Engineering Geology, History and Geography of the Pittsburgh, Pennsylvania Area

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ABSTRACT

The City of Pittsburgh, PA is located west of the Appalachian Mountains in the Appalachian Plateaus Province. The relatively flat surface of the plateau is dissected by drainage from the three principal rivers of the region, the Allegheny, Monongahela, and Ohio. The formation of Pittsburghs three rivers and drainages has a long history dating back to before the Pleistocene Epoch, linked closely to the advance and retreat of continental glaciation.

Western Pennsylvania is associated with the westernmost formation of the Appalachian Mountain chain with deformation in the form of a series of nearly flat-lying, gently warped Paleozoic sedimentary rocks. Rocks cropping out in the region range in age from Devonian to Permian. Pennsylvanian strata are dominated by thin cyclic sequences of sandstone, shale, claystone, coal, and limestone. Most of the geologic hazards present in the region include slope instability, expansive shales and slags, mine subsidence, acid mine drainage, pyritic acid rock and flooding. The region also has an abundance of natural resources including coal, natural gas, oil, salt, limestone, sand and gravel and water.

Pittsburgh's strategic location helped shape westward expansion during the formation of the Nation, largely because of the rivers, which served as an inexpensive, yet efficient means of transportation. Infrastructure was always significant in Pittsburgh. However, the existing aging infrastructure are deteriorating. Today, Pittsburgh has transcended the legacy name, "Steel City" and has revitalized itself with nationally-recognized universities and medical centers and a resurgence in natural gas exploration. However, many environmental legacy issues still burden the area.

INTRODUCTION

Geographic Setting

Although Pittsburgh has a long history as a major industrial center, it occupies a relatively small area, 56 square miles (145 km^2), and it has a population of approximately 305,000 (U.S. Census Bureau, 2010). Pittsburgh is located within Allegheny County, which is one of the 67 counties in Pennsylvania. The Greater Pittsburgh region is normally considered to include Allegheny County, the adjacent Armstrong, Beaver, Butler, Fayette, Greene, Washington, and Westmoreland Counties, and a few locations outside of this area that have a direct impact upon the metropolitan area. These counties comprise 5,921 mi^2 (15,334 km^2) and have a population of more than 2.3 million people (U.S. Census Bureau, 2010).

Pittsburgh is located to the west of the Appalachian Mountains in a moderately dissected portion of the Appalachian Plateau Province (Figure 1). Here, the relatively flat plateau surface is deeply dissected by drainages, which has produced steep-sided valleys having a relief ranging up to 600 ft (182 m). The upland areas generally lie at an elevation greater than 1,200 ft (365 m) above mean sea level and constitute only about 10 to 20 percent of the surface area of the region. Valley slopes account for about 50 to 70 percent of the

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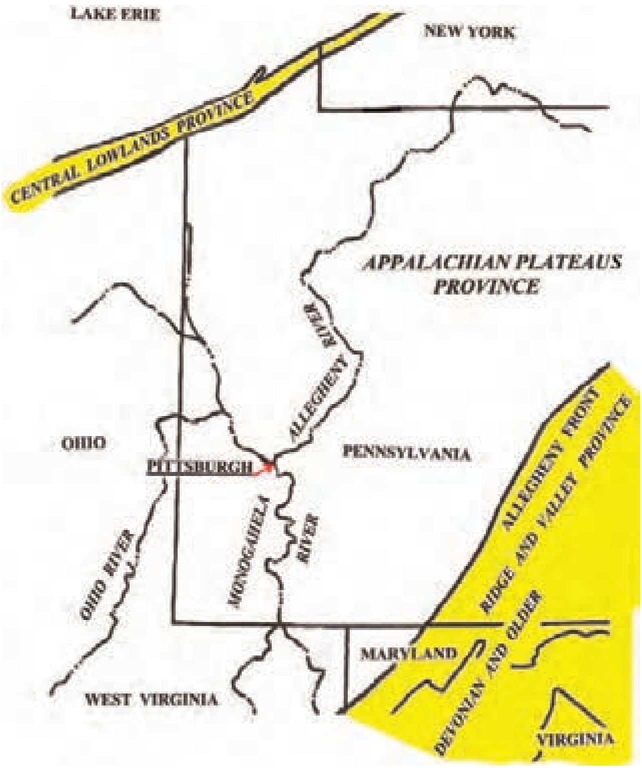

Figure 1. Appalachian Plateau, western Pennsylvania (modified from Gray et al., 1979).

area, while the bottomlands constitute 20 percent or less (Gardner, 1980).

