Field Trip Route

1 Old Bonne Terre Pb Mine
2 Missouri Mines Museum
3 C - PC contact, roadcut
4 Lambert's Cafe

Southeast Missouri Lead District and Sub-Districts

Fig. 1. Field trip route down to Sikeston, Missouri.

Fig. 2. Geologic overview of the lead-mining subdistricts in southeast Missouri. Exposures of Precambrian granites and rhyolites shown in light blue.
A Geologic and Historic Look at Lead Mining in Southeast Missouri

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Preview

This one-day GeoRaman field trip (see Fig. 1) highlights both the geological and historical aspects of lead mining in southeast Missouri. In 1720, French explorers became the first to find galena (PbS) and mine it for lead in this region, in Mine LaMotte (near present-day Fredericktown). This area was owned by France at the time, not becoming part of the “US” until the Louisiana Purchase in 1803. More lead deposits were found to the northwest in about 1864 (see Fig. 2) near the present towns of Bonne Terre, Flat River (both of which we will visit), and Desloge. This region is now referred to as the Old Lead Belt, where mining continued until 1972. The development of an ore-deposit model for this region guided exploration farther to the west in the 1950s, which led to the discovery of the Viburnum Trend (Fig. 2), where lead mining began in the 1960s and still continues (Kisvarsanyi and Hebrank, 1982; www.doerun.com; http://www.miningartifacts.org/Missouri-Mines.html).

The St. Joe Company was the major consolidator and operator of the lead mines in the Old Lead Belt and early in the history of the Viburnum Trend. All six of the active mines in the Viburnum Trend are now operated by the successor to St. Joe, the Doe Run Company. The latter is the largest producer of mined (i.e., primary) lead in the western world, supplying about 70% of the United States’ primary lead. Over 80% of that lead is used in the making of lead-acid batteries for vehicles and for back-up power, e.g., for computer networks and renewable energy facilities (www.doerun.com). The deposits in southeast Missouri constitute the world’s largest identified concentration of lead (Appold and Garven, 1999).

Geology

Regional Geology

The dominant geologic and topographic feature of southeastern Missouri is the Ozark uplift. This is a structure of Paleozoic age that led to the erosional uncovering of basement Precambrian rocks at the core of the St. Francois Mountains (see Fig. 3). Paleozoic sedimentary beds dip gently away from this core. Thus, in our drive south from St. Louis, we will progress successively down-section (see Fig. 4) from Mississippian limestones to Precambrian granites and rhyolites of about 1.5 billion years in age. In the areas we will visit, the exposures are of the Precambrian igneous rocks and Upper Cambrian units of the Lamotte (typically a sandstone, locally arkosic), Bonneterre (carbonates, typically dolomite in this area), Davis (shale to dolomitic shale), and Derby-Doerun (dolomite) formations (Kisvarsanyi and Hebrank, 1982, 1987).
Fig. 3. Generalized geologic map of Missouri (from Kisvarsanyi and Hebrank, 1982, p. 1.)
Fig. 4. Generalized stratigraphic column for southeast Missouri (from Kisvarsanyi and Hebrank, 1982, p. 3).
Description of Ore Mineralization

Lead mineralization is mostly confined to the Bonneterre dolomite, which is about 400 feet thick in the area we are visiting. Ore deposition is epigenetic, having taken place in the Permian (Brannon et al., 1996; Leach et al, 2010a,b), long after the original limestone deposition in the Upper Cambrian. The ores are located within the regionally dolomitized portions of the Bonneterre. The locations of the multiple ore bodies in the southeast Missouri lead district (see Figs. 2 and 5) are a function of the original sedimentary depositional environment (including facies changes), regional tectonics, and local features such as fractures.

The development of these Upper Cambrian sedimentary units on the Precambrian basement represents a major time discontinuity. The ~1.5-Ga igneous rocks underwent an extensive period of erosion that left a deeply incised surface of high relief marked by prominent erosional knobs made of granites and rhyolites. The incursion of a shallow sea in the early Paleozoic produced clastic sediments (Lamotte Fm.) and carbonates (Bonneterre Fm.) that were laid down on the ocean floor and lapped up against the granite knobs, in some cases covering the entire knob. The onlapping carbonates became part of a reef environment in this archipelago of exposed knobs (see Fig. 6). Pinch-outs of sediments against the granite knobs also represent locally abrupt changes in rock permeability, which were important in the flow of groundwater over the ensuing hundreds of millions of years.

Of particular importance in the location (and discovery) of the ore deposits are the algal reefs, i.e., stromatolites, that developed in the shallows created by the granite knobs. The ore-host rock relationships are particularly well described for the deposits in the Viburnum Trend (Fig. 6). Major controls on the siting of the deposits are “sedimentary ridge complexes,” which began as sand bars on the sea floor. The ridge crests often remained above the water level, allowing for extensive reworking of the carbonates. The flanks of the bars also encouraged 3-D features including algal reefs and interdigitation of sedimentary units. Many of these ridges are several thousand feet long (Harold Myers in Association of Missouri Geologists, 1969).

With regard to their enclosing sedimentary beds, the ore deposits are stratabound, i.e., they do not spatially conform in detail with individual thin sedimentary layering, but they typically do not cut across boundaries between formations. The Old Lead belt deposits are related to the northeast portion of the arcuate reef that developed around the system of igneous knobs (Figs. 2 and 5). The individualized spatial control on the ore deposits involved facies changes, primary sedimentary features, solution-induced collapse breccias, and fractures. Highly fractured dolomite often hosted high concentrations of ore minerals (Kisvarsanyi and Hebrank, 1982).

