DISTRIBUTION OF COGENETIC IRON AND CLAY DEPOSITS IN THE CENTRAL APPALACHIAN REGION

by

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Maps of more than 500 abandoned iron mines, 350 early iron furnaces, and numerous clay mines in the central part of the Appalachian region reveal the distribution and close association of siderite-limonite bearing ores and clay deposits. The deposits crop out from Lancaster County, Pennsylvania to Scioto County, Ohio, a distance of more than 300 miles. The geologic settings of the deposits are diverse. In the Valley and Ridge Province and Piedmont Province, mineralization follows structures such as major sub-horizontal thrust faults (e.g. Martic) and steep thrust faults, (e. g. Path Valley), that juxtapose carbonate units against other rocks. Carbonate units within the Plateau Province also contain economic deposits of iron ores and clay. The ores are commonly siderite and limonite principally in the form of nodules and other irregular masses in clayey, calcareous beds. Illite and kaolinite are the main clay minerals. Silica is a common constituent of the clayey rocks and in some of the iron-rich, ore horizons (e.g. Buhrstone). The working hypothesis for the formation of the iron ore and clay is that reactive fluids probably moved westward along structural and stratigraphic horizons in response to tectonic events and where they encounter carbonate rocks, clay formed and iron precipitated under favorable geochemical conditions. This hypothesis differs from other ideas such as weathering and consequent development of leached paleosols, and bog iron formation. Modern models of iron deposition are based on shallow groundwater transporting iron to the precipitation

site. The possible outflow of basinal fluids along deep thrust faults and cross strike discontinuities was considered as an alternative process for iron deposition and clay formation.

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PREFACE

I am grateful to the many people who have freely given their advice and expertise during my studies. The classes and lectures of my past professors gave me the framework for this research and I am truly grateful. But my deepest gratitude goes to Dr. Thomas H. Anderson, my graduate advisor. His acceptance of me as a graduate student and his guidance were vital to completing this thesis. He freely shared his lifetime of field observations to suggest study sites for this research and I benefitted from his insights on Appalachian tectonics. His superb editing has made this manuscript complete.

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sister, Ann Boldt, who took care of our mom in my place. My deepest appreciation goes to my mother and father who gave me an appreciation of nature which I have tried to pass onto my children, Thomas, Steve and Katy.

1.0 INTRODUCTION AND PURPOSE

This thesis assesses the distribution of associated, and presumably, co-genetic, economic iron and clay deposits as indicated by locations of historic iron mines, early iron furnaces and clay mines (Figure 1). The purpose of the research is to study the association of the iron oxides and clay with the objective of understanding the conditions and processes responsible for the distribution of sedimentary iron ore and clay across the central Appalachians. In order to assess the conditions under which the iron ore and clay is formed, a map was produced using GIS mapping techniques and employing historical references. The ultimate goal is to assess whether iron mineralization is indicative of basinal fluid movement across the orogenic belt through preferred fluid pathways.

The maps demonstrate that iron and clay have a geographic relationship to faults, cross-strike discontinuities and/or to porous and permeable stratigraphic units and that the deposits commonly are hosted in the same calcareous beds (Figure 2). In the Piedmont, Blue Ridge and Valley and Ridge Provinces, iron ore and clay commonly crop out along thrust faults. In the Plateau Province the deposits lie within calcareous units, among sub-horizontal coal, shale, carbonate and sandstone strata (Figure 3). These settings record the importance of carbonate beds and porous, permeable structural and stratigraphic conditions in the formation of iron ores and clay deposits. The distribution of ore and clay that record permeable pathways along thrust faults, cross-strike structural discontinuities, and permeable sandstone are postulated to have conducted warm reactive fluids rich in iron and silica probably from east to west. Where the fluids interacted with carbonate rocks, some of which are folded, iron precipitated as iron carbonate (siderite) which is commonly oxidized to limonite and other oxides, in clay-rich and locally siliceous horizons hosted within strongly altered carbonate beds. The deposits reveal the fluid pathways of the central Appalachian Mountains that extended from the Blue Ridge Province of Pennsylvania to the western edge of the foreland basin in Ohio, a distance of about 300 miles.

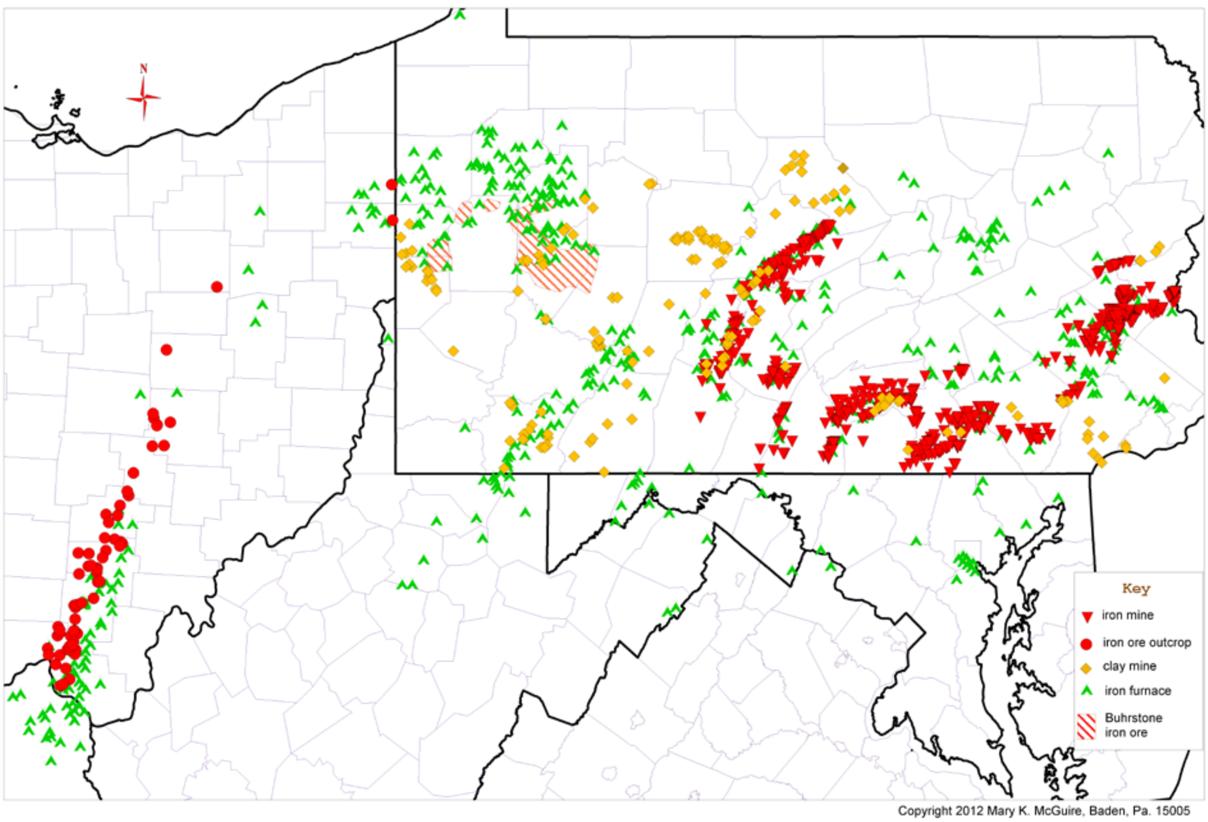


Figure 1: Iron furnaces, iron mines, clay mines and iron ore outcrops in Ohio and Pennsylvania

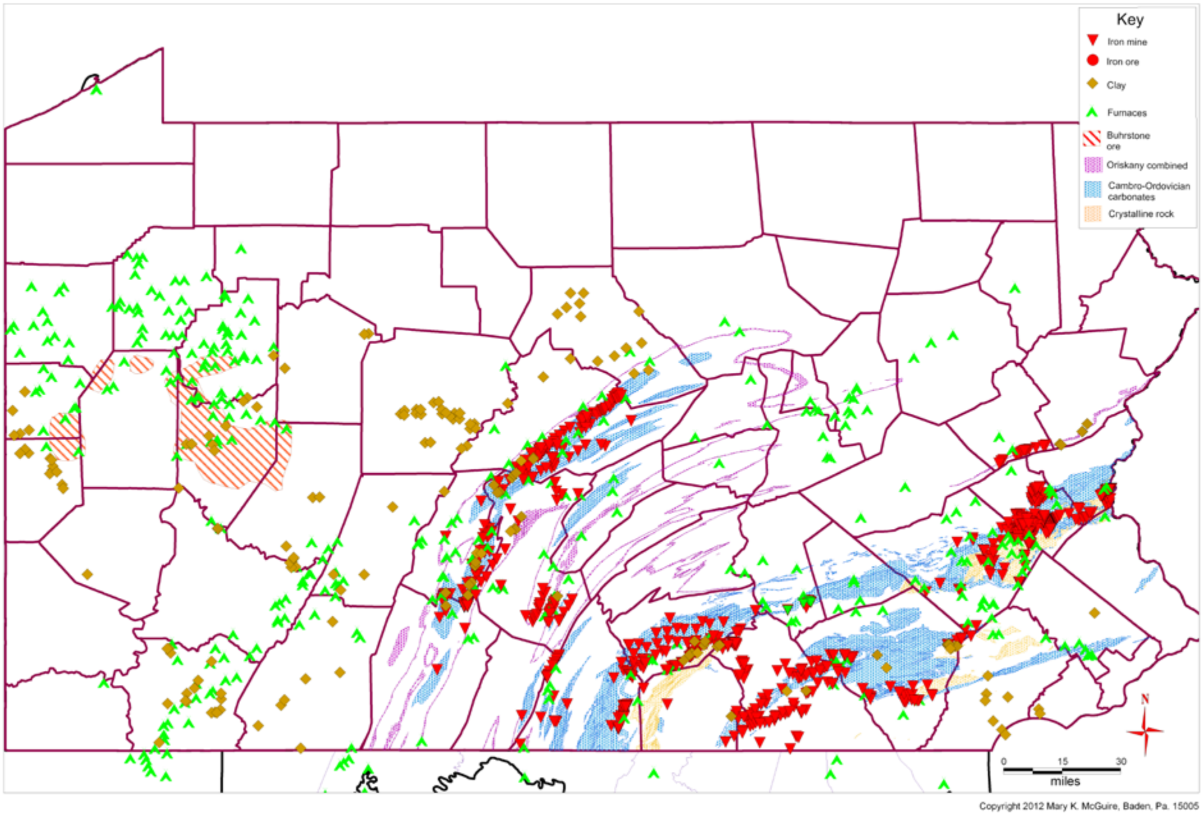


Figure 2: Iron and clay mines in relation to carbonate and crystalline rocks of Pennsylvania

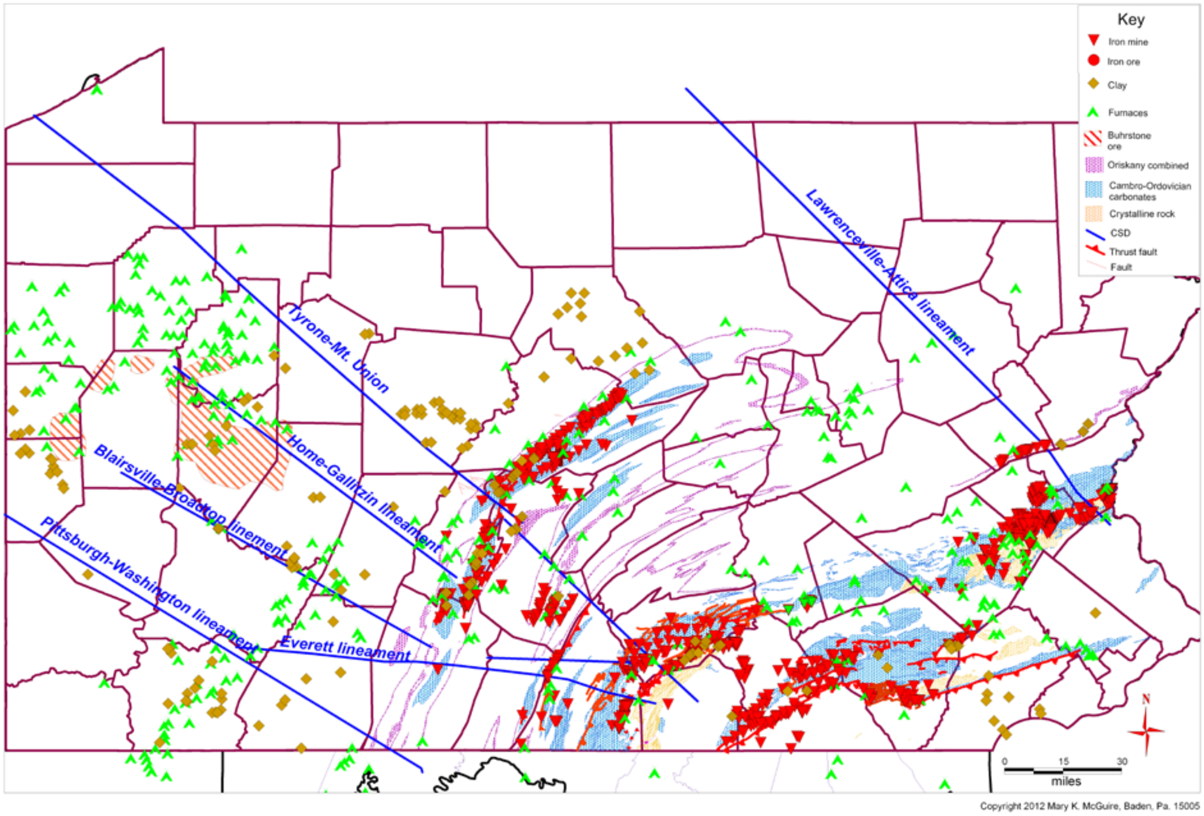


Figure 3: Iron and clay mines relative to cross strike structural discontinuities and faults in Pennsylvania

1.1 PREVIOUS WORK

Iron and clay

White clay, composed chiefly of kaolinite and illite, has been mined in Pennsylvania since about 1890 for use in the paper industry. Although most clay is light gray to white, some is stained yellow, pink, or brown by iron oxides. Kaolinite is the predominate clay mineral but illite is abundant in some deposits (Hosterman, 1984). Quartz is the only non-clay mineral in the whitest clay and reaches 50 per cent in some deposits. Goethite is present in some samples high in iron (Hosterman, 1984).

The source of the clay is believed to be residual clay from the chemical erosion of the carbonate bedrock or from weathering of feldspars in local sandstones (Slingerland, 1995). Since the surface of the white clay pocket is covered with sand and quartzite fragments, the clay deposits were discovered when prospecting for iron ore (Leighton, 1941).

Iron ore is defined as a mineral or group of minerals containing sufficient iron to be economically used in iron production (Eckel, 1914). Iron ore was mined within the Appalachian region until production shifted to the Lake Superior region in the 1870’s. Iron mining for the first charcoal furnace began in 1720 for the Colebrookdale Furnace, Berks County, Pennsylvania (Bining, 1938). In Pennsylvania magnetite was the principle ore mined along with brown ore (limonite). In 1910, 632,409 tons of magnetite compared to 106,544 tons of brown ore was produced (Eckel, 1914).

Iron ore in Pennsylvania is found in igneous, metamorphic and sedimentary rocks. In sedimentary rocks ore is present as iron oxides (limonite, goethite, or hematite), iron carbonate (siderite), and iron silicates (chamosite, glauconite, and greenalite) (James, 1966).

Igneous and metamorphic rocks, mainly in eastern Pennsylvania host magnetite and hematite ore (Inners, 1999). Hematite was mined at Durham, Bucks County, in the Reading Prong from within metasedimentary rock (Inners, 1999). The magnetite generally is present in quartz-oligoclase gneiss, amphibolite, pyroxene gneiss, quartz-potassium feldspar gneiss and marble skarn (Puffer, 1980; Eckel, 1914). Magnetite also is found as a replacement of carbonate rocks adjacent to Jurassic diabase intrusions in southeastern Pennsylvania. This ore is referred to as the Cornwall-type, named after the first known deposit in Cornwall, Pennsylvania where an estimated 153 million tons of magnetite ore have been produced from the Cornwall mine (Gray, 1999; Smith, 1988).

In Pennsylvania, sedimentary strata host some distinctive ores. The ores, which may be primary or secondary, include many compounds, mainly oxides. The ores discussed herein are associated with sedimentary rocks especially carbonate rocks. The minerals generally associated with sedimentary iron deposits within the Appalachian region include: limonite, siderite, magnetite, and hematite.

Multiple mechanisms account for the accumulation of these minerals as a potential ore. Iron may be incorporated into a sedimentary deposit at the time of deposition or may form later as a result of weathering or interaction with groundwater, a process known as secondary enrichment. Chemical sedimentation is the precipitation of an iron mineral out of the iron-bearing water. Clastic sedimentation is the physical accumulation of iron mineral grains within the sediment. Weathering is the physical degradation of a sedimentary rock, and the subsequent oxidation of an iron mineral. Solution–remobilization occurs when iron is chemically scavenged from adjacent lithologies, transported to another location and deposited (Guilbert, 1986).

Examples of iron deposits formed by chemical precipitation are the Clinton-type ore, the bog iron ore, the siderite ores and metallic sulfide deposits. Iron can be deposited within the pore space of sedimentary rocks by circulating iron-bearing water when changes in the geochemical environment favors the precipitation of iron minerals such as iron sulfide (pyrite, marcasite), iron carbonate (siderite) or an iron oxide/hydroxide (hematite, limonite, goethite). The geochemical factors include temperature, pressure, oxidation state Eh, pH, iron concentration, available sulfur and organic material. Precipitation of iron can occur prior to lithification of the sediments or at a later time during diagenesis. Additional iron minerals that may form during diagenesis are chamosite and glauconite. The exposure of sedimentary rocks to weathering can change the mineral form of the iron. For example, siderite beneath overburden changes to limonite at the outcrop.

Clinton-type Deposits

Oolitic ferruginous strata known as Clinton ores are included among sedimentary iron deposits (Guilbert, 1986). The Clinton ore deposit is an extensive deposit which crops out in the Appalachian region from New York to Alabama. The deposit is fossiliferous with fossils replaced by hematite (Guilbert, 1986). The Clinton Formation accumulated in shallow marine environment. CastaHo (1950) suggests that when ferrous iron is carried into a marine environment where solid calcium carbonate is in equilibrium with the sea water, iron will precipitate. The ferrous iron precipitates as ferric iron in the water and as a replacement of the calcium carbonate(CastaHo, 1950).

Pyrite Precipitation

Iron can combine with sulfur to form iron sulfides. Biochemical processes influence the precipitation of sulfide deposits (Guilbert, 1986). Reducing or anaerobic environments where sulfur is available favor pyrite formation as described in the phase diagrams by Garrels (1960). Rocks with high pyrite content are black shales or their equivalents with a large organic content (James, 1966). The presence of organic material and anaerobic sulfate-reducing bacteria in the sediment allows the development of pyrite because of the creation of a reducing geochemical environment with low oxidation potential necessary for sulfide formation (James, 1966). This association of organic material to pyrite formation is found in marine influenced, organic–rich horizons in the Mississippi delta sediments (Bailey, 1998).

Mississippi Valley-type (MVT) deposits are massive sulfide deposits of lead, zinc or iron and the gangue minerals of calcite, quartz, dolomite, jasperoid, fluorite and barite that precipitated from moderate temperature brines, typically 110 to 150 degrees Centigrade (Cathles, 1983; Ohle, 1959). Most deposits are hosted in limestone and dolomite with some deposits in sandstone (Ohle, 1952). The zinc, lead, and iron sulfide occur as replacements of the country rock and in open space fillings (Ohle, 1959). These deposits formed from brines expelled from sedimentary basins (Cathles, 1983). A recognized MVT deposit in Pennsylvania is the Friedensville deposit in Lehigh County which is a zinc and iron sulfide deposit.

Bog iron deposits are found in northwestern Pennsylvania. Bog iron forms where groundwater carrying dissolved iron enters an oxygenated zone and precipitates the iron as hydrous ferric oxide. Bog iron was utilized for the production in colonial iron furnaces in northwestern and northeastern Pennsylvania.

Bog iron deposits are found in northwestern Pennsylvania in bogs, marshes, meadows, etc. (Corbin, 1922). Bog ore is a soft, spongy deposit of limonite that forms as a precipitate from iron-bearing water (Inners, 1999). Bog ores are found within sedimentary rocks in which iron formed as the result of chemical precipitation. Bog ore style of precipitation occurs when the ground water carries dissolved ferrous iron until the iron is oxidized at the top of the water table or as it emerges into a marsh. Oxidized iron precipitates and forms ferruginous cement around the grains of the sand, silt and clay to form a hard crust. Repeated fluctuations in the water table level add to the thickness of the iron crust (Langmuir, personal communication). Bog ore is iron-red in color, and has a tabular, pisolithic, nodular, laminated or irregular aggregate form (Inners, 1999).

The deposition model for limonite ore above the Gatesburg Formation in central Pennsylvania is that iron is mobilized under anaerobic, acidic conditions and subsequently precipitated along the top of the Gatesburg. Iron may be mobilized into solution in a swamp in which decaying organic material creates a low Eh (reducing), low pH (acidic) condition (Rose, 1995). As the swamp water percolates downward the iron is transported to the bedrock-soil interface and comes into contact with an alkaline carbonate surface where the iron precipitates along joints to build up into massive, irregular limonite forms. If the iron-carrying groundwater enters a cave, the iron can deposit on the surface of stalactites and become incorporated into the limestone as an iron carbonate mineral. Continued dissolution of the carbonate results in the limonite masses remaining behind in the residual clay soil.

Siderite

Siderite (iron carbonate) is an iron ore mineral that composes beds or nodules that form during precipitation or as an alteration of preexisting carbonate concretions, respectively. Factors influencing the formation of iron sulfide or iron carbonate precipitation include the action of bacteria, the amount of marine sulfate in the sediment and a source of carbon. Iron carbonate nodules or concretions form in deltaic or brackish water (Pye, 1990).

Siderite has been found in bogs, marshes (Postma, 1977) and recent, unconsolidated mud in the Mississippi Delta in a sulfate-deficient system where terrigenous, siliclastic sediments have prograded into lacustrine environments (Aslan, 1999). Siderite forms around fragments of wood of metal or may form without a nucleus (Pye, 1990) where there is a deficit of sulfate in the porewater (Bailey, 1998). Siderite precipitates in the interstices of sediment incorporating the silt/clay particles within the concretion (Bailey, 1998).

Siderite layer adjacent to a bed is called blackband ore. The siderite layer is postulated to have formed contemporaneously with peat accumulation (Stout, 1944). The blackband siderite deposits require a low-sulfate, anoxic water chemistry (Olsen, 1991; Berner, 1981).

Weathering Processes

The association of iron and clay ores in Paleozoic rocks, attributed to the passage of reactive fluids contrasts with the idea that iron was mobilized and transported during deposition or during later weathering of late Paleozoic rocks (e.g. Rose, 1995). The weathering process or leaching of paleosols commonly was considered to be an important process in the formation of clay deposits (e.g.Williams, 1985b). Weathering of feldspathic sandstone, argillaceous and cherty limestone and phyllite was considered the source of the clay (Stose, 1907; Peck, 1922

Leighton, 1934). Iron ore in sedimentary rocks has been considered a product of shallow groundwater mobilizing and transporting iron during deposition or during later weathering of the rock (Rose, 1995). Ore may form laterite, a supergene enrichment deposit, in response to weathering. Weathering occurs when meteoric water attacks the minerals within the bedrock. Meteoric water is slightly acidic and contains humic acids as well as carbonic acid so that the pH can be as low as 4.0 or 5.0 (Guilbert, 1986). Meteoric water also is oxidized and can oxidize, hydrate and carbonatize rock-forming silicate minerals (Guilbert, 1986). The interaction of meteoric water and carbonate rocks leads to the dissolution of limestone and dolomite, leaving behind residual minerals that were incorporated into the carbonate rock at the time of deposition. During normal weathering conditions, exposure to meteoric water leads to the removal of alkalies and alkali earths, sodium, potassium, calcium, and magnesium from the residual soil developed on the bedrock (Guilbert, 1986). Oxides of iron, aluminum, chromium and titanium that are relatively immobile are concentrated in the residuum. The relative mobility of the alkalies, alkali earths, and oxides are shown in Table 1.

Table 1: Mobilities of oxides during weathering processes (taken from Guilbert, 1986)

Group	Oxides	Relative Mobility	
Sesquioxides	Cr_2O_3	60	1-100 = Low
	Al_2O_3	2	
	Fe_2O_3	30	
Dioxides	TiO_2	10-100	100-500 = Moderate
	SiO_2	300	
Alkalies, alkali earths	Na_2O	1000	500-10,000 = High
	K_2O	100-1000	
	CaO	500-2000	
	MgO	300-2000	

Laterite forms during intense weathering of rocks exposed to tropical conditions and subject to high rainfall. The resulting soil is enriched in iron and aluminum oxides, oxyhydroxides or hydroxides, kaolinite and quartz (Tardy, 1992). Laterite iron deposits form as the siliceous components of the soil dissolve without eroding the soil with the iron and aluminum oxides remaining in the soil (Guilbert, 1986). Iron laterites are formed over iron-rich, silica-poor rocks such as serpentine (Guilbert, 1986). In areas where the bedrock is rich in aluminum and low in iron and silica (such as syenites and nepheline syenites), bauxite is likely to form (Guilbert, 1986). Bauxites are a mixture of boehmite, gibbsite, diaspore and other hydrous aluminum oxides (Guilbert, 1986). Bauxites also form over argillaceous carbonate rocks along with terra rossa, a residual, ferruginous clay (Guilbert, 1986). Whether the weathering process leaches silica, iron or aluminum is dependent on the ph and Eh soil water conditions (Guilbert, 1986). Figure 4 shows that under acid, oxidizing conditions, iron and silica are relatively immobile and aluminum is leached from the soil. Under neutral pH and moderate oxidizing conditions, bauxite is created because the iron and silica are leached, leaving behind the aluminum oxides (Guilbert, 1986). In an iron-rich laterite, iron oxides are found as pellets of limonite. Most laterites have pisolitic, concretionary structures, or pisolitic crusts formed around grassroots (Guilbert, 1986).

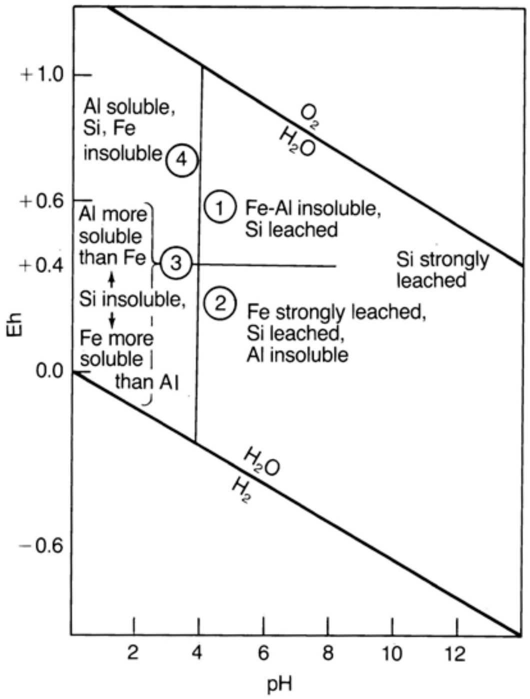


Figure 4: Laterite formation relative to pH and Eh conditions (taken from Guilbert, 1986), zone 1 is laterite field, zone 2 is bauxite field, zone 3 is podzol soil field and zone 4 is high-iron laterite field

Limonite ores are abundant in the Cambrian and Ordovician limestones in the Valley and Ridge and Piedmont Provinces where limonite is found as irregular chunks and stalactitic and botryoidal masses within variegated clays overlying carbonate rocks (e.g. the Gatesburg Formation (Sternagle, 1986). In addition to limonite, limonite ore may include hydrous ferric oxides, and hematite. Hydrous ferric oxides that differ in the amount of water held within the mineral. Chemical formulas for this group of minerals along with hematite are listed in Table 2. The mixture of compounds may lead to confusion about the mineral makeup of limonite ore deposit (Eckel, 1914). Limonite ore is used in this manuscript to describe the group of ferric oxides.

Table 2: Chemical formulae of ferric oxide minerals (taken from Eckels, 1914)

Mineral name	Chemical formula
hematite	2 Fe_2O_3, 0 H_2O
turgite	2 Fe_2O_3, 1 H_2O
goethite	2 Fe_2O_3, 2 H_2O
limonite	2 Fe_2O_3, 3 H_2O
xanthosiderite	2 Fe_2O_3, 4 H_2O
limnite	2 Fe_2O_3, 5 H_2O

Over the Gatesburg Formation in central Pennsylvania, limonite ore is associated with massive kaolinite clay deposits (Hosterman, 1984). Mined limonite ore occurs as irregular masses of varying size, in three forms: wash ore, lump ore and pipe ore. Wash ore consists of small fragments of limonite and limonite-impregnated sandstone and chert found interspersed within a clay and sand layer five to fifteen meters thick (Rose, 1995). The limonite fragments are soft, weathered and vary in size up to ten centimeters in diameter (Rose, 1995). The wash ore layer generally lacks internal structure, although layers of stiff white to pink clay may extend through the deposit (Rose, 1995). Lump ore are larger pieces of limonite ore up to fifty centimeters in size found at the base of the weathered zone above the Gatesburg (Rose, 1999). Lump and wash ore have breccia textures with angular fragments of chert or sandstone cemented with limonite (Rose, 1995). The term pipe ore was used for masses of limonite ore that had a linear or pipe-like shape. Pipe ore was recorded within limestone bedrock (D'Invilliers, 1884).

In Centre and Huntingdon Counties, weathering that leads to the dissolution of the carbonate component of the limestone leaving residual clays and iron is the commonly the accepted model for limonite formation. Another model of limonite formation in deposits situated along mountain slopes is that slightly acidic precipitation running off and through clastics near the top of the mountain will pick up small amounts of iron. The iron-bearing water as precipitation runoff encounters a carbonate unit further down the slope and dissolves the carbonate, leaving behind limestone residuum. Iron precipitates along the limestone surface as limonite. Continued dissolution of the carbonate leaves behind the limonite ore (Nichelsen, 1963).

Cornwall-type Iron Deposits or Metasomatic Carbonate Replacement Ore

Deposits of magnetite cropped out along the Mesozoic border faults in the Piedmont Province. These are contact metasomatic deposits that formed as replacements of carbonate rocks adjacent to the diabase intrusions (Rose, 1985). Traditional theory of ore implacement was that aqueous fluids from diabase magma flowed from the diabase into the surrounding limestone (Rose et al, 1985). Later, (Rose, 1985) proposed that circulating meteoric, connate and possibly some magmatic water became heated by the diabase intrusion, mobilized iron, and exchanged ´ ^{18}O with the adjacent shales, argillaceous sandstones and limestones at high temperature. This heated fluid came into contact with the carbonate rock at the contact zone of the diabase and replaced the carbonate with magnetite and silicates (Rose, 1985).

Clay Deposits

Deposits of clay are widespread in the central Appalachians and are known from each of the principal geologic provinces containing carbonate rocks from eastern Pennsylvania to eastern Ohio. In the Piedmont, clay deposits have been mined in the Cambrian Harpers phyllite, Antietam quartzite and Chickies quartzite. The source of the clay was feldspar minerals within the quartzites and phyllites which altered to clay (Leighton, 1941). Around South Mountain, the Cambrian quartzites and quartz schists are reduced to siliceous white clay (Leighton, 1941). A large clay mine at Toland was initially an iron mine (Way, 1986). The mine sits at the southeastern slope of South Mountain with the northern boundary is comprised of a fault so the clay is in contact with the Montalto Member of the Harpers Formation (Way, 1986). The south boundary of the clay pit grades into a grayish green to light gray phyllite, the Tomstown Formation which is thought to be the parent material of the clay (Way, 1986). Important commercial horizons of white clay were mined in Centre, Blair, Huntingdon, Cumberland and Monroe Counties. These clay deposits are found in the Gatesburg Formation and the Oriskany sandstone. Clay deposits in the Valley and Ridge were found in the Cambrian Gatesburg and Devonian Oriskany Formations. The clay is associated with limonite iron deposits (Hopkins, 1900). The clays vary from pure white to light gray in color and may be stained yellow, red, or black (Hopkins, 1900) The deposits are predominantly kaolinite with varying amounts of illite and quartz or chert (Hosterman, 1984).

Perhaps the best known clay deposits comprise numerous "underclays" that are commonly found adjacent to Pennsylvanian coal beds in the Appalachian Plateau. Underclay is non-laminated, non-bedded, and consists of kaolinite, illite, chlorite, vermiculite, as well as accessory minerals such as iron and quartz. Underclay can be composed of plastic clay and/or flint clay. Flint clay breaks with a conchoidal fracture and does not become plastic when mixed with water but will become plastic after grinding (Hopkins, 1897). Plastic clays are commonly hard enough to require drilling and blasting during mining and will crumble to soft, plastic clay when exposed to the weather (Hopkins, 1897). Flint clay and plastic clay may both occur under the coal or only one type may be present. Normally an underclay is directly beneath a coal seam; however, underclay may be separated from the coal by shale or sandstone (Hopkins, 1897).

