Tellurium Resources in New Mexico

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Abstract

Tellurium (Te) is one of the least abundant elements in the crust and tends to form minerals associated with gold, silver, bismuth, copper, lead, and zinc sulfide deposits. There are no primary tellurium mines in the world; most tellurium production comes from the anode slimes generated in metal refining, primarily from copper porphyry deposits. Tellurium is used as an alloying agent in iron and steel, as catalysts, and in the chemical industry. However, future demand and production could increase because tellurium is progressively used in thin film cadmium-tellurium solar panels and some electronic devices. In New Mexico, anomalous amounts of tellurium are found associated with porphyry copper deposits, as well as with gold-silver vein deposits, but were not considered important exploration targets in the past. The only tellurium production from New Mexico has been from the Lone Pine deposit (Wilcox district) in the Mogollon Mountains, where approximately 5 tons of tellurium ore were produced. Gold-tellurides are found with gold, silver, pyrite, and fluorite in fracture-filling veins in rhyolite at Lone Pine, with reported assays as much as 5,000 ppm Te. Tellurium-bearing deposits also are found in the Organ Mountains, Sylvanite, Tierra Blanca, Grandview Canyon, and Hillsboro districts. Additional detailed sampling and geologic mapping are required of the New Mexico deposits to fully understand the mineralogy and economic potential of tellurium.

Introduction

Tellurium (Te) is a metal of rapidly-growing importance because of its use as a semiconductor. Having an atomic number of 52 and atomic weight of 127.6, tellurium is one of the least abundant elements in the crust. The average concentration of tellurium in the crust is 5 ppb (parts per billion) (Ayres et al., 2003; Li and Schoonmaker, 2003). Most rocks contain less than 3 ppb Te (Goldfarb, 2014). Tellurium is a chalcophile element found in a variety of mineral deposit types. It tends to form minerals associated with gold, silver, bismuth, copper, lead, and zinc sulfide deposits. There are no primary tellurium mines in the world; most tellurium is recovered as a byproduct of milling and refining of copper and other base-metal deposits (Goldfarb et al., 2016). Generally, the anode slimes are received by a separate refinery and come from many different types of mineral deposits, therefore it is impossible to identify the specific mineral deposits from which the tellurium came from (Goldfarb et al., 2016). It is estimated that concentrations of 1–4% Te can be recovered from refining of copper porphyry deposits (Goldfarb, 2014; Goldfarb et al., 2016).

Currently, the primary producers of tellurium are Russia, Peru, Canada, and Japan (Table 1). Other countries besides the United States (U.S.) producing tellurium include Australia, Belgium, Chile, China, Colombia, Germany, Mexico, the Philippines, Poland, and Kazakhstan (U.S. Geological Survey, 2012). The world production of tellurium is estimated as 450–1,000 metric tons per year (Naumov, 2010; The tellurium supply conjecture and the future of First Solar, **http://seekingalpha.com/instablog/65370-jack-lifton/12427-the-tellurium-supply-conjecture-and-the-future-of-first-solar** (accessed on 11/12/15). Total world tellurium reserves are estimated as 24,000 metric tons (U.S. Geological Survey, 2012).

Tellurium has many industrial uses, primarily as an alloying agent and catalyst (U.S. Geological Survey, 2010, 2012). The predominant use of tellurium (approximately 50% of the current production) is for alloying agents in iron and steel to improve machinability; for example, tellurium was used in the construction of the outer shell of the first atom bomb. Secondary uses include catalysts and other chemical uses (25% of production) and in alloying with non-ferrous metals like copper and lead (10% of production). Approximately 8% of tellurium production is used in electronic applications and the remaining 7% is used in other applications. Tellurium is used in rewritable optical discs (CDs, DVDs, and Blu-ray) and for the generation of a type of random access memory (RAM) known as PRAM. Additional uses of tellurium include ingredients in blasting caps, pigments to produce various colors in glass and ceramics, fiber optics, refrigeration technologies, copying machines, air conditioning, and heat-resistant rubber.

Future demand and production could increase because tellurium also is used in thin-film cadmium-tellurium (CdTe) photovoltaics (TFPVs) in solar panels (Committee on Critical Mineral Impacts of the U.S. Economy, 2008; Goldfarb, 2014). The TFPVs in solar panels convert sunlight directly to electricity using thin films of semiconductors. The thin films are 3–300 microns and approximately 8 grams of tellurium are used per solar panel, or approximately 696.8 kg of tellurium for 10 MW of power production (Solar energy limits—Possible constraints in tellurium production? (**http://greenecon.net/solar-energy-limits-possible-constraints-in-tellurium-production/solar-stocks.html**, accessed 11/12/15). In 2008, CdTe TFPVs accounted for approximately 8% of the 7 gigawatt global TFPV market (U.S. Department of Energy, 2010). China flooded the solar panel market with silicon solar panels during 2009–2012, resulting in a decrease in demand for the higher-cost, but more efficient, TFPV. New tariffs may reverse this impact. As a measure of the growing importance of tellurium, the average price in 2000 was approximately $14/lb for 99.5% purity (Brown, 2000). In 2011 the price of tellurium averaged $349/kg (Table 1) and in 2015 it averaged $177/kg. Although the average price decreased in 2013–2014 (Table 1), like many other commodities, the long-term prediction is for future increase in prices as the demand increases.

Although tellurium-bearing minerals have been described from many well-known generic ore deposit types, there is very little reliable information about

TABLE 1. World refinery production, reserves, and prices of tellurium.

Year/ Country	2004 (kg)	2006 (kg)	2008 (kg)	2009 (kg)	2010 (kg)	2011 (kg)	2012 (kg)	2013 (kg)	2014 (kg)	Reserves (metric tons)
Canada	55,000	10,000	19,000	16,000	8,000	6,000	11,000	12,000	12,000	800
Japan	33,000	35,000	46,500	49,200	47,000	40,000	45,000	48,000	45,000	W
Peru	22,000	33,000	28,000	7,000	—	—	—	—	—	3,600
Russia	—	—	34,000	34,000	34,000	34,000	35,000	35,000	40,000	W
United States	W	W	W	W	W	W	W	W	W	3,500
Price*	22.50	89	175	130	221.25	349.35	149.66	111.95	117	

Data compiled from: George (2009, 2012); U.S. Geological Survey (2010, 2012); Anderson (2015). W=withdrawn. — no data. Naumov (2010) estimates the U.S. production of tellurium as 50 metric tons/yr.
*Dollars per kilogram, 99.95% minimum.

specific tellurium mineral deposits and, therefore, there have not been specific geologic mineral deposit models developed on how tellurium deposits form or how to explore for them (Cook et al., 2009; Goldfarb et al., 2016). One of the first steps in this process is to compile and describe known tellurium deposits in the world, including in New Mexico.

Tellurium-bearing deposits have been reported from New Mexico, but were not considered important exploration targets in the past because the demand for tellurium in the U.S. historically has been met by deposits elsewhere in the world or as a by-product from domestic copper refining. However, given that the price of tellurium has increased dramatically over the last decade and tellurium will be required to manufacture solar panels, this element might be economically significant in the near future. After a brief review of worldwide tellurium sources, this article will summarize the known occurrences of tellurium in New Mexico and their associated geologic/mineralogical setting. This article is updated from a previous SME preprint (McLemore, 2013). Note that metal names are abbreviated following the periodic table when reporting assay or production figures. Historic and recent production and reserve/resource data are reported in metric or English units, according to the original publication, in order to avoid conversion errors.