The ores in both the Old and New (Viburnum) Lead Belts are dominated by galena. Sphalerite and chalcopyrite in bulk are much less abundant, but can be highly enriched locally. Minor amounts of the cobalt-nickel sulfide siegenite (a sulfide analog to the spinel group) occur in very specific locations in some of the mines. Marcasite, pyrite, dolomite, and calcite are among the gangue (non-ore) minerals (Kisvarsanyi and Hebrank, 1982).
Fig. 5. Map of the Old Lead Belt, with mineralized regions shown by stippling (from Kisvarsanyi and Hebrank, 1982, p. 30.)

Fig. 6. Sketch of the relations between the deeply incised Precambrian basement and the onlapping Upper Cambrian sediments. Note development of algal stromatolite reefs in the shallows near the granite and rhyolite knobs (from Shelton et al., 1992, p. 677).
Stop 1 Historic Bonne Terre Mine in Bonne Terre, Missouri

History of the Current Bonne Terre Mine

As in most underground mines, water pumps constantly pumped ground water out of Bonne Terre while it was in operation. Much of the mine filled up with water within a few years after mining ended in 1961. In the 1980s, Doug and Cathy Goergens purchased the long-closed Bonne Terre Mine, installed pumps to keep the water level stable at a depth of about 80 feet, and opened it for two types of commercial business, i.e., 1) walking and/or boat tours and 2) scuba diving in what is called the Billion Gallon Lake (through the West End Diving Center). Divers from all around the world, including Jacques Cousteau and his video team, have come here to dive. The water remains a constant 58°F (14.5°C) and the air 62°F (16.7°C) year round. The underground workings are about 1 mile N–S, 2 miles E–W, and 375 feet high (1.7 km x 3.3 km x 112.5 m). We will take the hour-long, combined walking and boat tour of the mine.

History of Lead Mining in this Region

Recognition of lead ore in southeast Missouri dates back to the early French settlers and the native Americans with whom they interacted. As indicated above, efforts to mine the ore began in about 1742, but these were hand-diggings that produced very little usable metal. Significant mining in the area began in 1864, upon the incorporation in New York of the St. Joe Lead Company. The company purchased the La Grave mines tract (946 acres = 383 hectares) in what would become the Bonne Terre Mine in a future town of the same name. Mining began on the surface through manual labor in digging trenches and shallow downward inclines. Although the mine did not clear a profit in the early years (producing only 130 tons of lead in 1866), the company persisted (Kisvarsanyi and Hebrank, 1982).

A positive change finally occurred due to the foresight of the mine management, especially Mr. Wyman Jones who was president of St. Joe. He introduced the use of diamond drilling in order to locate additional deposits at depth. New ore bodies (Figs. 2 and 5) were found, which led to financial solvency for the company. Exploration led to discovery of yet additional ore bodies to the south and southwest (Leadwood, Desloge, Rivermine, Flat River, Leadington, Elvins), within only about 8 miles of Bonne Terre (Kisvarsanyi and Hebrank, 1982).

The Bonne Terre Mine’s first large expansion came in 1870, when the first shaft was dug – by hand. Disseminated galena of good grade was found, which led to the sinking of several more shafts. The rock-processing mill and the furnace for smelting were enlarged and upgraded. A town with shops, houses, and a general store grew up near the mining facilities. Other modernizations that aided the mine were the building of underground tramways for hauling out the ore. Ore carts were moved by horses and, later, by mules (see Figs. 7-9). Two blast furnaces had been added by 1880, and lead production was approaching 5000 tons per year (Kisvarsanyi and Hebrank, 1982).

As other mines opened in neighboring areas, southeast Missouri became the host to about 15 mining companies. By 1933, St. Joe had acquired all of those properties and was the sole mining operation in the whole area. The Bonne Terre Mine continued to be a major ore producer (see Fig. 9). After 97 years of continuous operation, even during the Depression of the 1930s, the Bonne Terre Mine closed in 1961. Over this time, the mine had produced about 1.1 million tons of pig lead from 34 million tons of ore, i.e., an average grade of 3 wt% Pb. By
Fig. 7. Scene underground in Bonne Terre Mine in early 1930s, when mules used to pull loaded mine cars (from http://www.rootsweb.ancestry.com/~mostfran/mine_history/stjoe_history.htm).

Fig. 8. So-called “trapeze miners” underground at Bonne Terre Mine ~1917. Each bright light indicates a miner’s helmet. From http://www.rootsweb.ancestry.com/~mostfran/mine_history/trapeze_miners_lg.jpg
the time the entire Old Lead Belt had closed down in 1972, Bonne Terre’s contribution represented about 13% of the production from the entire belt (Kisvarsanyi and Hebrank, 1982).

The Old Lead Belt held many mining records in its day. It was a world-class deposit in ore output. The region of interconnected mines here covered 35 square miles (91 sq km). Those mines were served by 280 underground miles (450 km) of haulage track that were supplied by innumerable mules, many of which were born and died underground without ever seeing the light of day. The entire district ultimately produced 285 million tons of ore. For most of the years that the mines operated, the district’s annual production of lead metal was over 100,000 tons (Kisvarsanyi and Hebrank, 1982).