Western Pennsylvania contains high-quality fire-clays in the Pennsylvanian Pottsville and Allegheny Formations (Leighton, 1941). An underclay of the Lower Kittanning coal, four to nine feet thick, was used commercially in the Beaver Valley, Pennsylvania and in East Liverpool, Ohio. The lower part of the bed is plastic clay that imperceptibly grades into a flaggy sandstone (Hopkins, 1897), therefore the thickness of usable clay is variable. The Lower Freeport clay is very plastic, and light-colored but in most places contains iron oxide fragments (Hopkins, 1897). At Bolivar, Westmoreland County, Pennsylvania, the Bolivar clay horizon below the Lower Freeport underclay and limestone was known to contain iron ore balls which exhibited concentric weathering (Hopkins, 1897).

Origin of underclay

The origin of the underclay has been debated and several origins have been proposed. Hopkins (1897) wrote that the origin of the underclay was linked with the coal bed and that the underclay formed in the bottom of a swamp or bog. The growth and decay of vegetation extracted iron and alkalies from the sediment (Hopkins, 1897); therefore, underclays contain less sodium, and potassium than ordinary clay soils.

Another early theory has it that underclay is a fossil soil which grew coal-forming plants (Rimmer, 1982). (Wanless, 1931) indicated that the underclay is similar to a poorly drained soil (Rimmer, 1982). Huddle and Patterson (1961) suggested that the underclay underwent in situ leaching before, during or after peat accumulation (Huddle, 1961) . Other theories included the alteration of volcanic ash, (Patterson, 1962; Seiders, 1965), and the deposition of colloidal clay from lateritic weathering in swamps (Patterson, 1962; Bolger, 1952; Burst, 1952).

Modern studies have involved mineral analysis of the clays and accessory minerals to understand the geochemical environment of the underclay as it evolved from sediment into current form. Williams and Holbrook (1985) used the mineralogical makeup of underclay in the Lower Kittanning underclay with respect to the amount of kaolinite and illite and the presence or absence of chlorite, iron and silica in the clay bed as a basis for his hypothesis for clay formation. The mineral content variations may reflect post-depositional changes in fine-grained, argillaceous sediment. For example, underclay which does not contain chlorite and is rich in kaolinite relative to illite and mica are believed to have been exposed on a topographic high (Williams, 1985b). Also, a vertical increase in the kaolinite/illite ratio and the kaolinite/mica ratio indicates that the sediment was exposed to leaching. Similarly, a vertical decrease in quartz and an increase in vermiculite also suggest leaching (Williams, 1985b). By mapping the kaolinite, illite, chlorite, vermiculite, and mica content in the Lower Kittanning underclay, Williams concluded that the underclay with more intense leaching covers paleotopographic highs.

In underclays that were considered not to have undergone such intense leaching, chlorite was present through the whole section, the kaolinite/mica ratio did not increase to the same degree, quartz content did not decrease toward the top and siderite nodules were present in the bottom of the section. In conclusion, leaching of soils above the water table results in the removal of chlorite, an increase in the kaolinite/illite ratio, and removal of quartz.

Underclays do not have iron oxide zonation seen in modern, well-drained soils and another process is needed to account for the removal of iron (Gardner, 1988). A possible process is gleying during which the clay is submerged. Gleying lowers the amount of oxygen in the soil, thereby producing an anaerobic environment (Gardner, 1988). Peat deposited over the clay would increase the amount of organic acids and lower the pH, creating an acidic condition. In this manner, gleying produces a reduced, acidic environment that is conducive to the mobilization of iron from the clay into the groundwater (Gardner, 1988). Williams (1985) concludes that underclay was soil that had been exposed to precipitation long enough to strongly leach the alkalies and silica, and then submerged long enough to reduce the amount of iron while coal swamps grew.

Williams (1985) applied his idea of leaching along paleotopographic highs to the origin of high-alumina deposits of the Mercer clay in Clearfield, Centre and Clinton Counties. High-alumina clays contain diaspore (AlO(OH), boehmite (AlO(OH), and gibbsite ($Al(OH)_3$) in addition to kaolinite ($Al2Si_2O_5(OH)_4$) and are valuable for refractory brick manufacture (Williams, 1985a). These deposits are found on top of the sandstones and redbeds of the Mississippian Mauch Chunk Formation and below the Mercer coal. This clay assemblage is known in only one other area in the United States, the Cheltenham fire clays of Missouri (Williams, 1985a).

Origin of flint clay

The origin of flint clay has also been debated and few theories exist to explain its origin. Flint clay is chemically similar to plastic clay and becomes plastic by grinding. Hodson (1927) suggested that fire clays were deposited in swamps and the iron and alkalis were leached out by water containing carbonic and organic acid (Hodson, 1927). Another theory is that flint clay may be derived from alteration of volcanic ash. Support for this theory comes from a flint clay parting that was identified within the Fire Clay coal bed in the eastern Kentucky coal field as altered volcanic ash (Rice, 1994) (Rice, 1994). Flint clay can also be the result of hydrothermally altered calcareous shale. Hanson and Keller (1971) studied a flint clay deposit in Estola, Guerrero, Mexico, that is an alteration of calcareous, silty shale into a well-ordered kaolinite (Hanson, 1970). Calcareous, silty shale could be seen grading into homogeneous, fine-grained, slightly off-white clay that fractures conchoidally. The color variations in the clay are due to iron mobilization and partial redeposition in the transition zone along the margin of hydrothermal refractory clay deposit in contact with limestone rocks (Keller, 1969).

Valley and Ridge

The clay deposits are considered to be residual deposits derived from argillaceous and cherty limestones and phyllites (Hosterman, 1984). Clay deposits are traditionally believed to have been formed by chemical weathering (Hosterman, 1984). The clay deposit at Toland near Mount Holly Springs has indications of hydrothermal action in addition to normal weathering. Hosterman (1984) conclusion is based on trace amounts of alunite and vertical variation in the white clay section in particle size, clay-mineral ratio, silica and iron oxide content. With normal weathering by precipitation, kaolinite increases at the upper zone while quartz decreases, iron decreases, and alkali content decreases (Williams, 1985b).

In samples taken from an auger hole at the Toland clay pit, alunite was seen in X-ray diffraction patterns between 4 to 24 meters. Hosterman (1984) concluded that the silica (SiO_2) content decreasing and Al_2O_3 content increasing with depth was not because of lithologic differences but was due to hydrothermal alteration (Hosterman, 1984). In the Silurian Clinton Formation Clinton-type ores consist of fossiliferous, oolitic sandstone and siltstone with hematite coated grains. Another sedimentary ore is Hamilton ore mined in Perry County (Inners, 1999). This hematitic ore was mined from oolitic, sandy, silt shale in the Middle Devonian Mahantango

Formation (Inners, 1999). Brown limonite ores are closely associated with extensive clay deposits and carbonate rocks. Two important formations hosting brown limonite ore are the Cambrian Gatesburg Formation and the Devonian Oriskany Formation in which brown limonite ore is imbedded in masses of clay. Sedimentary iron ore also includes limonite/siderite deposits, mostly nodules associated with the carbonate beds of Pennsylvanian age rocks.

1.2 METHODS

The location of early iron production sites (charcoal furnaces) was mapped in order to identify the geographic locations where iron ore was mined (Figure 1). Iron furnace locations in Pennsylvania were acquired from Lesley (1859) who provided a summary of working and abandoned furnaces throughout the Appalachian region. Additional western Pennsylvania furnace locations were acquired from works by Sharp (1964), Pearse (1876) and Parks (2011). These early maps were used to locate the early mines in eastern and central Pennsylvania. The locations of iron furnaces, presumably close to the ore source, were plotted in order to determine the iron ore localities.

In the 1800's, iron deposits were actively being sought for economic development by the state geologists of Pennsylvania and Ohio. Historical records of iron mining activity in the Pennsylvania Geological Survey Second Series reports and Geological Survey of Ohio Fourth Series documented the location of early iron mines. The reports used for locating iron mines are listed in Appendix A. References for locating clay mines are listed in Appendix B.

Ohio iron ore locations were researched in Geological Survey of Ohio Fourth Series, Bulletin 45 (Stout, 1944). Early county maps in the 1876 Historical Atlas of Berks County showed the furnace and mine locations in Berks County.

Mapping of the known iron and clay mines was performed on GIS database software so that the mine sites may be superimposed against the bedrock units as mapped in the Geologic Map of Pennsylvania (Berg, 1980). This process enabled the classification of the mines according to geologic settings and fault locations. Although some faults were mapped on the Geologic Map of Pennsylvania, additional mapping for faults was performed based on the geology maps published for 7.5 minute quadrangles, Map 61 (Berg, 1981). Faults identified in reports of Root (1968, 1971, 1977), Freedman (1967), Brown (2006), Faill (1989), and Jonas (1926) of the Pennsylvania Geologic Survey were also added to the GIS database.

Two modern databases of mine locations and activity prepared by the US Bureau of Mines (USBM) and the USGS were also used. The USBM Mineral Availability System and Mineral Industry Location Files (MAS/MILS) were compiled between 1975 to 1984 (http://research.archives.gov/description/628175). The accuracy of the locations of the mines within the database varies by commodities and by state (Shields, 1995). The MAS/MILS contains records compiled from sources dated from 1908 to 1984. Pennsylvania iron mines were selected from the database and then imported as a GIS layer.

A USGS database of metallogenic deposits, Open File Report 01-136, Lithochronologic Units and Mineral Deposits of the Appalachian Orogen from Maine to Alabama, was queried for Pennsylvania iron mines and imported as a GIS layer. U.S. Geological Survey mine information is published in USGS Open File Report 01-136, titled “Lithochronologic Units and Mineral Deposits of the Appalachian Orogen from Maine to Alabama” by J.D. Peper, J.E. Gair, M.P.

Foose, T.H. Kress, and C.L. Dicken (2001). This map was compiled in the 1980's to show the metallogenic character of the Appalachians. Both large and small deposits were included. The data was published in 2001 in GIS vector format. Because of the inaccuracy of the mine location and duplication among different databases, one mine may show as two or three mines in close proximity to each other.

2.0 STRUCTURE OF THE APPALACHIAN REGION

In Pennsylvania, five main tectono-physiographic provinces, are distinguished principally by their structural, stratigraphic and morphologic characteristics. They include: the Appalachian Plateaus Province, and, Valley and Ridge Province, underlain by Paleozoic strata, and the Blue Ridge Province, Reading Prong, and Piedmont Province, underlain mostly by Paleozoic as well as Precambrian crystalline units (Figure 5).

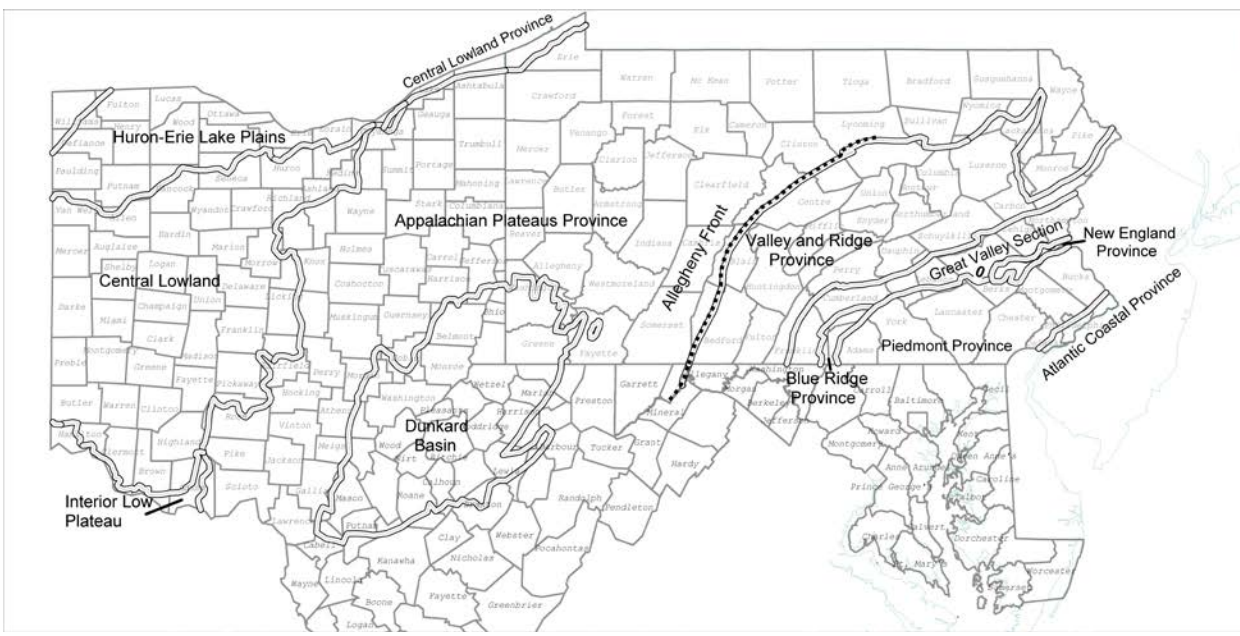


Figure 5: Physiographic provinces of Pennsylvania and Ohio (adapted from Pennsylvania Geological Survey Map 13 and Ohio Division of Geological Survey, 1998, Physiographic Regions of Ohio)

The Appalachian orogenic belt is composed mainly of sedimentary rocks that record three main episodes of contraction, - Taconic, Acadian, and Alleghenian - and one of extension since the Precambrian. The earliest sediments are clastics and overlying carbonate strata deposited on the continental margin of Laurentia during Cambrian and Ordovician time.

Appalachian Plateau

In the Appalachian Plateaus, the sub-horizontal geologic units record broad gentle folds that trend northeasterly, parallel to the Valley and Ridge structures. The folds are open with wavelengths between of 8 to 32 kilometers and amplitudes that range from less than 15 meters to more than 200 meters (Piper, 1933). The Plateau has rare thrust faults of local extent and small throw (2 to 5 meters) (Johnson, 1928).

At depth, the interval from the Silurian Salina to the Middle Devonian Onondaga Formations is faulted extensively (Beardsley, 1999). High-angle reverse thrust faults in the Devonian Tully to the Devonian Ridgeley units flatten at depth into a décollement surface within the Salina Group (Beardsley, 1999). In southwestern Pennsylvania, Tonoloway Formation and the Upper Ordovician Reedsville shale also accommodated detachment that resulted in faulting in the overlying Oriskany Sandstone (Wiltschko, 1977).

Valley and Ridge Province

In the Valley and Ridge Province, where long, limestone valleys are bounded by ridges capped with erosion resistant sandstone formations that coincide with fold limbs, folds and deep thrust faults are common. The ridges strike northeast as shown by the shaded relief map of the Ridge and Valley Province (Figure 6). The thrust faults generally dip southeast extend a regional décollement within the Lower Cambrian Waynesboro shale (Figure 7) (Faill, 1999). The décollement extends from the Allegheny Front southeastward beneath the Valley and Ridge at a depth of four to seven miles (Faill, 1999). West of the Allegheny Front, the deep décollement ramps upward to salt in the Silurian Salina Group that serves as the basal detachment beneath the Plateau (Laughrey, 2004; Gwinn, 1964 ; Frey, 1973); Gwinn, 1964.

Detachment faults and blind thrust faults accommodated much contraction in the Valley and Ridge (Faill, 1999). Short strike-slip faults or wrench faults cut across the major folds (Faill, 1999) and rare, small, normal faults, restricted to the vertical and over-turned beds in the northwest limbs of anticlines, may be present (Laughrey, 2004).

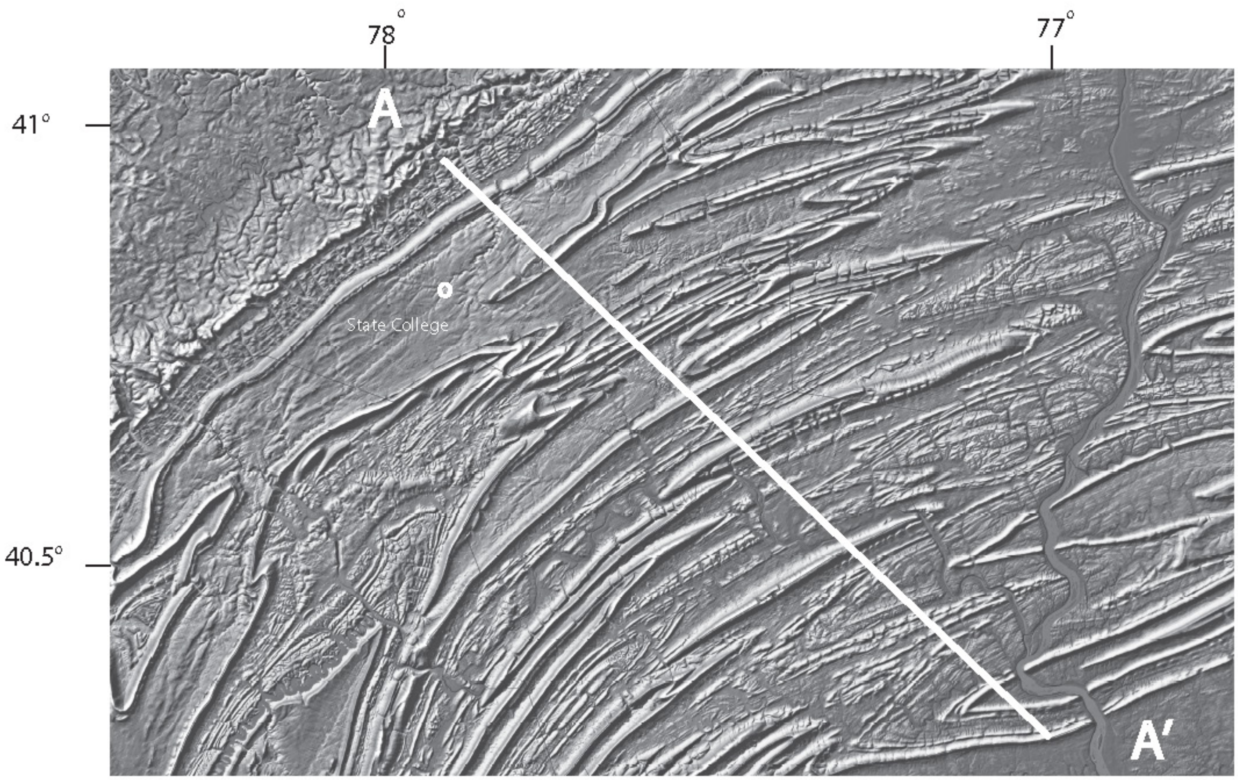


Figure 6: Orientation of folds in Valley and Ridge Province, Pennsylvania (based on Map 65, Pennsylvania Geological Survey Fourth Series)

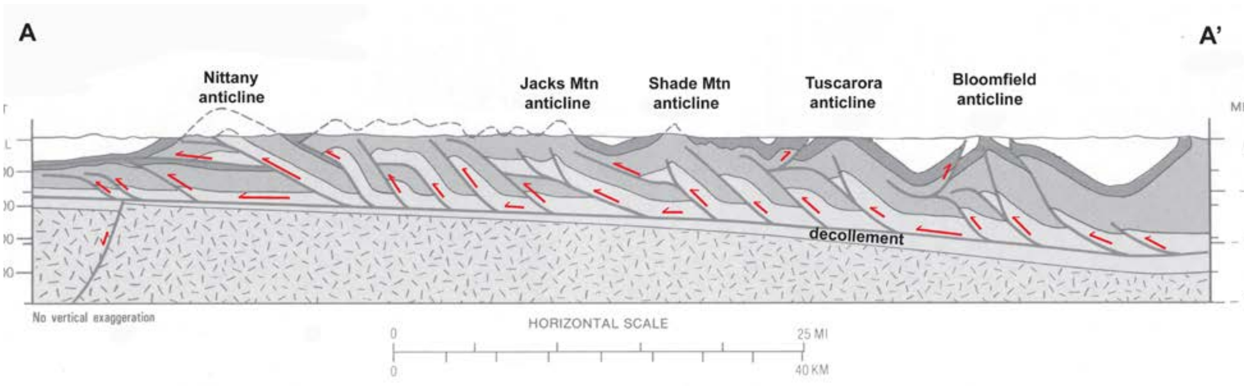


Figure 7: Valley and Ridge cross section (adapted from Faill and Nickelsen, 1999) showing the southeast-dipping thrust faults which extend to a décollement surface above the Precambrian basement

Blue Ridge

The Blue Ridge comprises a largely allochthonous mass of mainly Precambrian crystalline rocks that extends from Georgia to southern Pennsylvania, east of the Valley and Ridge Province. In Pennsylvania, it is characterized by the highland known as South Mountain in Franklin County, Pennsylvania, an anticlinorium of clastic, and carbonate rocks overlying volcanic units and a Precambrian granite and gneiss (Fauth, 1967) (Figure 8). East dipping thrust faults underlie the South Mountain area (Figure 9). Figure 10 shows that orientation of thrust faults roughly parallel to the Gettysburg Basin. An additional thrust fault has been mapped along the base of the Tomstown not shown in the Figure 10 which detached the overlying carbonate sequence from the underlying Chilhowee Group (Brezinski, 1996). Seismic reflection studies by (Harris, 1982) in Virginia, suggest that Blue Ridge metamorphic and crystalline rocks moved westward above a gently dipping thrust fault that cut Paleozoic carbonate strata. Because South Mountain is an extension of the Blue Ridge in Virginia, it is reasonable to consider that South Mountain in Pennsylvania is the result of a hanging–wall anticlinorium above a major, nonemergent thrust fault (Drake, 1999a). The base of the anticlinorium rests upon the Keedysville mylonite, derived from folded limestone at the base of the Tomstown Formation (Brezinski, 1996) at several locations from Pennsylvania to central Virginia (Brezinski, 1996). The presence of the mylonite indicates that much of the Blue ridge is allochthonous as suggested by earlier works (Freedman, 1967) and reached its position after multiple contractional events.

Younger, mainly normal faults, related to Mesozoic rifting, are evident at the northwest margin of the Gettysburg Basin on the eastern side of South Mountain (Root, 1991). Across the Gettysburg basin to the southeast, rocks in the Vintage formation, correlative with the Tomstown, again serve as the footwall of a major regional thrust fault, the Martic.

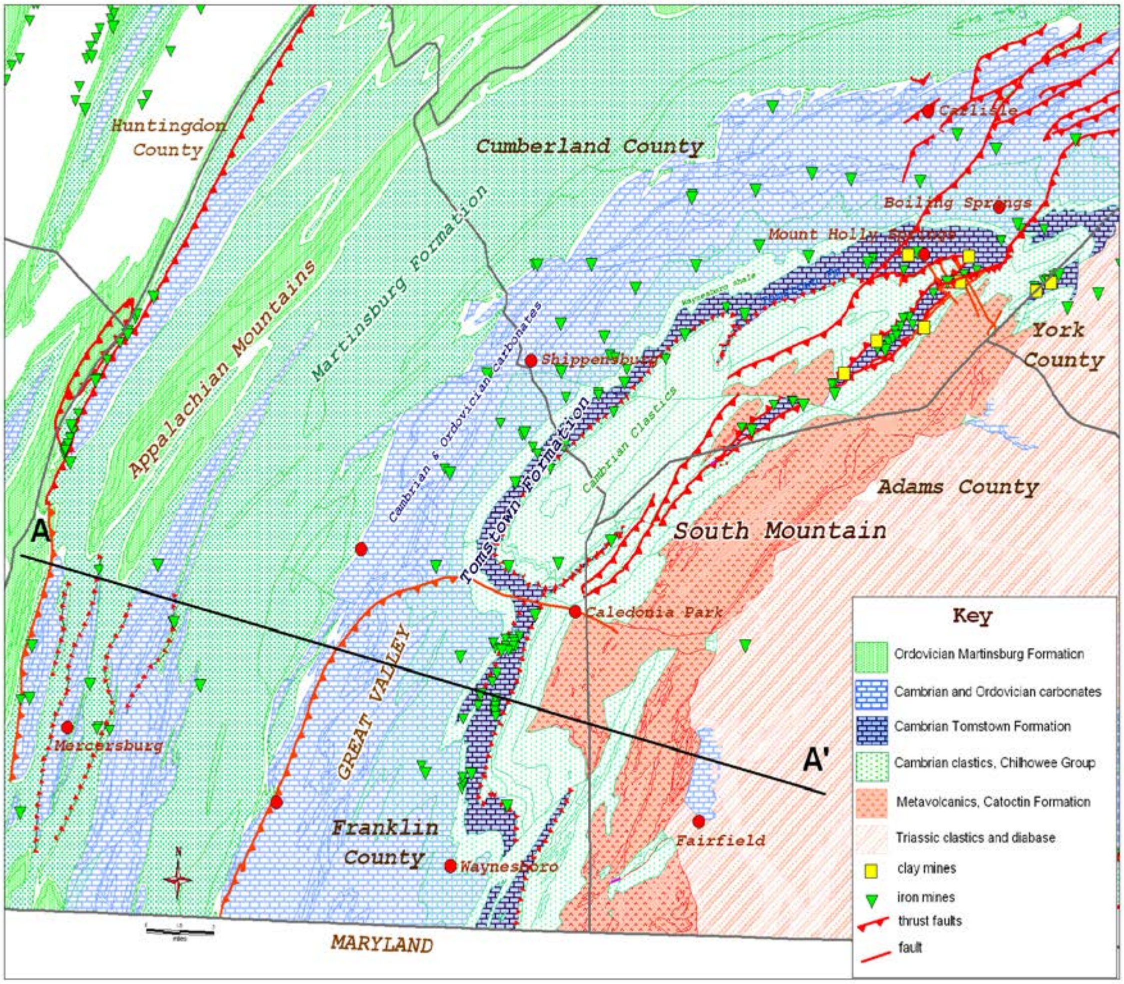


Figure 8: Geologic map of South Mountain (adapted from Berg, 1980)

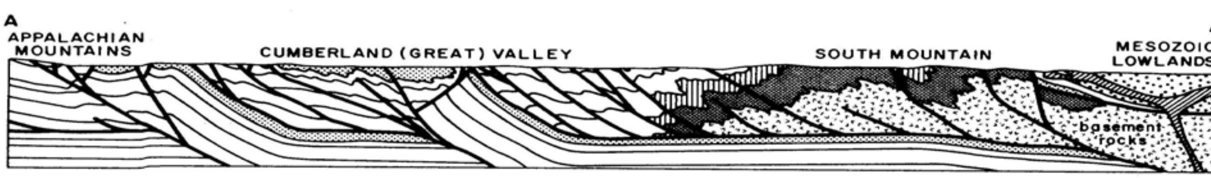


Figure 9: Geologic cross section of South Mountain (adapted from Way, J. H., 1986)

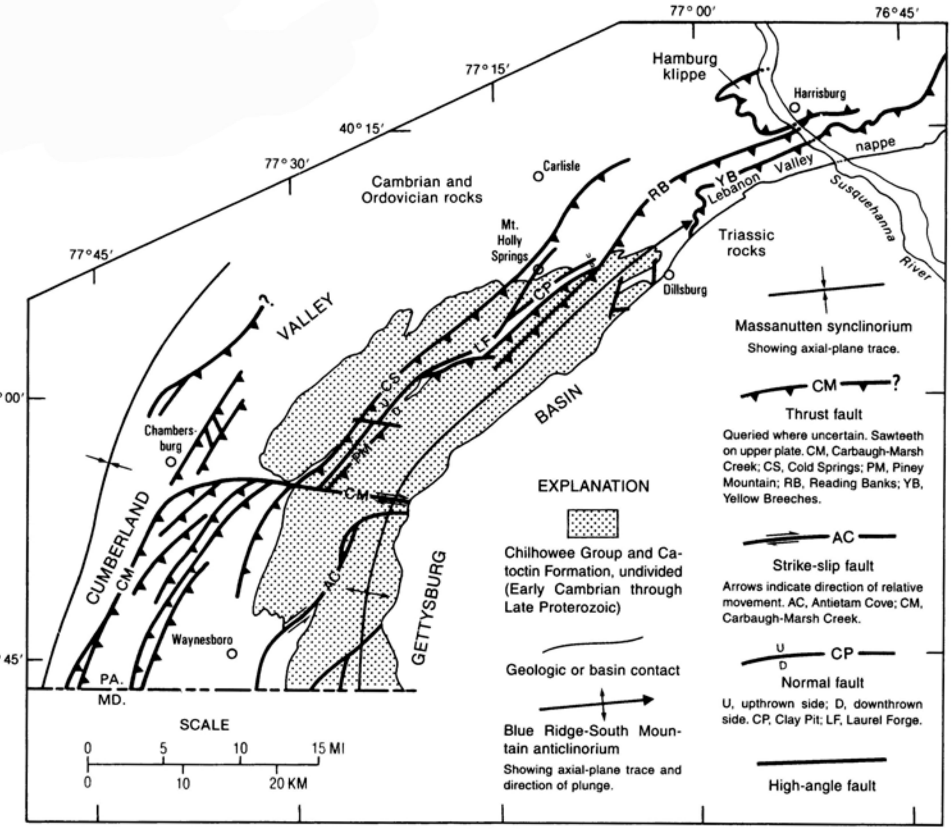


Figure 10: Tectonic sketch map of Blue Ridge and Great Valley (adapted from Root, 1971)

Reading Prong (New England Province)

The Reading Prong comprises crystalline rocks, perhaps comparable to the core of the Blue Ridge, that also are allochthonous although different tectonic histories have been proposed.

Originally, the southwestern Reading Prong was considered to be a large anticlinorium and autochthonous (Miller, 1925; Dallmeyer, 1974). Stose and Jonas (1935) proposed that the crystalline rocks were transported into place as a large thrust sheet over the Paleozoic carbonate rocks of the Great Valley as indicated by tectonic windows within the crystalline rocks in which carbonate rocks crop out (Stose, 1935). Isachsen (1964) proposed that the Reading Prong was a klippe composed of rocks older than Middle Ordovician emplaced during the Taconic orogeny.

(Drake, 1969) postulated the existence of a giant nappe (Musconetcong nappe) of crystalline rocks within which synclinal troughs preserving Cambro-Ordovician carbonate formed antiforms over the nappes. Refolding the nappe resulted in breaching the nappe core, thrusting the Precambrian rocks over the carbonates (Dallmeyer, 1974).

Drake amended Isachsen’s theory in that the northeast Reading Prong along the Delaware River is a thrust system in a duplex or schuppen structure (Drake, 1999b).

In the northeastern part of the Reading Prong an early theory was that high angle reverse faults accommodated the upward vertical movement of the crystalline core (Dallmeyer, 1974).

Mesozoic basin

Within the Piedmont Province, a Late Triassic to Early Jurassic rift basin cuts across southeastern Pennsylvania, from Adams County in south central Pennsylvania to Bucks County along the Delaware River. The rift basin is a half graben, bounded by normal faults on the northwest side (Root, 1999). The basin is divided into the Gettysburg Basin in Adams, York and Dauphin Counties and the Newark Basin in Berks, Bucks, and Montgomery Counties. The rift basin narrows in width between the two basins and this narrow interval is referred to as the “neck” (Root, 1999). Clastic sediments filled the basins with layers dipping to the northwest from five to forty degrees (Root, 1999). The rift basin separates the Cambrian and Ordovician carbonate rocks in York and Lancaster Counties from Cambrian and Ordovician carbonates in the Great Valley Province to the northwest.

Piedmont Province

Southeast of the Blue Ridge and across the Mesozoic fault basins, the Piedmont encompasses deformed Precambrian and Cambrian metamorphic rocks and Cambrian and Ordovician carbonates and clastic rocks.

The Martic fault is a major fault along which phyllite and schist of the Wissahickon and other Piedmont units have moved northwest onto carbonate beds. The Martic thrust fault extends northeast from the Maryland-Pennsylvania state line south of Hanover, York County to Morrisville, Bucks County, Pennsylvania (Hall, 1934). In places the Martic thrust comprises a zone in which several imbricates have been mapped (Wise, 2010). The imbricate slices record folds indicating multiple periods of contraction.

North of the Martic thrust zone, in the Hanover-York area, west of the Susquehanna River, Cambrian clastic and carbonate rocks have been thrust northwestward over early Ordovician Conestoga along the Stoner thrust fault, the Gnatstown thrust fault, the Ore Valley thrust fault, and the Chickies thrust fault. Stose (1944) mapped the Stoner thrust fault located in the valley between Hanover and York, which carried the Cambrian Harpers phyllite over the Vintage, Ledger, and Conestoga Formations. Northeast of Hanover, several small klippen of Harpers phyllite now lie on carbonate rocks (Stose, 1944). The thrust faults terminate at the Mesozoic basin to the west and extend eastward into Lancaster County.

East of the Susquehanna River, carbonate beds have been folded into recumbent structures in northern Lancaster Valley (Scharnberger, 1990). To the south, the folds are nearly upright with gently east and west plunging axes (Valentino, 1990). In places, irregular stratigraphic contacts record shallowly dipping limbs of potentially recumbent folds. Locally, limbs of folds with uniform thickness suggest upright, symmetric folds are overprinted upon the nappes.