Methods of Study

Data used in this report have been compiled from a literature review, field examinations, and unpublished analyses by the author. Limited new field investigation occurred in some areas. A summary of the mining districts in New Mexico containing known tellurium-bearing deposits and relevant references are listed in Appendix 1. Tellurium found in mining districts, mines, and other spatial data in New Mexico were plotted using GIS (Geologic Information System) ArcMap and are shown in Figure 1. For the purposes of this report, the districts in Appendix 1 and Figure 1 are reported to have tellurium-bearing minerals or have samples that assayed more than 20 ppm Te.

Summary of tellurium sources outside of New Mexico

The predominant worldwide source of tellurium today is from anode slimes or sludges that are recovered from processing of copper and lead ores, which are shipped after milling to a separate refinery (Goldfarb et al., 2016). So the geology of copper- and lead-bearing mineral deposits is important to consider in developing specific geologic models of tellurium deposits. It takes approximately 454 metric tons (500 short tons) of copper ore to produce 454 grams (1 pound) of tellurium (Goldfarb et al., 2016). Tellurium concentrations in porphyry copper deposits vary widely and can be as high as 6,000 ppm Te (Table 2), but are typically less than 1 ppm Te (Cox et al., 1995; Yano et al., 2013). The anode slimes remaining from copper refining can contain as much as 2% Te (George, 2012). The ASARCO LLC copper refinery in Amarillo, Texas was the only U.S. producer of refined tellurium between 2011 and 2015 (George, 2012; Anderson, 2015). Tellurium is recovered only from conventional milling and refining of porphyry copper deposits. It is not recovered from porphyry copper deposits that are processed using heap leaching methods because of low concentrations (Goldfarb et al., 2016). A potential problem in the future production of tellurium as a by-product will be the increasing shift of copper production from conventional milling and refining to lower-cost heap leaching and recycling.

Although, tellurium can be found as a native metal, it is more commonly found in more than 40 minerals, many of which are telluride minerals (Cook et al., 2009; Goldfarb et al., 2016). Tellurium is one of the few elements that can form a variety of minerals with gold (e.g. calaverite ($AuTe_2$), krennerite ($(AuAg)Te_2$), petzite (Ag_3AuTe_2) and sylvanite ($AgAuTe_4$)), typically in mineral deposits where gold is the principal economic component. These telluride minerals have been known for centuries and have long been reported in world-class precious metal deposits such as Cripple Creek (Colorado), Emperor (Fiji), Golden Mile (Australia) and Săcărîmb (Romania). Non-auriferous common telluride minerals include hessite

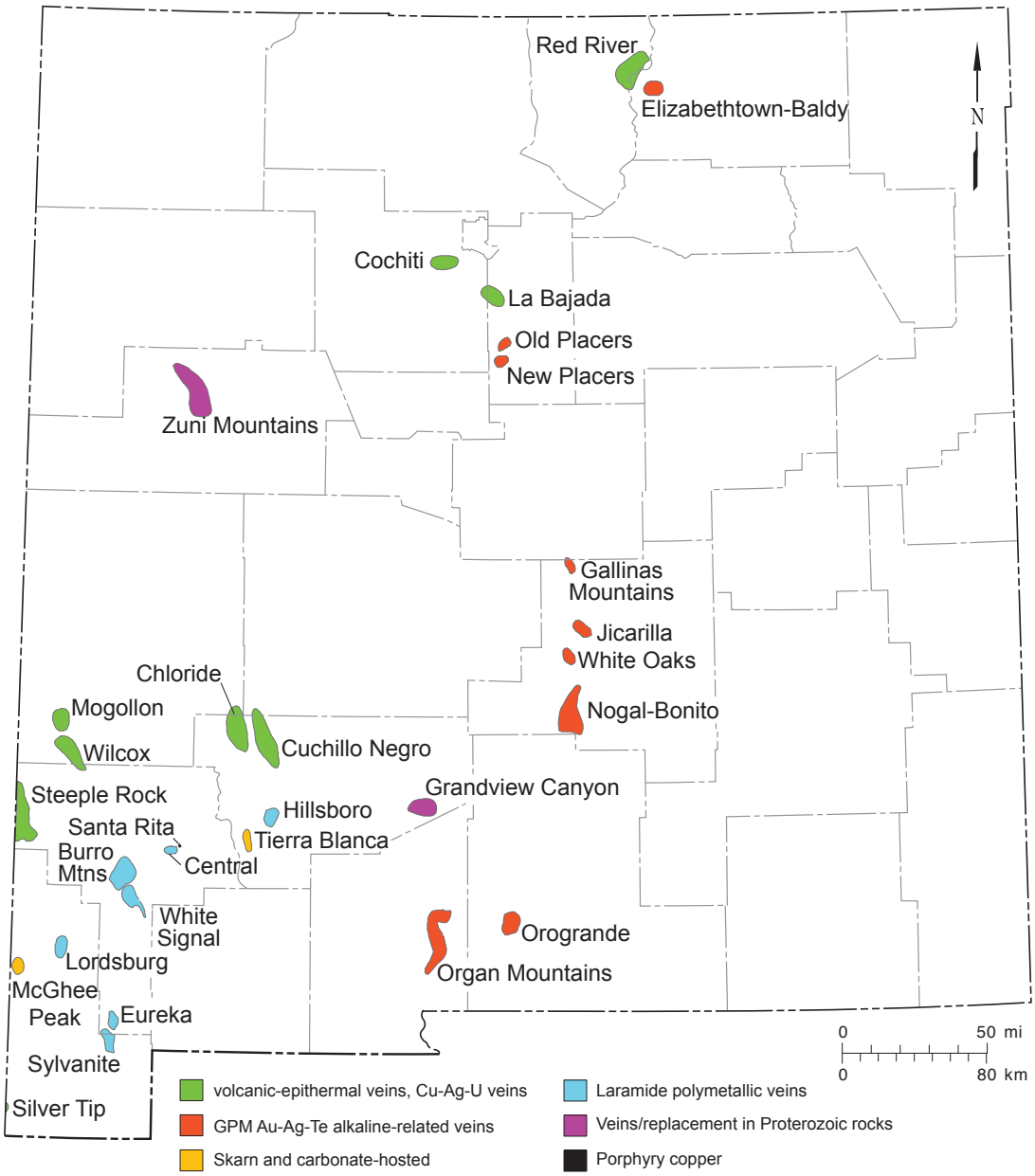

FIGURE 1. Mining districts in New Mexico with reported tellurium-bearing minerals or with more than 20 ppm Te in analyzed samples (Appendix 1). County boundaries shown as gray lines. GPM=Great Plains Margin.

(Ag_2Te), tellurobismuthite ($BiTe_3$), tetradymite (Bi_2Te_2S), and altaite (PbTe). Tellurium is found in many gold-silver vein deposits (Cook et al., 2009), but the amount of tellurium is generally so low (Table 2) that the deposits, although economic for gold and silver, historically have not been economic for by-product tellurium; this could change with the growing demand for tellurium.

A well-known telluride deposit in the U.S. is Cripple Creek (Colorado), but the tellurium concentration there is not sufficient for production even as a by-product in gold mining. The Cripple Creek mining district is the largest gold district in Colorado and is hosted within a Tertiary diatreme complex (Kelley and Luddington, 2002). Gold is found within thin quartz±fluorite veins with abundant tellurium-bearing minerals. The Cressen mine, operated by the Cripple Creek and Victor Gold Mining Company (now owned by Newmont Mining Company) is currently producing gold but not tellurium (Cripple Creek and Victor Gold Mining Company, **http://www.ccvgoldmining.com/ccv-modernmining.html**, accessed on 11/11/15).