**Inferred Mechanisms for Ore Deposition**

*Overview of the Formation of a Metallic Ore Deposit*

Ore deposits can be thought of in a variety of ways, e.g., the objects of business ventures, geochemical anomalies (metal concentrations well above those of the average crust), and evidence of vastly long-term local stability in crustal processes (since many ore deposits are the product of hundreds of thousands or more years of natural geologic development). Viewing ore deposits as geochemical anomalies focuses our attention on the issues of the nature, localization, and timing of geologic processes, which are critical to the development of a large body of crustal rock with metal concentrations many times those of the surrounding rocks.

There are some general questions that usefully can be asked about almost any ore deposit, e.g., 1) where did the metals in the ore ultimately come from; 2) how were those initially dispersed metals moved from their original sites to the site of ore deposition; and 3) if those metals indeed were transported from elsewhere, what made them “dump out” in the relatively small volume of crust that we now call the ore deposit? In the present case, lead is the metal of primary interest in the ore deposits of southeastern Missouri, although copper and zinc minerals also are mined and processed. If we were to crush up and homogenize the entire earth’s crust and then analyze an aliquot of this material, the analysis would be that of the “average earth’s crust.” By such a definition, the average crustal concentration of lead (Pb) is 0.00125 wt.% (12.5 ppm by weight). However, for a lead-enriched volume of the crust to be economically viable as a mine, the Pb concentration has to reach about 3 wt.%, i.e., 2400x more concentrated than that of the average earth’s crust. The goal of the economic geologist is to piece together information to explain how such a high concentration factor could have been attained, keeping in mind that the geologic processes that cause elevated concentrations of metals typically are very inefficient. The upshot of these considerations is that HUGE volumes of the earth’s crust typically undergo geologic processing in order to release the amounts of metals that ultimately become incorporated into an ore deposit.

**Mississippi Valley-type (MVT) Ore Deposits**

The Old Lead Belt and the Viburnum Trend are excellent examples of a type of Pb-Zn ore deposition that has occurred in many areas around the world, but primarily in the United States and Europe. Some of the best known deposits are in areas near the Mississippi River. Southeast Missouri ores (SMO) for the most part possess the typical characteristics of Mississippi-Valley-type (MVT) Pb-Zn deposits (Leach et al 2005; Leach et al 2010a), e.g.:
hosted by carbonate rocks, especially dolostone [SMO show dolomitization of limestone only in and close to the ore zone]

not associated with contemporaneous igneous activity

usually in platform carbonate sequences, especially on the edges of basins and/or near foreland thrust belts [SMO are directly north of a foreland thrust belt, and they show localization with respect to algal reef bodies]

ore formation commonly associated with extensional zones inboard of compressional tectonic belts of “clastic rock-dominated passive-margin sequences” (Leach et al., 2010b, p. 595) [explained in detail for SMO by Bradley and Leach, 2003; Leach et al., 2010b]

typically occur in large districts with many separate ore bodies [SMO covers ~ 3000 km². Compared to average MVT districts, SMO, especially the Viburnum Trend, has a high Pb + Zn average grade (~ 8 wt.% and large total ore tonnage (> 15 million tons)]

ore fluids were relatively typical basinal brines with 10 to 30 wt.% dissolved salts and of compositions indicating a large seawater component (at different stages of evaporation) [Old Lead Belt shows 19 to 20 wt.% salts; Viburnum Trend 20 to 26 wt.% salts]

ore depositional temperatures, based on fluid-inclusion analyses, were typically 75 to 200°C [Old Lead Belt indicates 100 to 120°C; Viburnum Trend shows wider range (Wenz et al., 2012]

both sulfur and metals are derived from the crust [SMO do not have isotopic signatures showing a mantle component]

epigenetic ore formation (ores formed after lithification of the rocks that host them)

stratabound but not stratiform (i.e., enclosed within a specific unit/stratum, but not conforming to any fine-scale laminar features within the unit)

localization of ores controlled dominantly by faults, fractures, dissolution-brecciation features, and changes in lithology [SMO associated with some dissolution, brecciation, and lithologic changes]

with dominant sulfide minerals sphalerite, galena, pyrite, and marcasite [SMO are lead/galena-dominated, rather than zinc/sphalerite-dominated. Some mines also have considerable chalcopyrite (CuFeS₂), as well as Co and Ag mineralization (Sverjensky, 1981).]

sulfide minerals typically replace carbonate rocks and, to a lesser extent, fill voids [Both mineralization types occur in SMO, which range from fine- to coarse-grained]

Over the past several decades, the understanding of hydrothermal ore deposition in southeast Missouri has moved from consideration of how the immediate localization of ore took place to broader-scale interpretation of how ore deposition came to occur in the entire district. At that broader scale, lead ores in the Old Lead Belt and the Viburnum Trend can be viewed as the product of collisional tectonics followed by regional-scale, gravity-driven fluid flow (Bradley and Leach, 2003; Leach et al., 2010b; Wenz et al., 2012) associated with the Alleghenian-Ouachita orogeny 325 to 250 Ma (Brannon et al., 1996). This ore district is located in the
foreland north of the Ouachita orogen (see Fig. 10), which is a fold-thrust belt created by the
collision between Laurentia’s passive margin and the accretionary wedge landward of an arc.
The collision ensued after subduction of arc-associated oceanic crust during the Mississippian
and Pennsylvanian.