The Martic thrust fault has brought the Octoraro Formation, a fine grained schist, into contact with the Conestoga Formation in Lancaster and Chester Counties. The fault dips to the southeast. The Conestoga Formation, a limestone, overlies the Antietam/Harpers quartzite and schist. The Chickies quartzite is situated below the Antietam/Harpers and is unconformably underlain by the Grenvillian basement Mine Ridge Gneiss which forms a topographically elevated area named Mine Ridge (Bosbyshell, 2007). Mine Ridge is in line with the Tucquan Anticline structure visible along the Susquehanna River. Aeromagnetic studies of Mine Ridge and the Honey Brook Upland suggest that Mine Ridge is not rooted and may only be one kilometer thick (Crawford, 1999). South of the Martic thrust fault are additional thrust faults such as the Embreeville fault in Parkesburg Quadrangle (Blackmer, 2006). Dextral shear zones have been mapped in the Piedmont. Thrust faults and shear zones are a result of multiple episodes of contraction and deformation during the Taconic and post-Taconic orogeny (Wise, 2010).

Lineaments and Cross Strike Discontinuities

In a broad sense, a lineament is a mappable linear feature that can be seen on the surface of the earth when viewed from a distance, such as an air photo or satellite image, and presumably reflects subsurface phenomena. Lineaments are depressions or lines of depressions and range in length from 1 mile to 300 miles (O'Leary, 1976). Cross-strike structural discontinuities (CSD) are lineal features commonly perpendicular to the trend of the major folds of the Plateau Province and the Valley and Ridge Province. CSDs may be defined by disturbed patterns of strike-parallel of folds and faults (Wheeler, 1980). A CSD commonly reflects high fracture density in the bedrock (Gold, 1999). Some CSDs of the Valley and Ridge Province traverse the entire width of the province and extend into an adjoining province. For example, the Everett lineament runs eastward from the eastern edge of the Allegheny Plateau through the Great Valley Section into the Blue Ridge Province of the Piedmont (Kowalik, 1976). Another major CSD is the Tyrone-Mt. Union lineament. This lineament traverses the Valley and Ridge (Kowalik, 1976) and has been extended into the Allegheny Plateau by Rodgers and Anderson (1981) (Figure 3). Other major lineaments are the Lawrenceville-Attica lineament, and the Pittsburgh-Washington lineament. Fracture traces are similar to lineaments but are shorter in length and vary from 300 feet to 1 mile.

The study and utilization of lineaments has been proven to be useful in fields concerning fluid flow though bedrock. Recognizing lineaments led to improved water well locations (Lattman, 1964) and gas wells (O’Neil, 1984), an indication that there is increased fluid flow in the subsurface in the vicinity of lineaments.

3.0 STRATIGRAPHY OF THE APPALACHIAN REGION

In a broad sense the Appalachian region extends from the Cincinnati Arch in central Ohio to the Piedmont of eastern Pennsylvania (Anonymous, 1984). The Region comprises the central Appalachian Basin (which includes the Dunkard Basin), the Allegheny Plateau, the Valley and Ridge with the Great Valley Section, the Blue Ridge, the New England/Reading Prong Province, and the adjacent part of the Piedmont.

3.1 ALLEGHENY PLATEAU PROVINCE

The Appalachian Plateau Province extends from central Ohio to eastern Pennsylvania. The Dunkard Basin is an elliptical, elongated depression within the Appalachian Plateau Province (Figure 5).

The Appalachian Plateau encompasses stratigraphic units of cyclical clastic, limestone and coal beds of mainly Silurian, Devonian, Mississippian and Pennsylvanian age. The Silurian rocks are approximately 1200 ft thick in northwestern Pennsylvania to about 4,000 ft in southeastern Pennsylvania (Laughrey, 1999). The Devonian deposits vary in thickness from 2,400 ft in northwestern Pennsylvania to over 12,000 ft in eastern Pennsylvania (Harper, 1999). The Mississippian deposits are about 300 ft thick in northeast Pennsylvania and increase in thickness to 5,000 ft or more in southeastern Pennsylvania (Colton, 1970; Brezinski, 1999). The thickness of Pennsylvanian deposits in the Basin is a maximum of 1,300 to 1,500 ft thick (Edmunds, 1999). In general, the thickness of the Pennsylvanian strata decreases to the north. Each exposed rock unit within the Appalachian Plateau is discussed below.

3.1.1 Silurian in Ohio

In the Allegheny Plateau Province of Ohio, the oldest rocks exposed at the surface hosting iron ore are the Silurian.

The Silurian Brassfield limestone crops out in southwest Ohio. The Brassfield limestone is the oldest Silurian Formation in Ohio and rests unconformably over the Ordovician age rocks (Camp, 2006). The thickness of the Brassfield is 20 to 60 feet in Adams, Clinton and Highland Counties where the Brassfield contains iron-rich zones near the top (Figure 11) (Camp, 2006). Silurian Niagara dolomite crops out in Adams, Highland, Pike, and Ross Counties, Ohio. Niagara iron ore was mined chiefly in Adams and Highland Counties where the surface of the Niagara dolomite has been exposed (Stout, 1944). The iron deposits are found as irregular masses in depressions and may vary in thickness from a few inches to ten feet. The lateral extent of the ore deposits may reach hundreds of feet (Stout, 1944). The Niagara ore is a soft limonite along its outcrop and under shallow overburden (Stout, 1944).

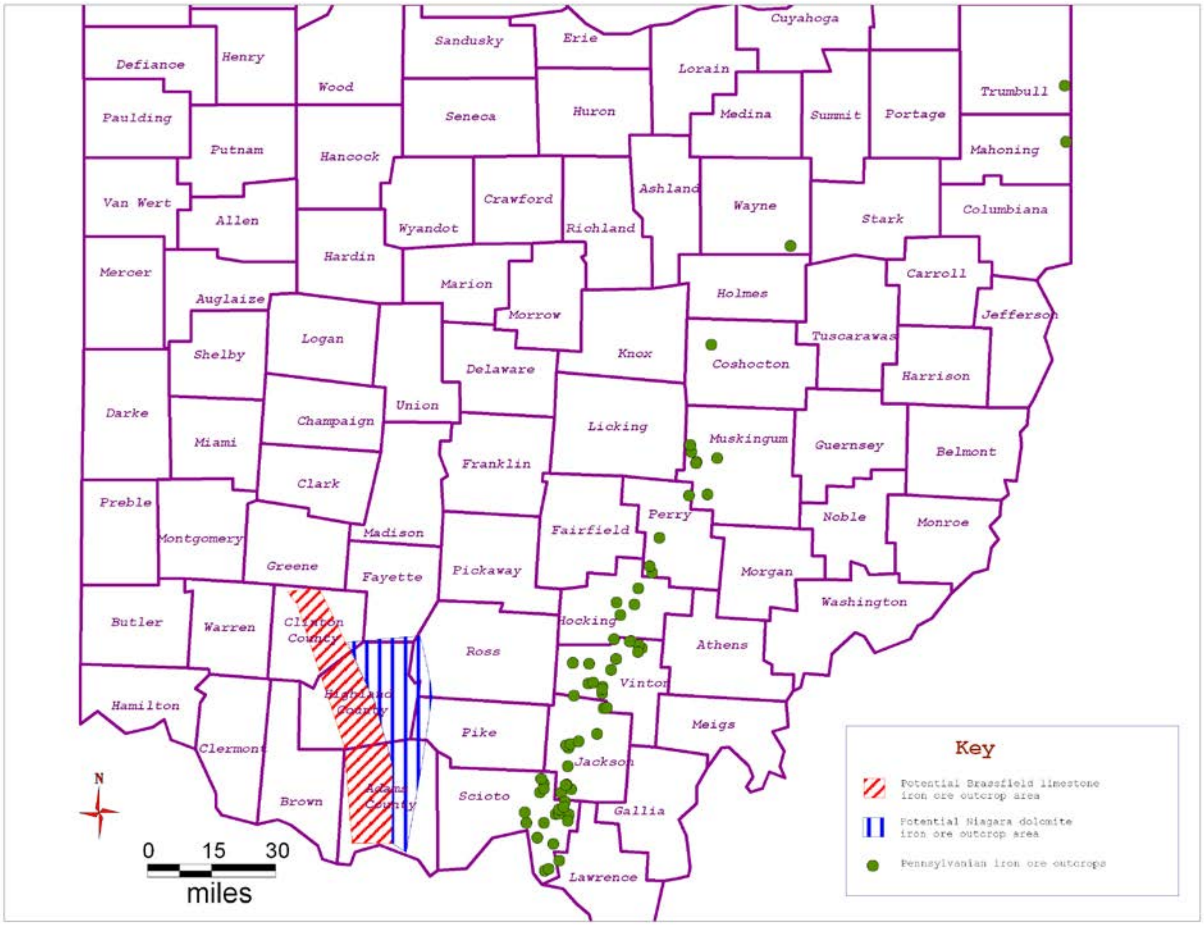


Figure 11: Outcrop area of iron ore deposits in Ohio (Stout, 1944)

3.1.2 Devonian in Ohio and Pennsylvania

Devonian and Mississippian strata in the Allegheny Plateau Province of Ohio and Pennsylvania are mainly clastic. In Ohio, Devonian and Mississippian rocks crop from Trumbull County, Ohio, south to Scioto County, Ohio.

The Devonian Bedford Shale is the oldest exposed Devonian rock in the Plateau of Ohio. It is approximately 95 feet thick and contains siltstone and sandstone (Camp, 2006). Devonian

Berea Sandstone that overlies the Bedford Shale, fills channels cut into the underlying shale and therefore has a variable thickness that reaches about 250 feet in Lorain County (Camp, 2006).

In Pennsylvania, Devonian units crop out along the margins of the Appalachian basin. A summary of the stratigraphic units found in the Devonian is given in Table 3.

Table 3: General stratigraphic chart for Devonian rocks in Central, South-Central and East-Central Pennsylvania (adapted from Harper, 1999)

Series	Central Pa.		South-Central Pa.		East-Central Pa.	
Upper Devonian	Rockwell Fm (part)	Huntley Mtn Fm. (part)	Rockwell Fm. (part)		missing	
	Hampshire Fm.	Catskill Fm.: Duncannon Mbr. Sherman Creek Mbr.	Hampshire Fm.		Catskill Fm.: Duncannon Mbr.	
					Catskill Fm.: Sherman Creek Mbr.	
			Foreknobs Fm.		Catskill Fm.: Irish Valley Fm.	
			Scherr Fm.			
	Foreknobs Fm.	Lock_Haven Fm.	Braillier Fm.		Trimmers Rock Fm.	
	Scherr Fm.	Trimmers Rock Fm.				
	Braillier Fm.					
	Harrell Fm.		Harrell Fm.		Harrell Fm.	
Middle Devonian	Hamilton Gp.: Tully ls.		Hamilton Gp: Tully ls.		Mahantango Fm.	
	Hamilton Gp.: Mahantango Fm.: Unnamed Mbr.		Hamilton Gp: Mahantango Fm.: Unnamed Mbr.	Sherman Ridge Mbr.		
	Clearville Mbr.		Clearville Mbr.	Montebello Mbr.		
	Frame Mbr.		Frame Mbr.			
	Chaneysville Mbr.		Chaneysville Mbr.	Dalmatia Mbr.		
	Gander Run Mbr.		Gander Run Mbr.	Turkey Ridge Mbr.		
	Hamilton Gp.: Marcellus Fm.		Hamilton Gp: Marcellus Fm.		Marcellus Fm.	
	Onandaga Fm: Selinsgrove ls.		Onandaga Fm: Needmore sh.	Selinsgrove ls.	Buttermilk Falls ls.	
					Palmerton ss.	Schoharie Fm.
	Onandaga Fm: Needmore sh.		Onandaga Fm: Needmore sh.		Schoharie & Esopus Fms., undivided	Esopus Fm.
Lower Devonian	(missing)		(missing)		(unconformity)	
	Ridgeley ss.		Ridgeley ss.	Old Port Fm: Ridgeley Mbr	Oriskany Gp: Ridgeley ss.	
	Shriver Chert	Licking Creek ls.	Shriver Chert	Old Port Fm: Lower Mbr.	Oriskany Gp: Shriver Chert	
	Mandata sh.				Helderberg Gp: New Scotland ls.	Port Ewen sh.
	Corriganville ls.		Corriganville ls.			Minisink ls.
						New Scotland ls.
	New Creek ls.		New Creek ls.		Coeymans Fm.	
	Keyser Fm (part)		Keyser Fm (part)		Rondout Fm.	

Lower and middle Devonian stratigraphy

Some rock units have been grouped. The New Creek, Corriganville, Mandata, Shriver and Ridgeley have been grouped together and referred to as the Old Port Formation in central Pennsylvania. In eastern Pennsylvania, the Coeymans Formation and New Scotland limestone are grouped and called the Helderberg Group. Also in eastern Pennsylvania, the Shriver Chert and Ridgeley Sandstone are together called the Oriskany Group (Table 3).

Early Devonian strata are generally calcareous whereas younger units are clastic. The calcareous Keyser Formation yields ages from the late Silurian to the early Devonian. The Keyser is medium gray, fossiliferous limestone which is 75 to 202 feet thick (Harper, 1999). Chert nodules are present in the upper part of the formation and a distinct chert bed is developed at the top of the formation (Harper, 1999). The lower boundary with the Silurian Tonoloway Formation is conformable and sharp (Harper, 1999). The upper contact is conformable and grades into the cherty limestone and shale. The New Creek above the Keyser is a thin (3 to 10 feet thick), coarse-grained limestone that grades into the overlying Corriganville limestone. The Coeymans Formation is equivalent to the New Creek limestone in the east (Harper, 1999). The Corriganville is 10 to 30 feet thick, fossiliferous, and may be difficult to distinguish from the New Creek (Harper, 1999). The Corriganville correlates to the New Scotland Formation in eastern Pennsylvania (Harper, 1999).

The dark gray, siliceous Mandata Shale overlies the Corriganville in western to central Pennsylvania. Thickness ranges from 20 to 100 feet thick in central Pennsylvania (Harper, 1999). The Mandata is not present in eastern Pennsylvania (Harper, 1999).

The Mandata Shale is overlain by the Shriver Chert. The Shriver is composed of silty, cherty, mudstones and calcareous, siliceous siltstones (Harper, 1999). The Shriver is thin-bedded and ranges from 80 to 170 feet thick (Harper, 1999).

The Shriver Chert grades laterally into the Licking Creek limestone in southwestern and central Pennsylvania. In Franklin County, Licking Creek is roughly 90 feet thick (Harper, 1999).

Overlying the Shriver Chert is the Ridgeley Sandstone which is found throughout the state except in northwest Pennsylvania. The underlying Shriver Chert and Licking Creek limestone grade upward into the Ridgeley. The Ridgeley varies from 8 to 150 feet thick at outcrop (Harper, 1999). The interval between the Shriver/Licking Creek and Ridgeley can be a cherty, calcareous siltstone or medium-grained calcareous sandstone or arenaceous limestone. The composition of the Ridgeley is predominantly a white to light–gray, medium-grained, silica-cemented, quartzose sandstone. The Ridgeley also may be a calcareous, fine-grained sandstone to a noncalcareous conglomerate (Harper, 1999).

The Needmore Shale is a gray to black, calcareous, fossiliferous shale that lies unconformably above the Ridgeley Sandstone and marks the beginning of the Middle Devonian Series. The Esopus and the Schoharie Formations are equivalent to the Needmore in eastern part of the state (Harper, 1999). The Needmore ranges from 100 to 150 feet thick (Harper, 1999).

In the subsurface of western Pennsylvania, Needmore grades into a dark-gray, slightly calcareous and locally glauconitic Huntersville that reaches a thickness of 250 feet in Fayette and Westmoreland Counties (Harper, 1999 ; Jones, 1957). Toward northwestern Pennsylvania, the Huntersville grades into dark brownish gray, somewhat argillaceous and cherty limestone of the Onondaga Formation (Harper, 1999; Fettke, 1961).

Above the Needmore Shale lies the Selinsgrove limestone. The Selinsgrove correlates to Buttermilk Falls limestone in the east. The Buttermilk Falls can be up to 200 feet thick in Monroe County (Harper, 1999; Epstein, 1967).

Overlying the Selinsgrove/Buttermilk Falls limestones is the Marcellus Formation. The Marcellus is 75 to 800 feet thick and consists of dark gray to black, carbonaceous shale. The Marcellus is highly fissile with abundant pyrite (Harper, 1999). The Tioga Ash Beds, present at the base of the Marcellus, are a series of thin, micaceous shales. The ash may contain up to 45 percent biotite (Harper, 1999; Roen, 1982).

The Mahantango Formation rests above the Marcellus Formation. A thick complex of interbedded shales, siltstone, and sandstone which ranges from 1,200 to 2,200 feet thick comprises the overlying Mahantango (Harper, 1999). The Tully limestone, which overlies the clastic Mahantango Formation, may be considered to be the upper member of the Mahantango (Harper, 1999). The Tully is a fossiliferous, shaly limestone or calcareous shale that may reach a thickness greater than 200 feet (Harper, 1999; Faill, 1974). The Tully marks the top of the Middle Devonian and the last unit prior to the Catskill delta deposition.

West of the Allegheny Front, the Mahantango grades into mostly shale interbedded with limestone, siltstone and sandstone comprising the Hamilton Group (Harper, 1999).

Upper Devonian stratigraphy

The Upper Devonian rocks were formed by the Catskill deltaic system prograding into the Appalachian Basin from the east. This has resulted in a complex series of contiguous deltas derived from the erosion of an active tectonic source (Harper, 1999). Therefore, the Upper Devonian consists mainly of clastic sediments: shale, siltstone, sandstone and conglomerate. In order to organize the individual rock units across the Appalachian Basin, the depositional environment has been used as a basis for grouping the formations into five facies.

The base of the Upper Devonian is the dark-colored, carboniferous shale facies. This facies consists of shale interbedded with lighter colored shale and siltstone. These shales may be sparsely fossiliferous and pyritic. The Harrell, Genesee, Sonyea, and West Falls Formations are examples of this facies (Harper, 1999).

The Brallier Formation is an example of the second facies. The Brallier is a fine to coarse grained, thinly-bedded siltstone. The Brallier has been described as a series of turbidites with sharp planar bases and undulatory upper contacts (Harper, 1999; Lundegard, 1980). The thickness of this facies can be as much as 2,500 feet in the Brallier or only a few hundred feet in the Trimmers Rock Formation (Harper, 1999; Frakes, 1967).

The next facies deposited represents shallow marine, open shelf, detrital sediments. These rocks are light to dark colored, greenish, brownish, purplish or red, fossiliferous shale, siltstone or fine-grained sandstone. The Chadokin, Riceville, and Oswayo Formations are examples of the facies (Harper, 1999).

The Lock Haven Formation, Scherr Formation, Foreknobs Formation, Elk Group, Venango Group, and Bradford Group are examples of the fourth facies seen in the Upper Devonian. This facies consists of deltaic sediments mixed with open marine carbonates. They are composed of interbedded silty, micaceous mudrock, siltstone, sandstone and conglomerate with occasional beds of highly fossiliferous limestone. Thickness of the facies can reach several thousand feet (Harper, 1999).

The fifth facies consists of gray to red mudstone, claystone, siltstone, sandstone, and conglomerate. The facies is a mixture of continental, deltaic and marine margin environments.

The Catskill and Hampshire Formations are examples of this facies. The Catskill and Hampshire are red, green or gray nonmarine rocks which can be as much as 8,600 feet thick in central Pennsylvania (Harper, 1999).

The Rockwell, Spechty Kopf, and Huntley Mountain Formations overlie the Catskill deltaic complex and are the transition into Mississippian rocks. These formations are nonmarine, non-red sandstones and mudrocks. The Spechty Kopf is a gray, fine to medium grained sandstone and dark gray argillaceous siltstone which is 435 feet thick in central Pennsylvania (Harper, 1999).

3.1.3 Mississippian in Ohio and Pennsylvania

Ohio Mississippian stratigraphy

In Ohio, Sunbury Shale rests upon the Devonian Berea Sandstone or Bedford Shale and forms the basal bed for the Mississippian age rocks. The shale ranges in thickness from 20 to 40 feet (Camp, 2006). Overlying the Sunbury is the Cuyahoga formation which is a fine-grained shale in the north that grades to a sandstone to the south. The Black Hand Sandstone member of the Cuyahoga reaches a thickness of 300 feet in Hocking Valley. The Cuyahoga Formation has a thickness of about 625 feet (Camp, 2006).

Overlying the Cuyahoga Formation is the Logan Formation made up of the Berne Conglomerate, Byer Sandstone, Allensville Conglomerate and Vinton Sandstone. The formation is 200 feet thick in central and southern Ohio (Camp, 2006).

The Mississippian Maxville limestone unconformably overlies the Logan Formation. The Maxville is discontinuous and averages 50 feet in thickness (Camp, 2006). The top of the

Maxville is the Mississippian – Pennsylvanian unconformity. In some areas, erosion of the Maxville limestone extends down into the Logan Formation, so that the upper Mississippian boundary in southeastern Ohio can be either the Logan Formation or the Maxville limestone. There can be as much as 400 feet of erosional relief (Slucher, 1994; Hyde, 1953). The Maxville limestone can be fossiliferous with bryozoan, brachiopod, clam and gastropod fossils (Camp, 2006).

Pennsylvania Mississippian stratigraphy

In Pennsylvania, Mississippian rocks crop out in northwestern and north central Pennsylvania, along the Allegheny Front, in the Broad Top coal basin, in the Anthracite Coal Fields, and in western Pennsylvania along Chestnut Ridge, Laurel Hill and Negro Mountain.

In Pennsylvania, the Mississippian rocks consist of the Mauch Chunk Formation, Burgoon Formation, Shenango/Rockwell/Huntley Mountain Formation, and the Cuyahoga Group/Riddlesburg Shale/Spechty Kopf Formation (Table 4).

The Mauch Chunk is a red to reddish-brown clastic unit comprised of mudstone and siltstone, brown to red and greenish-gray sandstone and conglomerate (Brezinski, 1999). The Mauch Chunk is thickest in the Anthracite Coal Fields where the estimated thickness is 3,000 to 4,000 feet and thins to the north and west (Brezinski, 1999). In the southwestern corner of Pennsylvania, the Mauch Chunk is interbedded with limestones such as the Loyalhanna, Wymps Gap, Reynolds and Deer Valley (Brezinski, 1999). In Washington and Greene Counties, the Loyalhanna, Wymps Gap and perhaps Reynolds are only separated by an unconformity and together are known as the Greenbrier Formation (Brezinski, 1999). The Greenbrier Formation is equivalent in part to the Greenbrier Group of West Virginia and to the Maxville Group of Ohio (Brezinski, 1999).

In southwestern Pennsylvania, the lower part of the Mauch Chunk Formation has marine sandstone, shale and limestone units (Brezinski, 1999). The Loyalhanna limestone as well as the Deer Valley, Wymps Gap, and Reynolds limestones are found within the Mauch Chunk. Loyalhanna, Wymps Gap and perhaps Reynolds form a continuous limestone bed known as the Greenbrier limestone in Washington and Greene Counties, Pennsylvania (Brezinski, 1999). The Greenbrier is correlated to the Mississippian Maxville Group of Ohio (Brezinski, 1999).

In the Anthracite Region, the Pocono Formation underlies the Mauch Chunk Formation. Earlier stratigraphic mapping applied the term ‘Pocono’ to non-red, coarse, clastic sediments between the predominantly red Devonian Catskill Formation and the Mississippian Mauch Chunk Formation. Today the term Pocono Formation is only used in the Anthracite Region (Brezinski, 1999).

Lying below the Mauch Chunk is the Burgoon Sandstone. The Burgoon is predominantly non-red, cross-bedded, medium to coarse grained sandstone. The Logan Sandstone of Ohio is equivalent to the Burgoon Sandstone (Brezinski, 1999). Locally, it can contain thin, discontinuous coal beds (Brezinski, 1999; Brezinski, 1987).

Below the Burgoon Sandstone lies the Rockwell Formation (south-central Pennsylvania), and its equivalents, the Huntley Mountain Formation (north-central Pennsylvania), Shenango Formation (western Pennsylvania) and Beckville Member (northeastern Pennsylvania). The Rockwell Formation consists of lenses of sandstone interbedded with reddish-brown siltstone and mudstone (Brezinski, 1999). The Huntley Mountain Formation is greenish-gray to tan, flaggy sandstone, sandy siltstone and reddish-brown silty shale (Brezinski, 1999). The Shenango

Formation is an interbedded sandstone, siltstone and shale approximately 150 to 180 feet thick (Brezinski, 1999).

The Loyalhanna limestone is exposed along Loyalhanna Creek in Westmoreland County, in the Broad Top basin in Fulton and Huntingdon Counties and along the ridges in Westmoreland and Somerset Counties. The Loyalhanna is a cross-bedded, sandy limestone or calcareous sandstone(Brezinski, 1999). In southwestern Westmoreland and Fayette Counties the Loyalhanna has a thickness of about 85 feet and thins to the north and east (Brezinski, 1999). Toward the east the Loyalhanna is interbedded with the Mauch Chunk Formation (Brezinski, 1999).

Table 4: General stratigraphic chart for the Mississippian in Pennsylvania (adapted from Brezinski, 1999)

<table>
<tr><th>System</th><th>Series</th><th>North West Pa.</th><th>South West Pa.</th><th colspan="2">South Central Pa.</th><th>Broad Top</th><th>North Central Pa.</th><th colspan="2">North East Pa. Anthracite Region</th></tr>
<tr><td rowspan="12">Mississippian</td><td rowspan="9">Upper Mississippian</td><td rowspan="10">(missing)</td><td rowspan="7">Greenbrier Fm.</td><td>Mauch Chunk Fm.</td><td rowspan="6">Mauch Chunk Fm.</td><td rowspan="6">Mauch Chunk Fm.</td><td rowspan="6">Mauch Chunk Fm.</td><td rowspan="9" colspan="2">Mauch Chunk Fm</td></tr>
<tr><td>Reynolds ls.</td></tr>
<tr><td>Mauch Chunk Fm.</td></tr>
<tr><td>Wymps Gap ls.</td></tr>
<tr><td>Mauch Chunk ls.</td></tr>
<tr><td>Deer Valley ls.</td></tr>
<tr><td colspan="2">Loyalhanna ls.</td><td>Trough Creek ls.</td><td>Loyalhanna ls.</td></tr>
<tr><td>(missing)</td><td colspan="2">Mauch Chunk Fm.</td><td>Mauch Chunk Fm.</td><td>Mauch Chunk Fm.</td></tr>
<tr><td>Mauch Chunk Fm.</td><td colspan="2">Mauch Chunk Fm.</td><td>Mauch Chunk Fm.</td><td>Mauch Chunk Fm</td></tr>
<tr><td rowspan="3">Lower Mississippian</td><td>Burgoon Ss.</td><td colspan="2">Burgoon ss.</td><td>Burgoon ss.</td><td>Burgoon ss.</td><td>Mt. Carbon Mbr.</td><td rowspan="2">Pocono Fm.</td></tr>
<tr><td>Shenango Fm.</td><td>Shenango Fm.</td><td colspan="2">Rockwell Fm.</td><td>Rockwell Fm</td><td rowspan="2">Huntley Mtn. Fm.</td><td>Beckville Mbr.</td></tr>
<tr><td>Cuyahoga Gp.</td><td>Cuyahoga Gp.</td><td colspan="2">Riddlesburg sh.</td><td>Riddlesburg sh.</td><td colspan="2">Spechty Kopf Fm.</td></tr>
</table>

At the base of the Mississippian is the Cuyahoga Group. The Cuyahoga is about 200 to 240 feet thick and is made up of clastics. In northwestern Pennsylvania, it is subdivided into the Orangeville Shale, Sharpsville Sandstone, and the Meadville Shale (Brezinski, 1999).

3.1.4 Pennsylvanian in Ohio

Pennsylvanian age rocks are made up of four groups or formations: Pottsville, Allegheny, Conemaugh, and Monongahela. A listing of the members in each group or formation is shown in Table 5.

Table 5: Generalized geologic column of Pennsylvanian and Permian age rocks within the Allegheny Plateau of Ohio (adapted from Hull, 1990; Larsen, 2000; Slucher, 2004)

System	Ohio Allegheny Plateau		
Permian	Dunkard Group	Greene Fm	
		Washington Fm	Upper Marietta sandstone
			Creston-Reds Shale
			Lower Marietta sandstone
			Washington coal
			Mannington sandstone
			Waynesburg sandstone
Pennsylvanian	Monongahela Gp		Waynesburg coal
			Uniontown coal
			Benwood limestone
			Upper Sewickley sandstone
			Meigs Creek coal
			Fishpot limestone
			Redstone-Pomeroy coal
			Pittsburgh coal
	Conemaugh Gp	Casselman Fm	Summerfield limestone
			Connellsville limestone
			Morgantown sandstone
			Skelley limestone
		Glenshaw Fm	Ames limestone
			Harlem coal
			Saltsburg sandstone
			Noble limestone
			Cow Run sandstone
			Portersville shale
			Cambridge limestone
			Buffalo sandstone
			Brush Creek limestone
			Rock Camp shale
			Mahoning coal
			Mahoning sandstone
	Allegheny Fm		Upper Freeport coal
			Upper Freeport sandstone
			Lower Freeport coal
			Washingtonville shale/limestone
			Middle Kittanning coal
			Obryan-Columbiana shale
			Hamden limestone
			Lower Kittanning coal
			Vanport limestone
			Clarion coal
			Zaleski flint/limestone
			Putnam Hill limestone
			Newland-Brookville coal
	Pottsville Fm		Homewood sandstone
			Upper Mercer limestone
			Lower Mercer limestone
			Lower Mercer coal
			Boggs limestone
			Massillon sandstone
			Quakertown coal
			Poverty-Lowellville limestone
			Sharon coal
			Sharon sandstone/conglomerate

3.1.5 Pennsylvanian Pottsville Formation in Pennsylvania

Erosion occurred between the Mississippian and Pennsylvanian time in most of Pennsylvania and eastern Ohio as shown by channels filled with Pottsville Sandstone scoured into the Mauch Chunk. The basal Pottsville Formation is predominantly sandstone and shale with beds of coal, clay, limestone, and iron-rich horizons. Coal beds within the Pottsville are the Sharon, Quakertown, and Lower Mercer coals which have no economic value. Sandstone beds in the Pottsville are the Sharon Sandstone/Conglomerate, Massillon (Ohio) and Homewood Sandstones. The Pottsville Formation varies from 100 to 350 feet in thickness. The Lower Pennsylvanian rocks are absent from the Dunkard Basin and the Appalachian Plateau (Edmunds, 1999). Only in the Middle and Southern Anthracite Coal Fields does the basal Pennsylvanian Pottsville Formation intertongue conformably with the Mississippian Mauch Chunk (Brezinski, 1999; Meckel, 1970).

The Pennsylvanian System is predominantly composed of clastics and includes economically valuable coal and limestone units. The Pennsylvanian is broken into the Lower, Middle and Upper Pennsylvanian Series. The Lower Pennsylvanian to Middle Pennsylvanian Series contains the Pottsville Formation. The Allegheny Formation overlies the Pottsville in the upper Middle Pennsylvanian Series. In ascending order the Glenshaw Formation, Casselman Formation, and Monongahela Group lie above the Allegheny Formation in the Upper Pennsylvanian Series. A summary of the formations within the Pennsylvanian is shown in Table 6.

Table 6: General stratigraphic chart for the Pennsylvanian in Pennsylvania (adapted from Edmunds, Skema, and Flint, 1999)

<table>
<tr><th>System</th><th>Series</th><th colspan="2">East Central Pa.</th><th colspan="2">North East Pa.</th><th>North Central Pa.</th><th colspan="2">North West Pa.</th><th colspan="2">South West Pa.</th><th>South Central Pa</th></tr>
<tr><td rowspan="13">PENNSYLVANIAN</td><td rowspan="4">Upper Pennsylvanian</td><td colspan="2">(missing)</td><td colspan="2" rowspan="3">(missing)</td><td rowspan="6">(missing)</td><td colspan="2" rowspan="2">(missing)</td><td colspan="2">Monongahela Gp.</td><td rowspan="3">(missing)</td></tr>
<tr><td colspan="2" rowspan="6">Llewellyn Fm.</td><td rowspan="4">Conemaugh Gp.</td><td rowspan="2">Casselman Fm.</td></tr>
<tr><td rowspan="3">Conemaugh Gp.</td><td>Casselman Fm.</td></tr>
<tr><td colspan="2" rowspan="4">Llewellyn Fm.</td><td rowspan="2">Glenshaw Fm.</td><td rowspan="2">Glenshaw Fm.</td><td rowspan="2">Conemaugh and Allegheny Fm. Undivided</td></tr>
<tr><td rowspan="6">Middle Pennsylvanian</td></tr>
<tr><td colspan="2" rowspan="2">Allegheny Fm.</td><td colspan="2" rowspan="2">Allegheny Fm.</td><td rowspan="2"></td></tr>
<tr><td>Allegheny Fm.</td></tr>
<tr><td rowspan="6">Pottsville Fm.</td><td>Sharp Mountain Mbr.</td><td>Pottsville Fm.</td><td>Sharp Mountain Mbr.</td><td rowspan="4">Pottsville Fm.</td><td colspan="2" rowspan="4">Pottsville Fm.</td><td colspan="2" rowspan="3">Pottsville Fm.</td><td rowspan="4">Pottsville Fm.</td></tr>
<tr><td rowspan="3">(missing)</td><td colspan="2">Campbells Ledge sh.</td></tr>
<tr><td colspan="2" rowspan="3">(missing)</td></tr>
<tr><td rowspan="3">Lower Pennsylvanian</td><td colspan="2" rowspan="3">(missing)</td></tr>
<tr><td>Schuylkill Mbr.</td><td colspan="3">(missing)</td><td rowspan="2">(missing)</td></tr>
<tr><td>Tumbling Run Mbr.</td><td colspan="5">(missing)</td></tr>
</table>

The Pottsville is predominantly massive, cross-bedded sandstone that unconformably overlies the Mississippian Mauch Chunk. The Pottsville also contains coal, clay, shale and marine limestone. It ranges from 20 to 250+ feet in thickness (Edmunds, 1999).