Pittsburgh is located at the confluence of the three largest rivers in the region, the Allegheny, Monongahela, and the Ohio (Figure 1). The Allegheny River flows from the north, originating in northern Pennsylvania and southern New York. The Monongahela River flows from the south, originating in east-central West Virginia. The Allegheny and Monongahela Rivers meet in Pittsburgh and form the westward-flowing Ohio River. The Ohio River is a major artery of drainage into the interior of the continent, joining the Mississippi River about 930 mi (1,500 km) downstream from Pittsburgh at Cairo, IL (Gardner, 1980).

Climate

The Pittsburgh area has four distinct seasons. Fall and spring are generally warm and mild, summers are hot and humid with occasional heat waves, and winters are cold and snowy. Based upon 30 year averages (NOAA, 2014), the mean monthly temperatures are warmest in July (72.6°F; 22.6°C) and coldest in January (28.4°F; −2°C). Pittsburgh averages 9.5 days per year when the temperature reaches 90°F (32.3°C) or higher and 5 days per year when the temperature goes below 0°F (−17.8°C). The highest temperature recorded in Pittsburgh, 103°F (39.4°C), has occurred on three occasions (July 1881, August 1918, and July 1988), whereas the lowest recorded temperature, −22°F (−30°C), occurred once in January 1994.

Average precipitation is 38.2 in. (97 cm) and is relatively evenly distributed through the year, with the driest month (October) averaging 2.29 in. (5.8 cm) of precipitation and the wettest month (June) averaging of 4.3 in. (11 cm) of precipitation. Records indicate that the largest one-day snowfall, 23.6 in. (59.9 cm), fell on March 13, 1993, and that the largest one-day rainfall event, 5.95 in. (15.11 cm), fell on September 17, 2004 (Hurricane Ivan). The second largest rainfall event, 3.6 in. (9.14 cm), fell on September 8, 2004 (Hurricane Frances), only 1 week before the Hurricane Ivan rainfall.

History and Founding

The first inhabitants of the Pittsburgh region were probably Paleo-Indians, who may have occupied the area about 16,000 years ago, as indicated by archaeological findings at Meadowcroft Rock Shelter located on a small tributary of the Ohio River about 25 mi (40 km) southwest of Pittsburgh. The Paleo-Indians were hunter-gatherers who exploited the abundant animal and plant resources of the region (Gardner, 1980).

The Paleo-Indian culture was followed by the Archaic hunter-gatherer culture, probably between 7,000 and 8,000 years ago, and the Archaic culture was supplanted by the Woodland culture about 3,000 years ago, when agriculture was first introduced in the area. Two mound-building societies developed along the rivers and streams of this region during the Woodland cultural period. The first were the Adena moundbuilders, who occupied the region from about 3,000 to 2,000 years ago, before they were displaced by the more advanced Hopewell culture, which lasted from about 2,000 years ago to A.D. 500 (Gardner, 1980).

It was the strategic location at the confluence of the rivers that first attracted the attention of European colonists to the "Forks of the Ohio" at what is now Pittsburgh. The conflicts between the British and French in Europe in the early and mid-1700s were transported to North America as both nations struggled for domination of the continent. The French claimed the area west of the Allegheny Mountains as theirs, including the combined Ohio and Allegheny Rivers; the English did not recognize these claims. A group of English colonials from Virginia formed an organization called the Ohio Land Company, whose members included Governor Dinwiddie of Virginia and Lawrence Washington, George Washington's older brother. The Ohio Land Company claimed over half a million acres of the area around the Forks of the Ohio for trade and land speculation, land that

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the French had previously marked as theirs. Ensuing clashes between the French and English trading in the area prompted Governor Dinwiddie to send a 21-year-old major of the Virginia Militia, George Washington, to deliver a protest to the French (Gardner, 1980).