The ore deposits are hosted by a thick wedge of carbonate-dominated rocks, a platform
facies that developed from the Cambrian to the Pennsylvanian and thickened seaward along the
Laurentian passive margin. Ore deposition occurred after the collision, unaffected by later
tectonics. Some of the high-angle faults in the Ouachita thrust belt provided local controls on
ore mineralization in the Early Permian, i.e., a few tens of millions of years after collision and
orogenesis (Bradley and Leach, 2003). In the post-collisional interval, the foreland basin
became infilled with sediments but remained topographically below the orogen (see Fig. 11).

Bradley and Leach (2003) postulated that the earlier stages of convergence between the
arc and passive margin pre-conditioned the platform carbonates to prepare them for ore
mineralization and to impose the replacement and infilling mechanisms of ore deposition that
are seen in the deposits today. During collision, the foreland basin was moved toward the
craton. The shallow-water carbonates were moved in a conveyor-like fashion through the
compressional forebulge (Fig. 11), causing them to be uplifted and subaerially exposed. Flexure
caused extensional faults that were important to later passage of fluids and subsequent ore
deposition. Tectonism eventually ceased, and both the foreland basin and the remnant orogen
experienced rebound. Rain recharge to these topographically elevated sedimentary layers
caused regional-scale, gravity-driven fluid flow northward into the present-day ore district.

*Where did the Metals Come from?*

The metals presumably were derived from the leaching of the conduit rocks through
which gravity-driven fluids flowed (Figs. 10 and 11). These would have included sedimentary
infill of the Arkoma Basin adjacent to the orogen, the Lamotte Sandstone immediately above the
Precambrian granitic basement, and the ore-hosting Bonneterre dolomite. Based on the low
estimated leaching and transport efficiencies of basinal fluids, it is clear that the volumes of rock
from which metals are scavenged are huge compared to the volume of the related ore deposits.
On the other hand, the fluid-volume fluxes in a midcrustal shear zone (like those that could act
as conduits for ore-forming fluids) are about five orders of magnitude greater than fluxes during
regional metamorphism (Ingebritsen and Appold, 2012).

Goldhaber et al. (1995) undertook an extensive isotopic study of uranogenic lead,
thorogenic lead, and sulfur in SMO lead ores, as well as in sulfide minerals in which lead was
only a trace component. Their goal was to trace the pathway along which lead was scavenged
and eventually precipitated in southeastern Missouri. The story that evolved is complex, as
already expected due to the variability in the isotopic signatures in galena of different
generations within the same deposit, as well as isotopic heterogeneities that can be
documented within individual galena crystals. The simplest summary of their results is that
much of the lead was derived from the ~1450 Ma basement granites/rhyolites, in large part via
the Lamotte Sandstone.
Fig. 10. Map showing geologic context of southeast Missouri lead deposits with respect to other mineralized areas, Proterozoic basement, and probable southern source of ore fluids (Shelton et al., 2009, p. 734).

Fig. 11. N-S cross-sectional depiction through Ouachita Orogen in Permian time, after plate convergence has ended. Note topographic gradient that would guide fluids northward. From Bradley and Leach, 2003, p. 660.
**How were the Metals Moved?**

“Hydrothermal ore deposits represent a convergence of fluid flow, thermal energy, and solute flux that is hydrogeologically unusual” (Ingebritsen and Appold, 2012, p. 559). As described above, the Ouachita orogeny caused a steep topographic gradient in the Ozark region during the late Paleozoic. Numerical simulations of combined heat transport, fluid flow, and solute transport in this region have produced a model for the transport of metals to the southeast Missouri ore district and a time-frame in which those metals could have been precipitated (e.g., Appold and Garven, 1999). Compaction-driven fluid flow from a basin is insufficient to account for the SMO deposits, but wider spread, topographically driven fluid flow is reasonable (Ingebritsen and Appold, 2012). The latter models assume vigorous, on-going recharge in the southern, elevated portion of the Arkoma basin, which gave rise to strong discharge of fluids that passed over the Ozark dome. As uplift continued to the south, increased ground-water temperatures and velocities became favorable for metal transport and ore deposition (Fig. 11). However, the meteoric influx in the recharge zone eventually produced strong dilution of the basinal fluids. Without some additional saline influx into the system, ore-formation in SE Missouri would have been limited to a window of a few hundred thousand years. In contrast, elevated temperatures sufficient for ore formation could have been maintained for a few million years after uplift ended, and fluid velocities sufficient for ore formation (several meters per year) could have continued for a few tens of millions of years (Appold and Garven, 1999).

Leach et al. (2010b) emphasize the importance of the secular evolution of the earth and its environment (aquatic and atmospheric) as a control on the dominant composition of sedimentary fluids. Modern sedimentary brines enriched in Pb and Zn are oxidized (most sulfur is dissolved as sulfate) and somewhat acidic, with pH of 4-6. They have Pb concentrations up to about 300 ppm, but fluid inclusions in sphalerite from some MVT deposits range up to 3000-5000 ppm Pb (Leach et al., 2010b). Brine compositions of the fluid in inclusions within SMO ore-stage minerals show Br/Cl ratios indicative of seawater that has been evaporated past the point of halite precipitation (Kendrick et al., 2002). Such fluids were ideal for the dissolution and transport of high concentrations and large amounts of Pb and Zn.

