index (a) is the ratio of Na_2O to the sum of K_2O and ACNK. ACNK is the molecular ratio of Al_2O_3 to total CaO, Na_2O, and K_2O and is calculated by $[(Al_2O_3/102)/((CaO/56)+(Na_2O/62)+(K_2O/94)]$. Potassic index (b) is the ratio of the sum of K_2O, Na_2O, and MgO by the sum of CaO and $(0.9Fe_2O_3+FeO)$. The alteration index (c) is the ratio of 100 times the sum of K_2O and MgO by the sum of K_2O, MgO, Na_2O, and CaO. The scatter in the data is a result of hydrothermal alteration. These diagrams were used to distinquish fresh from altered igneous rocks.

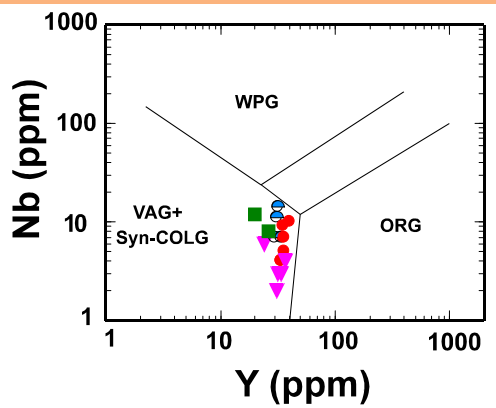




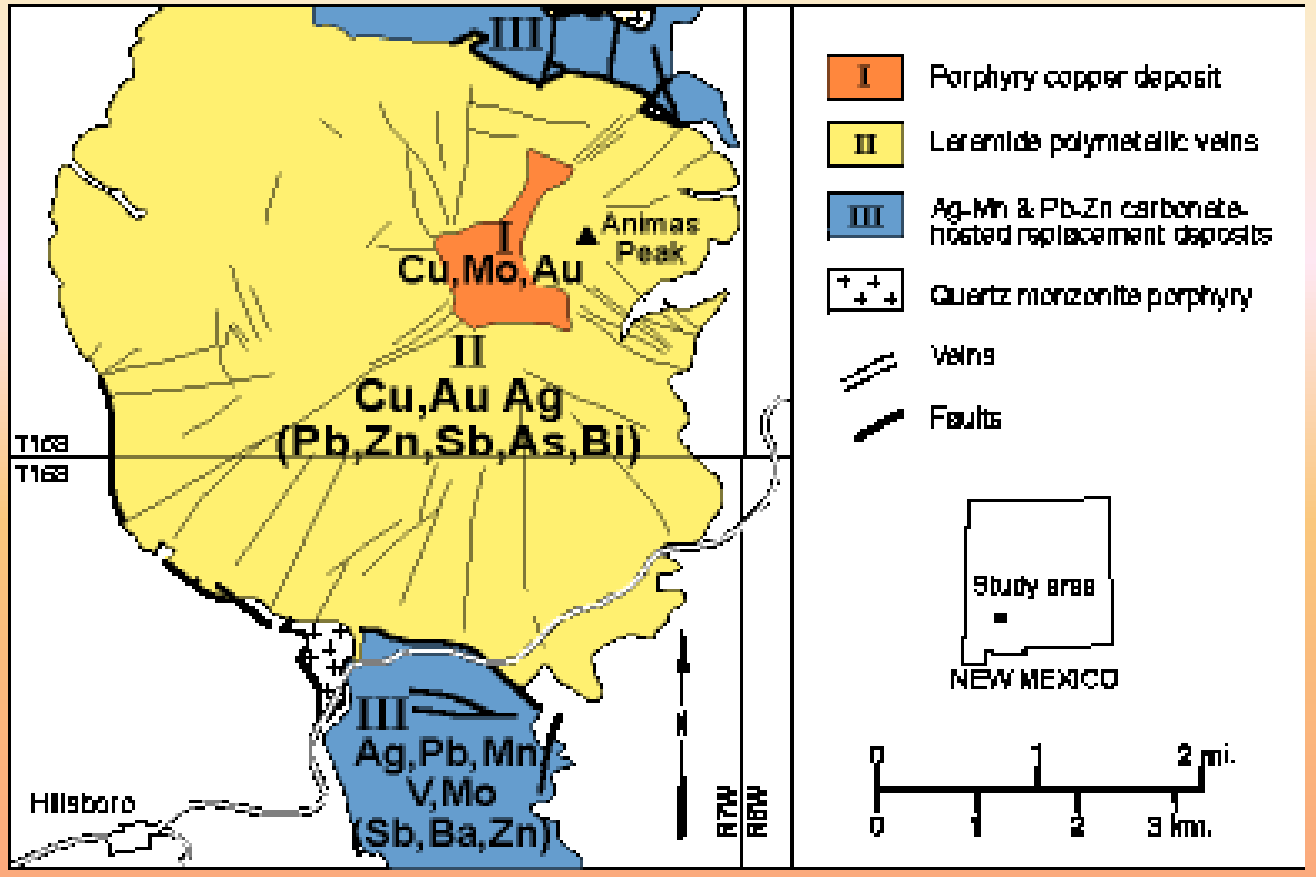


latite, quartz latite dikes
mineralized quartz monzonite
quartz monzonite
andesite



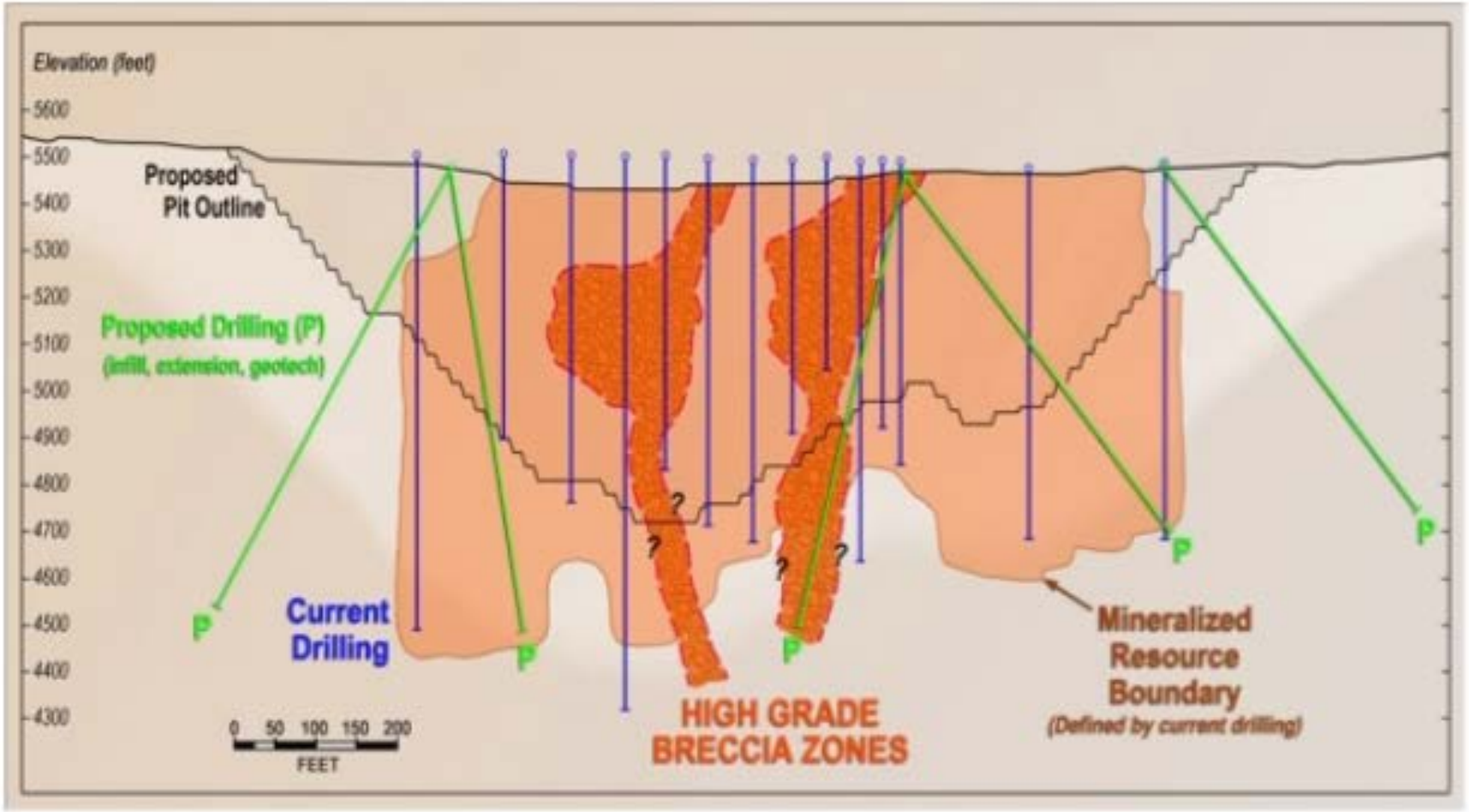


latite, quartz latite dikes
mineralized quartz monzonite
quartz monzonite
andesite