En route, Major Washington travelled by the Forks and noted:

> …I spent some time viewing the rivers, and the land in the Fork' which I think extremely well situated for a fort, as it has absolute command of both rivers…the Land at the point is 20 to 25 feet [6 to 7.5 m] above the common surface of the water; and a considerable bottom of flat, well-timbered land all around it, very convenient for building… (from Washington's *Chronicle*, *in* Lorant, 1975, p. 7)

The confrontations with the French prompted the Virginians to build a fort at the Forks of the Ohio, as suggested by Washington. Construction of Fort Prince George was initiated in March 1754, and it was the first recorded Euro-American construction on the land that is now Pittsburgh. The unfinished colonial fort was abandoned 1 month later when a superior force of French and Indians threatened attack. The French then erected their own fort, Fort Duquesne, at the Forks of the Ohio. The French controlled the Forks of the Ohio for 4 years, repelling several English attempts to regain control. In November of 1758, the French burned and abandoned Fort Duquesne in the face of imminent attack by British forces headed by General John Forbes and Colonel George Washington. The English erected their own fort on the ruins of Fort Duquesne, and Forbes named it Fort Pitt in honor of the then-current English Prime Minister, William Pitt. Fort Pitt received no attacks from the French, although it was besieged by Indians for 2 months during "Pontiac's Conspiracy" in 1763. The end of the Indian uprising reduced the need for Fort Pitt, and it was gradually dismantled in the mid-1760s (Gardner, 1980). Figure 2 shows Fort Pitt in 1776. A portion of Fort Pitt has been reconstructed in its original location at what is now Point State Park.

The community that developed around the fort continued to grow as a center of trade for the ever-increasing travel from east to west, as Pittsburgh developed as a gateway to the west. Figure 3 shows the locations of Fort Duquesne, Fort Pitt, and Pittsburgh in 1795. When the community was incorporated as a city in 1816, it was the major center for commerce in the west, since most travel from the eastern seaboard to the west went through Pittsburgh. Henry Steele Commager, a noted historian, summarized the situation as follows:

Figure 2. Pittsburgh's Golden Triangle—1776 (Brookline Connection, 2012).

> …The historical significance of Pittsburgh was determined from the beginning, by geography…The city that was to rise at this strategic point on the threshold of the Forks was at once the bridge from the East and the Gateway to the West, the most western of the great cities of the seaboard, the most eastern of the great cities of the valley: it is no accident that it has commanded that position now for a century and a half; its sovereignty unchallenged… (Lorant, 1975, p. 26)

Pittsburgh's economy was primarily based on commerce in the late 1700s and early 1800s, thereby living up to its "gateway" status. As Pittsburgh grew, it required an ever-increasing supply of goods, most of which were manufactured in the east. However, transporting large quantities of trade goods and pioneer supplies was incredibly difficult and expensive because the rugged Appalachian Mountain ridges between Pittsburgh and lands to the east were a formidable barrier. For this reason, Pittsburgh was forced to develop its own manufacturing industry, and by 1815, it was producing significant quantities of iron, brass, tin, and glass products. By 1830, the trade-commerce aspect of Pittsburgh's economy was eclipsed by manufacturing. Thus, Pittsburgh was founded and began to flourish as a center of commerce and manufacturing because of its geography. However, Pittsburgh was only born of its geography; it owes most of its growth and eventual status as a leading industrial center to its geology (Gardner, 1980). In 1901, U.S. Steel Corporation was formed in Pittsburgh, and by 1911, the city was the nation's eighth largest city, producing between a third and a half of the nation's steel.

The most important components affecting the growth of Pittsburgh were the mineral resources of the region, including salt, coal, oil, natural gas, some iron ore, and the availability of attendant requirements such as water, building materials, power, transportation capabilities, and marketability. However, the single most