**What Caused the Moving/Dissolved Metals to be Precipitated out?**

Three basic types of models have been investigated over the years to explain how the metals, primarily lead, were rendered insoluble and precipitated as sulfide minerals (Anderson, 1975). Because the very low solubility of metal sulfides (except at low pH) precludes the co-existence of high concentrations of dissolved metals and reduced sulfur (Wenz et al., 2012) in
the transporting fluid(s), the preferred models over the decades were: 1) cooling of a fluid containing dissolved metals and reduced sulfur at pH values one or two units below neutral (Sverjensky, 1981), 2) mixing of one fluid rich in dissolved metal but poor in sulfur with a second fluid that was rich in reduced sulfur but poor in dissolved metals (Goldhaber et al., 1995, based on isotopic studies), and 3) one fluid containing dissolved metals and sulfate that encountered reducing conditions that stabilized reduced sulfur, causing precipitation of metal sulfides. Models involving mixing of fluids must account for the differences in the two fluids, how they were transported separately to the same site, and how mixing was effectively carried out in the appropriate locality.

Lead and sulfur isotope studies on both galena samples and trace amounts of lead in other phases allowed Goldhaber et al. (1995) to delineate three isotopically differentiable fluids (and their conduit units) that gave rise to the MVT ores in southeastern Missouri. The first fluid, as indicated above, was the carrier of the lead for most of the main-stage galena ore in the Old Lead Belt and the Viburnum Trend. The lead was derived primarily from the 1450-Ma basement rocks and was transported, in the almost total absence of accompanying H₂S, through the Lamotte Sandstone. The transported lead was leached both directly from weathered basement rocks and the Lamotte Sandstone. The most plausible scenario, based on evidence from parts of the Lamotte that were not influenced by ore fluids, is that this sandstone was initially deposited as a red bed. Its high hematite content would have buffered the oxygen fugacity to levels that caused almost all available dissolved sulfur to be in the form of sulfate. Fluids migrating northward from the Ouachita orogenic belt later removed hematite from, i.e., bleached, the Lamotte Sandstone. However, they caused precipitation of potassium feldspar rather than a sulfide phase. Such a low-sulfide fluid could have carried large concentrations of dissolved lead, accounting for the deposition of such huge amounts of galena in SMO in a reasonable time period. A second fluid, one rich in isotopically heavy H₂S, moved through the upper Bonneterre formation in which siltstone members occur. The third fluid – like the first fluid -- transported lead, but it had a somewhat different isotopic signature and also included H₂S. Its pathway was through carbonates above and in the upper section of the Bonneterre formation (Goldhaber et al., 1995).

The culmination of this story is the precipitation of the sulfide ores. As has been inferred for many years, based on knowledge of the local stratigraphy and hydrogeology, the three fluids came together and underwent mixing in the region where the high-relief basement knobs were abutted by the lower Cambrian sediments. In particular, the pinching out of units, such as the permeable Lamotte sandstone against impermeable granite knobs and the lack of continuity of the impermeable silt upper beds in the relatively permeable Bonneterre, caused mixing of the above three fluids to occur. Dissolved metals interacted with reduced sulfide to cause saturation with respect to galena and other less abundant sulfide phases. Such mixing generated a drop in pH, accounting for ore textures suggestive of carbonate dissolution and infilling with sulfide. Such rapid attainment of (super)saturation with respect to sulfide minerals also could account for zones in which the sulfides are very fine-grained and, in some cases, colloidal in appearance (Goldhaber et al., 1995). Thus, the formation model incorporates aspects of both mechanisms 1 and 2 at the beginning of this section, due to the necessity of at least three independent fluids to account for the range and heterogeneity of lead and sulfur isotopic values within these ores. Wenz et al. (2012) favor two-fluid mixing of a) sulfur-rich but metal-poor with b) sulfur-poor but metal-rich fluid, both relatively reducing.
Stop 2 Missouri Mines State Historic Site

We remain within what is called the Old Lead Belt as we drive from the Bonne Terre mine to Missouri Mines State Historic Site in Park Hills. There, we are above the now-closed Federal Mine, at what remains of “Federal Mill No. 3 in Flat River” (now called Park Hills). The Federal Lead Company built the original facility in 1906-1907, when there were still 15 different mining companies operating in the Old Lead Belt. Like all such “mills” (including those now operating in the Viburnum Trend, or New Lead Belt), this one housed equipment for crushing ore rocks, grinding the rocks finer, and then concentrating the individual ore minerals (mostly galena, but also sphalerite and chalcopyrite). St. Joe Lead Company bought the Federal Lead Company and this mill in 1923. The mill facility grew to comprise 26 buildings on 25 acres of land, making it the largest such plant in the world (see Figs. 12 and 13). During its heyday, this mill was at the hub of 1000 miles of underground tunnels and 250+ miles of underground railroad track for transporting the ore out of the mines. By 1933, St. Joe Lead owned all the mines in the Old Lead Belt and was the employer of thousands of miners (Flader, 1992).

It eventually became too difficult and costly to mine in the Old Lead Belt. Mines closed one by one, followed finally in 1972 by the Federal Mill. The mining company itself had changed and broadened its operations, becoming St. Joe Minerals Corporation. In 1975, St. Joe offered the Federal Mill complex and 8,000 acres of adjacent land to the state of Missouri for use as a recreation site. This gift had great potential, but many hurdles remained before the land, with its remnants of decades of mining operations, could be opened to the public. The question of what to do with the huge, abandoned industrial mill complex loomed large (Flader, 1992).