DISTRICT ZONING

- I—porphyry-copper deposit forms the center of mineralization (Cu, Mo, Au)
- II—propagating outward radially from the Copper Flat quartz monzonite are Laramide Au-Ag-Cu veins (Pb, Zn, Sb, As, and Bi) hosted by many of the latite and quartz latite dikes
- III—carbonate-hosted replacement deposits in the southern and northern parts of the district, distal from the center (Ag, Pb, Mn, V, Mo Sb, Ba, Zn)



Drilling on approximate 100-foot spacing has indicated internal continuity and consistency of grade

Chemistry

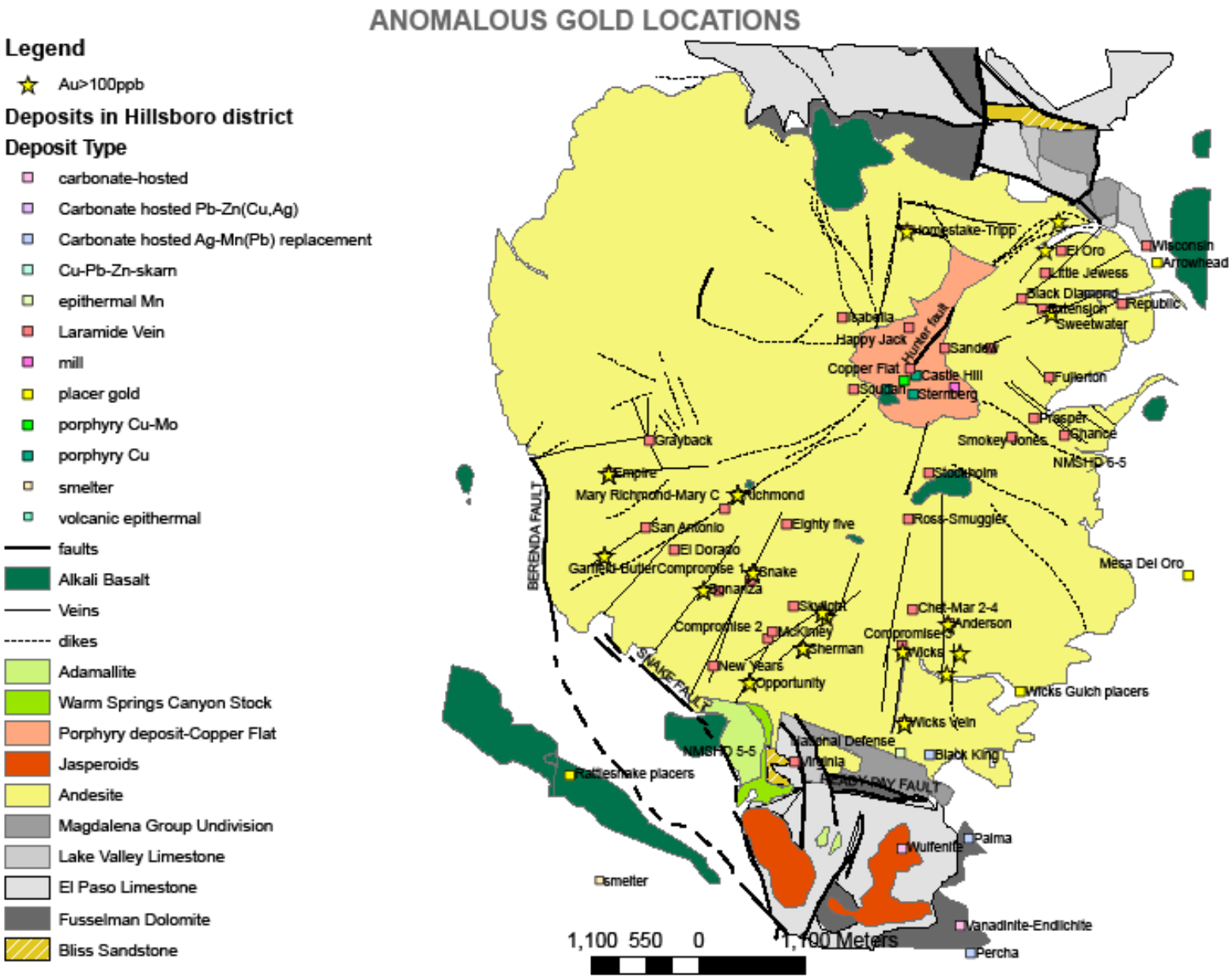
Laramide veins

- 8-64,600 ppb Au
- <0.2-590 ppm Ag
- 40-57,337 ppm Cu
- <1-475 ppm Mo
- 57-8906 ppm Pb
- 138-17,026 ppm Zn
- Recent drilling 40 ppm Te in veins