Outside of the U.S., only a few mines produce tellurium as a direct by-product of their gold production. The Kankberg gold mine in northern Sweden is operated by Boliden, and grades 4.1 g/metric ton (0.14 oz/ton) Au and 186 g/metric ton (6.5 oz/ton) Te (**http://www.boliden.com/Documents/Press/Presentations/Kankberg.pdf**, accessed on 11/11/15). Kankberg began production in 2012 and produces approximately 10% of the world's tellurium (Goldfarb et al., 2016).

Apollo Solar Energy, Inc., began developing two tellurium mines in Chengdu, located in the Sichuan Province in China. The Dashuigou mine contains an estimated 30,200 metric tons of ore (indicated and inferred) grading 1.09% Te, and the Majiagou mine

TABLE 2. Ranges in concentration of tellurium in selected mineral deposits

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

Data compiled from: Everett (1964), Boyle (1979), and Cox et al. (1995)

contains an estimated 13,400 metric tons of ore (indicated and inferred) grading 3.26% Te (**http://www.prnewswire.com/news-releases/apollo-solar-announces-results-of-independent-technical-review-of-dashuigou-and-majiagou-tellurium-projects-61824367.html**, accessed on 11/11/15). Telluride minerals were deposited in the second of three stages of vein mineralization and concentrations of grab samples range from 0.2 to 5% Te (Mao, 1995; Mao et al., 2002). The Dashuigou and Majiagou mines produce approximately 2–7% of the world's tellurium (Goldfarb et al., 2016). Many other gold deposits in China also contain significant concentrations of tellurium (Cook et al., 2009; Goldfarb et al., 2016).

Tellurium-bearing deposits are found elsewhere in the world. Deer Horn Metals estimated the indicated mineral resources at the Deer Horn gold-silver-tellurium deposit, in British Columbia, as 414,000 metric tons of 5.12 g/metric ton Au, 157.5 g/metric ton Ag and 160 ppm Te (Lane and Giroux, 2012). This deposit is still in the feasibility stage. Another exploration target is the La Bambolla mine in Moctezuma, Sonora, Mexico. Here, as much as 0.37 oz/short ton Au (11.6 g/metric ton) and 0.15% Te are found in quartz veins that are 1–2 m wide (Everett, 1964).

Tellurides also may be found in placer gold deposits. Because the tellurium-bearing minerals are generally resistant to weathering and relatively heavy, they will remain with the gold during formation of placer gold deposits (Boyle, 1979). However, there are no known economic targets for tellurium in placer gold deposits yet; this is an area of future research.

Types of Tellurium-bearing deposits in New Mexico

In developing a geologic model for tellurium-bearing deposits using New Mexico deposits as examples, one must be cognizant of the main types of mineral deposits in this state. Six general types of mineral deposits are summarized below, which also are plotted on Figure 1. Specific examples of mines and mineral districts that contain tellurium are briefly discussed in the following section. Supporting data regarding minerals and geology are compiled from deposits listed in Appendix 1, and more details on specific mineral deposit types are found in Lindgren (1933), Cox and Singer (1986), McLemore (1996a, b, 2001, 2016), and McLemore et al. (1996, 2005a).

Great Plains vein deposits

In eastern New Mexico, 46–19 Ma alkaline to subalkaline igneous rocks are found along a north-south belt roughly coinciding with the Great Plains physiographic margin with the Basin and Range (Rio Grande rift) and Rocky Mountains physiographic provinces. Associated deposits are termed Great Plains Margin (GPM) deposits by North and McLemore (1988) and McLemore (1996a, 2001, 2015) (Fig. 1). Great Plain Margin vein deposits are also known as Au-Ag-Te alkaline-related veins (Cox and Bagby, 1986; Bliss et al., 1992; Kelley, 1995; Kelley and Ludington, 2002; Kelley et al., 1995, 1998), alkalic-gold or alkaline-igneous related gold deposits (Fulp and Woodward, 1991; Mutschler et al., 1985, 1991), and gold-telluride deposits (Kelley et al., 1998). They are part of the North American Cordilleran belt of alkaline igneous rocks (Mutschler et al., 1991). GPM deposits contain gold as the predominant economic commodity, but locally contain anomalous concentrations of silver, copper, lead, zinc, tungsten, and tellurium. These deposits also are characterized by anomalous amounts of iron, molybdenum, fluorite, uranium, thorium, rare-earth elements, and niobium. GPM veins in New Mexico have high gold/base metal ratios and typically low silver/gold ratios (North and McLemore, 1988; Kelley et al., 1995; McLemore, 1996a, 2015). Native gold and a variety of silver minerals are found in the veins in most districts along with chalcopyrite, galena, sphalerite, and locally tungsten- and tellurium-bearing minerals. Pyrite, calcite, quartz, iron and manganese oxides, and clay minerals are common gangue minerals. Veins are hosted by both the Tertiary intrusions and surrounding sedimentary rocks. Veins are typically less than a 1 m wide, have steep dips, and occur along faults. Wall-rock alteration is typically weak propylitic to argillic (Douglass and Campbell, 1995; McLemore, 1996a, 2001, 2015). New Mexico GPM veins are similar to gold-telluride veins found in Cripple Creek, Colorado (Kelley et al., 1998; Kelley and Luddington, 2002). Although tellurides are common in many of the GPM veins in New Mexico, only a few districts have been examined in detail to determine their tellurium resource potential.

Volcanic-epithermal vein deposits

Volcanic-epithermal vein deposits in New Mexico, like elsewhere in the world, are found in structurally complex tectonic settings that provide an ideal plumbing system for circulation of hydrothermal fluids. Lindgren (1933) defined the term "epithermal" to include a broad range of deposits that formed by ascending waters at shallow to moderate depths (less than 1,500 m), low to moderate temperatures (50°–200°C), and which are typically associated with intrusive and/or volcanic rocks. It is now generally accepted that epithermal deposits were formed at slightly higher temperatures (50°–300°C) and relatively low pressures (a few hundred bars) based on fluid inclusion and stable isotope data (Simmons et al., 2005). Many volcanic-epithermal vein deposits in New Mexico occur along the margins of calderas, although other structurally complex volcanic settings, such as silicic domes and andesitic stratovolcanoes, are not uncommon for these deposits (Elston, 1978; 1994; Rytuba, 1981; McLemore, 1996b, 2001). Tellurium-bearing

minerals locally are found with gold and silver in some of these veins. Typically the volcanic-epithermal deposits in the state occur as siliceous vein fillings, breccia pipes, disseminations, and replacement deposits. Both gold and silver are commonly produced from these deposits with variable amounts of base-metal production. Other commodities produced from some deposits include fluorite, uranium, REE, and vanadium.