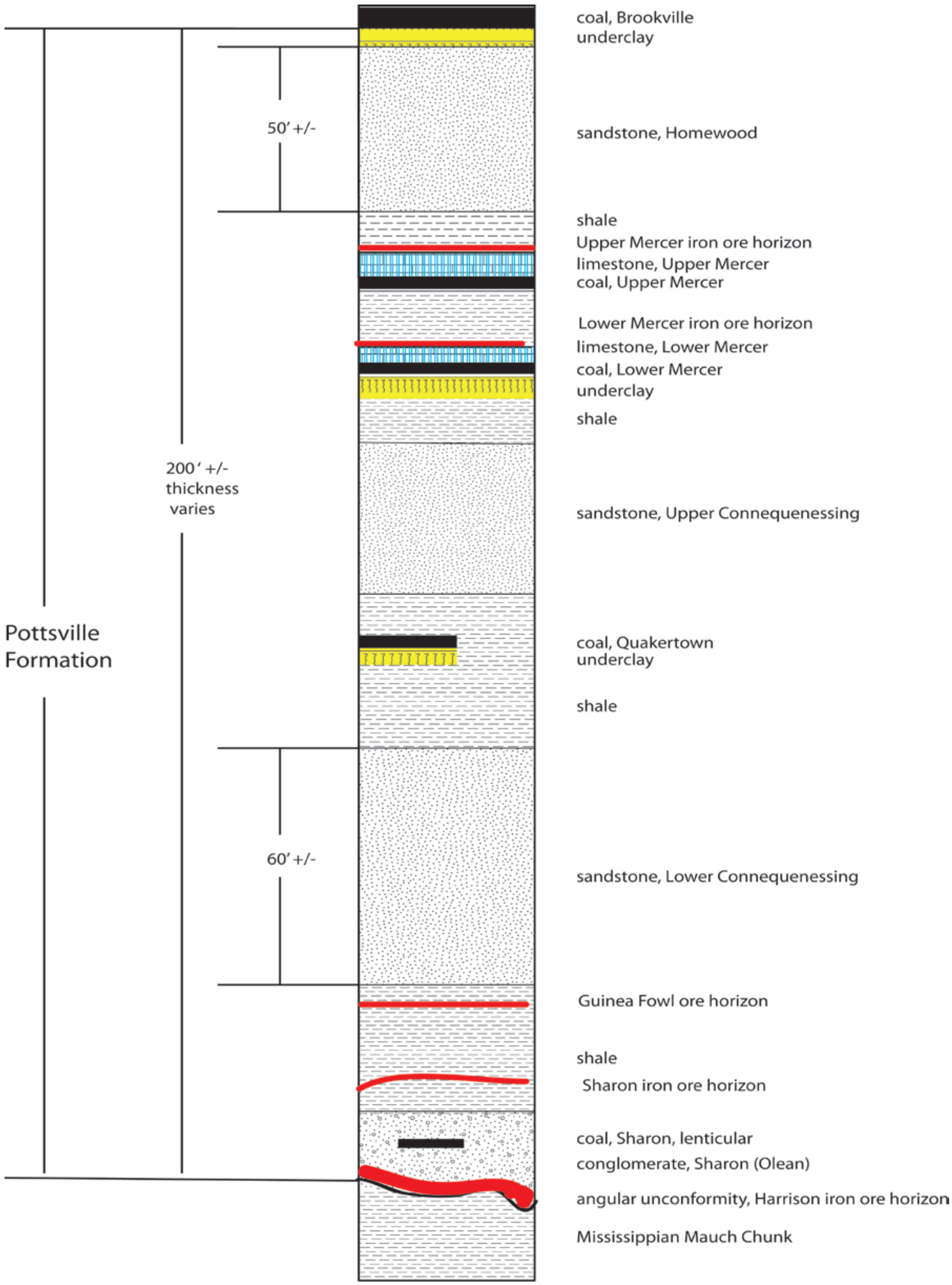


Figure 12: General stratigraphic column for the Pottsville Formation, Western Pennsylvania (adapted from Marks, W. J., and Pennsylvania Geologic Survey for Bureau of Abandoned Mine Reclamation, 1999)

The limestone and shale in the Pottsville are of marine origin based on the presence of Lingula fossils. The base of the Pottsville contains the Sharon coal and Sharon Sandstone and can be conglomeratic. The Sharon Sandstone fills channels in the Mississippian erosion surface (Edmunds, 1999). The Sharon coal is a lenticular, discontinuous channel coal which can be absent (Marks, 1999). Three massive sandstones and conglomeratic sandstones are found in the Pottsville above the Sharon, the Lower and Upper Connoquenessing Sandstone and the Homewood Sandstone. Between the Lower and the Upper Connoquenessing is the Quakertown coal with its underclay. In the interval between the Upper Connoquenessing and the Homewood are two sequences of marine shale, underclay, coal, marine limestone and shale. The lower sequence is the Lower Mercer limestone and coal and the higher sequence is the Upper Mercer limestone and coal (Figure 12).

The base of the Brookville coal marks the upper boundary of the Pottsville Formation. In descending order, the Pottsville is divided into the following members:

Brookville underclay
Homewood sandstone
Upper Mercer coal, limestone, and underclay
Lower Mercer coal, limestone, and underclay
Upper Connoquenessing sandstone
Quakertown coal and underclay
Lower Connoquenessing sandstone
Sharon coal
Sharon conglomerate

In Ohio, the Pottsville also overlies the Mississippian age rocks with an unconformity. The Pottsville is dominated by massive sandstones such as the Sharon Sandstone/Conglomerate, the Upper and Lower Connoquenessing Sandstone and the Homewood Sandstone as shown in Figure 12.

3.1.6 Pennsylvanian Allegheny Formation in Pennsylvania

The Allegheny Formation begins at the base of the Brookville coal and extends to the top of the Upper Freeport coal. The thickness in Pennsylvania ranges from 270 to 330 feet (Edmunds, 1999). The Allegheny is a repeating succession of coal, shale, sandstone, underclay, and, locally, limestone associated with the underclay (Figure 13). Some coal beds, marine shale and limestone are continuous over thousands of square miles (Edmunds, 1999). Within the Allegheny are six major coal units. Each unit locally may comprise closely-spaced lenses, or splits, or as multiple splays that merge into one bed, or as a continuous sheet (Edmunds, 1999). From bottom to top the main coal beds are:

Upper Freeport coal (“E” coal)
Lower Freeport coal (“D” coal)
Upper Kittanning coal (“C” coal)
Middle Kittanning coal (“C” coal)
Lower Kittanning coal (“B” coal)
Clarion coal (“A” coal)
Brookville coal (“A” coal)

Marine units in the Allegheny Formation are present only below the Upper Kittanning underclay (Edmunds, 1999). Limestone below the Lower and Upper Freeport coals and the Johnstown limestone are freshwater limestones.

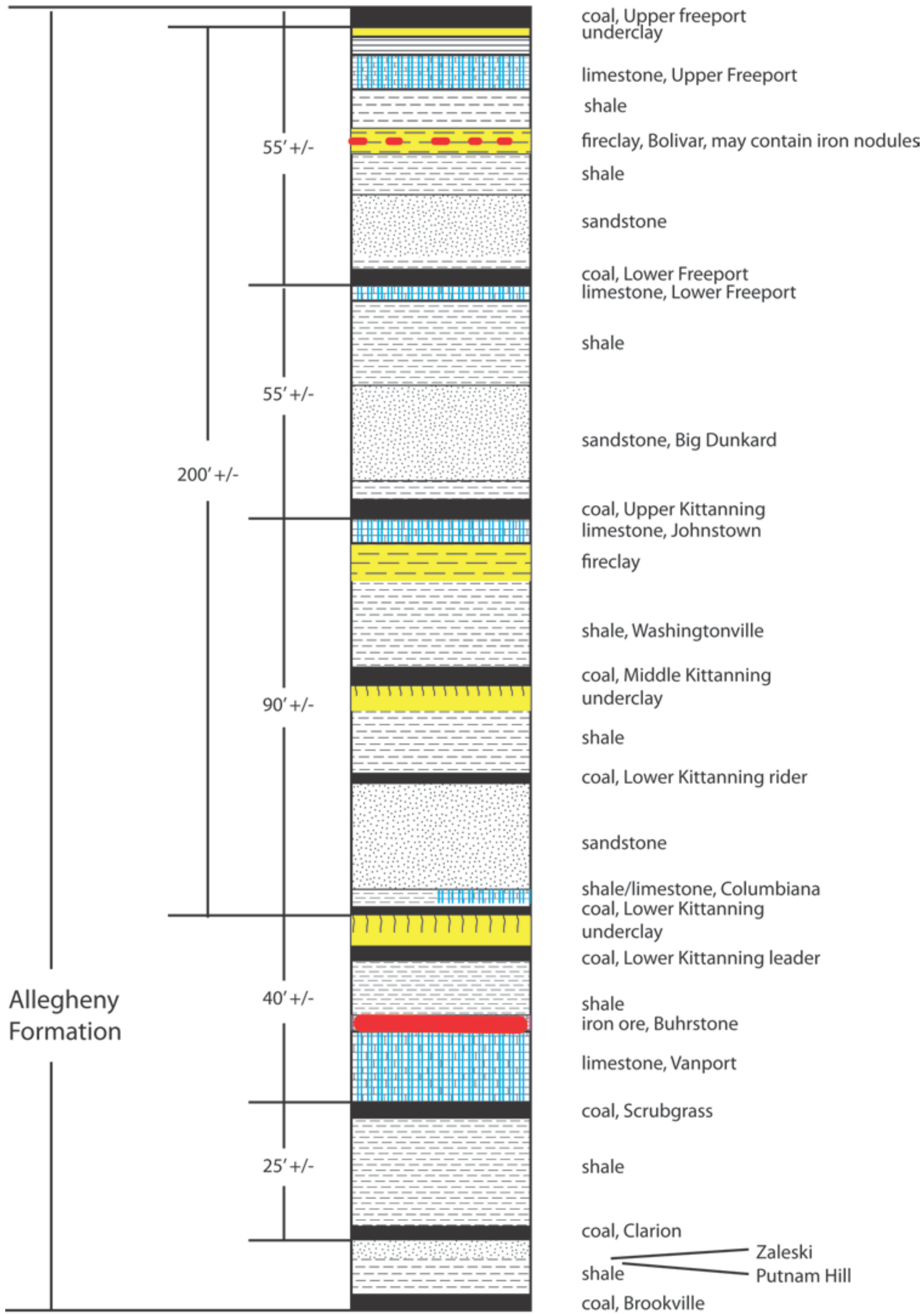


Figure 13: General stratigraphic column for the Allegheny Formation, Western Pennsylvania (adapted from Marks, W. J., and Pennsylvania Geologic Survey for Bureau of Abandoned Mine Reclamation, 1999)

3.1.7 Pennsylvanian Conemaugh Group in Pennsylvania

The Conemaugh Group includes the lower Glenshaw Formation and the upper Casselman Formation (Figure 14). The Conemaugh is defined by the interval between the Upper Freeport coal and the Pittsburgh coal. Overall the Conemaugh may vary from 520 feet in western Washington County to 890 feet in Somerset County (Edmunds, 1999). The Conemaugh is stratigraphically equivalent to the middle of the Llewellyn Formation of the Anthracite Region (Edmunds, 1999). The Conemaugh is known as the Barren Measures because of the lack of economic coal beds with local exceptions (Edmunds, 1999).

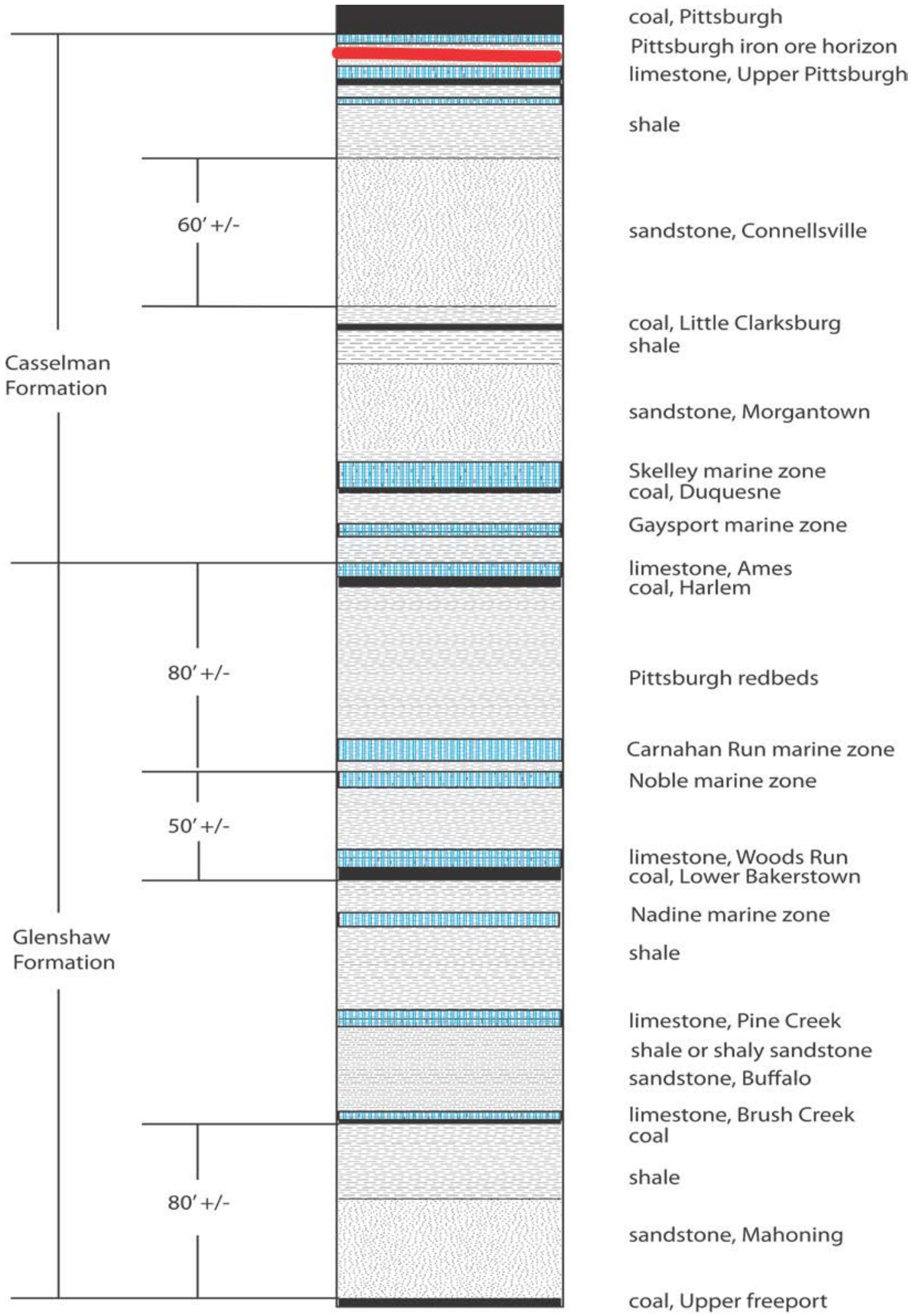


Figure 14: General stratigraphic column of the Conemaugh Group, Western Pennsylvania (adapted from Marks, W. J., and Pennsylvania Geologic Survey for Bureau of Abandoned Mine Reclamation, 1999)

The Glenshaw Formation ranges from 280 ft at the Ohio-Pennsylvania state line to 420 feet in Somerset County and southern Cambria County (Edmunds, 1999). The Glenshaw Formation is defined by the strata between the Upper Freeport coal and the top of the Ames limestone. The Glenshaw is known for several marine limestones: Brush Creek, Pine Creek, Woods Run, and Ames. Other marine horizons within the Glenshaw are the Nadine, Carnahan, and Noble. The fossiliferous and persistent Ames, which may be up to two feet thick, is a valuable marker bed in the Pittsburgh area where it crops out. The Ames marine zone is traceable over much of the Appalachian Plateau Province (Edmunds, 1999). Beneath the Ames is a thick bed of red claystone, siltstone, and shale known as the Pittsburgh red beds. Red beds are variable in thickness and discontinuous throughout the Conemaugh section (Edmunds, 1999).

The Casselman Formation ranges in thickness from 230 ft in western Pennsylvania to 485 feet in southern Somerset County (Edmunds, 1999). The Casselman extends from the top of the Ames up to the base of the Pittsburgh coal. Except for the Gaysport and Skelley marine zones, the Casselman consists of freshwater claystone, limestone, sandstone, shale, and coal with discontinuous red beds (Edmunds, 1999).

Two thick, prominent, massive sandstone units distinguish the Casselman, Morgantown and Connellsville. The sandstone beds range from 50 to 60 feet thick. Much of the Casselman is massive, silty to sandy, commonly calcareous claystone of gray to red to green color (Edmunds, 1999).

3.1.8 Pennsylvanian Monongahela Group in Pennsylvania

The base of the Pittsburgh coal defines the base of the Monongahela Group. The Monongahela Group ranges from 270 to 400 feet thick and extends up to the Permian Waynesburg coal. The

Monongahela is subdivided into the lower Pittsburgh Formation and the upper Uniontown Formation with the dividing line being the Uniontown coal (Figure 15). Four minor coals, the Pittsburgh rider, Redstone, Fishpot, and Sewickley are in the Monongahela. A thick section of freshwater limestone and dolomitic limestone, the Benwood limestone, along with calcareous mudstones, shales, and thin-bedded siltstones and laminites are also in the Monongahela. Economically important Pittsburgh coal is generally 4 to 10 feet thick and is a useful marker bed throughout the basin.

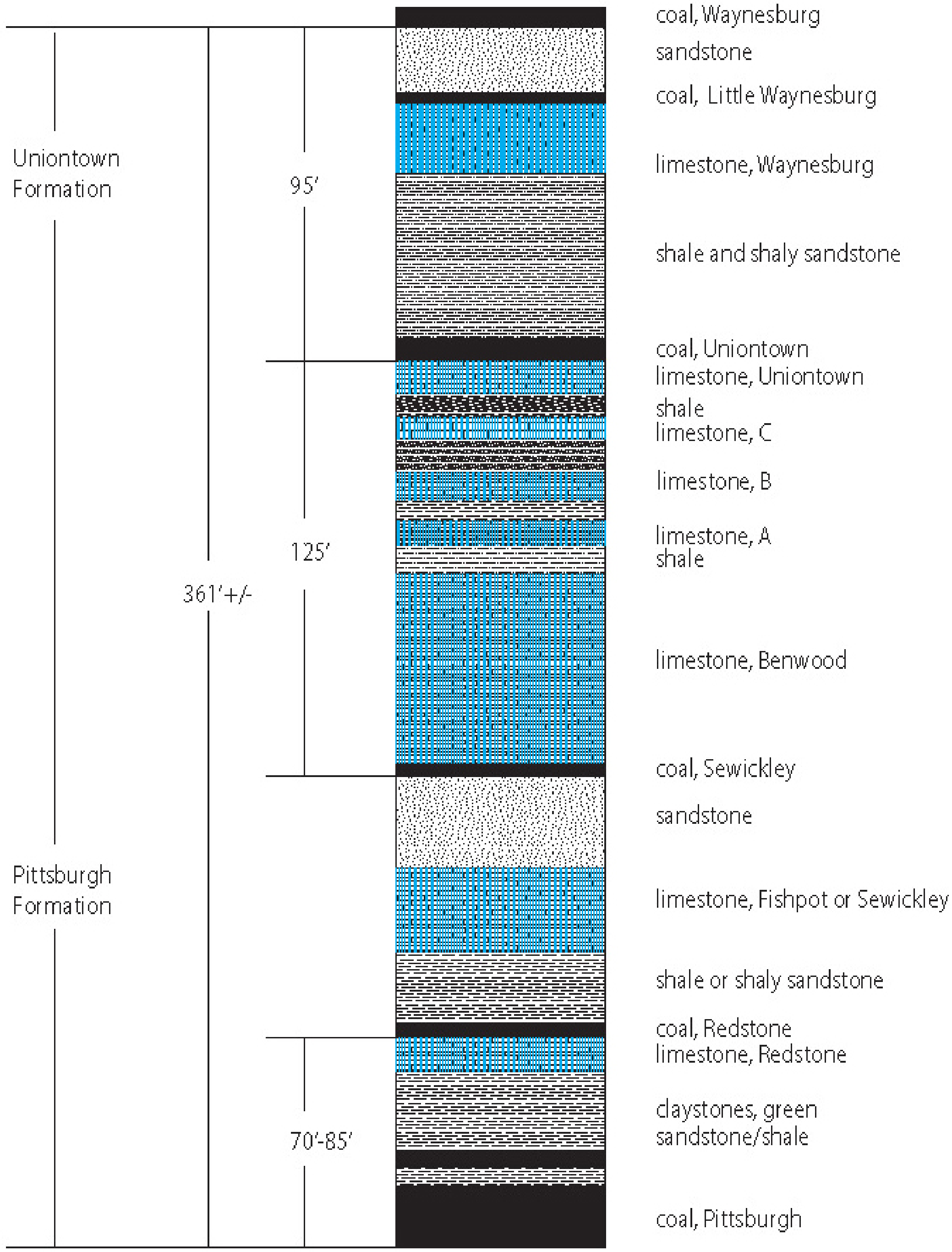


Figure 15: General stratigraphic column for the Monongahela Group, Western Pennsylvania (adapted from Marks, W. J., and Pennsylvania Geologic Survey for Bureau of Abandoned Mine Reclamation, 1999)

3.1.9 Permian in Pennsylvania

The Permian Dunkard Group consists of the Waynesburg Formation, Washington Formation, and Greene Formation (Figure 16). As with the underlying Pennsylvanian units, the Dunkard Group comprises of interbedded sandstone, siltstone, claystone, shale, limestone and coal (Edmunds, 1999). The Waynesburg coal and Upper Washington limestone are persistent throughout the area. The entire group is nonmarine. Maximum thickness of the Dunkard is estimated to be 1,190 feet beneath Fairview Ridge near Wileyville, Wetzel County, West Virginia (Fedorko, 2011).

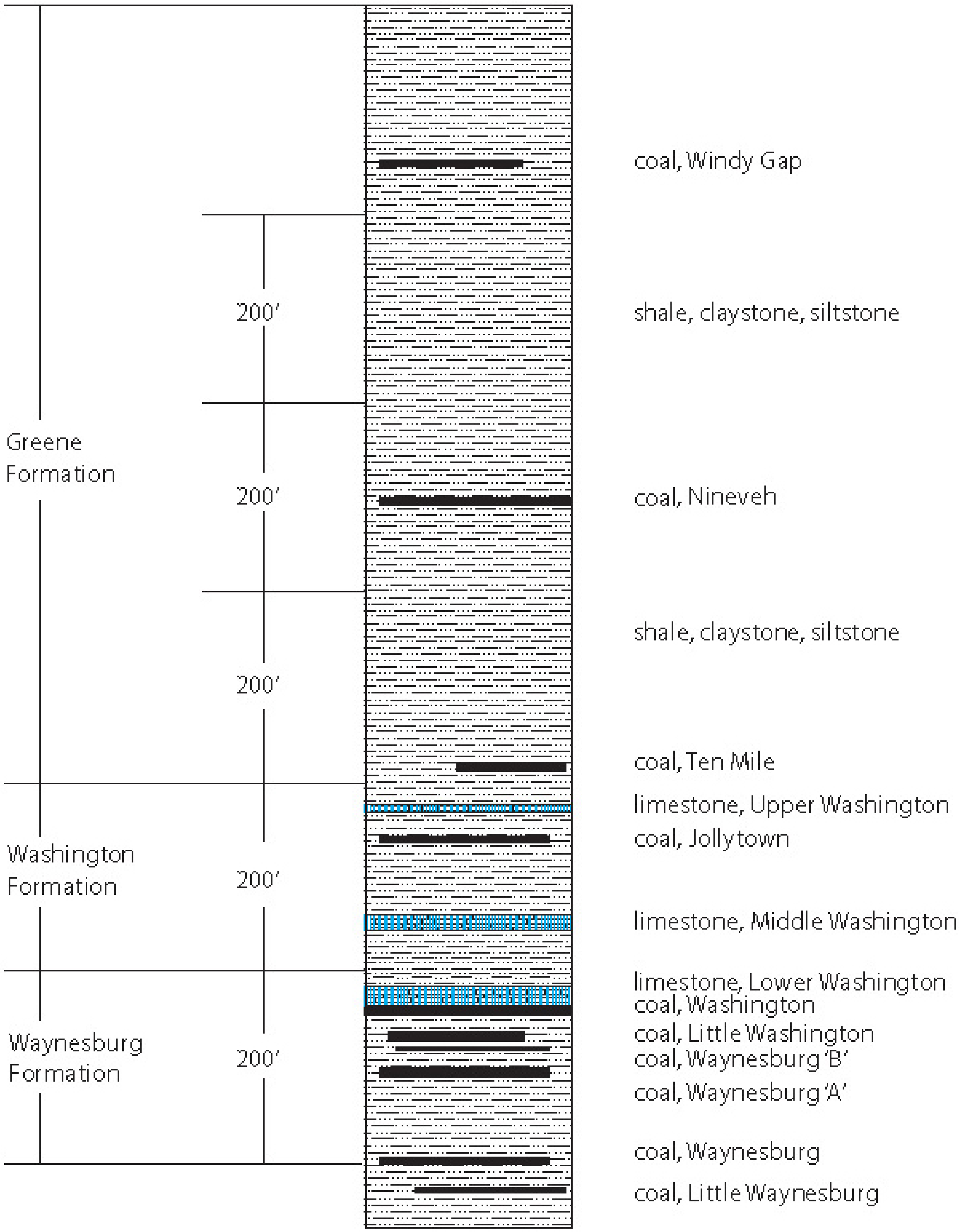


Figure 16: General stratigraphic column of the Dunkard Group in Western Pennsylvania (adapted from Edmunds, 1999)

3.2 SELECTED UNITS OF THE VALLEY AND RIDGE PROVINCE AND THE GREAT VALLEY

The Valley and Ridge Province characterized by long, limestone and shale valleys bounded by ridges underlain resistant sandstone that generally distinguish limbs of folds. Bordering the easternmost ridge of the Valley and Ridge is the Great Valley Section, generally underlain by folded Cambrian and Ordovician carbonate and shale. The Great Valley comprises a long, continuous series of lowland valleys that begin in Quebec and extends south to Alabama. Cambrian rocks are summarized in Table 7.

3.2.1 Cambrian

Table 7: Generalized Cambrian stratigraphic chart (adapted from Kauffman, 1999)

Erathem	System	Central Pennsylvania		Cumberland Valley			Lancaster & Lebanon Valleys				Lehigh Valley	
Paleozoic	Ordovician	Beekmantown Gp.			Pinesburg Station Fm.		Beekmantown Fm.	Ontelaunee Fm.				
					Rockdale Run Fm.			Epler Fm.			Cocalico Fm.	
			Larke Fm.		Upper Mbr.	Stonehenge Fm		Stonehenge Fm.	Conestoga Fm.			Richenbach Fm.
					Stoufferstown Mbr.							
	Cambrian	Gatesburg Fm.	Mines Mbr.		Shadygrove Fm.	Conococheague Gp.	Conococheague Gp.	Richland Fm.				missing
			Upper Sandy Mbr.		Zullinger Fm.							
			Ore Hill Mbr.									
			Lower sandy Mbr.									Allentown Fm.
			Stacy Mbr.									
		Warrior Fm.			Elbrook Fm.			Millbach Fm.				Leithsville Fm.
								Snitz Creek Fm.				
		Pleasant Hill Fm.					Buffalo Springs Fm.					
							Zooks Corner Fm.					
							Ledger Fm.		Ledger Fm.	Conestoga Fm.		
		Waynesboro Fm.			Waynesboro Fm.		Kinzers Fm.		Kinzers Fm.		concealed	missing
										Octoraro Fm.		Leithsville Fm.
		concealed			Tomstown Fm.		Vintage Fm.		Vintage Fm.			
				Chilowee Gp.	Antietam Fm.		Chilowee Gp.	Antietam Fm.	Antietam Harpers Fms.			Hardyston Fm.
Proterzoic	Eocambria				Harpers Fm.			Harpers Fm				missing
					Montalto Mbr.			Chickies Fm.	Chickies Fm.			
					Weverton Fm.							
					Loudon Fm.							
				missing								
				Catoctin Fm.			missing		missing			
				concealed			gneiss		gneiss			gneiss

The lowest unit exposed in the Valley and Ridge is the Cambrian Warrior Formation. The Warrior Formation in central Pennsylvania is a dark, argillaceous or platy, fine-grained limestone interbedded with a dark, finely crystalline, silty dolomite. The Warrior contains oolites, stromatolites and other fossils. The thickness of the Warrior Formation is approximately 400 feet in northwest Pennsylvania to 1,340 feet in north-central Pennsylvania (Kauffman, 1999). Above the Warrior Formation is the Gatesburg Formation. This unit is a sandy dolomite/limestone and has silicified oolitic chert which is a useful marker bed in the field. It contains five members, two thick interbedded sandstones and dolomite units, and three thinner dolomites with little or no sandstone (Kauffman, 1999). The members of the Gatesburg Formation in ascending order are:

-Lower Sandy member, a sandy dolomite and quartzose sandstone

-Upper Sandy member, containing some limestone beds in central Pennsylvania.

-Stacey Member is a dark, crystalline, massive dolomite.

-Ore Hill Member is a non-sandy, carbonate unit.

-Mines Member is a dolomite with chert and siliceous oolites.

3.2.2 Ordovician

Ordovician rocks outcrop in the Ridge and Valley Province, the Great Valley Section, the Piedmont of Lancaster County and along the Martic thrust fault in southeastern Pennsylvania.
The lower and middle Ordovician is predominated by dolomite and limestone units (Table 8). The Upper Ordovician contains clastic formations, namely the Cocalico, Martinsburg, Antes, Reedsville, Bald Eagle, Juniata and Queenston.

Along the foothills of Blue Mountain, the easternmost fold in the Valley and Ridge, a thick bed of Ordovician clastics, the Martinsburg Formation, overlies carbonates. The Martinsburg is a brown to black shale.

Table 8: Generalized Ordovician stratigraphic chart (adapted from Thompson, 1999)

Series	Western Pa.	Central Pa.	South Central Pa.	Eastern Great Valley	Hamburg Klippe	Piedmont Lowland
Upper Ordovician	Queenston Sh.	Juniata Fm.	Juniata Fm.	(missing)	(missing)	(missing) / (missing)
Upper Ordovician	Reedsville/ Bald Eagle Fm.	Bald Eagle Fm.	Bald Eagle Fm	(missing)	(missing)	(missing) / (missing)
Upper Ordovician	Reedsville Fm.	Reedsville Fm.	Martinsburg Fm.	Martinsburg Fm: Shochary Fm. / Windsor Twp. Fm.	(missing)	(missing) / (missing)
Upper Ordovician	Antes Fm.	Antes Fm.	Martinsburg Fm.	Martinsburg Fm: New Tripoli Fm. / Windsor Twp. Fm.	(missing)	(missing) / (missing)
Upper Ordovician	Coburn Fm.	Coburn Fm.	Martinsburg Fm.	Martinsburg Fm: New Tripoli Fm. / Windsor Twp. Fm.	(missing)	(missing) / (missing)
Upper Ordovician	Salona Fm.	Salona Fm.	Martinsburg Fm.	Martinsburg Fm: New Tripoli Fm. / Windsor Twp. Fm.	(missing)	(missing) / (missing)
Upper Ordovician	Nealmont Fm.	Nealmont Fm.	Myerstown Fm.	Hersey Fm. / Myerstown Fm. / Jacksonburg Fm.	(missing)	Cocalico Fm. / (missing)
Upper Ordovician	Linden Hall Fm.	Linden Hall Fm.	Allochthonous	(missing)	(missing)	Cocalico Fm. / (missing)
Upper Ordovician	Snyder Fm.	Snyder Fm.	Allochthonous	(missing)	(missing)	Cocalico Fm. / (missing)
Upper Ordovician	Hatter Fm.	Hatter Fm	Chambersburg Fm.	(missing)	(missing)	Cocalico Fm. / (missing)
Middle Ordovician	Loysburg Fm.	Loysburg Fm.	St Paul Gp.	Annville Fm.	Windsor Township Fm. / Virginville Fm.	Cocalico Fm. / (missing)
Middle Ordovician	Bellefonte Fm. (Beekmantown Gp.)	Bellefonte Fm. (Beekmantown Gp.)	Pinesburg Station Fm. (Beekmantown Gp.)	Ontelaunee Fm. (Beekmantown Gp.)	Virginville Fm.	Conestoga Fm.
Lower Ordovician	Nittany Fm. (Beekmantown Gp.)	Nittany Fm.: Axemann Fm. / Nittany Fm. (Beekmantown Gp.)	Rockdale Run Fm. (Beekmantown Gp.)	Epler Fm. (Beekmantown Gp.)	Virginville Fm.	Conestoga Fm.
Lower Ordovician	Larke Fm. (Beekmantown Gp.)	Larke Fm. / Stonehenge Fm. (Beekmantown Gp.)	Stonehenge Fm (Beekmantown Gp.)	Richenbach Fm. / Stonehenge Fm. (Beekmantown Gp.)	(missing) / Virginville Fm.	Conestoga Fm.