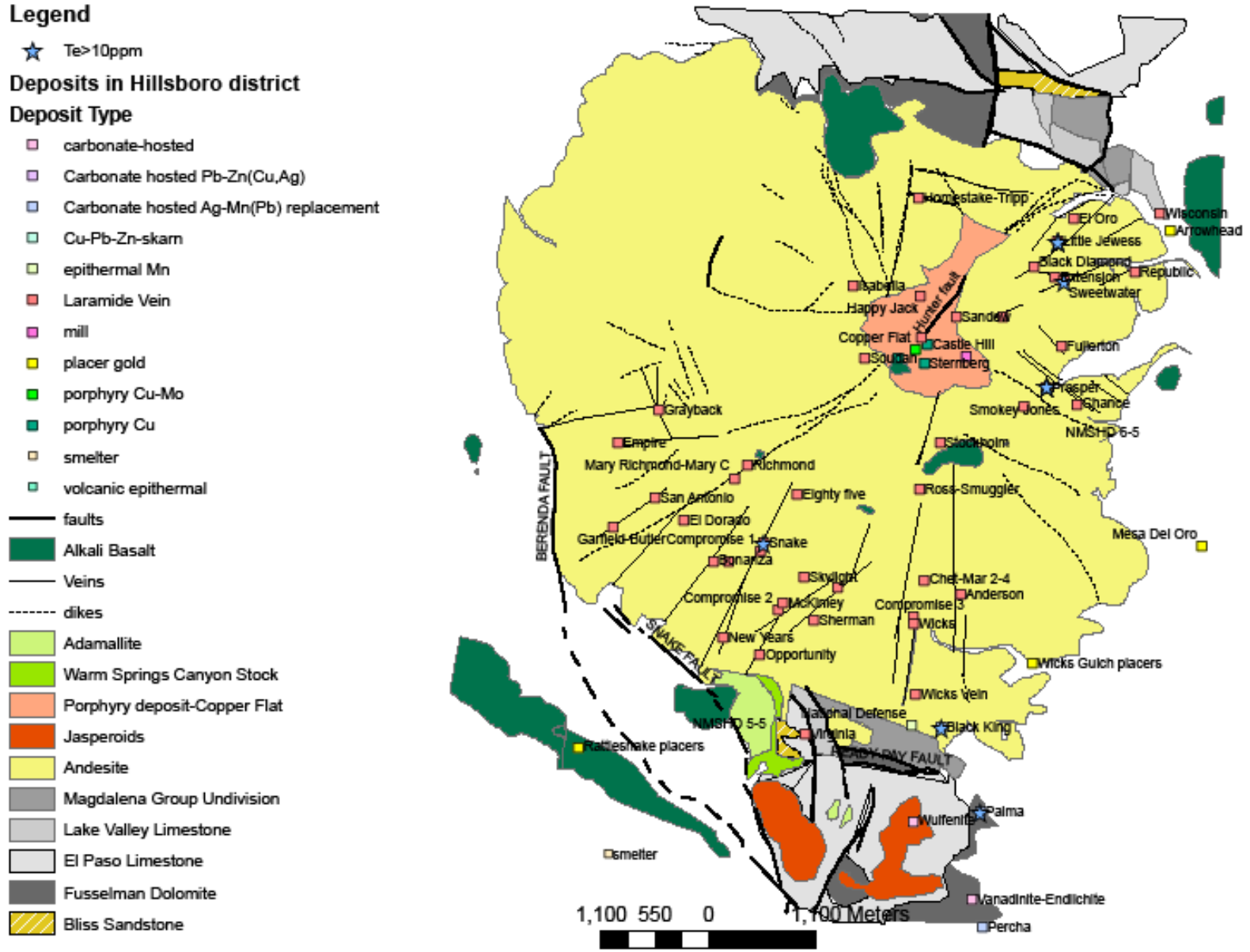
Carbonate-hosted replacement deposits

- <5-99 ppb Au
- 1-<50 ppm Ag
- 131-173 ppm Cu
- 2-140 ppm Mo
- 30->10,000 ppm Pb
- 123->20,000 ppm Zn
- <130 ppm Te
- <3400 ppm Bi