Skarns and carbonate-hosted deposits

Skarn deposits enriched in copper and other metals form near the contact between intrusions and carbonate-bearing rocks, such as limestone and dolomite. Skarn is a term for rocks that have similar mineral assemblages but potentially diverse origins. Typical skarn mineral assemblages include calcium-bearing varieties of garnet and pyroxene (Einaudi et al., 1981; Einaudi and Burt, 1982; McLemore and Lueth, 1996; Meinert et al., 2005). Whereas these types of deposits can form in a number of geological environments, they are most common in the southwestern U.S. in contact-metamorphic aureoles where hot igneous rocks have intruded calcareous country rocks (Einaudi, 1982). Hydrothermal fluids that exsolve from the igneous melt metasomatize the calcareous country rocks, converting them to mineral assemblages dominated by garnet and pyroxene. Magnetite and additional calc-silicate minerals also are commonly present, especially in magnesium-rich (dolomitic) host rocks. Three major types of skarns associated with calc-alkaline igneous rocks occur in southern New Mexico that contain tellurium-bearing minerals: copper skarns that typically are associated with porphyry copper deposits (Einaudi et al., 1981; Einaudi, 1982; Lueth, 1984, 1998), lead/zinc skarns that occur both proximal to intrusions and as more distal vein-type deposits (Meinert, 1987; Turner and Bowman, 1993; Lueth, 1998), and iron skarns (Lueth, 1984, 1998). Minor skarns and carbonate-hosted deposits also are associated with the GPM deposits associated with alkaline igneous intrusions.

Carbonate-hosted lead-zinc and silver-manganese replacement deposits in southwestern New Mexico were formed at about 40–20 Ma and include replacement bodies in carbonate rocks with small skarns and veins (McLemore and Lueth, 1996). They tend to be distally associated with calc-alkaline igneous rocks. These replacement deposits are typically lead-zinc or manganese-silver dominant, and also can contain by-products of copper, silver, and gold. Calc-silicate minerals typical of skarn deposits are rare to absent in most of these deposits, and, if present, they do not display typical skarn-type mineral zonation. Galena and sphalerite are the predominant ore minerals with lesser amounts of chalcopyrite and silver-bearing minerals. Many carbonate-hosted deposits found in New Mexico contain cerussite, anglesite, smithsonite, and manganese-rich minerals. The host rocks are predominantly Paleozoic carbonate rocks, with a few smaller deposits in Cretaceous carbonate rocks. Tellurium-bearing minerals are generally associated with pyrite in both the skarn and carbonate-hosted replacement deposits (V.T. McLemore, personal observations).

Laramide polymetallic veins

Laramide-age polymetallic veins generally consist of quartz, pyrite, clay, iron oxides, barite, free gold, copper sulfides, galena, and additional minor minerals (North and McLemore, 1988; McLemore, 2001). Some veins are as much as 1,500 m long and 0.8–3.0 m wide. They are typically en echelon and pinch and swell. The veins locally are associated with an alteration zone of sericite and pyrite with little or no concentrations of metals. The polymetallic vein deposits are locally associated with porphyry copper and/or skarn deposits near intrusions. The veins vary tremendously in chemical composition, but are typically enriched in gold, silver, copper, arsenic, bismuth, lead, zinc, antimony, and tellurium.

Vein and replacement deposits in Proterozoic rocks

Vein and replacement deposits containing base and precious metals occur sporadically throughout much of the Proterozoic terranes in New Mexico. Many of these deposits are structurally controlled by schistosity or shear zones of Proterozoic age and are, therefore, syn- or post-metamorphic (Zuni Mountains, Grandview Canyon; McLemore, 2001, 2013). In many districts, there is a strong spatial association of precious-metal-bearing veins with diabase or mafic dikes of presumed Late Proterozoic age. Tellurium-bearing minerals are locally associated with these deposits in New Mexico. Most of the precious-metal deposits in Proterozoic terranes are uneconomic because of small size and low grade, or are in areas that are withdrawn from mineral entry.

Porphyry copper (±molybdenum, gold) deposits

Porphyry copper (±molybdenum, gold) deposits are large, low-grade (less than 0.8% Cu) deposits associated with porphyritic intrusions generated by subduction magmatism at volcanic arcs. Copper and molybdenum sulfides precipitated within or around these intrusions are disseminated in the host rock or are in hydrothermal veins, breccias or stockwork veinlets (Schmitt, 1966; Kesler, 1973; Lowell, 1974; Titley and Beane, 1981; Cox and Singer, 1986; Cox et al., 1995; McLemore, 2001; Seedorff et al., 2005). These copper deposits typically are located in and surrounding relatively small porphyritic diorite, granodiorite, monzonite, and quartz monzonite plutons in New Mexico. These plutons were intruded at relatively high crustal levels, commonly within 1–6 km of the surface, and are surrounded by crudely concentric zones of hydrothermal alteration (Seedorff et al., 2005). Released hydrothermal solutions flow through fractures and react with the host rocks, altering them in a characteristic, concentric zonation. Tellurium is enriched in some porphyry copper deposits, but only in trace amounts (Yano et al., 2013). Recent SEM (scanning electron microscope) and LA-ICP-MS (Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry) studies by Yano et al. (2013) suggest that tellurium is found in micron-size inclusions within chalcopyrite or other copper minerals formed in porphyry copper deposits. As much as 220 ppm Te is found in tennantite at the Chupuicamata copper porphyry deposit in Chile (Yano et al., 2013). Similar detailed studies are needed for New Mexico porphyry copper deposits.

Descriptions of selected Tellerium deposits in New Mexico

Lone Pine, Wilcox district, Catron County

The Lone Pine deposit is in the Wilcox district in the Mogollon Mountains (Fig. 1), where 5 tons (4.54 metric tons) of tellurium were produced from gold-tellurium volcanic-epithermal veins (Davidson and Granger, 1965). Some of the first tellurium-bearing minerals recognized in New Mexico were reported from this deposit, including native tellurium (Ballmer, 1932; Gillerman, 1964; Ratté et al., 1979; Lueth et al., 1996, Lueth, this vol.). Indeed, Jones (1904) designated the Lone Pine area as the Tellurium mining district. McLemore et al. (1996) and McLemore (2001) included the area as part of the Wilcox district. At most areas in the district, primary mineralization occurs as fracture fillings and veinlets in silicified flow-banded rhyolite (V.T. McLemore, personal observations). Disseminated mineralization also is present in a large zone of silicified flow-banded rhyolite and silicified andesite (Fig. 2). Primary mineralization consists of pyrite, fluorite, native tellurium, molybdenite, and gold-tellurides. A vertical zonation is apparent, where pyrite is the stratigraphically lowest and grades upwards into a pyrite-tellurium assemblage, which in turn grades into a fluorite-rich zone at the highest elevations (Lueth et al., 1996). Tellurium concentrations are highest at the pyrite-fluorite transition zone. Selected samples assayed as much as 3,500 ppm Te (Ratté et al., 1979) to 5,000 ppm Te (New Mexico Bureau of Geology and Mineral Resources (NMBGMR), unpubl. data). Detailed geologic mapping of the mineralization and alteration along with mineralogical and geochemical studies are required of the deposit.