3.2.3 Silurian

The Silurian rocks are exposed in central and northeastern Pennsylvania in the Valley and Ridge Province and along the northwestern edge of the Great Valley. The stratigraphic units within the Silurian System are summarized in Table 9.

Table 9: Generalized stratigraphic chart of the Silurian in Pennsylvania (adapted from Briggs, R. P., 1999)

<table>
<tr><th>System</th><th>Series</th><th colspan="3">Western Pa.</th><th colspan="3">Eastern-Southeastern Pa.</th></tr>
<tr><td rowspan="8">Silurian</td><td rowspan="4">Upper Silurian</td><td>Bass Island Dolomite</td><td colspan="4">Keyser Fm</td><td>Decker Fm</td></tr>
<tr><td colspan="3">Salina Gp</td><td colspan="3">Tonoloway Fm</td></tr>
<tr><td colspan="2">Salina Gp</td><td>Wills Creek Fm</td><td colspan="3">Bloomsburg Fm</td></tr>
<tr><td colspan="3">Lockport Dolomite & McKenzie Fm</td><td colspan="3">Bloomsburg Fm</td></tr>
<tr><td rowspan="3">Middle Silurian</td><td rowspan="3">Clinton Gp</td><td rowspan="3">Rochester Sh</td><td colspan="3">Mifflintown Fm</td><td rowspan="4">Shawangunk Fm</td></tr>
<tr><td colspan="3">Keefer Fm</td></tr>
<tr><td colspan="3">Rose Hill Fm</td></tr>
<tr><td>Lower Silurian</td><td colspan="2">Medina Gp</td><td colspan="3">Tuscarora Fm</td></tr>
</table>

The base of the Silurian is the Tuscarora Formation, a quartzose sandstone that forms the tops of ridges in central Pennsylvania. The Tuscarora is a massive, white sandstone with argillaceous sandstones and shales. The Tuscarora has a conformable contact with the underlying Juniata Formation and the overlying Rose Hill Shale in central Pennsylvania (Laughrey, 1999). The Tuscarora grades into the Shawangunk Formation in eastern Pennsylvania where it is exposed in the Delaware Water Gap. In western Pennsylvania, it grades into the Medina Formation

Overlying the Tuscarora in central Pennsylvania are the Rose Hill, Keefer and Mifflintown Formations. The Rose Hill Formation is mainly shale and mudrock with thin beds of hematitic sandstone and limestone near the top (Laughrey, 1999). The Rose Hill has two layers of grayish red to reddish black, very fine to coarse grained, siliceous, thin to medium bedded, hematitic sandstone and siltstone (Wells, 1973). The Keefer Formation, with a thickness of 40 feet (Wells, 1973), is comprised of locally hematitic, quartzose sandstone, oolitic sandstone, and small amount of mudrock (Laughrey, 1999). The Keefer is light to dark gray, fossiliferous, thin to thick bedded and locally conglomeratic (Wells, 1973). The Mifflintown Formation is comprised of interbedded dark gray, silty, calcareous shale and limestone (Wells, 1973). The limestone is medium to dark gray, medium to thin bedded, planar bedded limestone (Wells, 1973). To the west, the Rose Hill, Keefer and Mifflintown grade into the Clinton Group which is dominated by Rochester Shale. The lower part of the Clinton Group is equivalent to the Brassfield limestone in Ohio.

The Upper Silurian is comprised of the McKenzie Formation, Bloomsburg Formation, Wills Creek Formation, Salina Group, Tonoloway Formation, Keyser Formation, Decker Formation and the Bass Island Dolomite (Table 9). Overlying the Mifflintown is the locally fossiliferous, grayish-red Bloomsburg Formation comprised of claystone and shale with grayish red, very fine to fine grained, hematitic sandstone at the base and top in central Pennsylvania (Wells, 1973). The McKenzie Formation underlies and interfingers with the Bloomsburg Formation in central Pennsylvania (Laughrey, 1999). The McKenzie is a dark-olive to gray marine shale interbedded with marine limestone and minor siltstone (Laughrey, 1999; Patchen, 1975). The Wills Creek conformably lies above the Bloomsburg. The Wills Creek Formation is gray or variegated calcareous shale with interbedded calcareous sandstone, medium gray limestone and grayish red silty claystone (Wells, 1973). The Tonoloway Formation conformably overlies the Wills Creek and is medium gray, laminated to thin-bedded limestone with thin beds of calcareous shale. The uppermost Silurian unit is the Keyser Formation, which is mainly a limestone. In eastern Pennsylvania, the Keyser is about 125 feet thick and consists of gray, argillaceous, fossiliferous, nodular limestone with interbedded calcareous shales (Laughrey, 1999 ; Inners, 1981). In central Pennsylvania, the Keyser is a gray, fossiliferous limestone with laminated and thin bedded gray chert nodules in the upper part (Laughrey, 1999).

3.2.4 Devonian

The stratigraphy of the Devonian in the Valley and Ridge Province has been covered in Section 3.1.2, Devonian in Ohio and Pennsylvania.

The Blue Ridge Province

The Blue Ridge Province is the northernmost extension of the Appalachian Blue Ridge into Adams and Franklin Counties, Pennsylvania. The Blue Ridge Province has the structure of an anticlinorium (Drake, 1999a) and is characterized by a core of Middle Proterozoic crystalline rock overlain by early Cambrian clastic beds which are listed in Table 10 (Drake, 1999a).

Table 10: Generalized stratigraphic chart for South Mountain and Reading Prong, Pennsylvania (adapted from Drake, A. A., Jr., 1999)

<table>
<tr><th>Era</th><th>System</th><th>Series</th><th colspan="3">South Mountain</th><th>Reading Prong</th></tr>
<tr><td rowspan="5"></td><td rowspan="5">Cambrian</td><td rowspan="5">Lower</td><td colspan="3">Tomstown Dolomite</td><td>Leithsville Fm (lower part)</td></tr>
<tr><td rowspan="6">Chilhowee Group</td><td colspan="2">Antietam Fm</td><td>Hardyston Fm</td></tr>
<tr><td rowspan="3">Harpers Fm</td><td>Harpers Fm</td><td rowspan="4"></td></tr>
<tr><td>Montalto Mbr</td></tr>
<tr><td>Harpers Fm</td></tr>
<tr><td rowspan="4">Late Proterozoic</td><td rowspan="8"></td><td rowspan="8"></td><td colspan="2">Weverton Fm</td></tr>
<tr><td colspan="2">Loudoun Fm</td><td>Chestnut Hill Fm</td></tr>
<tr><td colspan="3">Catoctin Fm</td><td rowspan="2">(missing)</td></tr>
<tr><td colspan="3">Swift Run Fm</td></tr>
<tr><td rowspan="4">Middle Proterozoic</td><td colspan="3" rowspan="3">Granodiorite (not present at surface)</td><td>Byram Intrusive Suite</td></tr>
<tr><td>Quartzo-feldspathic and calcareous rocks</td></tr>
<tr><td>Losee Metamorphic Suite</td></tr>
<tr><td colspan="3">Biotite granite gneiss(not present at surface)</td><td>Hexenkopf Complex</td></tr>
</table>

The core of the mountain is the Middle Proterozoic basement rocks of granodiorite and biotite granite gneiss. The Swift Run Formation is a sequence of tuffaceous slates, detrital quartzite and locally some marble which lies above the basement rocks and not exposed in Pennsylvania (Drake, 1999a; Stose, 1946).

Lying over the Swift Run Formation is a thick sequence of Late Proterozoic volcanic rock, the Catoctin Formation. The Catoctin is overlain by the Late Proterozoic to Cambrian sedimentary rock, the Chilhowee Group. Overlying the Chilhowee Group is the Cambrian Tomstown Dolomite. Only the Catoctin, Chilhowee and Tomstown outcrop at the surface.

The Catoctin Formation consists of metabasalt and metarhyolite (Drake, 1999a); Stose, 1932 ; Fauth, 1968, 1978). These metamorphosed basalts and rhyolites occur in alternating layers and were metamorphosed to the greenschist facies (Drake, 1999a; Reed, 1971). The thickness of the Catoctin Formation is approximately 2,500 feet (Drake, 1999a).

Above the Catoctin is the Chilhowee Group composed of Loudon, Weverton, Harpers, Chickies, and Antietam Formations in which clastic rocks predominate. At the base of the Group, the Loudon Formation is approximately 200 feet thick and a phyllite interbedded with a laminated, very fine-grained greywacke at the bottom and polymict conglomerate near the top (Drake, 1999a). The Loudon is a sericitic slate and purple-gray, poorly consolidated and poorly sorted, arkosic sandstone and conglomerate (Kauffman, 1999). The Weverton Formation which overlies the Loudoun is laminated and cross-bedded quartzose greywacke, conglomeratic at the base with a minimum thickness of 900 feet (Drake, 1999a). The Weverton is exposed at Hammond's Rocks along Ridge Road, 4.5 miles south of Mount Holly Springs as a resistant, ridge-forming, quartz sandstone and conglomerate. Above the Weverton is the Harpers Formation, a dark, greenish-gray phyllite and schist with a 2,500 feet minimum thickness (Kauffman, 1999). Montalto Member of the Harpers is a massive, white to gray metaquartzite which crops out along the west and north side of South Mountain (Kauffman, 1999). In the Lancaster and Lebanon Valleys, the Chickies Formation underlies the Harpers and is a thick-bedded, light colored, metaquartzite (Kauffman, 1999). The Antietam Formation is above the Harpers. The Antietam is a gray to blue-gray to white metaquartzite and weathers to a brownish tan (Kauffman, 1999). Antietam contains beds of very pure quartzose sandstones with many Skolithos tubes and ranges from 500 to 800 feet in thickness (Kauffman, 1999).

Above the Chilhowee Group carbonate strata predominate with the Tomstown, Waynesboro, Elbrook, Pleasant Hill, Ledger, and Zooks Corner Formations. In the South Mountain area, the Tomstown Formation is a massive, blue magnesium limestone with some black chert at the top, a dark blue limestone in the middle and a dolomite interbedded with shale at the base (Fauth, 1967). Throughout the Tomstown are thin, shaly interbeds (Kauffman, 1999). The Tomstown thickness is estimated at 1,000 to 2,000 feet (Kauffman, 1999).

The Waynesboro Formation overlies the Tomstown Formation. The Waynesboro comprises 1000 feet or more of interbedded red to purple shale and sandstone in the lower part and upper parts separated by a middle unit of dolomite and blue, impure limestone (Kauffman, 1999). In central Pennsylvania, the Waynesboro is a coarse-to medium-grained brown sandstone interbedded with red and green shales (Kauffman, 1999). In central and eastern Pennsylvania, the Pleasant Hill Formation or the Elbrook Formation overlies the Waynesboro. The Ledger Formation and Zooks Corner Formation also overlay the Waynesboro. The Pleasant Hill is a thinly layered, argillaceous, sandy, and micaceous limestone with some calcareous shale. The upper part can be a thick-bedded, fine-grained, dark-gray limestone (Kauffman, 1999; Butts, 1945).

3.3 READING PRONG

The Reading Prong is an upland area located in Berks, Lehigh and Northampton Counties which is underlain by metamorphosed igneous rocks and Early Cambrian sandstone. The Reading Prong is situated between the Triassic rift valley on the southeast and the Great Valley on the northwest. The structure of the Reading Prong has been debated, but current theory (Drake, 1999a) is that the crystalline rocks are largely allochthonous, underlain by thrust faults that may have been active during the Taconic and Alleghenian orogenies. A stratigraphic chart of the units found in the Reading Prong is in Table 10.

The Chestnut Hill Formation exposed along the northern border of the Reading Prong near the Delaware River is a sequence of arkose, ferruginous quartzite, quartzite conglomerate, metarhyolite and metasaprolite rocks (Drake, 1999a) . The formation contains biotite and thought to be of Late Proterozoic age (Drake, 1999a).

The Hardyston Formation is the basal Cambrian sedimentary unit overlying the Reading Prong. The Hardyston is an arkosic conglomerate at the base, changing upsection to arkosic sandstone, orthoquarzite, carbonate-cemented sandstone, silty shale and jasper. At one exposure the Hardyston grades into the overlying Leithsville Formation (Drake, 1999a).

3.4 NEWARK AND GETTYSBURG BASIN OF THE PIEDMONT PROVINCE

The sedimentary rocks within the Newark and Gettysburg Basin represent fluvial and lacustrine clastic sediments of Late Triassic age (Smoot, 1999). Both marine and freshwater fossil assemblages are found in the sediments. Pyrite has been seen in the dark shales in the Newark Basin in New Jersey by this author. The red color reflects the occurrence of hematite within the rock.

4.0 GEOLOGIC SETTINGS OF IRON ORE AND CLAY DEPOSITS

The extent of iron ore that was of economical importance at one time in Ohio and Pennsylvania is shown Figure 1. The economic deposits of iron ore and clay shown by mines and pits and iron furnaces are widely distributed throughout Pennsylvania and Ohio. The map reveals the association of the deposits with stratigraphic horizons and faults and fractures. The presence of calcareous rocks is common to all deposits.

Today, local iron deposits in sedimentary rock are not economically viable because they are too thin, varying from a few inches to less than 2 feet in thickness. This thesis will refer to the early iron deposits as ore or ironstone. The geologic setting for associated iron and clay deposits in each of the five physiographic provinces is described below.

4.1 APPALACHIAN PLATEAU AND DUNKARD BASIN

Pennsylvanian and underlying uppermost Mississippian rocks host most of the iron and clay deposits in the subhorizontal sedimentary rock in the Appalachian Plateau. In Ohio local ore was used in Ohio over a period of 119 years from 1804 to 1923 (Stout, 1944). In Pennsylvania, local iron from sedimentary and limestone replacement deposits were utilized from about 1720 to 1972, ending the period of iron production when Hurricane Agnes closed the Grace Mine, a magnetite deposit in Berks County. Significant production of limonite ore ended in the period of 1910 to 1915 (Inners, 1999).

The principal ores used for iron production in the eighteenth and nineteenth centuries are found in multiple horizons mainly in the Pottsville and Allegheny Formations of Ohio and Pennsylvania, Tables 11 and 12 (Stout, 1944; Inners, 1999). The geologic setting of iron deposits are described by location.

Table 11: Iron ore horizons in the Allegheny Formation and Conemaugh Group, western Pennsylvania and eastern Ohio (based on Stout, 1944), blue shaded blocks are limestone rock units, red shaded blocks are iron ore horizons, yellow shaded blocks are clay units

System	Group or Formation		Stratigraphic unit In Ohio	Ore name	Ore name	Stratigraphic unit In Pennsylvania
Pennsylvanian	Conemaugh Gp	Casselman Fm	Pittsburgh coal			Pittsburgh coal
					Pittsburgh ores	
			Connellsville ls			Connellsville ls
			Morgantown ss			Morgantown ss
					Blacklick ore	
				Big Red shales ore		Barton coal
			Skelly ls			Skelly ls
			Ames ls			Ames ls
			Noble ls			Noble ls
			Saltsburg ss			Saltsburg ss
		Glenshaw Fm		Fulton ore on Round Knob sh		
			Ewing ls			
			Cambridge ls			Pine Creek ls
			Buffalo ss			Buffalo ss
					Brush Creek ore	Brush Creek ls
			Mahoning coal			Mahoning coal
			Mahoning ls	Mountain ore		
			Mahoning ss		Johnstown ore	Mahoning ss
				Blackband ores, Buchtel,		
	Allegheny Fm		Upper Freeport coal			Upper Freeport coal
			Upper Freeport underclay			Upper Freeport underclay
					Upper Freeport ore	
			Upper Freeport ls			Upper Freeport ls
			Bolivar clay	Little Yellow Kidney		Bolivar flint clay
						Lower Freeport coal
						Lower Freeport underclay
					Lower Freeport ore	
			Lower Freeport ls			Lower Freeport ls
			Upper Kittanning ls	Straitsville ore		Upper Kittanning ls
			Upper Kittanning coal			Upper Kittanning coal
			Upper Kittanning underclay			Upper Kittanning underclay
			Johnstown ls		Kittanning ore	Johnstown ls
						fireclay
			Washingtonville sh			Washingtonville sh
				Red kidney		
			Middle Kittanning coal			Middle Kittanning coal
			Middle Kittanning/underclay			Middle Kittanning underclay
			Obryan lm/Columbiana sh	Hamden ore		Columbiana ls/sh
			Lower Kittanning coal			Lower Kittanning coal
			Lower Kittanning underclay			Lower Kittanning underclay
					Kittanning ore	
			Vanport lm/sh	Buhrstone ore	Buhrstone ore	Vanport lm/sh
			Scrubgrass coal			Scubgrass coal
			Clarion coal			Clarion coal
			Zaleski flint horizon			Zaleski
				Canary ore		
			Putnam Hill lm/sh		Brookville ore	Putnam Hill ls/sh
			Brookville coal			Brookville coal
			Brookville underclay			Brookville underclay

Table 12: Iron ore horizons in the Pottsville Formation, western Pennsylvania and eastern Ohio (based on Stout, 1944)

System	Group or Formation	Stratigraphic unit in Ohio	Ore name	Ore name	Stratigraphic unit in Pennsylvania
Pennsylvanian	Pottsville Fm	Homewood ss			Homewood ss
		Tionesta coal			Tionesta coal
		Upper Mercer lm	Upper Mercer ore		Upper Mercer lm
		Bedford coal			
			Sand block ore	Mercer ore	
		Upper Mercer coal			Upper Mercer coal
					Upper Mercer underclay
		Upper Mercer lm	Upper Mercer ore		
		Lower Mercer lm	Lower Mercer ore		
		Middle Mercer coal			
		Flint Ridge coal			
		Boggs lm	Boggs ore	Mercer ore	
		Lower Mercer coal			Lower Mercer coal
					Lower Mercer underclay
				Mercer ore	
		Lowelville lm	Lowellville ore		Lowelville ls horizon
		Massillon ss			Upper Connequenessing ss
				Quakertown ore	
		Quakertown coal			Quakertown coal
		Quakertown underclay			Quakertown underclay
					Lower Connequenessing ss
			Guinea Fowl ore		
		Anthony coal			
		Sciotoville clay			
			Sharon ore	Sharon ore	
		Sharon coal			Sharon coal
		Sharon sandstone/conglomerate			Pottsville ss
			Harrison ore		
Mississ-ippian		Maxville lm			
		Logan Fm		Mauch Chunk ore	Mauch Chunk

Silurian

Iron ore was mined for the early charcoal furnaces in Adams, Highland and Clinton Counties from the Silurian Brassfield limestone and the Niagara dolomite. The ore layer in the middle of the Brassfield is a hematitic, oolitic, and resembles the Clinton-type ore (Stout, 1944). The hematite bearing layers are four inches to one foot eight inches thick. Results of an analysis of the ore indicate that the main mineral components are 3.31 percent kaolinite, 8.43 percent limonite, 5.82 percent hematite and 77.54 percent limestone (Stout, 1944). Limonite ore was developed on the Silurian Niagara dolomite. The iron deposits are found as irregular masses of limonite in depressions on the top of the dolomite and may vary in thickness from a few inches to ten feet. The lateral extent of the ore deposits may reach hundreds of feet (Stout, 1944).

Devonian

Ohio Devonian rocks contain iron concretions in the lower part of the Ohio shale, but the amount of iron was not enough to mine as ore (Stout, 1944). This is not the case in Pennsylvania, where the Devonian contains iron ore in the base of the Marcellus Formation and within the Ridgeley (Oriskany) sandstone which crop out in the Valley and Ridge Province.

Mississippian

In Scioto County, Ohio, thin lenses (2 to 6 inches thick) of iron ore in the Mississippian Waverly Group near the Allensville horizon (a conglomerate) was smelted for ore at the Harrison furnace. The ore is sheet-like and fossiliferous (Stout, 1944). The Waverly rocks were not used extensively for iron (Stout, 1944). However, in Pennsylvania, the Mississippian Mauch Chunk Formation contains iron ore that was mined on the western slope of Chestnut Ridge. The Mauch Chunk ore was the most important ore to the furnaces on Chestnut Ridge (Stevenson, 1877).

Mississippian – Pennsylvanian Unconformity

In Ohio, ironstone was mined at the unconformity between the Mississippian and Pennsylvanian strata. Iron-cemented angular siliceous fragments and/or well-rounded quartz pebbles are present at the base of the Pottsville below the Sharon Conglomerate. The conglomerate overlies the Mississippian Maxville limestone or Logan shale where the Maxville has been eroded away. The ore, known as, the Harrison, was mined in Scioto and Licking Counties, southern Ohio (Stout, 1944). The ore is variable. In Scioto County, the thickness may be as much as four feet. The ore is composed of angular, siliceous fragments, well-rounded quartz pebbles, chert (flint), sandstone fragments, boulders, shale and ferruginous clay (Stout, 1944). The siliceous fragments may contain marine fossils, therefore, it is believed that the fragments were originally angular limestone pieces replaced by silica prior to iron cementation (Stout, 1944). Harrison ore was used in the Harrison furnace in Scioto County and the Granville and Mary Ann furnaces in Licking County. Harrison ore is known from the Ohio River in Scioto County to the Ohio-Pennsylvania line in Mahoning and Trumbull counties.

Pennsylvanian

Most of the marine limestone horizons in the Pottsville and Allegheny Formations contain iron ore (Stout, 1944). In general, the ore mined from Pennsylvanian strata exposed on the Plateau was the mineral siderite and its weathering products, limonite and goethite. Thin to thick, continuous siderite layers referred to as block ore, are found associated with limestones. The Big Red Block and Little Red Block ores are found with the Mercer limestone in the Pottsville Formation in Ohio. The Big Red Block ore, 4 inches to 18 inches thick, forms laterally continuous layers that rest directly upon the Upper Mercer limestone in Scioto County, Ohio

(Stout, 1944). The Little Red Block ore lies on or a few feet above the Lower Mercer limestone when the both are present (Stout, 1944). This ore weathers red and is commonly fractured along vertical joints producing a block-like appearance.

Ferruginous beds are found above several marine limestones in Perry County, Ohio (Flint, 1951). In the Pottsville and Allegheny Formations, the marine limestones which are associated with ironstone are the Lowellville, Boggs, Lower Mercer, Zaleski, Vanport, Hamden and Washingtonville (Stout, 1944). The ironstone is found overlying the limestone or as a replacement of the limestone. For example, in Vinton County, Ohio, the Zaleski horizon may be composed of calcareous flint, siliceous limestone, calcareous shale or siderite (Stout, 1944).

Iron nodules may replace or accompanied the limestone layer as in the case of the Yellow Kidney ore and the Lower Freeport limestone (Stout, 1944). Another ore associated with calcareous shale or nodular limestone is the Hamden ore immediately above the Lower Kittanning Coal (Stout, 1944) which is the horizon of the Columbiana limestone/shale. The ore is found with clay as reported in stratigraphic logs for the Hamden ore in Vinton County, Ohio. The Hamden ore is at the base of the Oak Hill clay which also has scattered nodules. The Hamden is two feet above the Lower Kittanning coal (Stout, 1944).

Siderite in layer form has been found in or immediately overlying the Upper Freeport coal. A siderite layer within a coal bed is carbonaceous and referred to as “blackband”. Clay is found beneath the coal horizons as underclay.

Iron ore may be also intermingled with silica and limestone such as the Buhrstone iron ore found at the top of the Vanport limestone in Armstrong, and parts of Beaver, Lawrence, Butler and Clarion Counties, Pennsylvania. The amount of silica and siderite contained within the Buhrstone ore in Ohio ranges 0.62 to 26.32 percent and 40.91 to 68.44 percent respectively (Table 13).

Table 13: Chemical analysis of Buhrstone ore, Ohio (adapted from Stout, 1944)

Analyses from Various Sources of Ferriferous Ore

Number.	Iron. Fe.	Siliceous matter, SiO_2.	Alumina, Al_2O_3.	Phosphorus, P.	Lime, CaO.	Magnesia, MgO.	Sulphur, S.	Manganese, Mn.	Ignition loss.	Water combined, H_2O.	Water hydroscopic, H_2O.	Manganese dioxide, MnO_2.	Phosphoric acid, P_2O_5.	Iron carbonate, $FeCO_3$.	Iron sesquioxide, Fe_2O_3.	Lime phosphate, $C_3P_2O_8$.	Lime carbonate, $CaCO_3$.	Magnesium carbonate, $MgCO_3$.	Specific gravity.
1	45.50	24.20	6.50	.155	1.50	.55	.580	......	......	......	......	......	......	......	......	......	......	......	......
2	54.81	7.27	......	.108	trace.	......	.063	......	......	......	......	......	......	......	......	......	......	......	......
3	47.90	6.25	......	.116	.71	......	.172	......	......	......	......	......	......	......	......	......	......	......	......
4	40.88	5.00	......	.232	7.00	......	.282	1.49	21.95	......	4.00	......	......	......	......	......	......	......	......
5	30.26	22.24	1.69	.430	2.95	1.19	.79	.75	26.28	2.63	......	......	......	......	......	......	......	......	......
6	31.65	22.45	1.91	.740	2.77	1.08	.48	.83	26.22	1.72	......	......	......	......	......	......	......	......	......
7	47.81	7.00	1.32	.980	1.23	......	.097	trace.	21.00	......	......	......	......	......	......	......	......	......	......
8	35.57	9.76	2.20	.260	5.15	......	......	.76	......	......	......	......	......	......	......	......	......	......	......
9	36.76	12.28	2.78	.120	5.65	......	......	.46	......	......	......	......	......	......	......	......	......	......	......
10	35.20	7.66	7.38	.176	14.74	......	......	.41	......	......	......	......	......	......	......	......	......	......	......
11	38.91	15.42	.75	......	......	......	.12	......	......	1.10	......	1.55	.38	63.27	7.20	.87	5.40	3.44	3.585
12	44.14	.62	3.03	......	......	......	.95	......	......	......	......	3.10	.57	58.39	22.79	1.24	6.00	3.12	3.125
13	41.89	7.52	.51	......	......	......	.15	......	......	......	......	.13	.35	68.44	13.51	.76	6.12	2.11	3.583
14	54.39	2.00	......	......	3.67	......	trace	......	......	5.60	......	1.90	......	......	77.70	......	9.09	trace.	3.066
15	36.81	26.32	.60	......	......	......	trace	......	......	......	......	1.05	trace.	40.91	24.37	......	4.20	2.65	3.439
16	50.20	9.58	6.53	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
17	41.81	23.74	3.67	.155	5.53	......	.784	......	......	......	......	......	......	......	......	......	......	......	......

In Pennsylvania, well-developed siderite beds were mined along Chestnut Ridge in Fayette County on the west limb of the regional Uniontown syncline. Siderite was mined from five calcareous layers between the Pittsburgh coal and the lower Pittsburgh limestone, within 25 feet below the bottom of the coal (Stevenson, 1877). Small amounts of ore are seen north of the Youghiogheny River, with minor amounts of ore as far north as Westmoreland County (Stevenson, 1877).

A generalized section shows the order and distance below the Pittsburgh coal (Table 14).

Table 14: Generalized stratigraphic section for the Pittsburgh ore (Stevenson, 1877).

Rock unit	Thickness, ft
Pittsburgh coal	-----
clay	2’ – 8’
Blue Lump Ore	0” to 1’ 6”
clay	4” – 1’ 6”
Condemned Flag ore	0” – 1’
clay	4” – 2’ 6”
Big Bottom	1’ – 1’8”
clay	10” – 5’
Red Flag ore	2” – 6’
clay	1’ – 3’
Yellow Flag	4”
Pittsburgh limestone	-----

The five siderite layers were given the names: “Blue Lump”, “Condemned Flag”, “Big Bottom”, “Red Flag”, and Yellow Flag” (Stevenson, 1877). The “Blue Lump” was a layer of flattened siderite nodules, closely packed in a continuous layer with an average one inch thickness (Stevenson, 1878). The Blue Lump was reported along the Monongahela River and in the area between the Cheat and the Monongahela River. The ore was mined at Fairchance and South Union. The quality diminished on the western side of the Uniontown Syncline and was missing in Brownsville, Fairmont, Clarksburg (Stevenson, 1877). It is known in Morgantown, West Virginia (Stevenson, 1877).

The Condemned Flag is a fine-grained, blue carbonate ore that can be in the form of a layer or as lenticular nodules four to seven inches thick (Stevenson, 1877). This layer is not persistent.

Big Bottom, ten to eighteen inches thick, was mined at Fairchance, Oliphant's, Fuller's and Beatties's furnaces at the base of the base of Chestnut Ridge. The surface color is yellow-brown and is bluish-gray on a fracture surface.

Siderite nodules

Siderite nodules and concretions that were used for ore can be seen within the shales associated with coals of Pennsylvanian age. They can be distributed randomly or in distinct layers in the shale above coal units. Concretions can be internally fractured and the fractures filled with quartz, barite, or calcite (Skema, 2005).

Nodules and concretions can be also concentrated as a placer deposit in streams. This type of deposit was mined in Columbiana County, Ohio where gravel beds in the Middle Fork of the Little Beaver were dug for the iron nodules (Stout, 1944). Where the iron ore is protected by thick overburden, the ore is siderite. The ore is a limonite near the surface (Stout, 1944).

Nodular or kidney ore is found in shale between the Middle and Lower Kittanning coal seams. The crust of the nodules has been converted to limonite (Stout, 1944).

Another nodular iron ore is embedded in the white Bolivar clay about 15 ft above the Lower Freeport coal in Perry County, Ohio (Stout, 1944). This is the Sour Apple or Straitsville ore. It is 10 to 30 ft below the Upper Freeport coal and 60 to 70 ft above the Middle Kittanning coal (Stout, 1944).

Dark, carbonaceous, siderite layer(s), blackbands, associated with coal seams, may be present either within the coal seam, or just above the coal seam. The blackband normally looks like black shale with slightly higher density (Stout, 1944). The test for a blackband ore was to burn a heap of suspected black shale outdoors. If there is enough iron, the shale will agglutinate and form a dense, scoriaceous mass (Stout, 1944).The Sharon blackband ore found in the Sharon coal from Trumbull and Mahoning Counties was important to the development of the iron industry in the Mahoning Valley of Ohio.

Other mined blackband ores in Ohio are known from the Lower Kittanning coal, and the Freeport coal (Stout, 1944). The black, bituminous shale ore above the Upper Freeport coal in Tuscarawas County, although not extensive and of variable thickness, contains 25 to 40 percent iron (Stout, 1944). The largest blackband deposit described by W. Stout (1944) had an average thickness of eight feet and the geographical extent of mainly Tuscarawas County (Stout, 1944).

Iron found in clay beneath coal layers

Iron nodules have been reported in the clays beneath the Upper Freeport coal in the Bolivar clay in Bolivar, Westmoreland County, Pennsylvania (Leighton, 1932). At the town of Bolivar extensive mining for clay took place and nodules of iron carbonate called “iron balls” were found in the Bolivar clay, eleven feet below the Upper Freeport coal (Leighton, 1932).

4.2 VALLEY AND RIDGE PROVINCE AND THE GREAT VALLEY SECTION

Iron and clay ore mined in the Valley and Ridge Province is hosted by Cambrian through Devonian age carbonate rocks. As described above, four types of iron ore are known from sedimentary rocks in the Valley and Ridge Province and the Great Valley Section. The ore types include: brown limonite iron ore found embedded in massive clay above carbonate bedrock, hematitic fossil ore in the Silurian Clinton Group, a sideritic layer at the base of the Devonian Marcellus Shale and a hematitic cemented sandstone and limonite nodules in the Ridgely Formation in association with the Oriskany Sandstone and its underlying limestone and chert beds. The association of iron and clay deposits is present along calcareous horizons and along faults where calcareous rocks are present either in the footwall or hanging wall.

4.2.1 Limonite ore present in Cambrian and Ordovician Age rocks

A map of the historical mine locations indicate where iron ore and white clay mines were mined from rocks of Cambrian and Ordovician age (Figure 2). In central Pennsylvania iron commonly has been mined from saprolitic, residual clay soil overlying the Cambrian Gatesburg Formation. Residual ferric oxide ores were mined in Centre, Bedford, Blair and Huntingdon Counties in central Pennsylvania (Inners, 1999). In Centre County alone 93 limonite ore bank mines or tracts were listed in 1884 (D'Invilliers, 1884) The limonite ore was found in the form of nodular, botryoidal, cellular and stalactitic masses of limonite or goethite embedded in clay (Inners 1999; Foose, 1945). Surface pits called “banks” were dug into deep kaolinitic clay pockets (Inners, 1999; Foose, 1945) within limestone and dolostone to mine for ore. The percentage of iron in the deposit varies from 10 to 50 percent (Lesley, 1892). The brown ore was washed free of clay and then used in charcoal furnaces. For example, the Pennsylvania Furnace ore bank was 1400 feet long by 600 feet wide and 65 feet deep (Lesley, 1892).