ANOMALOUS GOLD LOCATIONS

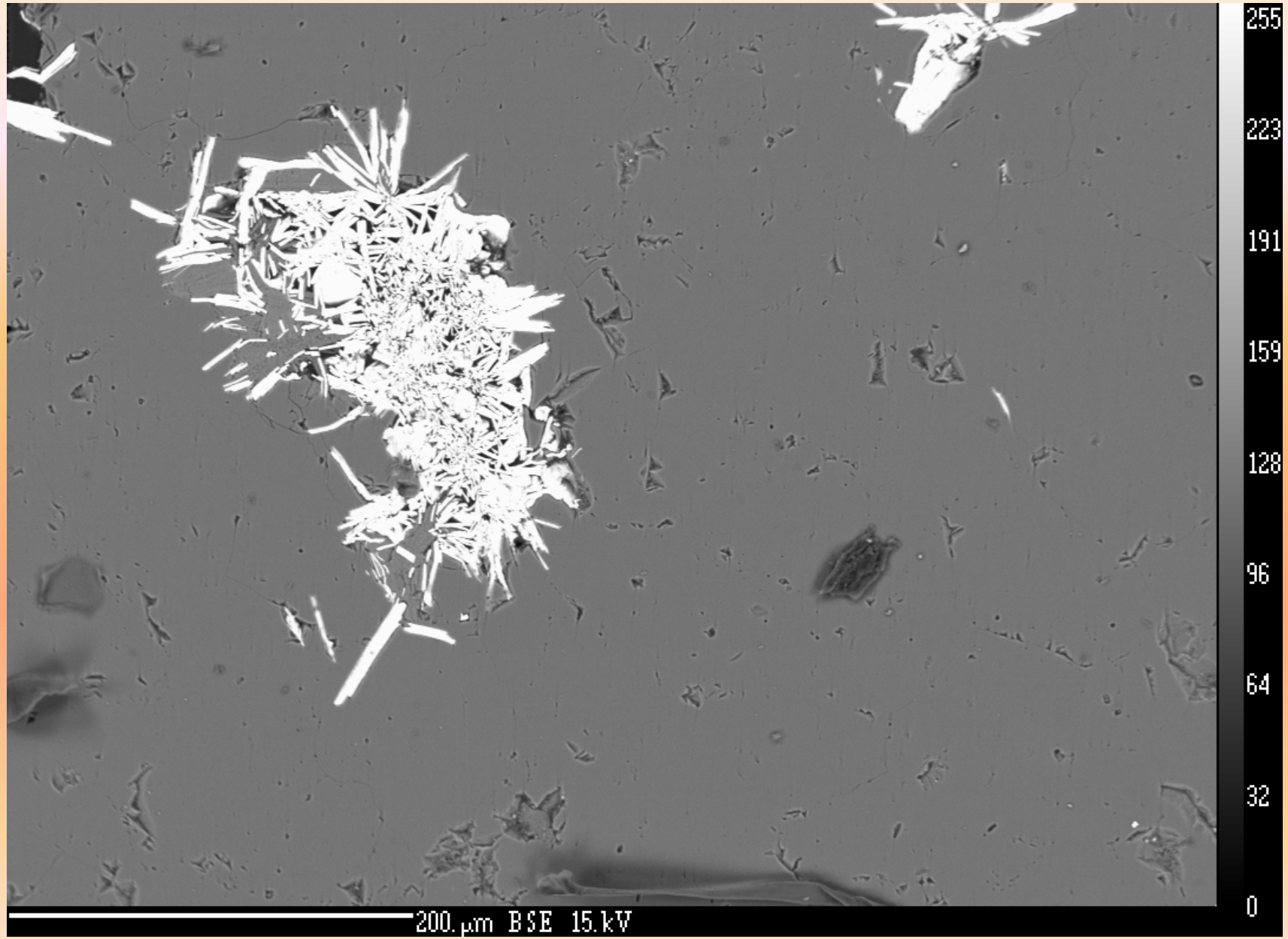


ANOMALOUS TELLURIUM LOCATIONS



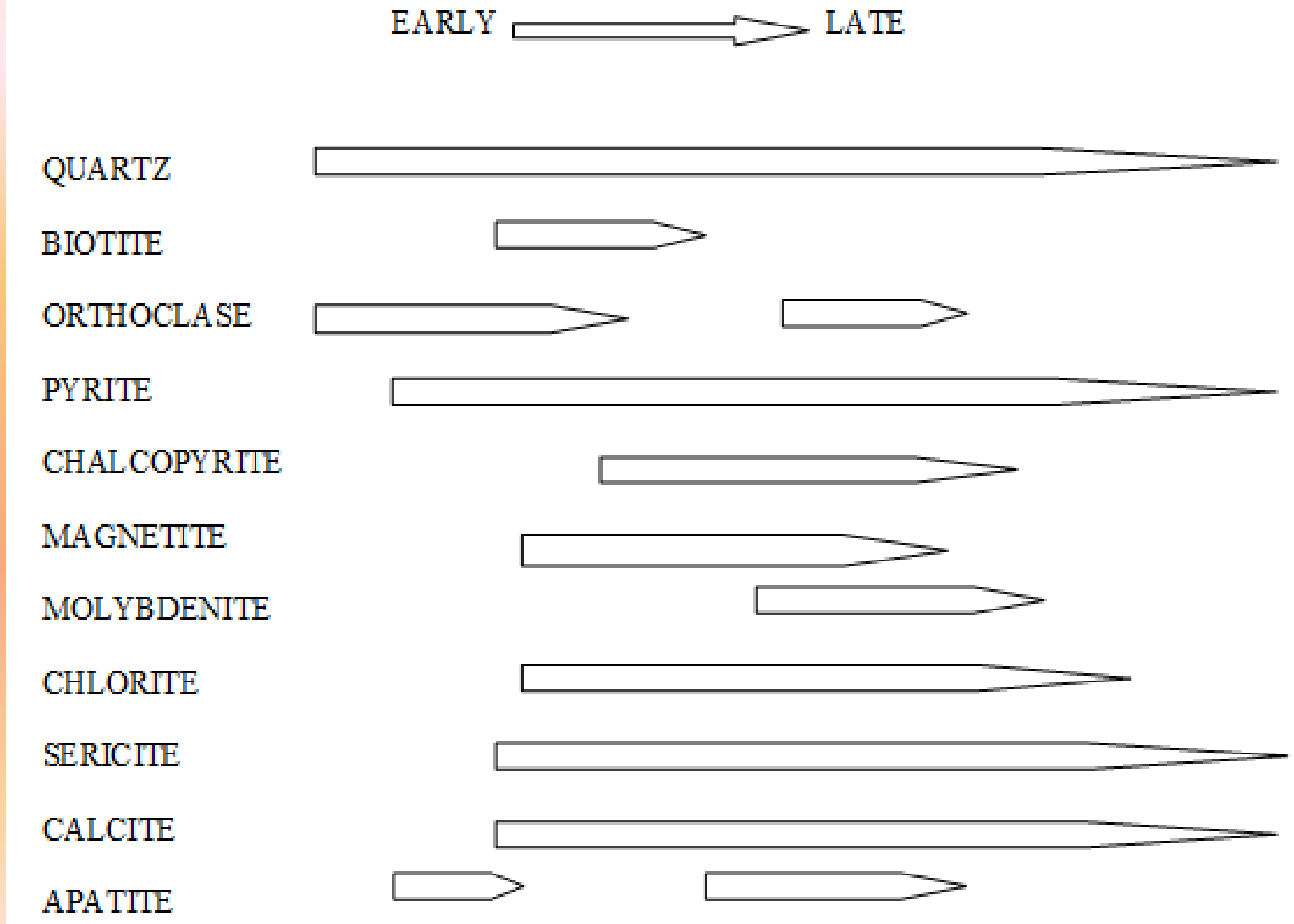
Microprobe studies

- Au and Ag were identified
- Au, Ag, and Mo are found in sulfides
- Molybdenite
- But Te, Se, Cd, Bi, and As are not detected