Very early in the discussions, some Missouri park officials presented the idea of a mining museum. Missouri actually has had a number of major mining operations throughout its history, e.g., iron, copper, zinc, silver, barite, and coal, in addition to lead. Mining had a large impact on the state’s economic and immigration history; it was argued that a mining museum would be an important contribution to the preservation of Missouri’s cultural heritage. Before vacating the complex, St. Joe asked the park staff to select which equipment they would like to retain for the museum. A locomotive, ore cars, and various diggers, including a famous St. Joe shovel, were retained. The museum is well on its way to becoming the unique interpretive center that initially was envisioned (Flader, 1992).

The museum resides in the converted old powerhouse of the Federal Mill. The building now contains excellent photographs, models, and preserved equipment that represent mining practices at the time the Old Lead Belt was active. The museum also houses a beautifully displayed collection of minerals from all over the world.

For a brief overview of what is available to visit at the historic site, see the short video at http://www.youtube.com/watch?feature=player_embedded&v=bb1zN0t43E4, the photo gallery of the old mill facilities at https://www.flickr.com/photos/47969339@N02/sets/72157625976412812/show/, a virtual tour of the outside of the old mill facilities at http://www.mostateparks.com/virtual-tour/60341/virtual-tour, and what is displayed in the museum at http://www.mostateparks.com/location/56331/powerhouse-museum. An essay on the museum’s history (in Flader, 1992), whose information formed the basis of the above narrative, is reproduced at http://thelibrary.org/lochist/periodicals/ozarkswatch/ow601g.htm.
Fig. 13. Guide to the outbuildings of the old Federal Mill at the Missouri Mines State Historic Site, Park Hills, Missouri.


LEGEND
1 Powerhouse (Museum) 12 Scale House
2 Primary Crusher Building and Headframe 13 Dorr Thickener Tanks
3 Secondary Crusher Building 14 Filter And Dryer Building
4 Gatehouse 15 Supply House
5 Safety Building 16 Carpenter Shop
6 Mill Building 17 Electric Shop
7 Floatation Plant 18 Transfer Houses (Foundations)
8 Machine Shop 19 Storage Shed and Yard
9 Pump House 20 Storage Shed and Yard Foreman's Shed (Foundation)
10 Water Tower 21 Truck Shed (Foundation)
11 Hoist House
22 Sawmill (Foundation)
23 Babbitt House (Foundation)
24 Dynamite Cap Storage Building
25 Acetylene Generator House (Foundation)
26 Carbide Storage Building (Foundation)
27 Sulphur Dioxide Generator House (Foundation)
28 Water Tank

SCALE IN FEET
0 150 300
The drive from stop 2 to stop 3 brings us closer to outcrops of the Proterozoic basement of the St. Francois Mountains. This ~1.45 Ga epizonal granite-rhyolite terrane forms a SW-NE belt that “represents significant addition of sialic material to the continental crust” of the North American craton (Kisvarsanyi and Hebrank, 1987, p. 161). Several granitic ring complexes and accompanying calderas have been mapped in this area. As we drive along U.S. 67 south of Farmington, we are on the eastern edge of the Butler Hill caldera, whose collapse gave rise to the Grassy Mountain Ignimbrite. The St. Francois terrane has multiple ignimbrites, i.e., rocks that result from volcanic gas-rich flows (fluidized masses) of pumice and ash (pyroclastics). Along MO 72, immediately west of U.S. 67, roadcuts reveal the nonconformity between underlying Precambrian basement and sedimentary rocks of late Cambrian age (Hayes, 1961; Kisvarsani and Hebrank, 1987; Berri, 2009).

**Stop 3a.** About 1.3 miles west of the intersection of MO 72 with U.S. 67 is an outcrop on the north side of the road (see Fig. 14). This is the Upper Cambrian Bonneterre Dolomite. Here it is thin-bedded and contains small vugs and borrowing structures from ancient marine life. Close proximity to a rhyolite knob (seen at Stop 3b) indicates that these beds originally were carbonate mud in a shallow lagoon (www.geocaching.com). Some of the pinch-and-swell features also suggest possible algal beds. Occasional grains of metallic gray galena can be found in the dolomite, attesting to the migration of ore-bearing fluids.

**Stop 3b.** About 0.4 miles farther west are outcrops along the north and south sides of the highway, showing the erosional surface on the Grassy Mountain Ignimbrite. On the south side of the highway (see Fig. 15), the ignimbrite is nonconformably overlain by a basal boulder conglomerate and (not so easily distinguished) overlapping coarse sandy dolomite of the Bonneterre Formation. Boulders, gravel, and mud originally were deposited on the top and flanks of the Precambrian erosional remnant when it was an island (one of many, in a tropical archipelago) in the Paleozoic sea (Kisvarsanyi and Hebrank, 1987; Malone, 2001; http://www.geocaching.com/geocache/GCH7RM_roadside-geology-fredericktown).

In both the north and south outcrops, a diabase dike (probably one of the Skrainka-group mafic dikes) about 4-5 feet thick, has intruded the Grassy Mountain Ignimbrite. The latter is a rhyolite porphyry with well developed jointing that formed during cooling. The maroon- to black-colored porphyry contains phenocrysts of perthitic feldspar and quartz in a totally recrystallized matrix of feldspar and quartz. It also shows occasional collapsed pumice fragments, confirming its origin as an ash flow. This is a high-silica rhyolite that shows very little compositional variation (Malone, 2001).