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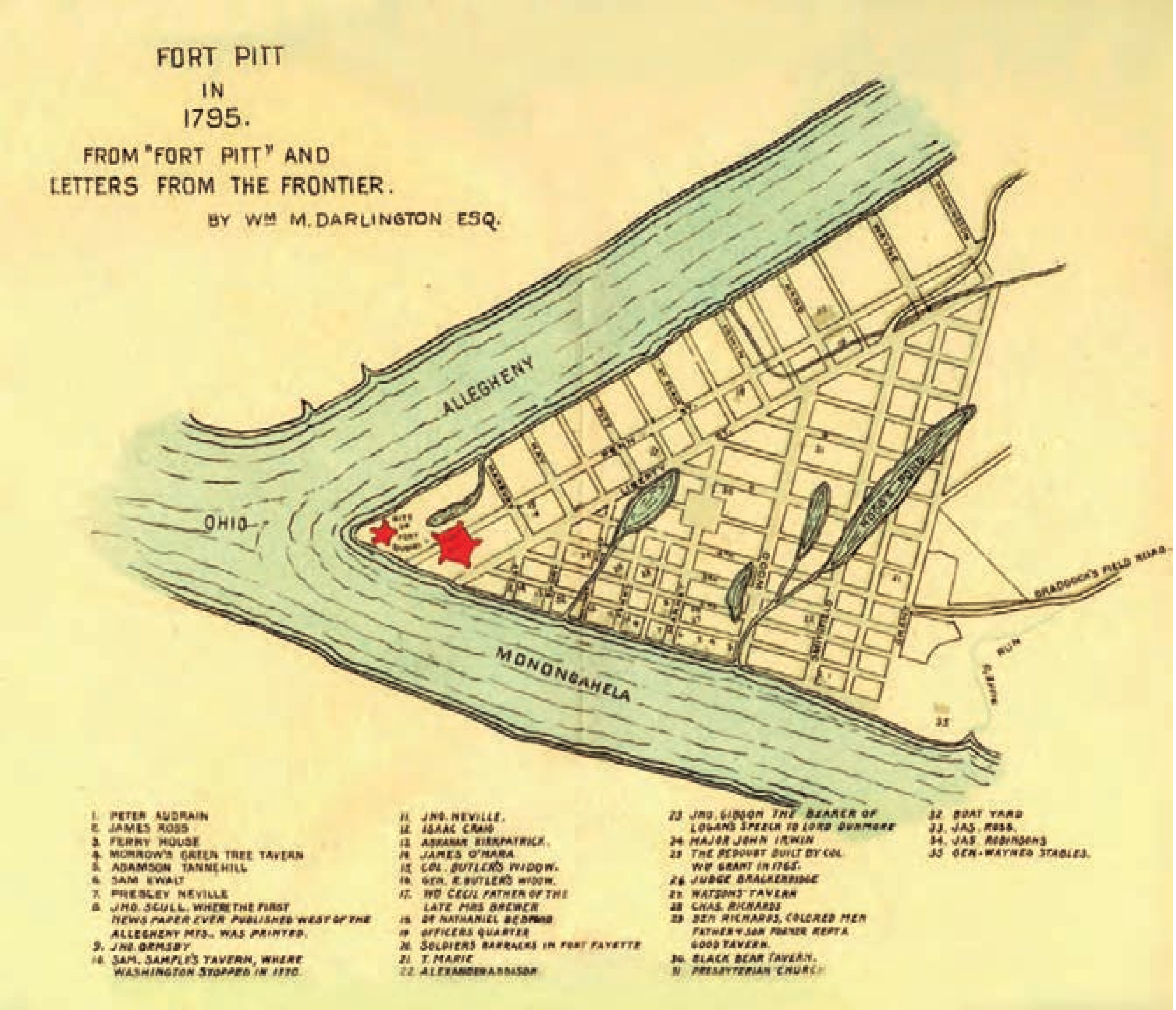

Figure 3. Map of Pittsburgh in 1795 (Albert, 1896).

important resource to affect Pittsburgh's growth and industrial stature was coal (Gardner, 1980).

Coal

There are two significant coals that are mined in the Pittsburgh region, the Pittsburgh and Upper Freeport seams. They are two of at least 13 coal seams that have been strip mined and/or deep mined at one place or another in the region.

The Pittsburgh Coal Seam is considered to be one of the richest economic deposits in the world. The U.S. Geological Survey (USGS) estimated that the Pittsburgh Coal alone yielded eight billion tons from the early 1900s to 1965, comprising 35 percent of all bituminous coal in the Appalachian Basin and 21 percent of the cumulative production for the entire United States. The Pittsburgh coal is essentially "worked-out" and no longer deep mined in Pittsburgh (Gardner, 1980), but it is still mined in the southwest corner of the state, where the seam is much deeper.