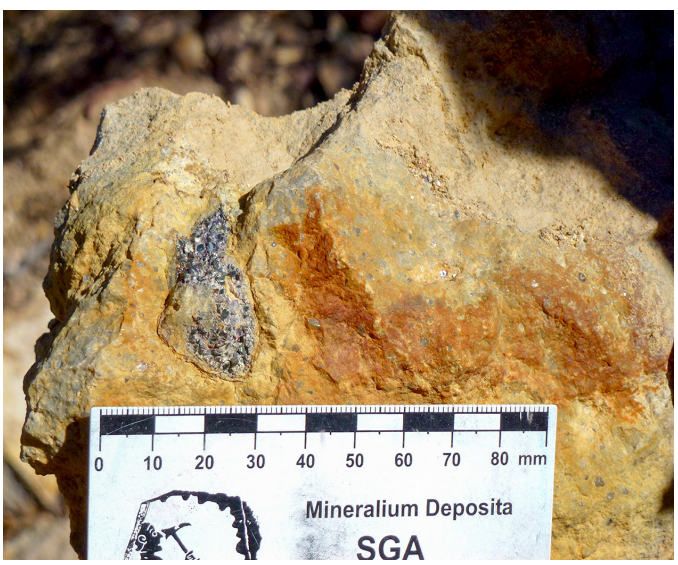

FIGURE 2. Tellurium-bearing pyrite in altered rhyolite, Lone Pine mine. V.T. McLemore photograph, 2013

Organ Mountains district, Doña Ana County

Metal production from GPM mineral deposits in the Organ Mountains district (Fig. 1) amounts to 4,636,000 lbs Cu, 11,500 oz Au, 820,000 oz Ag, 25,000,000 lbs Pb, and 1,700,000 lbs Zn (McLemore et al., 1996; McLemore, 2016). Major mines and metal zonation in and surrounding the 34.5 Ma Organ Mountain batholith (McLemore et al., 1995, 1996; Zimmerer and McIntosh, 2013) are illustrated in Figure 3. Three major mineral zones are associated with the Organ batholith: 1) a central zone (red, Fig. 3) with a copper-molybdenum porphyry deposit that is surrounded by 2) zinc-lead (orange, Fig. 3) and 3) lead-zinc veins and carbonate-hosted deposits (blue, Fig. 3). GPM gold-silver and fluorite-barite veins surround and overlap the outer parts of the base-metal zones (Fig. 3; Lueth and McLemore, 1998; Lueth, 1998). Discrete tellurium-bearing minerals are found at several mines in the district (Appendix 1. Lueth, this vol.). Samples collected from selected carbonate-replacement and skarn deposits in the district range from less than 0.1 to 160 ppm Te (McLemore et al., 1996, table 23). Most of the district is on the White Sands Missile Range and withdrawn from mineral entry.

Sylvanite district, Hidaldo County

The Sylvanite district is in the Little Hatchet Mountains (Fig. 1) and includes Laramide skarn, Laramide polymetallic vein, and placer gold deposits. Mineral production is estimated at approximately 2,500 oz Au, 35,000 oz Ag, 130,000 lbs Cu, and 80,000 lbs Pb (McLemore and Elston, 2000; McLemore, 2016). In 1908, placer gold and tetradymite were identified at the Wake Up Charlie mine. Native gold and tetradymite also were discovered in veins at the Gold Hill, Green, and Little Mildred mines (Jones, 1904; Short and Henderson, 1926; Lasky, 1947), and tellurobismuthite was found at the Buckhorn mine (Lasky, 1947; McLemore and Elston, 2000).

Tierra Blanca district, Sierra County

The Tierra Blanca or Bromide No. 1 district lies south of the Kingston district in the Black Range of western Sierra County (Fig. 1). Production form this district included 100,000 short tons of ore containing 165,000 oz of Ag. In addition, 100 lbs Cu, 1 oz Au, 318,687 lbs Pb and 464,055 lbs Zn were produced from 1919 to 1955 from carbonate-hosted silver-manganese replacement deposits (McLemore, 2016). Volcanic epithermal vein and sedimentary-iron deposits also are found in the district. Tellurium-bearing minerals were discovered at the Lookout and other mines. As much as 2,800 ppm Te is reported from selected samples of the deposits (Korzeb et al., 1995).

Grandview Canyon district, Sierra County

Vein and replacement deposits in Proterozoic rocks are found in the Grandview Canyon district in the San Andres Mountains (Fig. 1). Total metals production from the district is unknown, but low amounts of copper, gold, silver, and lead have been reported. Approximately 20,000 lbs of tungsten were mined from Grandview Canyon in 1907–1920 (Dale and McKinney, 1959). In 1918, 1,500 lbs of ore containing 70.2% WO_3 and minor gold and silver were shipped from the Pioneer mine (Lasky, 1932). In addition, George Stone produced mineral specimens of bismutite from the claims in the early 1900s (NMBGMR unpubl. data).

Ore deposits are found as minor replacements, thin mineralized veins and seams, and fracture coatings along faults and shear zones in Proterozoic granite and schist adjacent to amphibolite dikes (V.T. McLemore, personal observations). The mineralized bodies consist of malachite, bornite, chalcopyrite, chalcocite, scheelite,

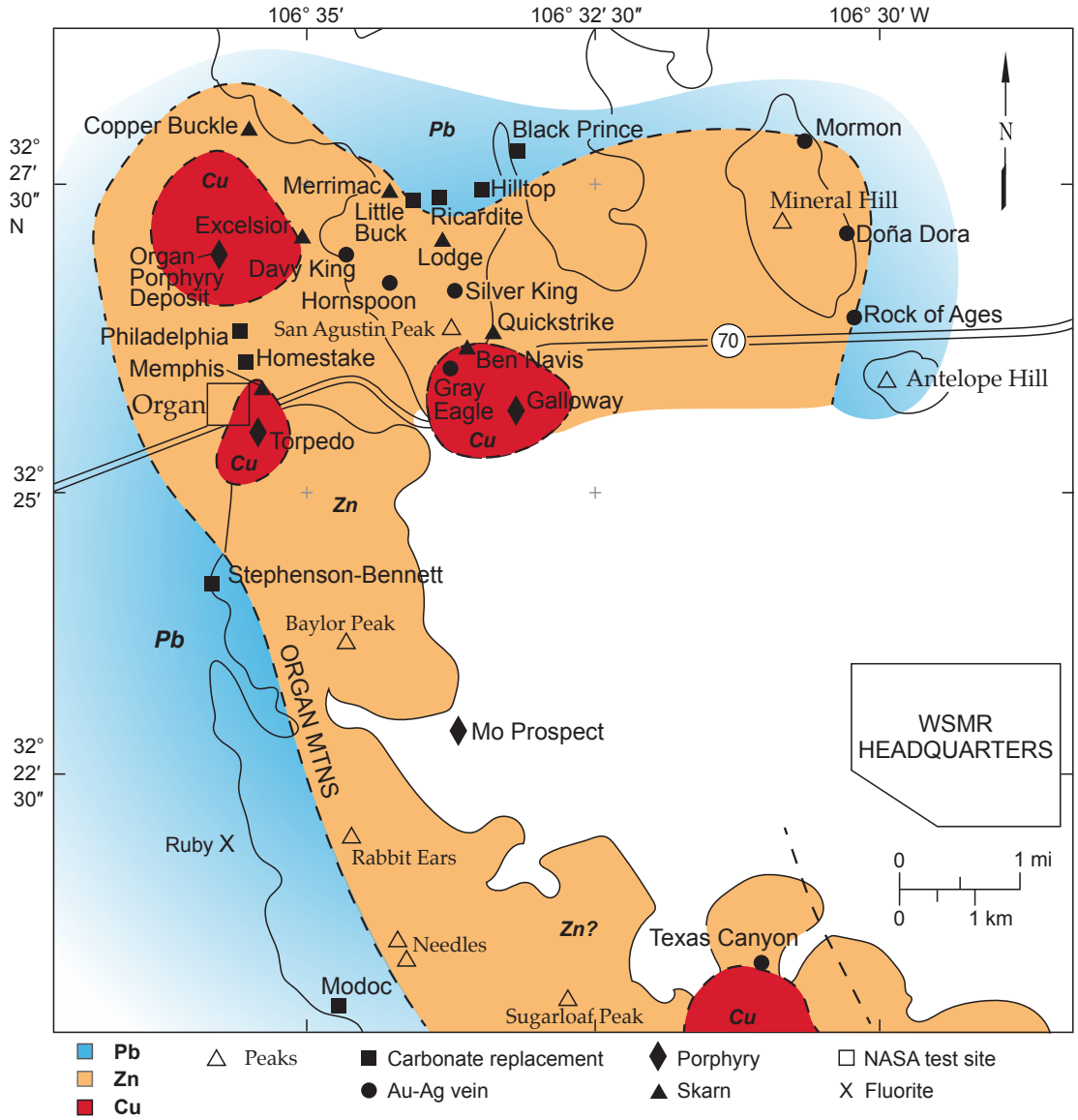

FIGURE 3. Major mines and metal zoning in the Organ Mountains district (modified from Lueth and McLemore, 1998).