The dike occupies one of the northeast-trending joints (N 15° E). It is a medium- to fine-grained olivine diabase containing about 7-8 wt.% MgO (Malone, 2001). In the south outcrop, the dike is highly weathered and deeply eroded, but shows well its upper truncation by a boulder conglomerate. Across the road, the dike is much better preserved, but the boulder bed is missing. The dike’s sharp contacts are fractured and sheared; calcite and quartz fill narrow fractures along the dike’s sheared contacts with the ignimbrite (Kisvarsanyi and Hebrank, 1987). There has been obvious movement along some of the joints, which produced faults and fault gouge (clay-like, ground rock). Some portions of the rhyolite show drill holes from a mining company that unsuccessfully searched for platinum ores in the 1990s (www.geocaching.com).
Fig. 14. Map of the outcrops to be visited on Stop 3. We will examine outcrops at Stops 3a and 3b, but only drive by Stop 3c. From Kisvarsanyi and Hebrank, 1987, p.161.
Fig. 15. Diagrammatic sketch of exposure on south side of Missouri Highway 72, at Stop 3b. Grassy Mountain Ignimbrite and weathered mafic dike are nonconformably overlain by basal boulder conglomerate and sandy Bonneterre dolomite. Drawing by Susan Dunn.
Farther to the west are outcrops dominated by boulders and gravel, indicating the oldest sediments that are preserved from the weathering and erosion of the (here unseen) rhyolite knob. Still farther west, close to Oak Grove (see Stop 3c marked on Fig. 14), are outcrops of flat-lying, thin-bedded Lamotte Sandstone, which appears to be the remnants of ancient beaches on the flanks of the knob. We may have time to drive by these outcrops. The reddish color of the Lamotte Sandstone comes from oxidized iron released from the weathering of the rhyolites (http://www.geocaching.com/geocache/GCH7RM_roadside-geology-fredericktown). The pink color of the potassium feldspar in both the granites and rhyolites in this terrane indicates the high iron concentration of the igneous rocks, which also is reflected in several iron mines that historically operated in the area.

Stop 4 Lambert’s Cafe in Sikeston, Missouri

There are many types of entrepreneurs in the Midwest, and the couple who opened Lambert’s Cafe in 1942 are good examples. Earl and Agnes Lambert, with just 14 cents between them, borrowed $1500 from a friend in order to open a café in Sikeston. Their small building had a counter and 8 tables, which together seated 41 customers. With 5 employees, Earl and Agnes took 12-hour shifts in order to keep the café open 24 hours a day. During and even after World War II there were rationing and shortages of goods, which made it especially difficult to start up and operate a restaurant business. Because of this situation, though, the Lamberts knew that the public would find appealing their policy of serving meat, vegetables, and dessert with every meal. Throughout the 1940s and 1950s, Lambert’s Cafe was the place to be, for both good food and friendly conversation (http://www.throwedrolls.com/shopcontent.asp?type=Aboutus).

At the death of his father Earl in 1976, Norman and his wife joined his mother Agnes in running Lambert’s. Family history has it that Norman was a rather retiring man until he stepped up to the business and social responsibilities of running a bustling restaurant. He personally served many of the pies and rolls, while joking with customers. The café grew in size, but it still could seat only 50 people at a time – with another 150 waiting in line! The story goes that one day the café was so full that Norman was having trouble reaching customers who wanted more rolls. One frustrated diner apparently yelled across the room to Norman, “Throw the danged thing!” The rest is history (http://www.throwedrolls.com/shopcontent.asp?type=Aboutus).

Fourth-generation Lamberts now run not only the much-expanded café in Sikeston, but also two more Lambert’s Cafes in Ozark, Missouri, and Foley, Alabama. The hallmarks of all three restaurants are plenty of good food at a reasonable price, threwed rolls (which have to be seen and eaten to be believed!), and “pass arounds” (food carried around in buckets and given to all who want them: fried potatoes and onions, macaroni and tomatoes, black-eyed peas, fried okra, sorghum molasses, and apple butter). The souvenir-rich decor of the restaurant with the family-friendly bench-seating in wooden booths continues to attract huge numbers of customers from great distances, diners who clearly enjoy the home-style food and surroundings together with the friendly service (http://www.throwedrolls.com/shopcontent.asp?type=Aboutus).
Lead—Soft and Easy to Cast

Lead is a corrosion-resistant dense metal that is easily molded and shaped. The chemical symbol for lead, Pb, is an abbreviation of the Latin word plumbum, meaning soft metal. Archeological research indicates that lead has been used by humans for a variety of purposes for more than 5,000 years. Water pipes that date back to the Roman Empire, glazes on prehistoric ceramics, and the cosmetic kohl, used by ancient Egyptians to darken their eyelids, are a few examples of ancient uses of lead. Today, lead, which has been mined on all continents except Antarctica, is one of the most important metals to industrialized economies.

Lead is rarely found in native form in nature but it combines with other elements to form a variety of interesting and beautiful minerals. Galena, which is the dominant lead ore mineral, is blue-white in color when first uncovered but tarnishes to dull gray when exposed to air.