The Upper Freeport Coal Seam lies about 660 ft (201 m) below the Pittsburgh Coal and has been deep mined in a north-south belt east of the city and just north of the city. However, it is relatively thin and is currently not deep mined under the city.

The first record of coal mining in Pittsburgh was made by Captain Thomas Hutchins in 1759, when he noted a coal mine on the hillside across the

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Monongahela River from Pittsburgh. The mine was developed in the coal outcrop by the British soldiers on "Coal Hill," which is now called Mount Washington. Coal was mined on a small scale until industrialization created a greater fuel demand by the mid-1800s.

The principal user of coal in the Pittsburgh region was the iron and steel industry. The iron industry began almost at the birth of the community. The first iron furnace reported in Pittsburgh was built on Two Mile Run (Shadyside) in 1793, and it closed after only 1 year of operation for lack of iron ore and local timber for fuel. Although Pittsburgh's first iron furnace was unsuccessful, numerous furnaces operating in outlying areas closer to the local ore deposits did succeed. Because Pittsburgh was the center of commerce, trade, labor, and marketing, the industry took advantage of these resources, and local iron forging became a lucrative business (Gardner, 1980).

REGIONAL GEOLOGY

Physiography

The physiographic provinces of Pennsylvania are sub-divided into regions that generally have a similar geologic structure, geomorphic history, and climate. Pennsylvania is divided into seven physiographic provinces according to the Pennsylvania Geologic Survey. Additionally, these seven provinces are made up of smaller sections, which themselves have unique characteristics. Figure 4 shows the physiographic provinces in Pennsylvania (Sevon, 2000).

The Pittsburgh region is part of the upland area of the Appalachian Plateau Province. This upland area is a relatively flat surface with deeply dissected drainages that have produced steep-sided valleys with vertical relief on the order of 600 ft (182 km) along the major drainages. The terrain is a dissected mature landscape developed on gently folded to essentially flat-lying sedimentary strata. In southwestern Pennsylvania, the structural geologic trends are northeast to southwest. The province is bounded to the southeast by the Ridge and Valley Province and to the northwest by the Central Lowlands Province.

The Appalachian Plateau Province in southwestern Pennsylvania is divided into the Pittsburgh Low Plateau Section, Waynesburg Hills Section, and the Allegheny Mountain Section. The city of Pittsburgh is located in two of the sections, with the Pittsburgh Low Plateau Section to the north and the Waynesburg Hills Section to the south, as shown in Figure 4.

The Pittsburgh Low Plateau Section has a smooth to undulating surface composed of narrow and relatively shallow valleys having a modified dendritic drainage pattern. It has low to moderate relief, with the underlying rock composed mostly of shale, siltstone, and sandstone. The geologic structure consists of moderate- to low-amplitude folds that decrease in frequency and amplitude in a northwestward direction.

The Waynesburg Hills Section is composed of relatively hilly terrain with narrow hilltops and steep-sloped narrow valleys with a modified dendritic drainage pattern. It has moderate relief, with underlying rock types of shale, sandstone, limestone, red shale, and claystone. The geologic structure ranges from low-amplitude folds to horizontal bedding.

A small portion of the northwest section of the Appalachian Plateaus Province, called the Northwestern Glaciated Plateau Section, was glaciated during the Pleistocene Epoch. The closest approach of Wisconsinan ice was about 30 mi (48 km) north of the city. This was the last ice advance in the area.

Tectonic Setting

The tectonic history of western Pennsylvania is associated with the westernmost formation of the Appalachian Mountain chain. Four different tectonic episodes produced the Appalachian Mountain chain. A geologic time scale of the major geologic events is shown on Table 1.

The three earliest tectonic events were the Grenville Orogeny, the Taconic Orogeny, and the Acadian Orogeny. These tectonic episodes had some effect on Pittsburgh and the southwestern Pennsylvania area in the way of deeper flexures, compressional stresses, and subsequent minor surface expressions of these deeper mechanisms.

The fourth and final mountain-building event, the Alleghany Orogeny, had the most effect on southwestern Pennsylvania. This event began approximately 300 million years ago during the Pennsylvanian Period and extended into the Permian Period (Hatcher, 2004). It resulted from the collision between the North American and African Plates. Southwestern Pennsylvania received less deformation due to its distance from the collisional area, but stresses imposed by the orogeny resulted in gentle folding of the in-place rocks, creating minor anticlines and synclines triggered by deeper thrust faulting (Schultz et al., 2013).