powellite, bismutite, bismuthinite, pyrite, and quartz (Lasky, 1932; Clemmer and Holstein, 1974; NMBGMR unpub. files). Tellurium is associated with the tungsten- and bismuth-bearing minerals in thin quartz veins and mineralized seams that cut across the schistosity. Samples from the Pioneer mine contain as much as 200 ppb Au, 1.5 ppm W, 11,000 ppm Bi, and 90 ppm Te (NMBGMR unpubl. data). The district is on the White Sands Missile Range and withdrawn from mineral entry.

Hillsboro district, Sierra County

The Hillsboro mining district in the Animas Mountains (central New Mexico) contains one of the oldest Laramide porphyry copper deposits in the Arizona-Sonora-New Mexico porphyry copper belt (Fig. 1). Polymetallic vein deposits at Hillsboro propagate radially outward from the Copper Flat porphyry copper deposit along latite dikes (Geedipally et al., 2012). Tellurium, in concentrations as much as 130 ppm Te, characterizes some veins in the northern part of the district, where as much as 3,400 ppm Bi, 385 ppm Cd, and 8,600 ppm As are detected in some Laramide vein samples (Hedlund, 1985; Geedipally et al., 2012). Distal carbonate-replacement deposits, with enrichments in silver, lead, manganese, vanadium, molybdenum, zinc, and tellurium, are present in the southern and northern parts of the Hillsboro district. Geologic, geochronological, and geochemical evidence suggests that these mineral deposits were formed by large, convective magmatic-hydrothermal systems related to the Copper Flat volcanic/intrusive complex (McLemore et al., 1999, 2000a).

Mining districts in New Mexico with porphyry copper deposits

In addition to the Hillsboro district, there are eight additional Laramide porphyry copper deposits in southwestern New Mexico (Table 3; Fig. 4; McLemore, 2008). Many other areas in the state have potential for porphyry copper deposits, but there are no reported reserves or production (McLemore, 2008). Only the Chino (Santa Rita district) and Tyrone (Burro Mountains district) mines (Fig. 1) are currently in production. The largest Laramide porphyry copper deposit in New Mexico is the Chino mine, where copper sulfides occur in the upper part of a highly fractured granodiorite and adjacent sedimentary

rocks (McLemore, 2008, 2016). Although there are no chemical data for tellurium in these deposits; tellurium, precious metals, platinum group elements (PGEs), indium, germanium, and gallium have been recovered from the refinery anode slimes after processing (McLemore, 2008, 2016). These trace elements likely occur as micron-size inclusions within chalcopyrite or other copper minerals (Yano et al., 2013); they may also occur as solid solutions or exsolved species in sulfide minerals.

Post-Laramide Oligocene to Miocene porphyry copper deposits, locally with significant quantities of gold and molybdenum, are associated with some GPM deposits in

TABLE 3. Laramide porphyry copper deposits in southwestern New Mexico.

Mine Identification Number*	Porphyry Deposits	District	County	Latitude (decimal degrees)	Longitude (decimal degrees)	Year of Discovery	Commodities
NMGR0029	Chino**	Santa Rita	Grant	32.791667	108.06667	1909	Cu, Au, Ag, Mo, Te
NMGR0084	Tyrone	Burro Mountains	Grant	32.643889	108.36722	1903	Cu, Au, Ag, U, F, Te
NMGR0033	Cobre	Fierro–Hanover	Grant	32.845	108.091667	1900s	Cu
NMGR0160	Little Rock (Ohio)	Burro Mountains	Grant	32.646698	108.40675	1970s	Cu, Au, Ag
NMSI0610	Copper Flat**	Hillsboro	Sierra	32.806667	108.12222	1970s	Au, Ag, Pb, Zn, Cu, V, Te
NMGR0478	Gold Lake	White Signal	Grant	32.55270	108.32957	1970s	Cu, Au, Ag, Bi, U, Mo
NMGR0208	Hanover Mountain	Fierro–Hanover	Grant	32.833	108.083	1970s	Au, Ag, Cu, Zn, Pb, Fe, F, Mn, Bi
NMGR0409	Lone Mountain**	Lone Mountain	Grant	32.718056	108.17667	1970s	Cu, Au, Ag
NMHI0327	Steins	McGhee Peak	Hidalgo	32.186111	109.020833	1970s	Au, Ag, Pb, Cu, Zn

(McLemore, 2008). *Mine identification number is from the New Mexico Mines Database (McLemore et al., 2005a, b).
** skarn or carbonate-hosted replacement deposits also present.

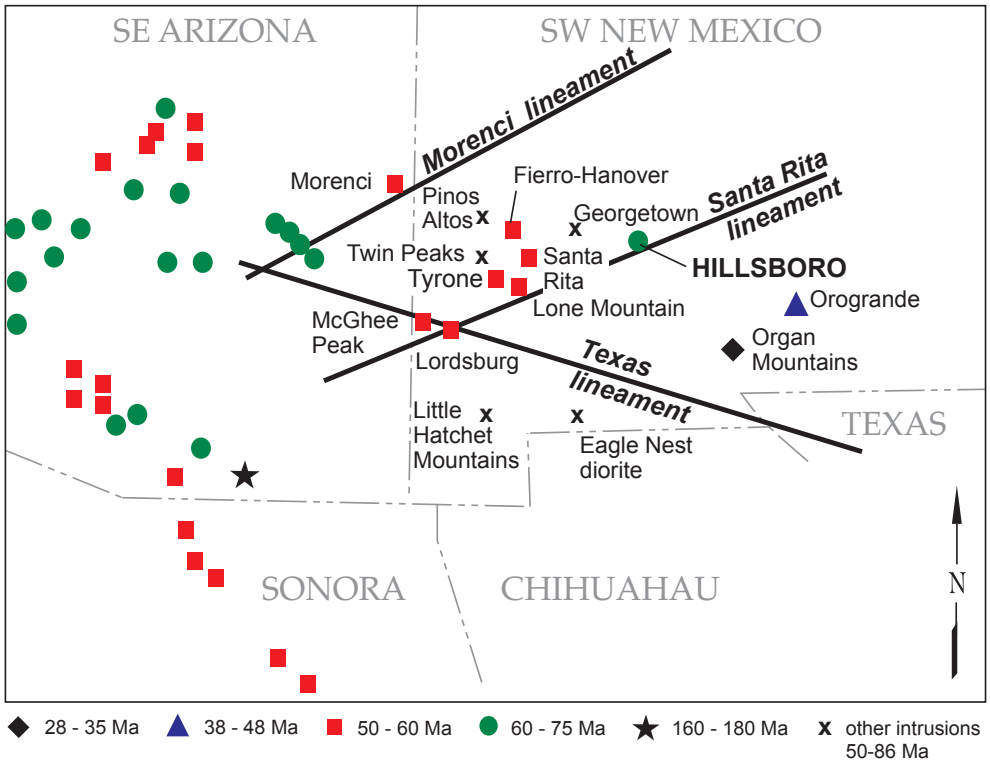

FIGURE 4. Porphyry copper deposits in southwestern United States and northern Mexico (McLemore, 2008).