In central Pennsylvania, many limonite and clay mines were operated in the residual clay soil overlying the Gatesburg Formation. The Gatesburg subcrops in Centre, Huntingdon, Blair and Bedford Counties. The distribution iron and clay mines are shown on Figure 17.

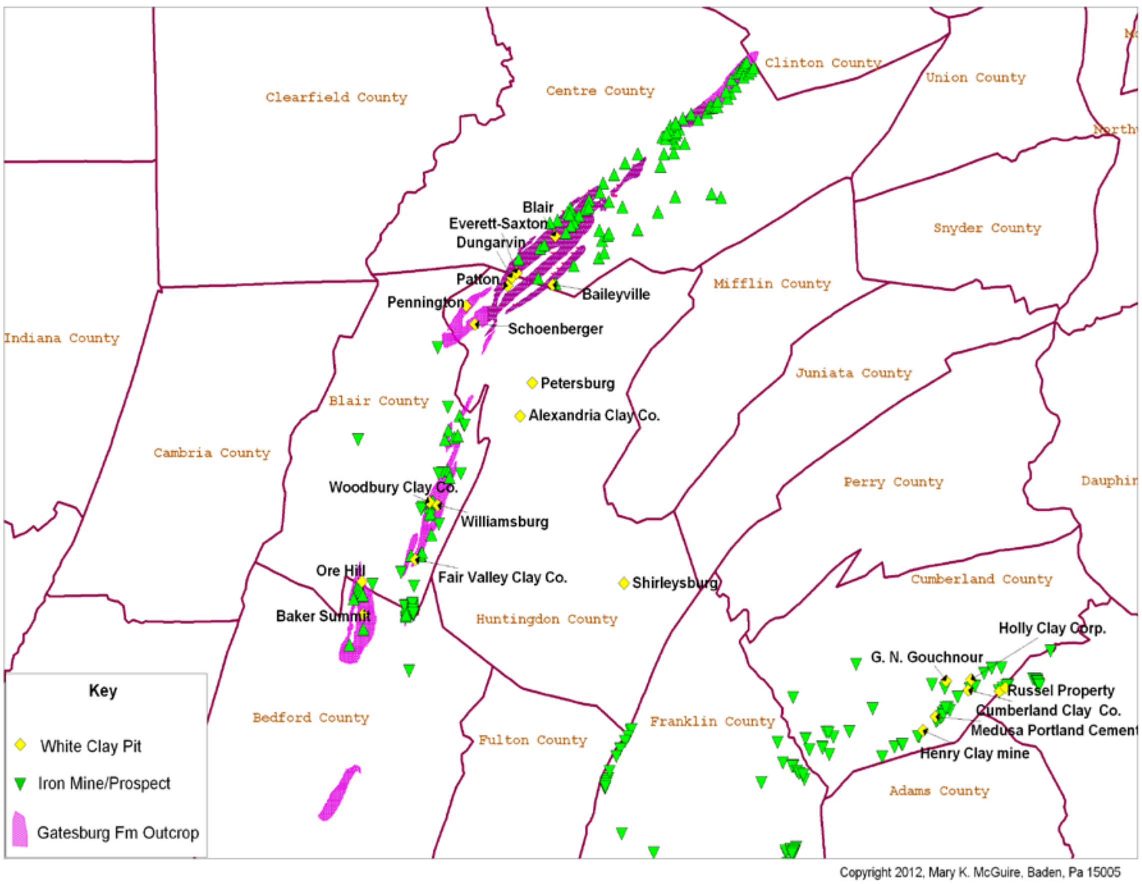


Figure 17: White clay mines and limonite iron ore mines along the Gatesburg subcrop, central Pennsylvania (adapted from Berg, 1980)

In the Valley and Ridge, the ore banks mined along the northern side of the Nittany Valley, Centre County, on the Gatesburg exposure are close to a major thrust fault, the Birmingham fault. In Huntingdon, Blair and Centre Counties, the Birmingham fault runs parallel to a line of limonite mines which are 1.5 to 0.5 miles southeast from the fault (Figure 18). The Birmingham fault is a thrust fault seen at the surface along the base of the eastern slope of Bald Eagle Mountain. The fault dips southeast at a low angle beneath Sinking Valley. Two fensters, Birmingham and Knarr, along the south boundary of Huntingdon County reveal the rock units beneath the Birmingham fault. The older rocks of the Gatesburg Formation overlie the younger rocks seen in the fensters. Within the fensters are exposed thrust faults (Tormey, 1996) which are aligned with the Birmingham thrust fault. The iron ore banks are within a thick, weathered soil above the Gatesburg which could hide a fault. On the map by Moebs and Hoy (1959), the southwest extension of the Birmingham fault extends to the zinc sulfide mine shown on the Figure 18. A second line of limonite ore banks which includes the Pennsylvania Furnace ore bank, is situated on the southeast side of the Nittany Valley.

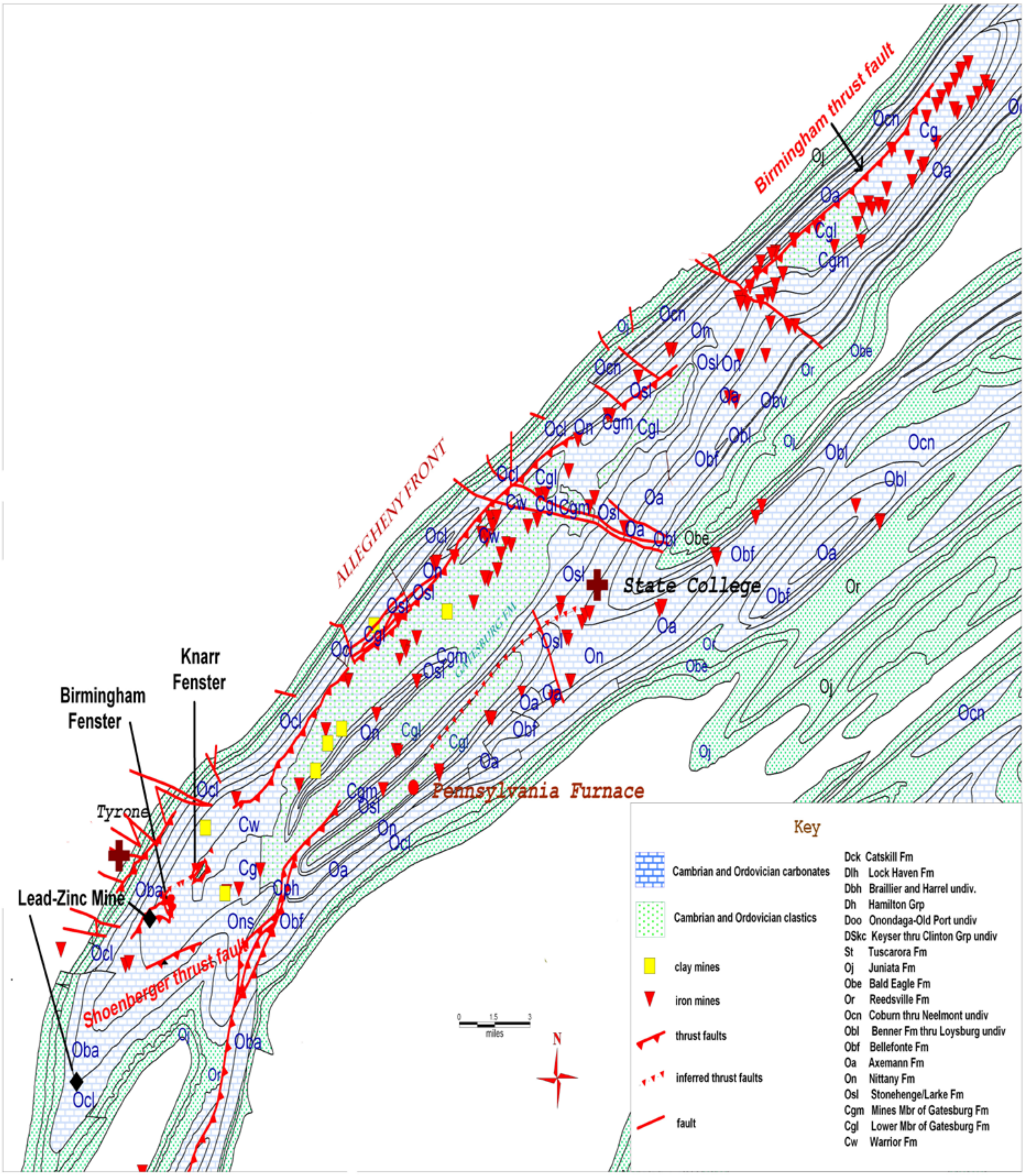


Figure 18: Iron, lead-zinc and clay mines in Sinking Valley, Centre County, Pennsylvania (adapted from Berg, 1980)

In addition to finding iron above the Gatesburg Formation, iron mines have also been recorded in the lower Ordovician carbonates, in the Julian, State College, Bellefonte and Mingoville quadrangles, northeast of State College, Centre County. A line of mines marks the southeast side of the Nittany Valley from which ore was mined from pits in Ordovician Stonehenge limestone, Nittany dolomite and Axemann limestone (Rose, 1995). These Ordovician limestones are not generally known for being ferruginous. The typical iron content of the limestone is 0.5 % +/- 0.2 % (Rose, 1995).

Near the town of Metal, south of Fannettsburg, Franklin County, Pennsylvania, iron mines developed on the southeast side of Tuscarora Mountain comprise a linear array along the Path Valley thrust fault (Figure 19).

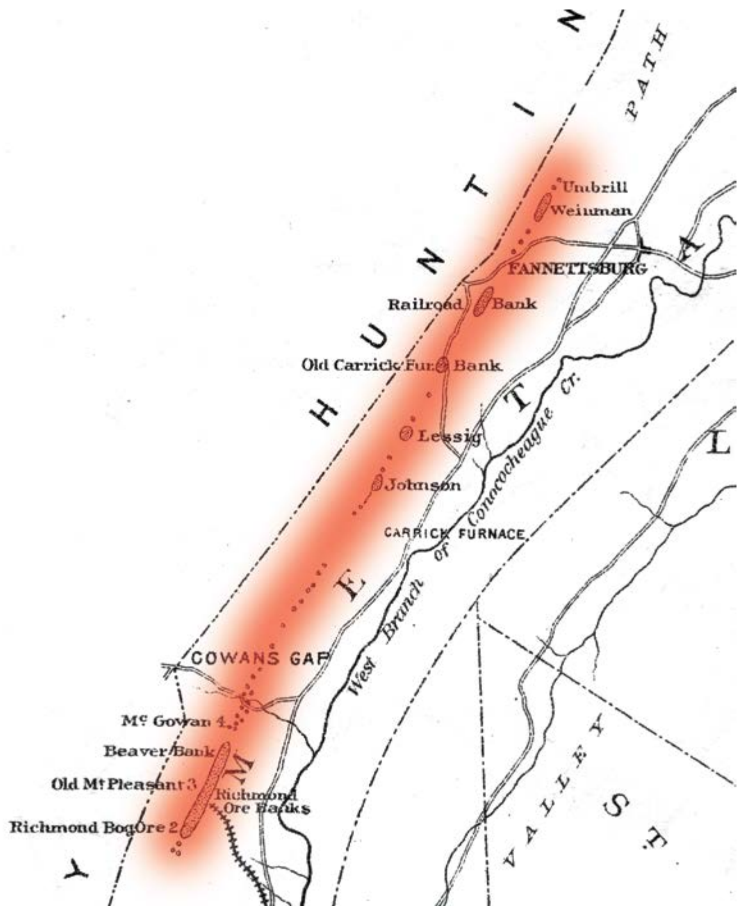


Figure 19: Path Valley historic iron mines in Western Franklin County along red shaded region (adapted from D'Invilliers, 1886)

The mines and sinkholes coincide with the Path Valley thrust fault (Nichelsen, 1996) along which Ordovician Martinsburg or Silurian Tuscarora Formation (Figure 20), and (Figure 21), Cross Section A – A', has been emplaced above Middle Ordovician Bellefonte dolomite and St. Paul Group limestone. The hanging wall rocks comprise the Ordovician Juniata/Bald Eagle Formation (Ojb) or the Ordovician Martinsburg Shale (Om), whereas the footwall is composed of carbonate rocks of Ordovician Bellefonte Formation (Obf) or the St. Paul Group (Osp).

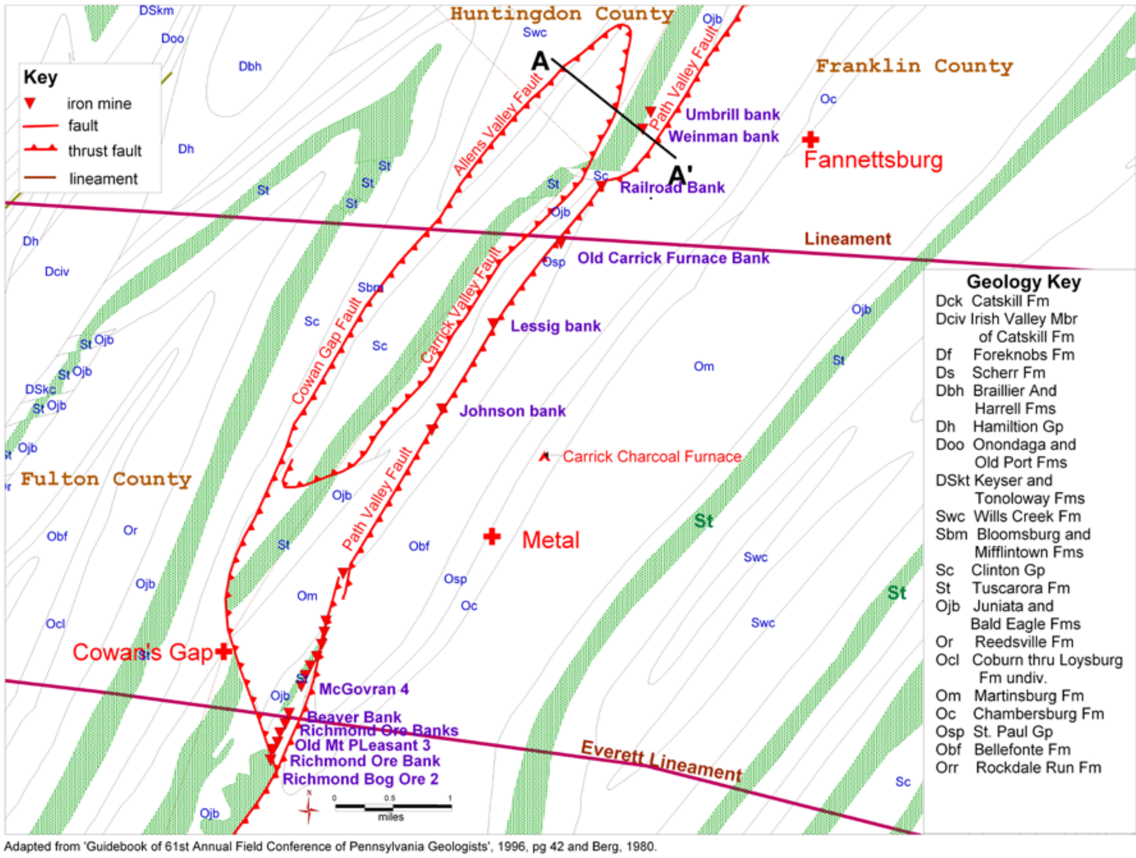


Figure 20: Iron mines aligned along Path Valley fault near Metal, Pennsylvania and cross section A-A' location (adapted from Nichelsen, 1996)

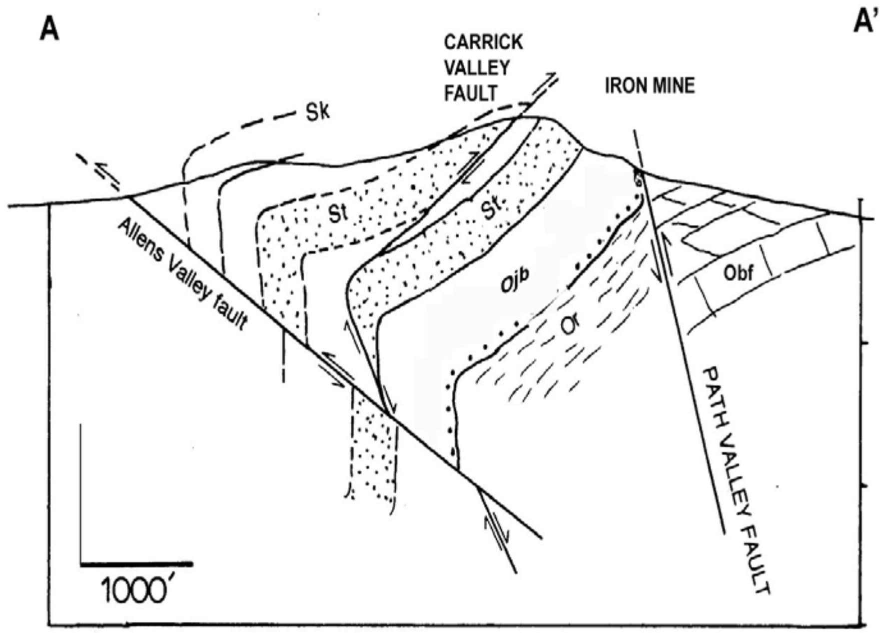


Figure 21: Cross section A-A' through Path Valley fault (adapted from Nichelsen, 1996), rock unit abbreviations are: St – Tuscarora Fm., Ojb – Juniata/Bald Eagle Fm., Or – Reedsville Fm.

Nickelsen (1996) suggests that the presence of the Hanover ore bank along the Cove fault (Figure 22) on the eastern slope of Dickeys Mountain is a similar circumstance of carbonate rocks thrust over clastic rocks. Along this fault Cambrian carbonate rocks of the Nittany/Stonehenge/Larke Formations, have been thrust over clastic units of the Ordovician Reedsville Formation as shown in cross section B-B' (Figure 23). Nickelsen (1996) suggests that the Cove fault extends down to the decollement at the base of the Cambrian carbonates (Figure 24).

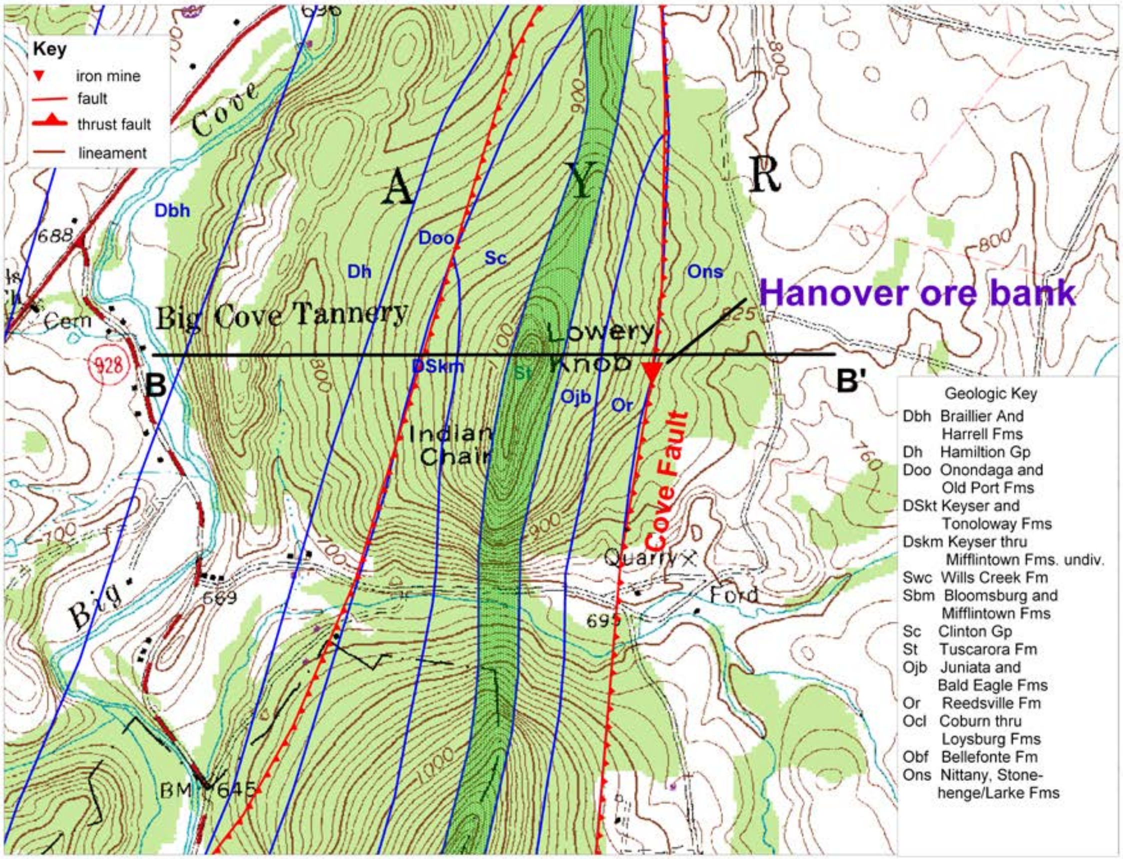


Figure 22: Cove Fault iron mine (adapted from Nickelsen, 1996 and Berg, 1980)

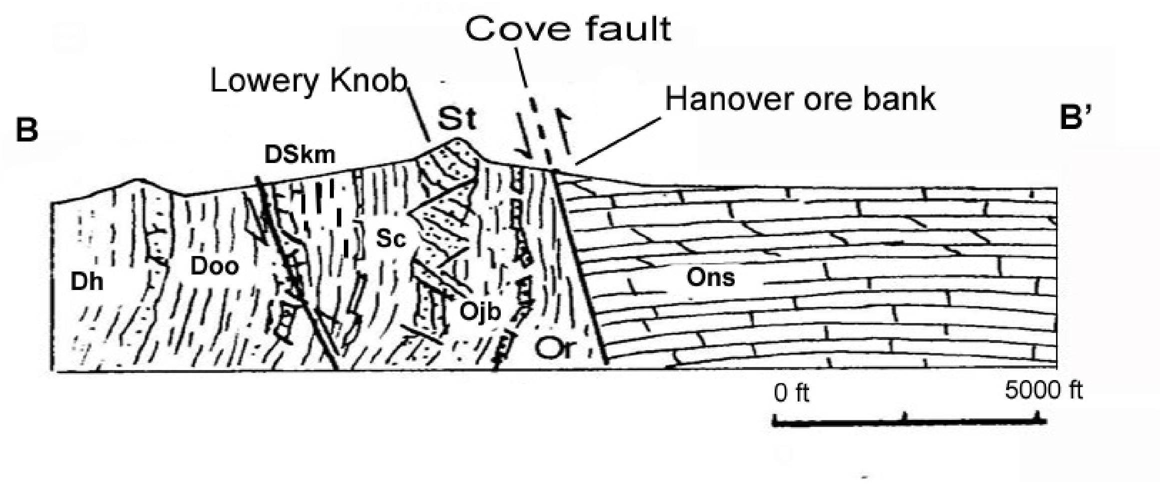


Figure 23: Cross section B – B' through Hanover ore bank, Cove fault and Lowery Knob (adapted from Nickelsen, 1996), rock unit abbreviations are: Dh – Hamilton Gp., Doo – Onondaga and Old Port Fms., Dskm – Kinzer through Mifflintown Fms. undivided, Sc – Clinton Gp., St – Tuscarora Fm., Ojb – Juniata/Bald Eagle Fms., Or – Reedsville Fm., Ons – Nittany, Stonehenge/Larke Fms.

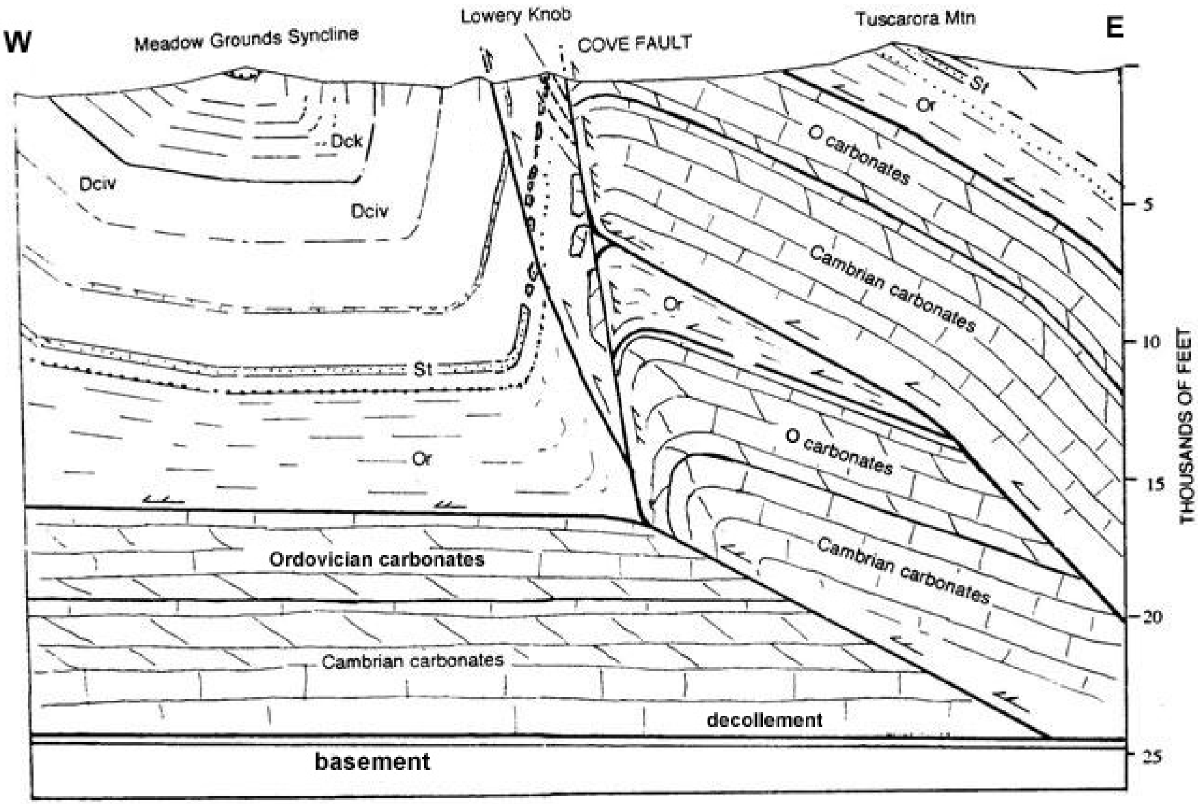


Figure 24: Cross section through Lowery's Knob and Cove fault showing fault extending to decollement (adapted from Nickelsen, 1996), rock unit abbreviations are: Dck – Catskill Fm., Dciv– Irish Valley Member of Catskill Fm., St – Tuscarora Fm., Or – Reedsville Fm.

South of Cowens Gap, no mines were reported by D'Invilliers (1886) when he conducted a survey of iron mines and limestone quarries for the Second Pennsylvania Survey. In this area the Path Valley fault separates Ordovician Martinsburg Shale from Silurian Tuscarora quartzite. The absence of deposits may be attributed to the lack of carbonates that generally host the iron ore. Farther south D'Invilliers (1886) mapped one iron mine, the Bowers furnace bank, near the town of Sylvan close to the Pennsylvania state line. However, the mine is not along the Path Valley fault, and its location on Devonian Hamilton and Onondaga Formations probably indicates the source was Hamilton iron ore.

Iron mines cluster around the intersection of structural cross strike discontinuities and the Path Valley fault (Figure 20). No mines were reported north of Fannettsburg where the Bellefonte carbonates are in contact with clastic beds, the Juniata/Bald Eagle sandstone and the Martinsburg Shale. The absence of iron deposits in this area may be attributed to the lack of carbonate rocks adjacent to the Path Valley fault. Therefore, the cross strike structural discontinuities are a possible factor in formation of limonite deposits along with thrust faults and carbonate host rocks in mountain settings.

4.2.2 Silurian Clinton-type Ore Beds

The Middle Silurian Clinton Group hosts as many as six hematite ore beds in central Pennsylvania within the Rose Hill and Keefer Formation (Inners, J., 1999). The Rose Hill is an olive shale with thin hematitic sandstone layers. Above the Rose Hill is the Keefer Formation which includes an oolitic, fossiliferous, hematitic sandstone member.

This ore is found throughout the Appalachians, from New York to Alabama, and is known as the Clinton-type ore. In Pennsylvania, the ore occurs in the Rose Hill Formation, the overlying Keefer Formation, and the Wills Creek Formation, (Table 9). It can occasionally occur in the Mifflintown Formation overlying the Keefer Formation (Cotter, 1993).

The lower part of the Clinton Group correlates to the Silurian Brassfield limestone of southern Ohio, which was locally mined (Stout, 1944).

4.2.3 Ore hosted in Devonian Strata

Iron ore has been mined from the Oriskany Sandstone and Marcellus Formation adjacent to calcareous rock units. Approximately 100 feet below the Marcellus is the Oriskany (Ridgeley) sandstone. The Lower Devonian Oriskany Sandstone may consist of calcareous, fine-grained sandstone to noncalcareous conglomerate Harper, 1999) and vary in thickness from 25 to 160 feet (Dewees, 1878). When the sandstone is well-cemented, it is a ridge former and resists erosion as individual rocks as in the case of Pulpit Rocks of Huntingdon County. The Oriskany can be composed of an upper laminated shale bed and a soft, argillaceous sandstone, 30 to 40 feet thick (Dewees, 1878). At its base, the Oriskany grades vertically to a cherty, calcareous sandstone or arenaceous limestone (Harper, 1999).

In Hill Valley, Huntingdon County, brown hematite ore five to ten feet thick can be found within soft, argillaceous beds along the Oriskany outcrop (DeWees, 1878). The argillaceous beds are colored red, purple and white (Dewees, 1878). The ore is found in seams and cracks which cut through the sandstone. Erosion of the sandstone leaves behind the ore scattered on the slope below the Oriskany outcrop (Dewees, 1878). Iron ore was also mined in a soft, argillaceous or clay zone associated with the Oriskany Formation in Saylorsburg, Monroe County (Dewees, 1878; Peck, 1922). Iron ore is found in pockets within the sandstone over the Oriskany in the Orbisonia area of Huntingdon County (Dewees, 1878).

White clay was also formed in association with the Oriskany Formation; examples are at Alexandria, Petersburg and Shirleysburg (Figure 26). Another Oriskany Formation associated clay deposit occurs at Saylorsburg, Monroe County, Pennsylvania. The Oriskany Formation consists of an upper, coarse, thick-bedded sandstone, the Ridgely member, and a lower, thin-bedded, siliceous limestone, the Shriver member (Butts, 1918). The Shriver member weathers to a white to gray, siliceous clay (Leighton, 1941). In central Pennsylvania, the Ridgely member is about 100 ft thick overlying the layer of chert, Shriver Chert and a bed of shale. The clays develop in the cherty and shaly beds below the sandstone (Hosterman, 1984).

At the Alexandria white clay pit three miles southeast of Alexandria, Huntingdon County, the clay occurs between two steeply dipping ridges of Ridgely Sandstone and Shriver shale. The upper ridge of sandstone steeply dips to the west and the lower ridge is shale that has not weathered to clay. Between the two ridges is siliceous clay with impressions of trilobites and brachiopods. This clay interval is about 50 feet wide (Leighton, 1941).

At Shirleysburg, Huntingdon County, the clay has weathered in the lower shale member. Here the clay is darker, has no grit or chert fragments, and shows distinct shale laminations. The clay bed has a steep west dip and the coarse upper Oriskany crops out nearby (Leighton, 1941).

The Saylorsburg white clay deposit occurs on the north side of Cherry Ridge and Chestnut Ridge near the town of Saylorsburg, Monroe County (Peck, 1922) (Figure 25). Cherry Ridge is a syncline with the Ridgely (Oriskany Sandstone) forming the ridge. The elevation of the ridges is 870 to 900 feet. Beneath the Ridgely is over 200 ft of impure limestone and shale which in turn overlies the Bossardsville limestone (Peck, 1922). The clay is mined by the caving system. The clay is reached by shafts sunk into the north side of the ridge at about elevation 800 ft which extend down to 116 to 100 ft. Horizontal crosscuts are driven 40 to 100 ft to the south until the hard sandstone (Ridgely Member) is encountered in the hanging wall. The sandstone dips 70 degrees to the south and strikes 65 to 70 degrees east. The clays are believed to be a result of altering the impure clayey limestones beneath the Ridgely Sandstone based on the fine sand and chert found in the clay (Peck, 1922).