Back scattered image of molybdenite

MINERAL PARAGENITIC SEQUENCE



Sequence of Events

- Eruption of andesite volcano (75 Ma)
- **Intrusion of quartz monzonite porphyry and formation of breccia pipe deposit (75 Ma)**
- Latite and quartz latite dikes (70-75 Ma)
- Formation of jasperoids (35-75 Ma)
- Burial? or possibly minor erosion? (35-75? Ma)
- Eruption of Sugarlump and Kneeling Nun Tuffs (Emory caldera) (35-34 Ma)
- Uplift of the Copper Flat volcanic/intrusive complex followed by erosion (21-22 Ma)
- Eruption of alkali basalt (4 Ma)

Summary

- Need more work to determine where Te resides

Te-rich **ferromanganese crusts**

- Hydrogenetic ferromanganese oxyhydroxide crusts (Fe-Mn crusts) precipitate out of cold ambient ocean water onto hard-rock surfaces (seamounts, plateaus, ridges) at water depths of about 400 to 4000 m throughout the ocean basins

Areas of Major Potential in the US

- Ducktown, TN (**Massive Sulfides**)
- Leadville, CO (**Massive Sulfides**)
- Joplin, MO (**Massive Sulfides**)
- WV, IL, IN (High-Sulfur Coal Waste Dumps)
- Hydrothermal Deposits (CA, NV, CO, NM, …)

- **Note: World's best may be mountainous Cu-slag heaps on Cyprus (*e.g.*, Troodos)**

ECONOMICS Te

Exploration methods

- Gravimetric
  - Many are surrounded by mafic alkaline rocks (gravity high) or sedimentary rocks (gravity low)
- Geochemical
- Drilling, trenching

Exploration methods

- The Au-Ag-Te and the Te-Bi mineral assemblages may be an indicator for the size of the ore deposit.
- When Au occurs exclusively as tellurides (calaverite or Au-Ag tellurides (sylvanite, krennerite) at the intrusion outskirts, as in the case of Au-Ag Emperor Mine, calaverite precipitates in fissures on the margins of the igneous body, followed by later Au-Ag tellurides.

Exploration methods

- The economic feasibility is also indicated by the Bi and Te content; for instance, when such contents are around or below 10 ppm, the mineralization is economically uninteresting.
- When concentrations span between 10 and 300 ppm, the ore deposit is economic, subject to the reserves and mining capacity.
- Values over 300 ppm are economically interesting regardless of mining capacity.

Exploration methods

- The zoning of Te-Bi ore deposits is less known to many geologists.
- Two aspects of zoning should be underlined; one refers to the vertical zoning with respect to the intrusive bodies, as in the case of Larga ore deposit in Metaliferi Mts., where the Au-Te zone is located in the upper part, whereas the Te-Bi zone occurs at 1 km in depth, marginal to the intrusive body. In Henan province, China, the Au-Te mineralization lies between 2 and 10 km lateral to the intrusive body.