Southwestern Pennsylvania has experienced multiple cycles of tectonic construction followed by erosion and deposition. Sedimentation in the Northern Appalachians is considered to be complex, with both basin-wide and local factors controlling deposition. The depositional area of the Appalachian Plateau Province in western Pennsylvania is part of a major structural basin referred to as the Appalachian Coal Basin or Allegheny Synclinorium. The northern portion is often referred to as the Pittsburgh-Huntington

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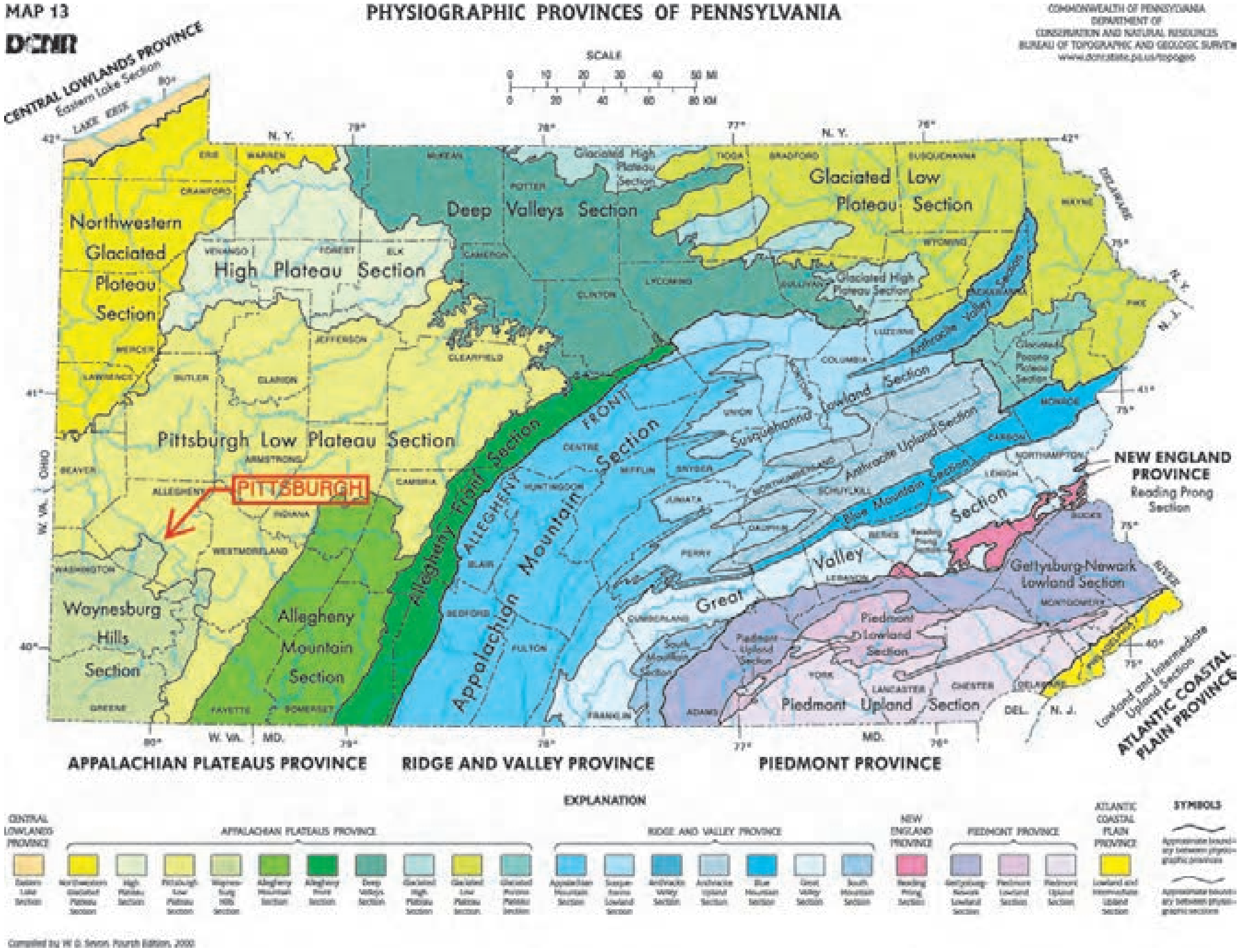

Figure 4. Physiographic province map (Sevon, 2000).