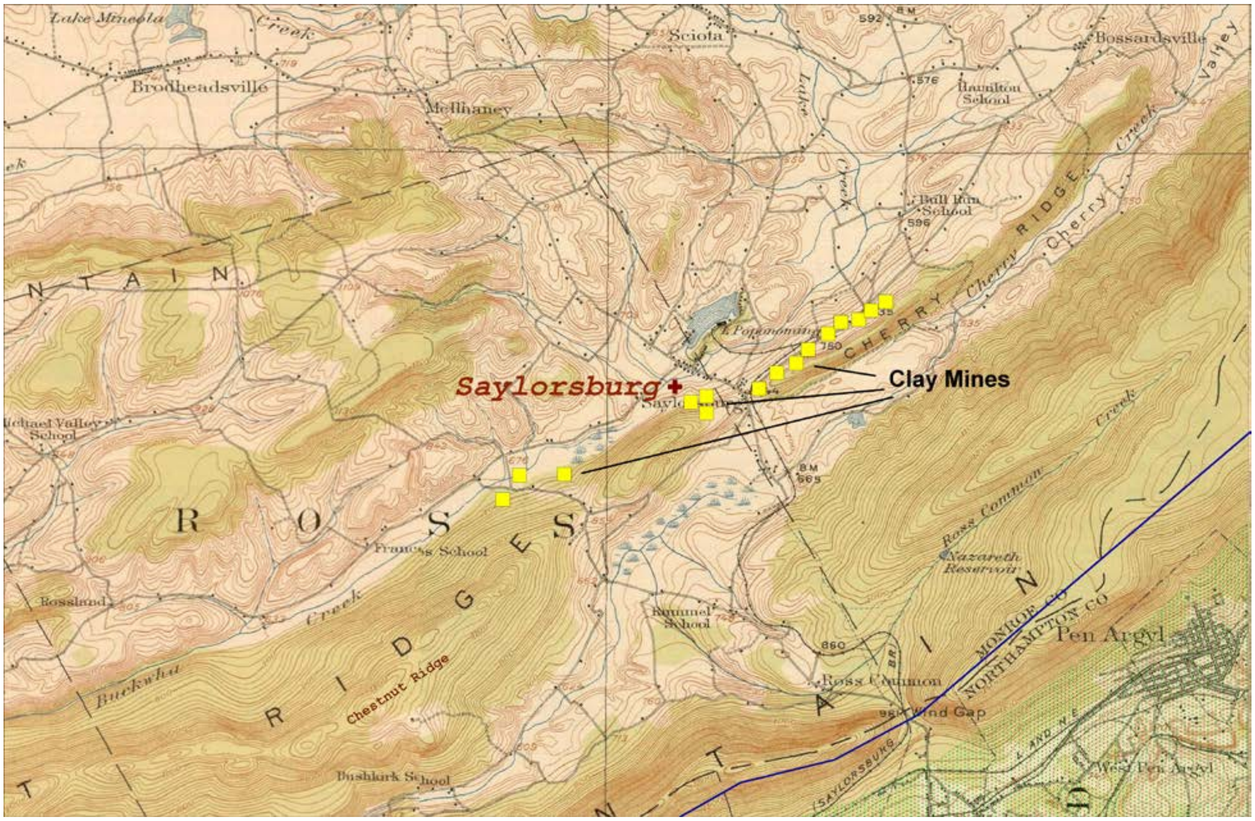


Figure 25: Location of clay mines in Saylorsburg, Monroe County, Pennsylvania, marked as yellow squares on Wind Gap 15 minute quadrangle, 1916, U.S. Geological Survey topographic map

The Shriver Member of the Oriskany Formation has been observed to produce a whitish, 'unctous' clay in Bedford County (unctous meaning that the clay has a soapy or greasy feel) (Knowles, 1966). In Bedford County, the Ridgely Member is a 111 to 122 ft thick unit composed of 3 to 10 ft thick layers of whitish to light gray, medium-grained calcareous and siliceous orthoquartzites (Knowles, 1966). The Ridgely may have siliceous or calcareous cement.

Calcareous cement is usually leached leaving crumbly sandstone (Knowles, 1966). The Oriskany is also noted to have ferruginous cement in Bedford County (Knowles, 1966).

4.2.4 Marcellus Ore Bed

The Marcellus iron ore bed is an iron oxide deposit of brown hematite which underlies the black Marcellus Shale and overlies Selinsgrove limestone/calcareous shale (Dewees, 1878), which comprises the upper member of the Onondaga Formation (Harper, 1999). The ore is continuous but the thickness of the ore bed can vary from a trace to ten or twelve feet thick (Dewees, 1878). The ore bed is brown hematite ore down to a depth of 60 to 150 feet, where it becomes an impure earthy carbonate or dirty clay ironstone. Still deeper, the bed is pyritic clay (Dewees, 1878). Claypoole (1885) reported that near the surface, the ore is embedded in clay but that at depth, the ore is an iron carbonate. The Marcellus iron ore has been mined in Perry, Carbon, Mifflin and Bedford Counties. The stratigraphic section description in Perry County was given by Claypoole (1885) (Table 15):

Table 15: Marcellus ore stratigraphic section, Perry County, Pennsylvania (adapted from Claypoole, 1885)

Rock unit	Rock description	Thickness, ft	Total thickness, ft
Hamilton	upper shale	200’ – 300’	1200’ +/-
Hamilton	middle sandstone	500’ – 800’	
Hamilton	lower gray shale	300’ – 500’	
Marcellus	black shale	80’ – 120’	100’ +/-
Marcellus	iron ore bed	2’ – 14’	
Marcellus	limestone	10’ – 30’	
Onondaga	limestone	10’ – 30’	100’ +/-
Onondaga	lime shale	20’ – 40’	
Onondaga	iron ore	2’ – 3’	
Oriskany(Ridgeley)	sandstone	0’ – 20’	20’

In 1839, in Perry County, Oliver Township, south of Newport, an iron mine for the Juniata furnace reported a 8 to 10 ft thick bed of hematite ore at 100 ft above the Oriskany, lying between black slates, a few feet above the limestone and dipping 45 degrees north west (Lesley, 1892; Rogers, 1858).

Additional mines were opened by 1858 in Perry County, the Reeder mine and the Clauder mine. Here is how the ore was described by Lesley (1892): “Two or three distinct, regular (ore) beds run through a mass of white clay; irregular strings of ore also penetrate the clay. The ore being in forms of wash, lump, honeycomb and pipe ore.” The miners recognized that if the ore was thick, the underlying limestone would be missing; correspondingly, if the underlying limestone was thick, then there would be little or no ore (Lesley, 1892).

Lesley reported that there was often confusion whether the iron ore in clay was developed within the limestone at the base of the Marcellus or was in the clay developed at the top of the Oriskany (Ridgeley) which is about 100 ft below the Marcellus ore (Lesley, 1892).

Near the Lehigh Gap in Carbon County, Pennsylvania, an impure iron carbonate (“paint-ore deposit”) containing clay and calcium carbonate underlies Marcellus black slates (shale) and above 2 to 20 ft of clay above the Oriskany Sandstone (Eckel, 1907). Grains and nodules of iron pyrite are scattered through the ore (Eckel, 1907). It was thought that this “paint-ore” deposit was a replacement of the underlying limestone. The ore is thickest when it occupies the thickness between the Marcellus black shale and the underlying Oriskany Sandstone (upper member in the Ridgely Formation). Where the ore bed has not been altered, the ore is a siderite (Claypole, 1885).

The Marcellus ore was mined along the Juniata River in Mifflin County and along Yellow Creek in Bedford County (Claypole, 1885). Other Marcellus mining activity took place in Perry County (Claypole, 1885).

4.2.5 Devonian Hamilton oolitic ore

The Middle Devonian Mahantango Formation contains a hematitic, oolitic iron ore bed referred to as the Hamilton oolitic ores (Inners, 1999). This ore was only mined in Perry County (Claypole, 1885). The ore lies at the top of the Hamilton sandstone and is generally 2 feet thick in Perry County (Claypole, 1885).

4.2.6 Iron ore hosted in the Mississippian Mauch Chunk Formation

Along Chestnut Ridge in Fayette County, Pennsylvania, Mauch Chunk ore was found from 0 to 20 feet below the Pottsville conglomerate in as many as five separate layers (Stevenson, 1877).within upper shale beds of the Mauch Chunk Formation (Stone, 1908). The ore is comprises siderite layers that vary from 27 to 80 feet thick. The ore bodies extend roughly 50 miles (Stevenson, 1877).

In Broad Top Township, Bedford County, in the Broad Top Synclinorium brown hematite ore (aka limonite) is present a few feet thick above the base of the Mauch Chunk Formation (Stevenson, 1882).

In the vicinity of Scranton, Pennsylvania, (Rogers, 1858) described iron ore beds in the Umbral (Mauch Chunk) Formation that were used at the Scranton furnaces. The ore bed is situated near the bottom of the Mauch Chunk and is conformal with the dip of the shales. The ore is embedded in a six foot thick layer of fireclay or clay-shale as an 18 inch thick, continuous band or as flattened balls 12 inches in diameter or less (Rogers, 1858). Thirty feet above the ore layer is another one foot thick layer of fireclay containing scattered balls of iron ore. The ore is a concretionary deposit composed of iron oxide and iron carbonate (Rogers, 1858).

4.2.7 Clay

Clay mines are widely distributed across Pennsylvania (Figure 2). Associated with the iron is extensive clay development. Fourteen commercial clay pits were identified and located (Figure 26) (Hosterman, 1984). According to Hosterman (1984), the clay pits are mostly distributed on the northwest side of the Gatesburg outcrop near faults.

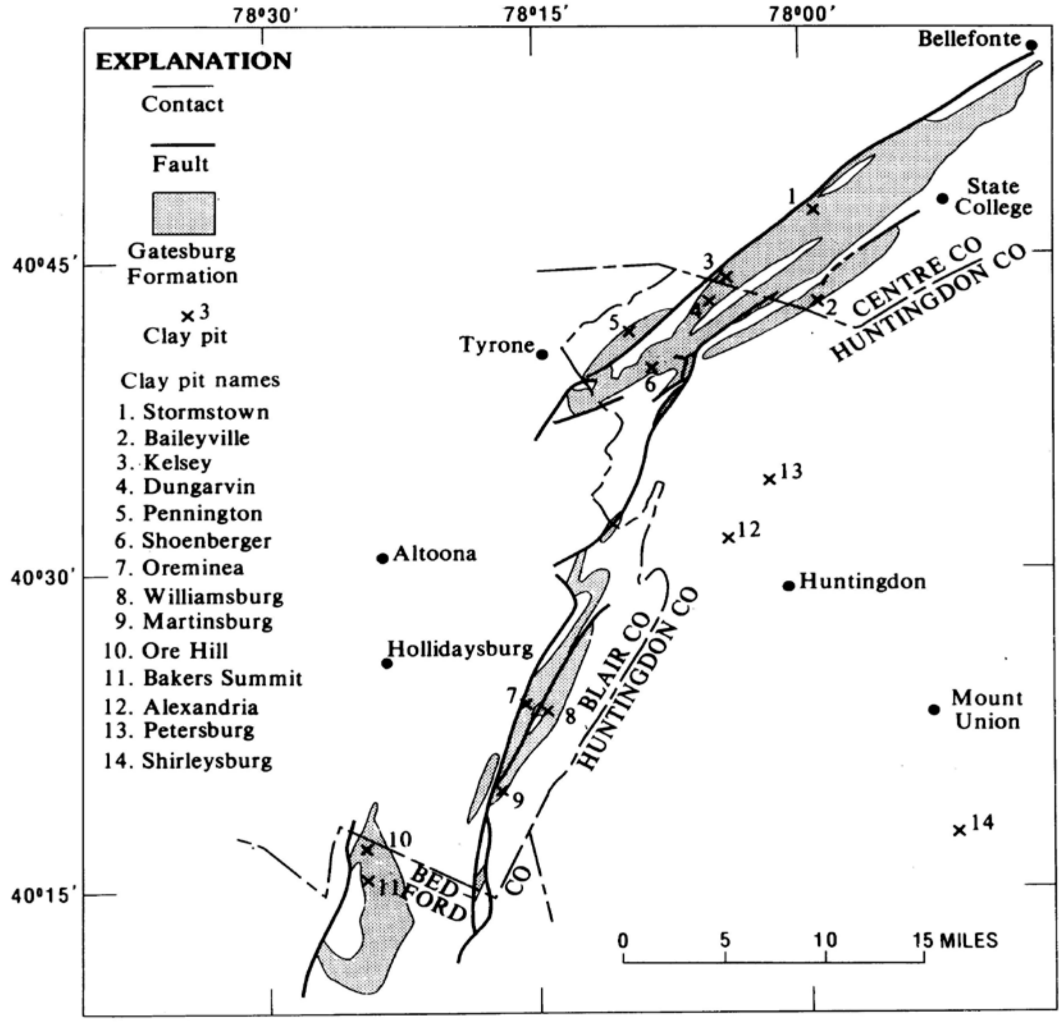


Figure 26: Clay pits in the Gatesburg Formation (adapted from Hosterman, 1984).

J. P. Lesley (1874), reported on the geologic setting and character of the brown limonite ore in Centre, Huntingdon and other Counties. He reports that he saw lumps of pyrite in bombshell ore in the sides of a funnel shaped hole which were coated with white sulfates in fields north of Pine Grove Mills on the property of John Ross (Lesley, 1874). Lesley describes the iron ore deposit at Pennsylvania Furnace:

"At first sight of the bank the ore deposit looks as if it were a grand wash or swash of mingled clay and fine and coarse ore grains and balls, occupying hollows, caverns and crevices in the surface of the earth and between the solid limestone rock ; and some of it undoubtedly has been thus carried down into the enlarged cleavage partings of the limestones; and into sink holes and caverns formed by water courses; where it now lies, or lay when excavated, banked up against walls or faces of the undecomposed lime rocks. But as a whole the ore streaks and "main vein" of ore must occupy nearly the same position originally occupied by the more ferruginous strata after they had got their dip and strike. The ore is taken out with the clay, and hauled up an incline, by means of a stationary steam engine at its head, and dumped into a large washing machine, with revolving screens; whence after the flints and sand stones have been picked out, it is carried on an ironed tramway, to the bridge house of the Furnace. The ore forms from 10 to 50 per cent of the mass excavated, and the small amount of handling makes the ore cheap. The floor of the excavation is about sixty (60) feet below the level of the wash machine. Shafts sunk from 30 to 35 feet deeper, in the floor, to a permanent water level, have shown that other and even better ore deposits underlie the workings, covered by the slanting undecomposed lime rocks. This is an additional demonstration of the correctness of the theory above stated." (Lesley, 1874).

Moore (1922), then Dean of the School of Mines, Pennsylvania State College, observed that:

"The bulk of the clay comes from the borders of abandoned iron mines and a great deal of it was taken out in the past, while the iron was being worked. It has been found as lenses, seams, and irregular masses associated with the limonite ore but as a rule outside the ore body. The clay within the area worked for ore is usually stained with iron. There are all gradations from clay carrying considerable iron and of no use in the ceramic industries through red and pink to pure white clay, just as there are all gradations between the pure clay and clay high in sand. The association of the clay and iron is believed to be due to the fact that the iron has been carried in solution by underground water and concentrated where beds of argillaceous dolomite in the sandstone have weathered out, permitting the sandstone to break down and thus create an area through which the water very readily circulates. The circulating waters remove the soluble constituents, depositing the iron oxide through replacement of the dolomite, and leaving the insoluble argillaceous materials as clay. The tendency would be to carry all soluble materials toward the centre of this area, where the downward circulation of the water is good, and to leave the insoluble materials around the border of what in time develops into a sort of basin. In the basin there will be more resistant masses which will not crumble down and these may be comparatively free from iron and contain some white clay. The waters entering the basin are, of course, carried away by good circulation underground, in some places being directed and aided by fractures in the strata. It is probable that faults have often directed the course of the circulating waters producing these iron and clay deposits."

There are other clay producing areas developed on the Gatesburg, the Woodbury clay pit near the Oreminea area, six miles south of Williamsburg in Blair County (Moore, 1922). This pit was 275 meters long and as much as 12 meters deep. The color of the clay varies from white to dirty gray, but weathers to white (Moore, 1922). The clay grades into a sand and is seen filling cracks and pores in the weathered.

Leighton (1934) describes the stratigraphic relationship between the white clay and the overlying beds. The bottom of the clay pit contains about 40 feet of white or tinted clay in irregular pockets. Above the clay is 10 feet of chert followed by 50 feet of yellowish stony soil and chert. There are chimneys of white clay extending from the bottom white clay strata upward into the yellowish soil (Leighton, 1934).

4.3 BLUE RIDGE PROVINCE

In Pennsylvania the topographically distinct Blue Ridge Mountains, comprising clastic and volcanic rocks, rise above a low, subdued terrain underlain principally by carbonate rocks comprising the Tomstown Formation. However, a colluvial apron of Antietam Quartzite west of the Blue Ridge front commonly obscures the carbonate and the poor exposure requires that the outcrop be inferred from stratigraphic position (beneath the Waynesboro and above the Antietam) and the presence of iron ore pits and solution features (Fauth, 1967). Residual iron ore was mined from shallow pits along the west and north side of South Mountain. As mining activities progressed it became clear that Tomstown is the source of iron, mainly limonite, and clay that were mined extensively.

Tomstown runs along the entire length of the western flank of South Mountain and was the locus of iron mining. Limonite ore commonly was mined along the slopes of South Mountain as limonite lumps embedded in clay and from thick clay deposits along the northwest foot of South Mountain and Piney Mountain of Franklin, Adams and Cumberland Counties (Figure 27) (Way, 1986).

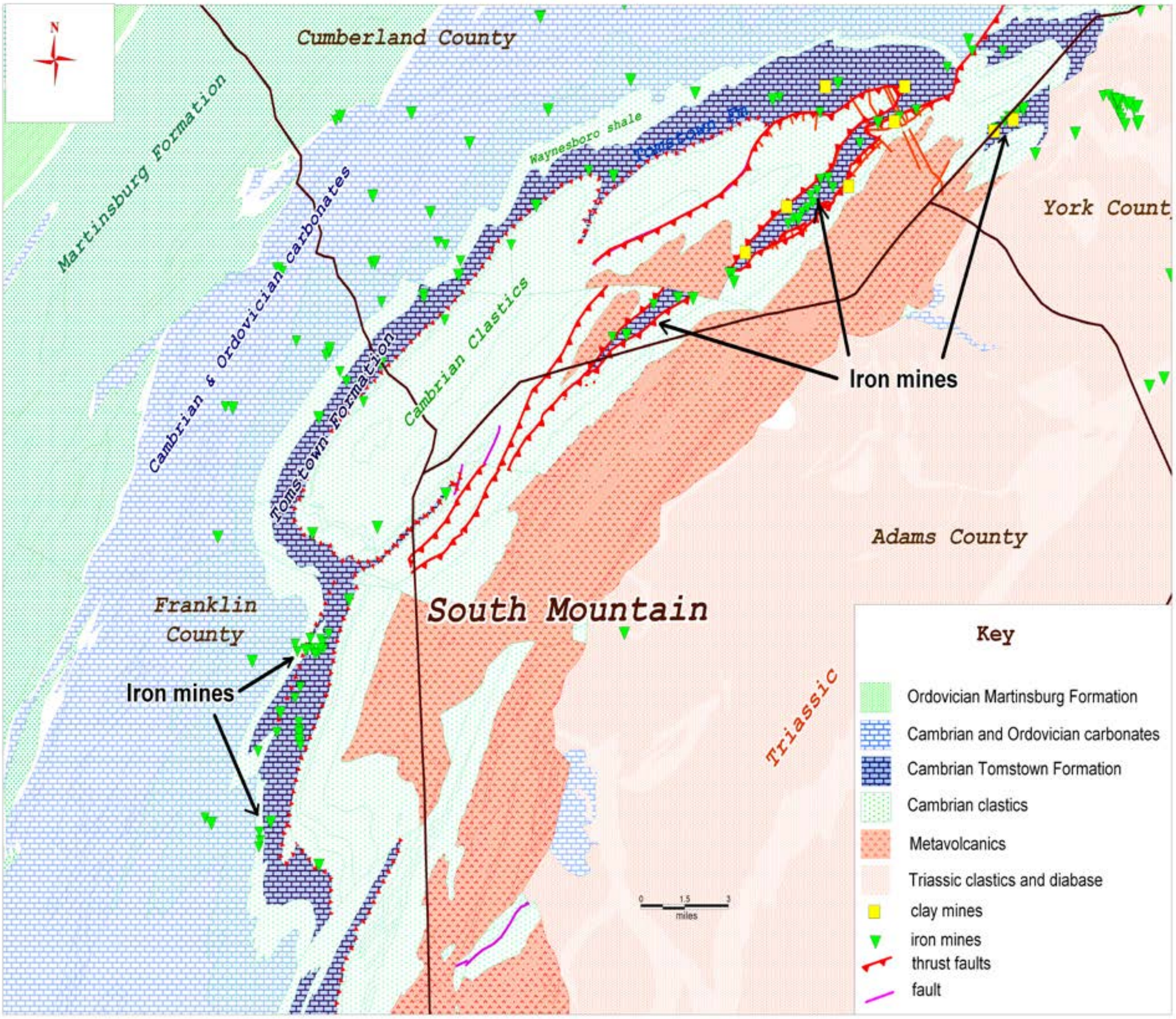


Figure 27: South Mountain geology with iron and clay mine locations (adapted from Berg, 1980)

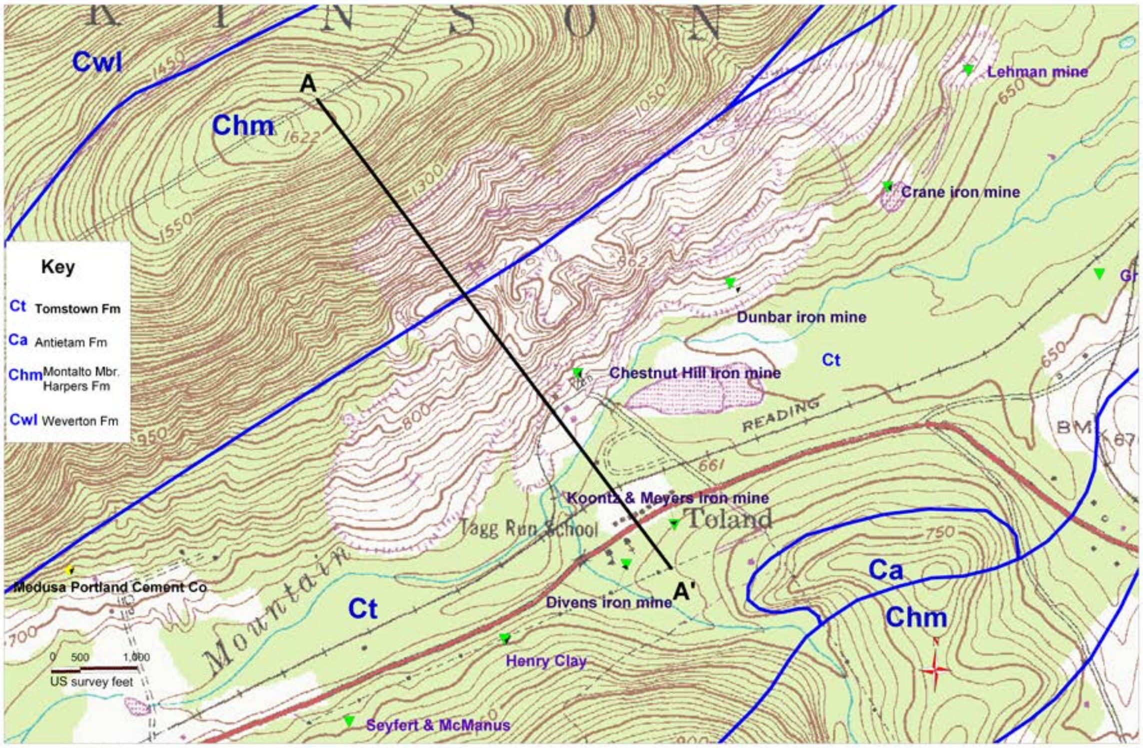
Fuller Lake now occupies the pit where a large ore body was dug for use in the Pine Grove Furnace (Way, 1986).

The Toland Clay mine is situated at the southeast slope between South Mountain and Piney Mountain, (Figure 28) and some geologic relationships of the iron ore, clay and faults are demonstrated. Where the clay is exposed at Toland clay mine, it underlies the Antietam Quartzite that has been thrust over the Tomstown Formation (Freedman, 1967).

The Toland clay pit was originally an iron mine which uncovered the clay (Way, 1986). The extent to which the clay has developed beneath the ore deposits is illustrated by a 435 foot deep boring taken at the Leland bank northeast of the Toland Clay Mine, reported by Lesley (1891):

"Lehman bank, opposite the Grove bank, idle in Oct. 1886 for want of water; a bore hole went down through the ore for 340'; then through blue clay, 40'; then white clay, 30'; then "mountain clay," 25' to "Potsdam sandstone" (Mt. Holly quartzite) = 435' " (Lesley, 1891).

This boring log indicates that the ore deposit is 340 feet deep and the clay beneath the ore is 95 feet. The bottom of the boring is interpreted to be Weverton quartzite (Figure 29). The cross section A – A' (Figure 29) doesn't reflect the allochthonous nature of the Blue Ridge. An inferred thrust fault along the top of the Tomstown would separate the Mont Alto Harpers Member from the Tomstown Formation.



Source: USGS Mount Holly Springs 7.5 minute quadrangle map, Pa. Topographic and Geologic Survey Map 61, and d'Invilliers, 1886.

Note: Iron mine locations are approximate, no accuracy is implied.

Figure 28: Geology at Toland clay mine and cross section location A-A', (adapted from USGS Mount Holly Springs 7.5 minute quadrangle, PA Topographic and Geologic Survey Map 61, and D'Invilliers, 1886)

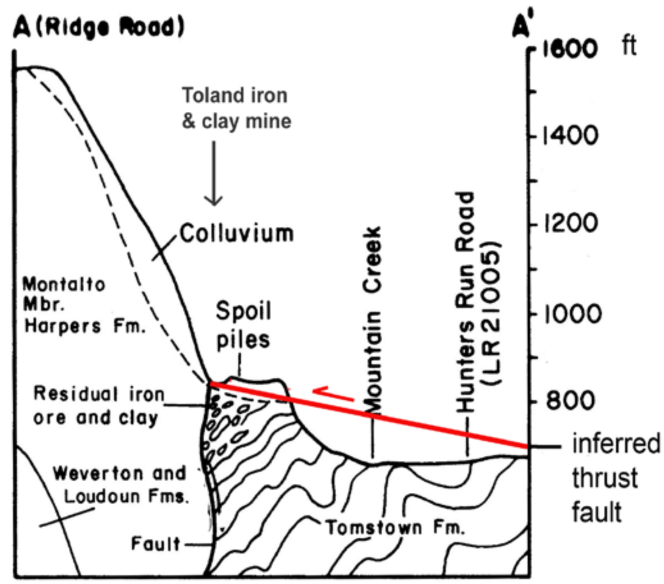


Figure 29: Cross section A-A' at Toland, Pennsylvania (adapted from Way, 1986). Inferred fault based upon Freedman (1967)

Iron and clay deposits in the Virginia Blue Ridge area

The distribution of limonite ores along the margin of the Virginia Blue Ridge resembles that of Pennsylvania (Figure 30) in that the ore is present along the contact of the Paleozoic sediments and the crystalline rocks.

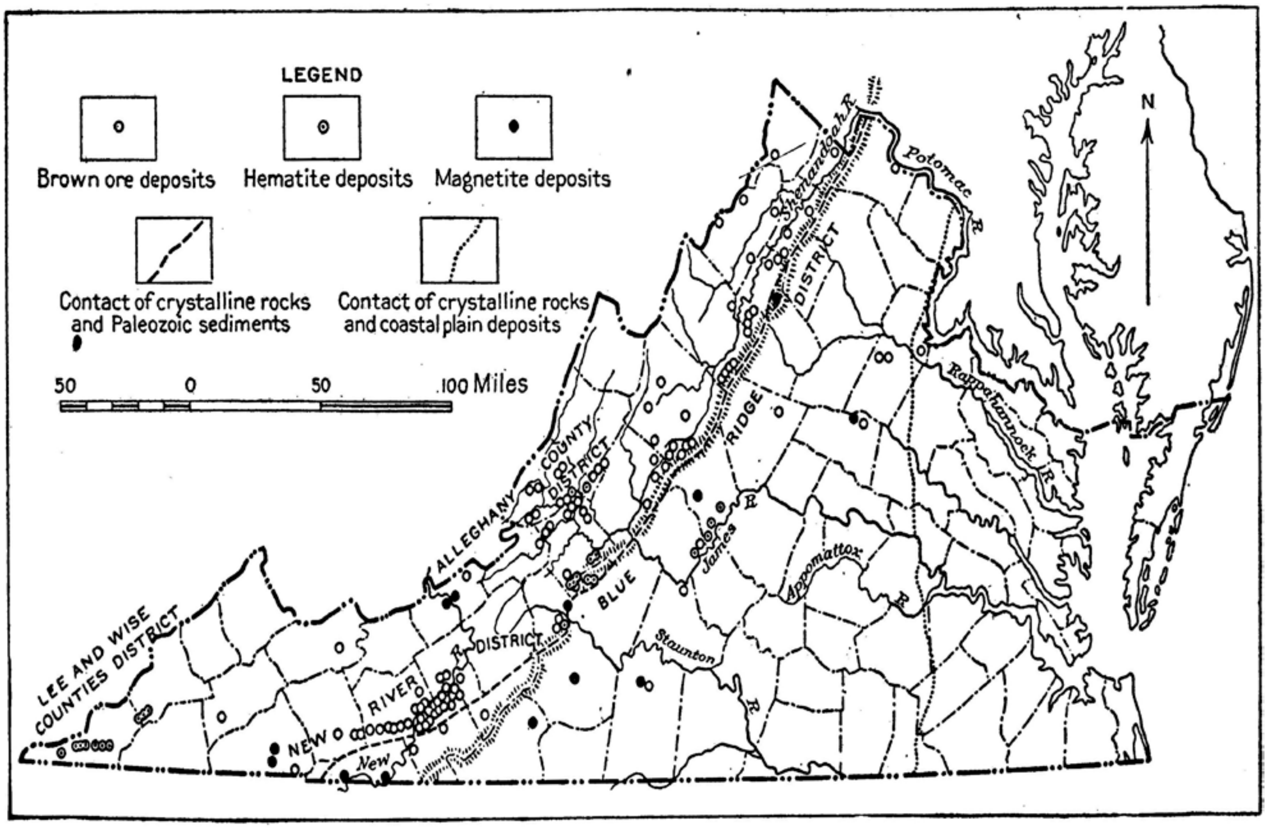


Figure 30: Distribution of iron ore deposits in Virginia (adapted from (Eckel, 1914; Harder, 1909)

Elkton area, Virginia

A well-known iron producing district at Elkton, Frederick County, Virginia (Figure 31) produced iron from 1836 to the end of World War I (King, 1950) and provides insight into relevant geologic relationships between the Tomstown and Antietam Formations and the iron ore deposits along the western border of the Blue Ridge Province.

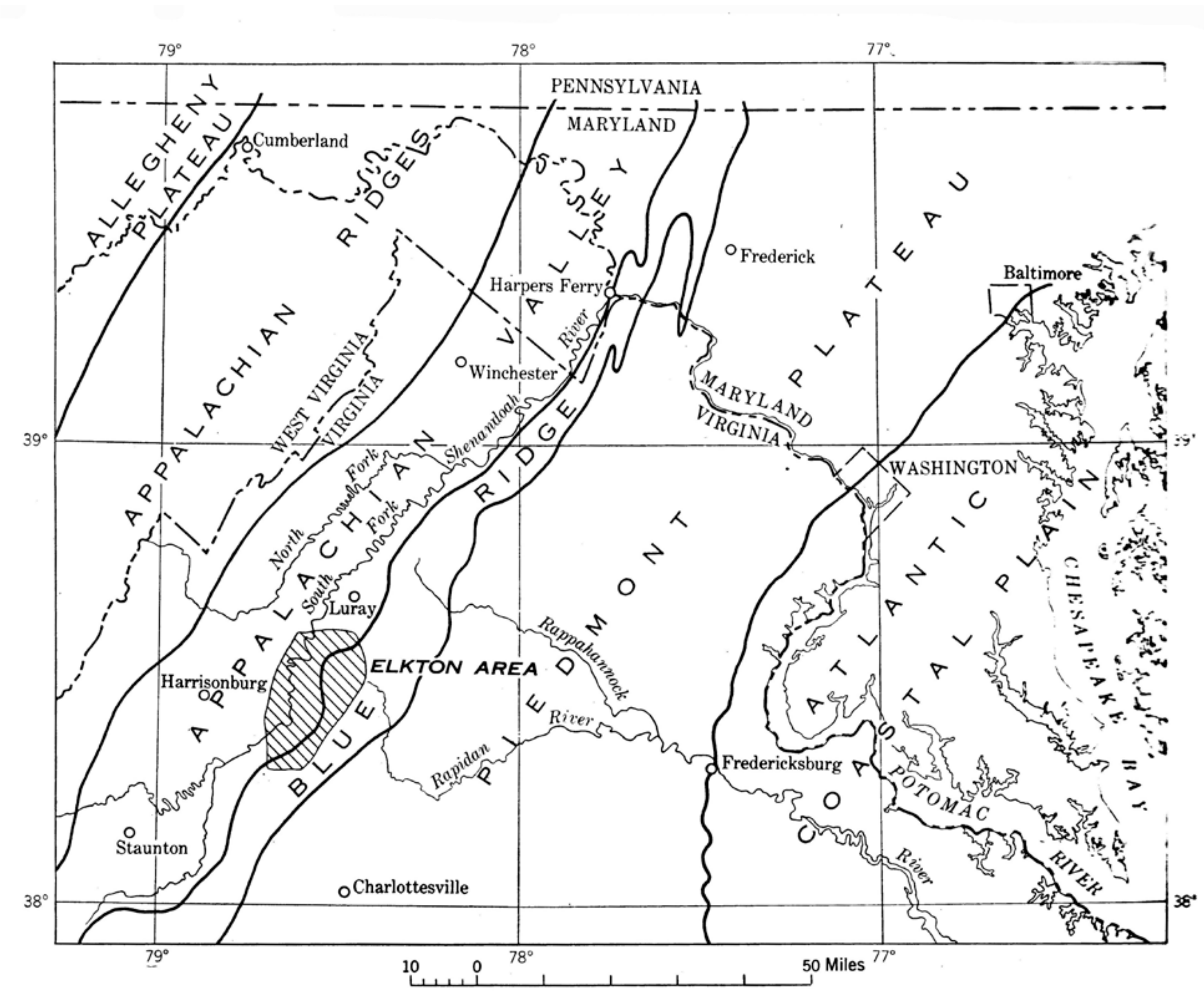


Figure 31: Location of the Elkton mining district, Virginia (adapted from King, P. B., 1950)

The tectonic setting of the Blue Ridge has been controversial for several decades. Stose et al, (1919) and Butts (1933) mapped a thrust fault on the west flank of the Blue Ridge either (1) above the Chilhowee Group (containing the Antietam Formation) and below the Precambrian or (2) below the Chilhowee Group, between the Tomstown and the Chilhowee. An alternate theory by Bucher (1933) and later King (1950) suggested that Blue Ridge-Catoctin Mountain anticlinorium is a great “welt” which is the result of overfolding and faulting against the Great Valley Paleozoic sediments, not the clean break within the basement rock along a thrust fault.