Mining

- Underground
- Porphyry copper deposits are open pit

Production Necessities

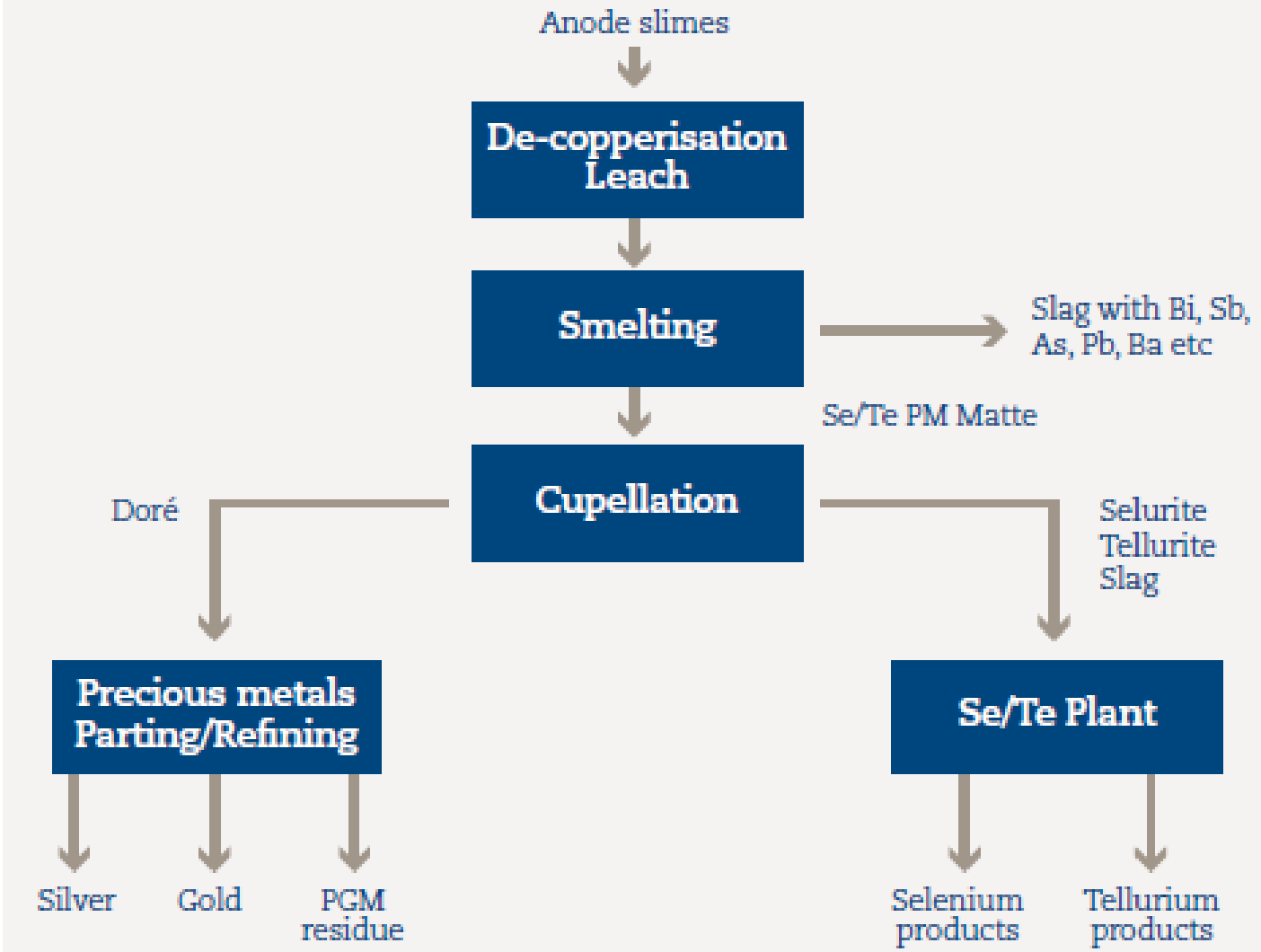
- Existence of desired commodities in economic concentrations, etc.
- Logistics (roads, electrical, water, labor, …)
- Availability of properties for mining
- Financing
- Permitting (regulations & legalities)
- **An assured long-term market**

PROCESSING

PROCESSING

- Electrolytic Copper Refining-Anode Slime Processing
- Lead Refining-Soda Slag Processing
- Platinum Group Metals Refining - Nickel/Copper Leaching
- Gold Milling-Gold/Telluride Processing

Tellerium from copper anode slimes



Source: Ullman & Bohnet (2012)

Substitutions

- Se, Bi, Pb can substitute in some metallurgical uses
- Se, S can substitute in rubber

Environmental issues

- No case histories
- Pyrite is generally presence=acid drainage potential
- If U and Th are present=radioactive wastes

Economic risks

- Less than 1 in 10,000 deposits become mines
- Estimated 1 in 2,000 or 3,000 prospects become mines
- Ore processing is very deposit specific because of the mineralogy

Recommendations

- Detailed geochemical analyses of all potential Te deposits to find out where Te resides
- Develop specific geologic models on how tellurium deposits form and how to explore for them
- Continue research on mineralized areas and mine/smelter waste dumps, etc., to enable generation of reasonable supply/demand data

ASSIGNMENT

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