Scientific research demonstrating how accumulated ingested lead is toxic to human health and how accumulations of lead in the soil, air, and water are toxic to ecosystems is changing both how lead is used and how it is disposed of after use.

How Do We Use Lead?

Prior to the early 1900s, lead was used in the United States primarily in ammunition, burial vault liners, ceramic glazes, leaded glass and crystal, paints or other protective coatings, pewter, and water lines and pipes. Following World War I, the demand for lead increased because of growth in the production of motorized vehicles, many of which use lead-acid batteries to start their engines. The use of lead as radiation shielding in medical analysis and video display equipment and as an additive in gasoline also contributed to an increase in the demand for lead.

According to the U.S. Agency for Toxic Substances and Disease Registry, environmental levels of lead have increased more than 1,000-fold over the past three centuries as a result of human activity. The greatest increase took place between 1950 and 2000 and reflected the increased use of leaded gasoline worldwide. During this period, the U.S. Government established Federal regulations and made recommendations to limit lead emissions to protect public health in the United States.

By the mid-1980s, a significant shift in the uses of lead had taken place in the United States as a result of compliance with environmental regulations and the substitution of other materials for lead in nonbattery products, such as gasoline, paints, solders, and water systems. By the early 2000s, 88 percent of apparent U.S. lead consumption was in lead-acid batteries, which was a substantial increase from 1960 when only 30 percent of global lead consumption was in lead-acid batteries. Today, the other significant uses of lead are in ammunition, oxides in glass and ceramics, casting metals, and sheet lead.

Where Does Lead Come From?

Research to better understand the geologic processes that form mineral deposits, including those containing lead, is an important component of the USGS Mineral Resources Program. Lead commonly occurs in mineral deposits along with other base metals, such as copper and zinc. Lead deposits are broadly classified on the basis of how they are formed. Lead is produced mainly from three types of deposits: sedimentary exhalative (Sedex), Mississippi Valley type (MVT), and volcanogenic massive sulfide (VMS).

Sedex deposits account for more than 50 percent of the world’s lead resources. They are formed when metal-rich hot liquids are released into a water-filled basin (usually an ocean) or in basin sediments, which results in the precipitation of ore-bearing material within basin-floor sediments.

MVT deposits are found throughout the world and get their name from deposits that occur in the Mississippi Valley region of the United States. The deposits are characterized by ore mineral replacement of the carbonate host rock; they are often confined to a single stratigraphic layer and extend over hundreds of square kilometers. MVT deposits were a major source of lead in the United States from the 19th century through the mid-20th century.
In contrast to Sedex and MVT deposits, VMS deposits have a clear association with submarine volcanic processes. They also can contain significant amounts of copper, gold, and silver, in addition to lead and zinc. The “black smoker” sea vents discovered during deep ocean expeditions are examples of VMS deposits being formed on the sea floor today.

Galena is the dominant lead ore mineral. Lead is a corrosion-resistant, dense, ductile, and malleable metal with a low melting point. Among the industrialized countries, lead ranks fifth in the tonnage of metal consumed after iron, aluminum, copper, and zinc.

Worldwide Supply of and Demand for Lead

Currently, approximately 240 mines in more than 40 countries produce lead. World mine production was estimated to be 4.1 million metric tons in 2010, and the leading producers were China, Australia, the United States, and Peru, in descending order of output. In recent years, lead was mined domestically in Alaska, Idaho, Missouri, Montana, and Washington. In addition, secondary (recycled) lead is a significant portion of the global lead supply.

World consumption of refined lead was 9.35 million metric tons in 2010. The leading refined lead consuming countries were China, the United States, and Germany. Demand for lead worldwide is expected to grow largely because of increased consumption in China, which is being driven by growth in the automobile and electric bicycle markets.

How Do We Ensure Adequate Supplies of Lead for the Future?

To help predict where future lead supplies might be located, USGS scientists study how and where identified lead resources are concentrated in the Earth’s crust and use that knowledge to assess the likelihood that undiscovered lead resources exist. Techniques to assess mineral resource potentials have been developed and refined by the USGS to support the stewardship of Federal lands and to better evaluate mineral resource availability in a global context.

In the 1990s, the USGS conducted an assessment of U.S. lead resources and concluded that about as much lead remained to be found as had already been discovered. Specifically, the USGS found that 92 million metric tons of lead had been discovered and estimated that about 85 million metric tons of lead remained undiscovered in the United States.

Mineral resource assessments are dynamic. Because they provide a snapshot that reflects our best understanding of how and where resources are located, the assessments must be updated from time to time as better data become available and new concepts are developed. Current research by the USGS involves updating mineral deposit models and mineral environmental models for lead and other important nonfuel commodities and improving the techniques used to assess for concealed mineral resource potential. The results of this research will provide new information and decrease the amount of uncertainty in future mineral resource assessments.

For More Information

- On production and consumption of lead: http://minerals.usgs.gov/minerals/pubs/commodity/lead/
- The USGS Mineral Resources Program is the sole Federal provider of research and information on lead and other nonfuel mineral resources. For more information, please contact: Mineral Resources Program Coordinator U.S. Geological Survey 913 National Center Reston, VA 20192 Telephone: 703-648-6100 Fax: 703-648-6057 E-mail: minerals@usgs.gov Home page: http://minerals.usgs.gov

The English words plumbing, plumber, plumb, and plumb-bob derive from the Latin word for lead.
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