New Mexico (Cerrillos, Orogrande, Nogal-Bonito, Organ Mountains; McLemore, 1996a; McLemore et al., 2014a, b; McLemore, 2015). These porphyry copper deposits are younger and much smaller than the Laramide porphyry copper deposits, but are recognized for their higher gold grade. Although tellurium is common in several mines in the Organ Mountains (discussed above, Appendix 1), none of the GPM porphyry copper deposits have been examined for tellurium potential.

Production Potential of New Mexico Tellurium Deposits

Like most areas in the world, because tellurium is a by-product the resource potential for tellurium production from New Mexico deposits depends upon the economic potential of gold-silver in veins or of copper in porphyry deposits. Mining of these commodities increases the likely significance of tellurium as an economic by-product. Although tellurium-bearing minerals are found throughout a number of districts in New Mexico (Appendix 1), as is common in many localities throughout the world, rarely does tellurium occur in economic concentrations (Cook et al., 2009; Goldfarb et al., 2016). Additional detail sampling and geologic mapping are required in the New Mexico deposits to fully understand the mineralogy and economic resource potential of tellurium. Tellurium likely is found in significant trace amounts in the porphyry copper deposits, but detailed mineral chemistry is required to determine what minerals host abundant tellurium. Tellurium concentrations at Lone Pine (Wilcox district), as well as deposits in the Organ Mountains, Hillsboro and Sylvanite districts, should be examined in more detail in order to determine the future potential economic recovery along with other metal resources.

Although mineral deposit models are well established for the general types of deposits in which tellurium is found, no specific geologic mineral deposit models have been developed which explain how tellurium enrichment occurs or how to explore for tellurium. The New Mexico deposits should be examined, in part, to further our understanding of the formation and future resource potential of tellurium, with particular attention to porphyry copper deposits and placer deposits. This compilation of tellurium occurrences in New Mexico and their associated geology should serve as a useful guide in model development and evaluation of our state's tellurium resource potential.

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Appendix 1

APPENDIX 1—Mining districts in New Mexico with tellurium reportedly present (as tellurium minerals or >20 ppm Te).

District ID*	District** (Aliases)	Year of Discovery	Years of Production	Commodities Produced (Present)	Age of Deposits	Type of Deposit	Comments
Catron County							
DIS010	Wilcox (Seventy-four, Savton Mesa, Tellurium)	1879	1941	Au, Ag, Cu, F, Te (Pb, Zn, Mo, Cd, Mn)	—	volcanic-epithermal veins	5 tons Te produced from Lone Pine mine. Samples assay as much as 5,000 ppm Te (NMBGMR unpubl. data; Everett, 1964; Davidson and Granger, 1965; Lueth et al., 1996).
DIS007	Mogollon (Coney, Alma, Glenwood)	1875	1875–1969	Au, Ag, Cu, Pb, Zn, U (Mo, F, Ba, Mn, Fe, Te)	—	volcanic-epithermal veins	Tellurium reported by Northrop (1996).
Cibola County							
DIS017	Zuni Mountains (Copper Hill, Diener)	1800	1905–1965	Cu, Pb, Ag, Au, F (Fe, U, Ba, V, REE, Te)	—	vein and replacement deposits in Proterozoic rocks	Unverified tellurium in veins (Northrop, 1996).
Colfax County							
DIS019	Elizabethtown-Baldy (Ute Creek, Moreno, Ponil, Aztec, Cimarron, Wiloc Creek, Copper Park, Eagle Nest, Hematite, Iron Mtn)	1866	1866–1968	Au, Ag, Cu, Pb (W, Mo, Bi, Te)	29.1 Ma (Kish et al., 1990)	GPM veins, placer gold	Tetradymite found at the Aztec mine (Lee, 1916; Chase and Muir, 1922; Crawford, 1937).
Doña Ana County							
DIS030	Organ Mtns (Mineral Hill, Bishops Cap, Organ, Gold Camp, Modoc, South Canyon, Texas)	1830s (perhaps as early as 1797)	1847–1961	Cu, Au, Ag, Pb, Zn, U, F, Ba, Bi (Mo, Te, W, Sn, Mn, Fe)	34.5 Ma ($^{30}Ar/^{29}Ar$, McLemore et al., 1995; Zimmerer and McIntosh, 2013)	GPM carboate-hosted/skarn, GPM veins, porphyry copper-molybdenum, vein and replacement deposits in Proterozoic rocks	Tellurium minerals found at Hilltop, Memphis, Black Quartz, Excelsior, Ben Nevis, Crested Butte, Rickardite and Texas Canyon mines (Everett, 1964; Lueth, 1998; Lueth and McLemore, 1998).
Grant County							
DIS043	Central (Bayard, Groundhog, San Jose)	1858	1902–1969	Cu, Pb, Au, Ag, Zn, V, Fe, limestone (W, Mo, Te, Ba)	—	polymetallic veins, placer gold	Tetradymite found (Everett, 1964).

Appendix 1 continued.

DIS046	Burro Mtns (Tyrone)	1871 (earlier mining by Spanish and Indians)	1879–present	Au, Ag, Cu, Mo, Pb, Zn, F, W, Mn, Bi, U, turquoise (Te, Be)	Tyrone stock, 54.5 Ma(^{40}Ar/^{39}Ar; McLemore, 2008)	placer gold, porphyry copper, polymetallic veins	Tetradymite and tellurium found (Anderson, 1957; Davidson and Granger, 1965; Northrop, 1996). Tellurium in anode slimes produced from porphyry copper production.
DIS065	Santa Rita (Chino)	1800	1801–present	Cu, Au, Ag, Mo (Zn, Pb, Fe, Sb, Be, U, Te)	Santa Rita stock, 58.3 Ma (^{40}Ar/^{39}Ar; McLemore, 2008)	porphyry copper, skarn	Tellurium in anode slimes produced from porphyry copper production (McLemore, 2008).
DIS068	White Signal (Cow Spring)	1880	1880–1968	Cu, U, Au, Ag, Pb, Bi, F, Ra, garnet (Th, Zn, Nb, Ta, turquoise, Zn, Be, REE, Ba, Te)	—	polymetallic vein, placer gold	Unverified tellurium in veins (Northrop, 1996; McLemore et al. 1996).
DIS053	Eureka (Hachita)	1871	1878–1957	Au, Ag, Cu, Pb, W, Zn, As, turquoise (Be, Te, Bi, Mo, Ba, F)	Hidalgo Formation 71.4 Ma, (^{40}Ar/^{39}Ar, Channell et al., 2000)	polymetallic veins, skarn, placer gold	Tellurium minerals at Ridgewood, Clemmie, and Pearl mines (Lasky, 1947).
DIS066	Steeple Rock	1860	1880–present	Au, Ag, Cu, Pb, Zn, F, Mn (Ba, Mo, U, Be, Te)	—	volcanic-epithermal vein	Unverified tellurium reported in veins.
Hidalgo County							
DIS088	Sylvanite	1871	1902–1957	Cu, Pb, Au, Ag, W, As (Sb, Te, Zn, Ge, Be, Mo, Bi, Ba, F)	32.3 Ma (^{40}Ar/^{39}Ar), Hidalgo Formation, 71.4 Ma (^{40}Ar/^{39}Ar, Channell et al., 2000)	skarns, polymetallic veins, placer gold	Tellurium in Gold Hill, Creeper, Hand Car, Buckhorn, Wake Up Charlie, and Little Mildred mines (Lasky, 1947; McLemore and Elston, 2000).
DIS083	McGhee Peak (Granite Gap, San Simon, Steins Pass, Kimball)	1894	1894–1956	Cu, Pb, Ag, Au, Zn (Te, Mo)	—	skarn/ carbonate-hosted	257 ppm Te reported from Silver Star mine (Hoag, 1991).
DIS087	Silver Tip (Bunk Robinson, Whitmore, Cottonwood Basin)	1930	none	(Au, Ag, Cu, Pb, Zn, Mo, F, Ba, Bi, Te)	—	volcanic-epithermal vein	Samples contained as much as 4,540 ppb Au and 1,400 ppm Te (Armstrong, 1993).
DIS082	Lordsburg (Pyramid, Shakespeare)	1854	1870–1999	Cu, Pb, Au, Ag, F, Zn (Ge, Ba, Mo, Be, Te)	Gran-odiorite, 58.5 Ma (^{40}Ar/^{39}Ar; McLem-ore et al., 2000b)	polymetallic vein, porphry-copper	Unverified tellurium reported in veins.