According to seismic studies in central Virginia, the western flank has been interpreted to be the front edge of the Blue Ridge thrust fault which emplaced the Precambrian Catoctin volcanic over the Paleozoic rocks in the Great Valley to the west (Harris, 1982).

At Elkton, the iron ore is within the Tomstown Formation and its residual soil where the Tomstown carbonate is in contact with the Antietam Quartzite. A general geology view of the mining district is in Figure 32.

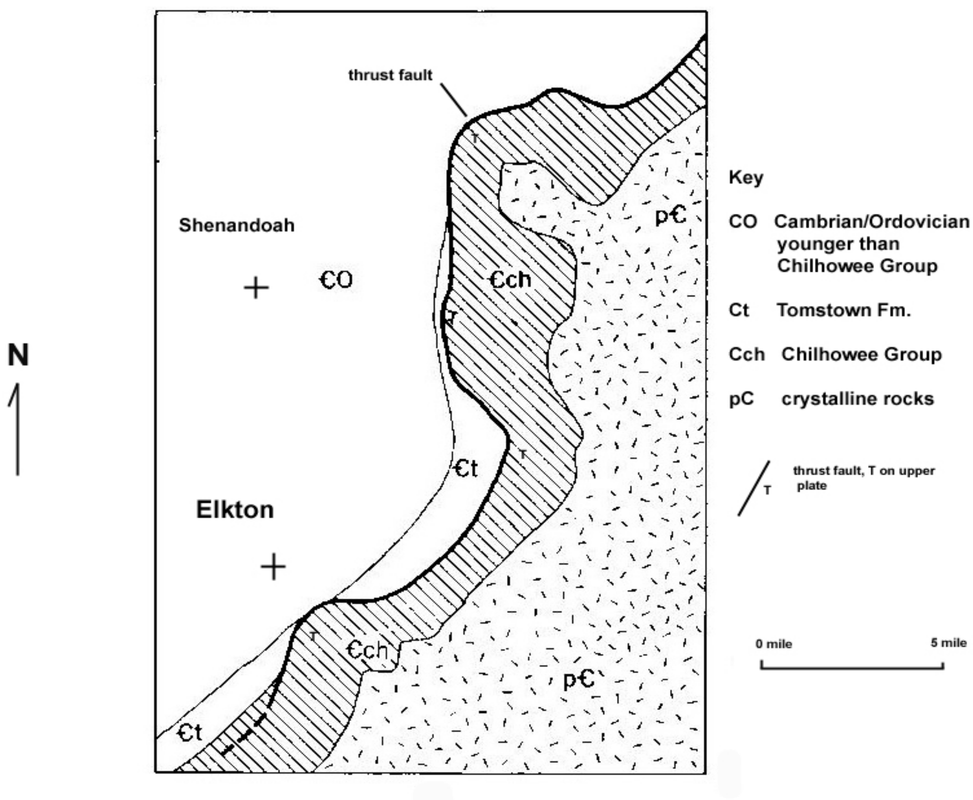


Figure 32: Geology Elkton area, Virginia, as interpreted by C. Butts, 1933 (adapted from King, P. B. 1950)

At Elkton, an incline 540 feet long was driven into Grindstone Mountain at the Watson tract to assess the amount of manganese ore present along the base of the Tomstown dolomite. Manganese ore was present along the incline with iron ore, clays of various colors, quartzite breccias and quartzite beds but there was no ore body of large size. The ore was found in layers within clays and scattered within white sand and quartz breccia. Clay was seen throughout the incline and the opening had to be timbered to keep it open. Similar to the Toland mine, the thickness of clay derived from Tomstown dolomite is remarkable. The slope of the incline was 20 ft rise over ~55 ft run or 33 percent to a depth of 80 ft after which the slope was 20 ft rise over ~165 ft run or 12 percent. At its deepest, the incline was about 190 feet below ground. Location of the incline is shown on cross section R-R’, Figure 33.

Cross section R-R’, Figure 33, and T-T’, Figure 34, reveals the ore within the residual clay, where the Tomstown limestone/dolomite is in contact with the Antietam Formation. The Bureau of Mines extended an incline into the clay overlying the Tomstown to prospect for manganese deposits. The clay above the Tomstown contains iron and manganese in narrow veins, nodules, or irregular massive lenses (King, 1950). This relationship is comparable with Tomstown and Antietam in the South Mountain area of Franklin County, Pennsylvania.

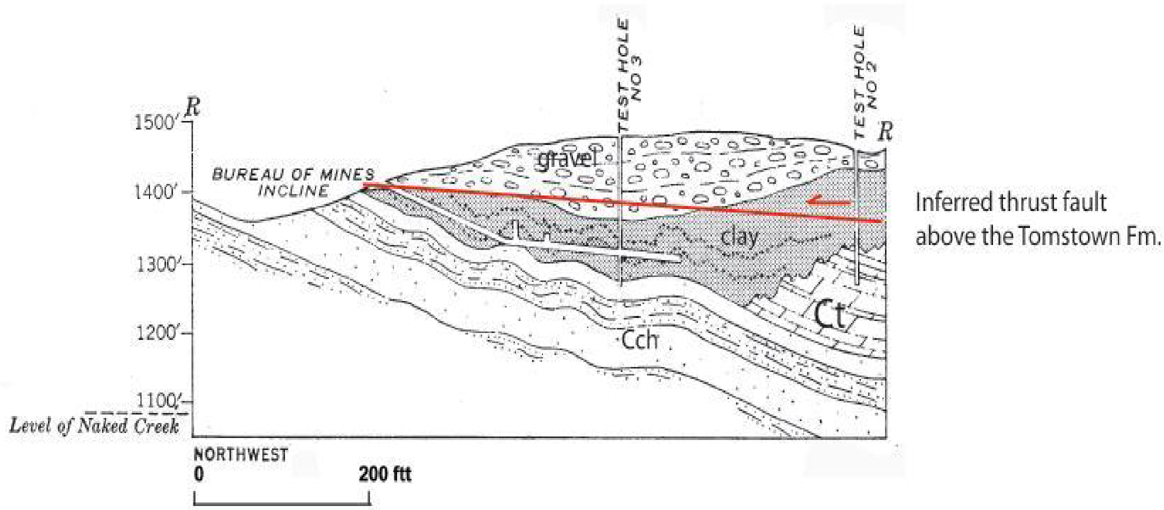


Figure 33: Cross section R-R' through Bureau of Mines incline into Tomstown residual soil. Note inferred thrust fault over Tomstown Fm (Ct) (adapted from King, 1950). Cch = Chilhowee Group, Ct = Tomstown Fm.

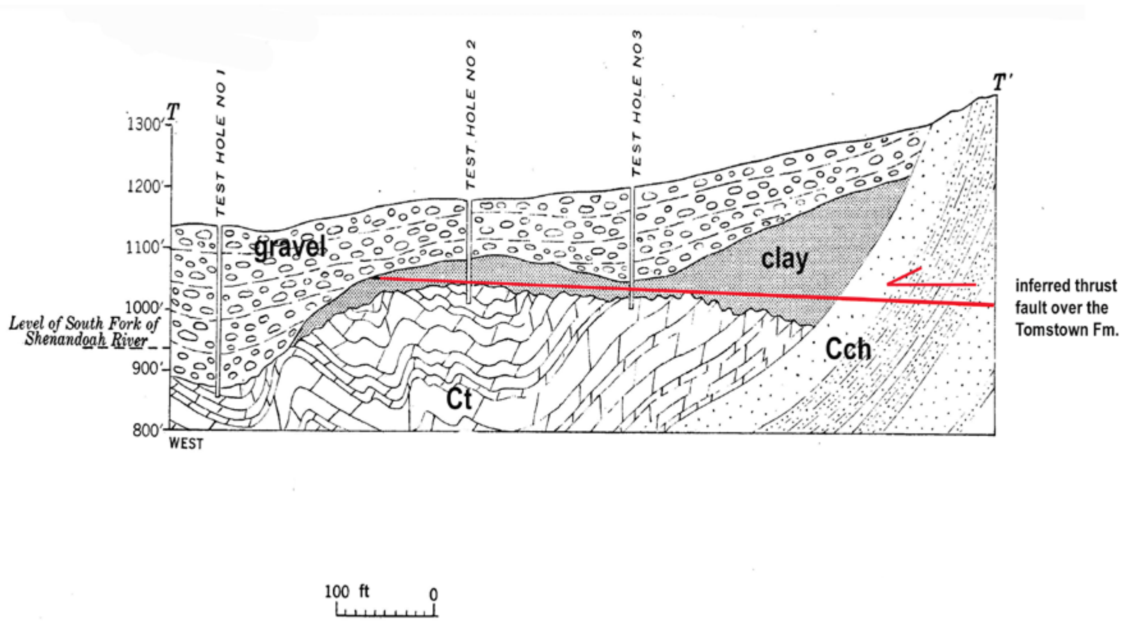


Figure 34: East-west cross sections T-T' along the western flank of Blue Ridge, Elkton, Virginia (adapted from King, 1951). Note inferred thrust fault above Tomstown dolomite, cf. Figure 33. Ct = Tomstown Fm., Cch = Chilhowee Group

Great Valley – Cumberland, Lebanon, Berks, Lehigh Counties, Pennsylvania

Ordovician limestone is host to numerous pits of iron ore deposits in the Cumberland Valley (Figure 35). The iron occurs as residual limonite, similar to that in the Tomstown.

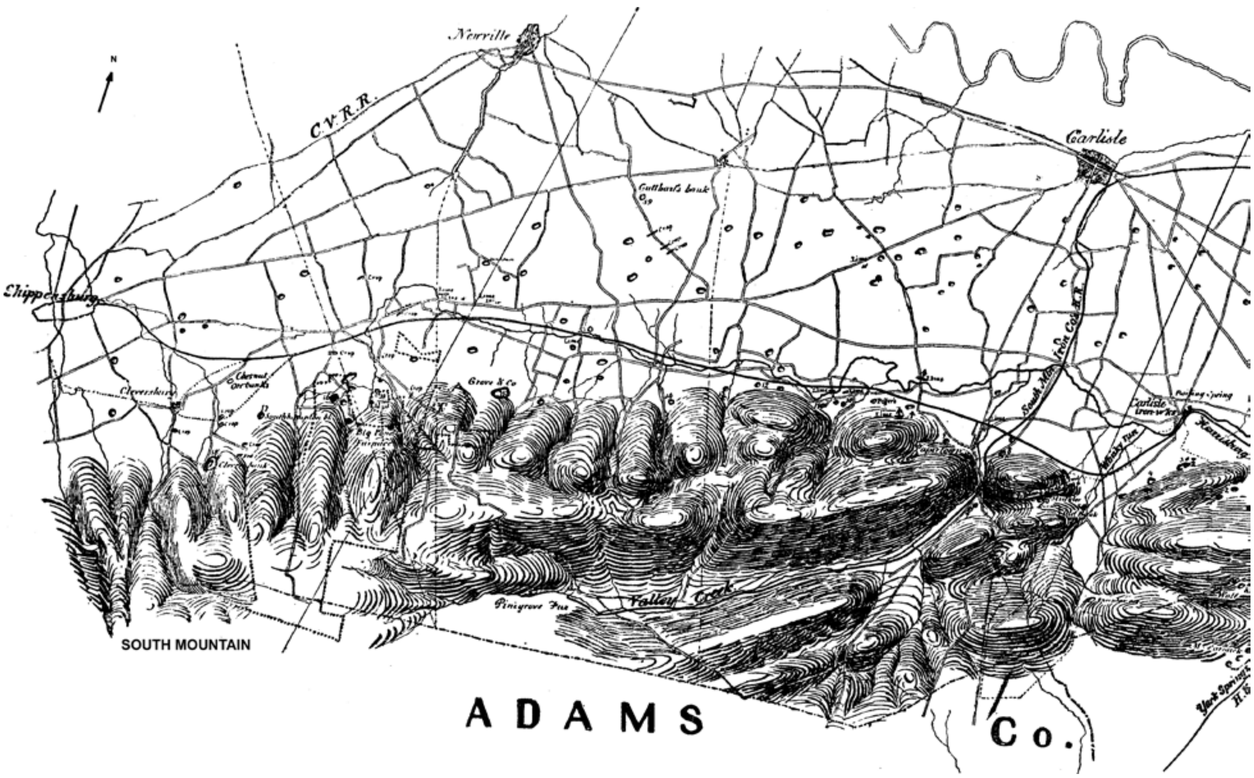


Figure 35: Distribution of iron ore pits in Cumberland Valley between Shippensburg and Carlisle, Cumberland County, Pennsylvania (taken from Lesley, 1873)

Ore is present as concentrations along the top of the limestone or imbedded within the overlying clay soil (Figure 35). If the distribution is similar to Tomstown then it may be possible that the ore may have formed beneath a hanging wall of Cambrian clastic rocks and older crystalline units overlying the carbonates. Iron mineralized along the thrust fault was preserved in the underlying carbonate residuum. An example of an ore bank in the Great Valley Section is the Moselem mine in Berks County. At the Moselem iron ore bank, five miles west-southwest of

Kutztown, the ore is developed within the soils overlying the carbonate bedrock of the Great Valley. The ore is twenty to forty feet below the surface and is found in irregular layers and "nests" from one to eight feet thick (Lesley, 1859). Some of the ore is bluish and dolomitic and white clay is found within the mining pit (Lesley, 1859).

4.4 PIEDMONT PROVINCE

Limonite ores were mined in York and Lancaster Counties in the area north of the Martic thrust fault, Figure 36 and Figure 37. In Lancaster County, many thrust faults are found in the vicinity of the area known as the Chestnut Hill ore banks (Frazer, 1880). The ore banks contained limonite embedded in clay and at one mine a layer of limestone was found in the clay (Frazer, 1880). Frazer (1880) describes a typical ore as a limonite, concretionary, and testudinous (resembling the shell of a tortoise) (Frazer, 1880). The ore occurs in layers between a bed of clay and decayed, sandy schist (Frazer, 1880). The clay is white to variegated in color.

Along the Martic thrust fault, Stose (1944) recorded numerous iron mines in York County in the Hanover and York area (Stose, 1944). Stose (1944) postulated that the mines were located in the Cambrian Antietam Quartzite, a white, ferruginous, granular quartzite and the ore accumulated as float within the soil over the Cambrian Vintage dolomite at the foot of dip slopes below hills underlain by the Antietam (Stose, 1944). Stratigraphically, the Vintage overlies the Antietam and is equivalent to the Tomstown dolomite in the South Mountain area. Figure 36 shows the location of the mines relative to the thrust faults. The following numbered locations are shown in Figure 36. Mines northwest of the Stoner thrust fault were located:

1. along the southeast side of Pigeon Hills from Mt. Carmel School northeast to Nashville
2. at Jacobs Mills
3. 1.5 miles north and 1.5 miles west of Spring Grove
4. 1 mile northwest of Stonybrook

Other iron mines also located in the Antietam were developed where the Antietam was in contact with the younger Conestoga limestone (Stose, 1944). A contact between the Antietam and the Conestoga implies a thrust fault contact since the intervening beds of Vintage dolomite, Kinzers formation and Ledger dolomite are absent. These mines were located along the Martic thrust from (Stose, 1944):

5. Jefferson northeastward to Seven Valleys,
6. in the syncline south of Margarette Furnace,

Mines within the Conestoga near the Antietam contact along the Ore Valley thrust fault are at (Stose, 1944):

7. in the syncline at Ore Valley
8. west of Margarette Furnace
9. south of Delroy, north of the Ore Valley thrust

The mines west of East Prospect and southwest of Klein School are in the Conestoga limestone near the Antietam contact but not in the vicinity of a mapped fault:

10. west of East Prospect
11. southwest of Klein School

Mines within the Conestoga along the Stoner thrust fault are at (Stose, 1944):

12. east of York Road

13. in the valley at Penn grove

14 south of Iron Ridge

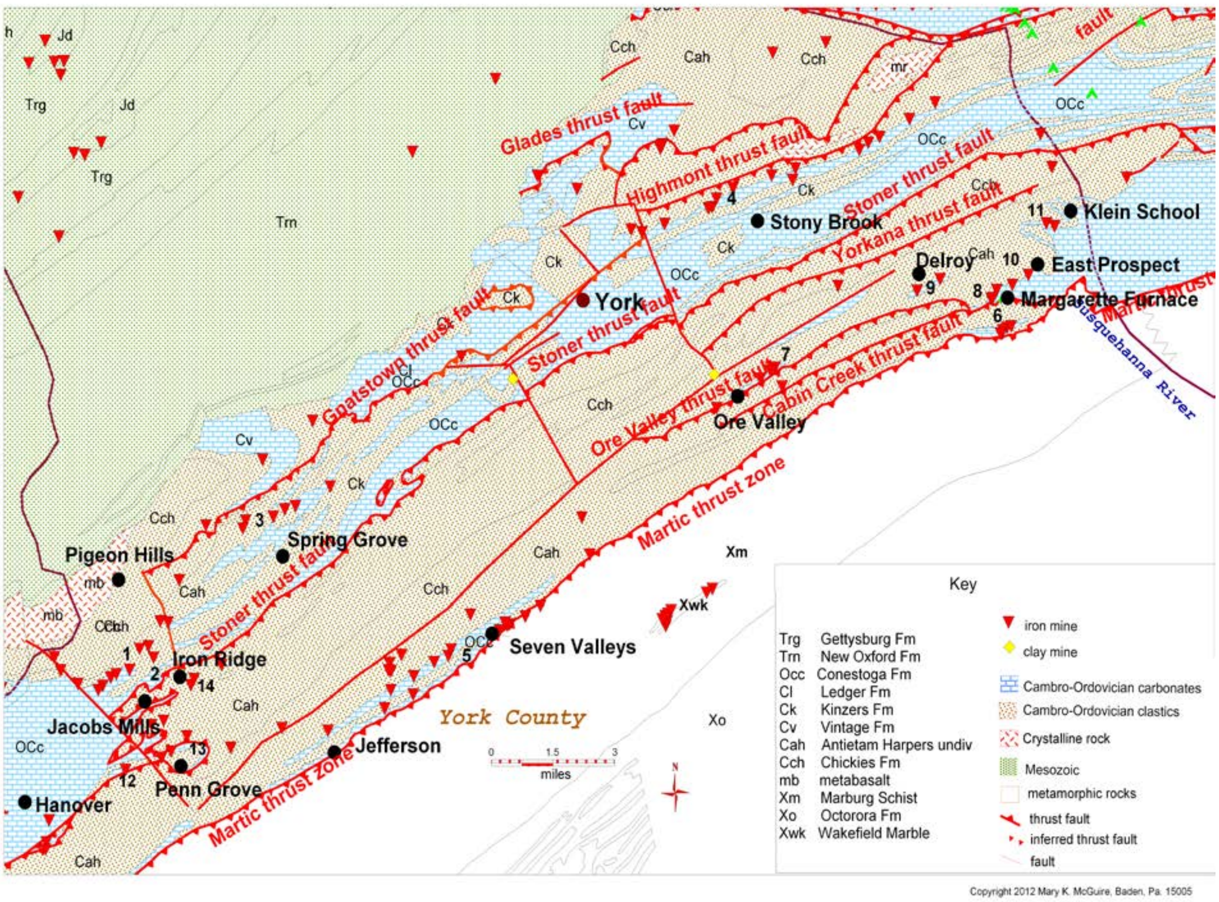


Figure 36: Geologic map showing iron mine locations in York County, Pennsylvania

In Lancaster County, Frazer recorded the location of thirty two ore banks which are mostly in the Conestoga Formation, close to the contact with the Antietam/Harpers Formations, undivided (Figure 37). The Antietam Harpers has the lithology of a quartzite, phyllite or schist and the Conestoga is a limestone. Magnetite disseminated through the schists of the Antietam Formation was mined at an ore bank 1.25 miles southeast of Conestoga, Lancaster County, Pennsylvania (Inners, 1999). Frazer reports that at the Peacock mine the ore is a ferruginous mica schist or gneiss (Frazer, 1880).

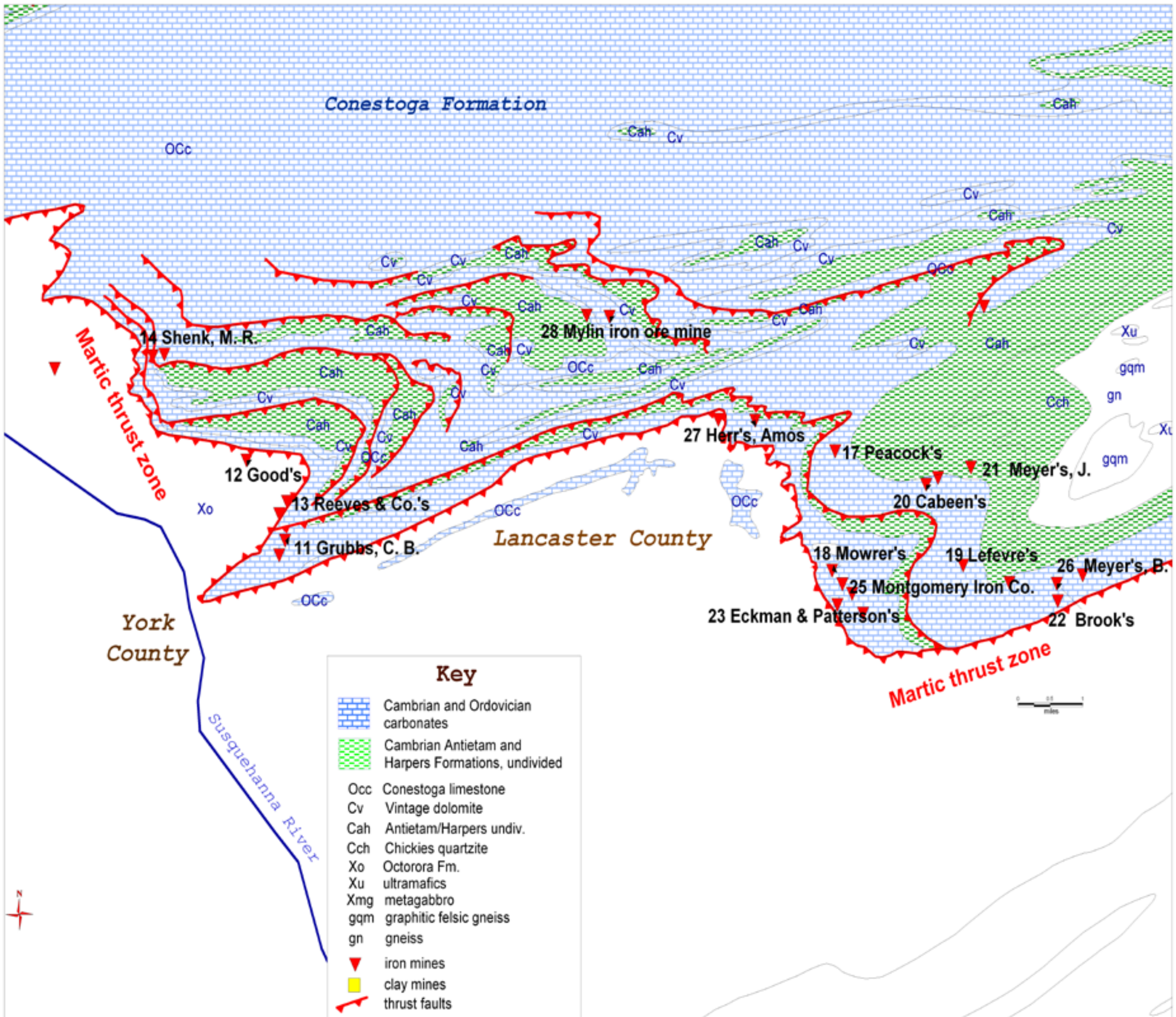


Figure 37: Location of Martic ore mines, Lancaster County, Pennsylvania based on iron mines mapped by Frazer, 1878

4.5 READING PRONG

In the Reading Prong area iron ore was found as limonite deposits in the soil above the carbonate rocks in the valley and along the northern base of the Precambrian crystalline highlands (Figure 38).

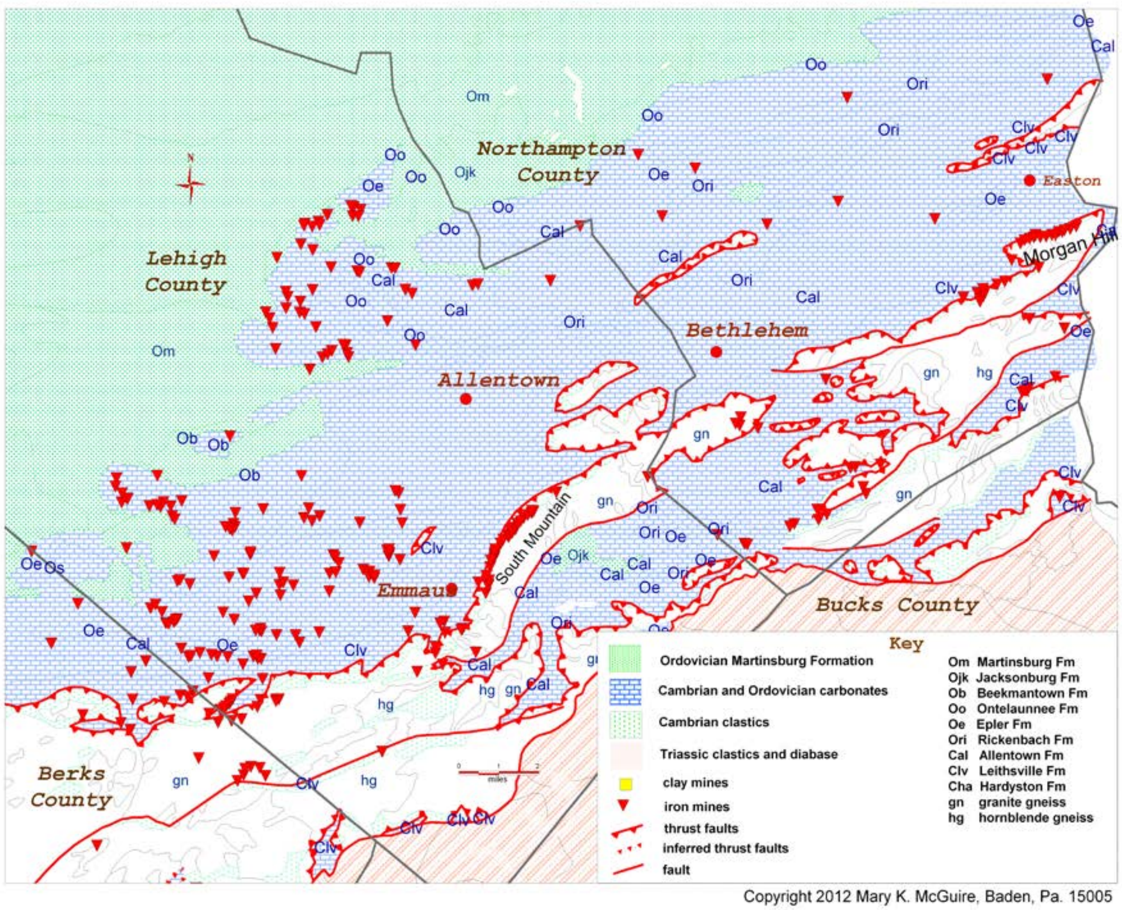


Figure 38: Distribution of iron mines in the Reading Prong area of Lehigh and Northampton Counties, Pennsylvania (adapted from Berg, 1980)

Mines were concentrated along a thrust fault at the base of South Mountain 2.5 miles south of Allentown northeast of Emmaus, Lehigh County. Mines clustered along the contact of crystalline rocks of South Mountain (perhaps because the ore has not been disseminated by erosion following removal of the hanging wall rocks). Similarly, one and third miles south of Easton, Northampton County, mines define a linear array between the Cambrian Hardyston Formation near the contact with the Cambrian Leithsville Formation along the northern border of Morgan Hill. The northern base of South Mountain and Morgan Hill are defined by a thrust fault which extends southwest. Other mines can be seen along this thrust fault.

On Figure 38, a cluster of iron deposits are in thick soils overlying Cambrian and Ordovician limestones five miles northeast of Allentown (Lesley, 1859). Another cluster of mines can be seen one to five miles west of Emmaus, Lehigh County. In all likelihood these ore deposits were developed in the carbonate beds beneath the now eroded clastic and crystalline rocks (Figure 38).

5.0 CONCLUSIONS

The manner of mineralization and the distribution of the ore suggest multiple modes of ore genesis within carbonate rocks across the entire basin. In the Piedmont, the Blue Ridge and Valley and Ridge Provinces, thrust faults are the foci of mineralization especially where intersected by cross strike structural discontinuities. Maps of economic deposits of iron associated with clay may reveal pathways of reactive fluids across the Appalachian mountains over a distance of 450 miles.

In the topographically high region of the Allegheny Plateau and the adjacent Dunkard Basin into Ohio, almost every carbonate horizon in the Pennsylvanian section contains iron and clay mineralization. Abundant iron staining within sandstone units suggest that reactive iron carrying fluids followed permeable layers, joints and bedding planes. Along mineralized faults, limonite is the principal ore mineral. In the subhorizontal rocks of the Plateau and Dunkard Basin, some limonite was mined but the main ore consisted of siderite in nodular or layer form in clayey carbonates. In some deposits, silica may be present in clay as well as with iron ore, e.g. Buhrstone ore above the Vanport limestone.

Siderite is widely distributed as nodules and concretions in fine-grained, Paleozoic clastic rocks suggesting that iron-bearing fluids had access to carbonate-rich concretions.

The distribution and association of iron and clay deposits mainly in the carbonate rocks suggests a co-genetic origin. The development chiefly in carbonate rocks is inamicable to the idea that this type of ‘limonite in clay’ deposit is related to the development of paleosols and weathering. Other iron bearing deposits, Cornwall-type and Clinton-type, do not show an association with clay.

Residual ores such as those found along the flanks of the Blue Ridge are principally distributed along the erosion surface of the Cambrian Tomstown Formation in which the iron deposits were hosted. The iron-rich clasts were released from the clayey Tomstown, during weathering and concentrated along the flanks as colluviums. In the Blue Ridge area, map relations indicate that iron and clay formed along thrust faults separating crystalline rocks from structurally underlying Cambrian and Ordovician rocks.

Pipe ore and stalactitic forms of limonite are probably the result of remobilizing previously formed ore deposits in response to weathering and redeposition in limestone caves and within solution-enlarged joints.

The mapped relations of iron and clay deposits to stratigraphic and structural settings in which carbonate rocks serve as hosts support the model of alteration of carbonate and penecontemporaneous precipitation of iron in response to interaction with a reactive iron-, and to a lesser degree, silica-bearing fluid. This process contrasts strongly with processes related to weathering and related formation of paleosoils or formation in bogs. Although bogs and paleosoils exist, they fit within the mapped relations documented in this thesis. Where erosion exposed iron and clay deposits to surficial processes, weathering took place and iron ore was locally incorporated into clay-rich colluvial deposits.

APPENDIX A

LITERATURE REFERENCES FOR IRON MINES AND OUTCROP LOCATIONS

The reference sources used to locate historic iron mines and outcrops are listed below:

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APPENDIX B

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