Appendix 1 continued.

Lincoln County							
DIS092	Gallinas Mountains	1881	1909–1956	F, Cu, Pb, Au, Ag (Mo, Te)	—	GPM veins, Fe skarn, placer gold	Samples assay 5–78 ppm Te (NMBGMR unpubl. data).
DIS093	Jicarilla	1850	1850–1957	Au, Ag, Fe, Cu, Pb (Zn, Mo, Ni, Co, U, Te)	—	GPM veins, placer gold	As much as 20–252 ppm in samples from Lower Black Gold mine (NMBGMR unpubl. data).
DIS095	Nogal–Bonito (Cedar Creek)	1865	1865–1942	Cu, Au, Ag, Pb, Zn (Mo, Te)	—	GPM veins, placer gold	Tetradymite in the Bear Canyon area. 1–4 ppm Te in Parsons mine (Segerstrom et al., 1979; Fulp and Woodward, 1991; McLemore et al., 2014b).
DIS099	White Oaks (Lone Mtn)	1850	1850–1953	Au, Ag, Cu, Pb, W, Fe (W, Te)	—	GPM veins, iron skarn	Tellurium reported but unverified in exploration samples (NMBGMR unpubl. Data).
Otero County							
DIS129	Orogrande (Jarilla, Silver Hill)	1879	1879–1966	Cu, Au, Ag, Pb, Fe, W (U, Th, Zn, Te)	—	GPM carbon-ate-hosted/ skarn, GPM veins, porphyry copper-molybdenum	As much as 450 ppm Te reported in samples (Korzeb and Kness, 1994; McLemore et al., 2014a).
Sandoval County							
DIS168	Cochiti (Bland, Golden)	1880	1894–1963	Ag, Au, Cu, Pb (U)	—	volcanic-epithermal veins	Tellurium in ores (Jenks, 1908).
Santa Fe County							
DIS184	La Bajada (La Cienega, Cerrito, Santa Fe)	1900s	1914–1966	scoria, U, V, Cu, Ag, Mn (Zn, Te, Cd, Ni)	—	Cu-Ag-U veins	Unverified tellurium reported in veins (Everett, 1964).
DIS186	New Placers (San Pedro)	1839	1839–1968	Au, Ag, Cu, Pb, Zn, Mn, garnet (W, Mo, Fe)	—	GPM Au-Ag-Te veins	Tellurium reported by Statz (1909).
DIS187	Old Placers (Ortiz, Dolores)	1828	1828–1986	Cu, Au, Ag, Pb (W, Te, Fe)	—	GPM Au-Ag-Te veins, placer gold, porphyry copper	Tellurium at Carache Canyon. Tellurides found in fractures with gold at Cunnigham Hill mine. Calaverite and petzite found (Maynard, 2014).
Sierra County							
DIS191	Chloride (Black Range, Apache, Grafton, Phillipsburg)	1879	1879–present	Cu, Pb, Zn, Ag, Au, Sn (F, Ba, Sn, Be, Mo, Sb, Te, V, U)	—	volcanic-epithermal veins	Tellurium reported by Northrop (1996) and Korzeb et al. (1995). Lovering and Heyl (1989) report 70 ppm Te from jasperoid at Iron Mountain.

Appendix 1 continued.

DIS192	Cuchillo Negro (Cuchillo Negro, Chise, Iron Mtn, Limestone)	1879	1880–1970s	Cu, Pb, Zn, Ag, F, U, W, Fe (Mo, Au, Be, Sn, Te)	—	volcanic-epithermal veins, carbonate-hosted/skarn	Tellurium in jasperoids and veins; 70 ppm Te at Iron Mtn (Lovering and Heyl, 1989; Korzeb et al., 1995).
DIS197	Hillsboro (Las Animas, Copper Flat)	1877	1877–1968	Au, Ag, Pb, Zn, Cu, V, Mn (As, Te)	Copper Flat, 75 Ma ($^{40}Ar/^{39}Ar$, McLemore et al., 2000a)	porphyry-copper, polymetallic veins, placer gold, carbonate-hosted/skarn	Tetradymite from Copper Flat (Harley, 1934). Te in samples in northern part of district (Hedlund, 1985; Lovering and Heyl, 1989; Korzeb et al., 1995; Geedipally et al., 2012).
DIS205	Tierra Blanca (Percha, Bromide No. 1)	1900s	1919–1955, 1971–1972	Au, Ag, Cu, Pb, Zn (W, Te)	—	carbonate-hosted, volcanic-epithermal veins	As much as 2,800 ppm Te (Korzeb et al., 1995). Hessite found at Lookout and Gray Eagle mines (Northrop, 1996).
DIS195	Grandview Canyon (Sulfur Canyon)	1896	1907–1920	Au, Ag, Cu, Pb, W, Bi, Fe (Mo, Mn, Te)	—	vein and replacement deposits in Proterozoic rocks	90 ppm Te in samples from Pioneer mine (NMBGMR unpubl. data).
Taos County							
DIS238	Red River (Rio Hondo, Midnight, La Belle, Keystone, Anchor, Black Copper Canyon)	1826 (possible Spanish mining prior to 1680)	1902–1956	Au, Ag, Cu, Pb, Zn, U (Mo, F, Te)	—	volcanic-epithermal veins, placer gold, GPM Au-Ag-Te veins (?)	Petzite reported in 1904 (Jones, 1904; Crawford, 1937; Anderson, 1957). Te reported at Sampson, Memphis, and Independence mines (Northrop, 1996).

*Names of districts are after File and Northrop (1966) wherever practical, but some districts have been combined and added. Districts may extend into adjacent counties or states or into Mexico.
**District ID is from the New Mexico Mines Database (McLemore et al., 2005a, b).