Basin or the Dunkard Basin, depending on the location. A highly generalized section through the Allegheny Synclinorium is presented in Figure 5. Updated and more detailed cross sections of the Appalachian Basin are being completed by the USGS to document and improve the understanding of the geologic framework and petroleum systems of the Appalachian Basin. More enhanced cross sections are available, and a recommended publication is by Ryder et al. (2012), titled *Geologic Cross Section C-C' through the Appalachian Basin from Erie County, North-Central Ohio, to the Valley and Ridge Province, Bedford County, South-Central Pennsylvania*.

During the Appalachian tectonic events, eroded sediment was transported generally westward from the ancestral Appalachians. Figure 6 illustrates the paleogeography of the basin and source area during the Late Pennsylvanian. An evaluation of sediment deposition into this basin identified multiple sequenced events. This sequencing occurred in conjunction with sea-level changes in southwestern Pennsylvania. See Table 1 for a timescale of the major activities affecting the Pennsylvania region and subsequent rock deposits associated with the activity. A generalized depositional history of the rocks in southwestern Pennsylvania, starting at the base of the stratigraphic column and progressing upward to the surficial rocks of the Pennsylvanian–Permian Periods, is as follows (Slingerland and Beaumont, 1989):

- Lower Cambrian (also Catoctin Greenstone) clastic wedge sequence, consisting primarily of sandstones with faulting during late Grenville Orogeny;
- Cambrian–Ordovician a carbonate sequence composed mostly of limestone and dolostone with some quartzose sandstone;

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Table 1. *Geologic timescale of major geologic events in Pennsylvania (Barnes and Sevon, 2002).*

Years ago	Era or Eon	Period	Activity Affecting Pennsylvania	Main Rock Types or Deposits in Pennsylvania	Dominant Life Forms in Pennsylvania
0 to 1.8 million	Cenozoic Era	Quaternary	Glaciation; periglacial erosion and deposition	Sand, silt, clay, gravel	Mammals, including humans
1.8 to 66 million		Tertiary	Weathering and erosion; creation of present landscape	Sand, silt, gravel	Mammals, grasses
66 to 146 million	Mesozoic Era	Cretaceous	Erosion and weathering	Clay, sand	Dinosaurs, mammals, birds
146 to 200 million		Jurassic	Diabase intrusions; opening of Atlantic Ocean	Diabase	Dinosaurs, mammals, birds
200 to 251 million		Triassic	Separation of North America from Africa; sedimentation in rift valley	Shale, sandstone, diabase	Dinosaurs, mammals, birds
251 to 299 million	Paleozoic Era	Permian	Alleghanian Orogeny: collision of Africa and North America; mountain building, thrust faulting, and folding; much erosion	Sandstone, shale	Insects, amphibians, reptiles
299 to 359 million		Pennsylvanian and Mississippian (Carboniferous)	Alluvial deposition; eastward advance of shoreline followed by development of low, flat alluvial plain	Sandstone, siltstone, shale, coal, limestone	Trees, ferns, amphibians, air-breathing molluscs, insects
359 to 416 million		Devonian	Acadian Orogeny: collision of Avalonia, Europe, and North America; formation of Catskill Delta	Conglomerate, sandstone, shale	Fish, amphibians, insects, land plants
416 to 444 million		Silurian	Erosion of mountains; deposition of sand and mud	Conglomerate, sandstone, limestone	Corals, fish
444 to 488 million		Ordovician	Taconic Orogeny: thrusting of volcanic arc; development of Appalachian basin	Shale, limestone, dolomite	Molluscs, bryozoa, graptolites
488 to 542 million		Cambrian	Transgression of the sea; carbonate deposition	Limestone, dolomite, quartzite	Trilobites, brachiopods
542 million to 2.5 billion	Proterozoic Eon		Accretion of microplates to form Laurentia	Schist, slate, marble	Blue-green algae, jellyfish, worms
2.5 to 4 billion	Archean Eon		Bombardment by meteorites and comets; creation of continental crust	None identified	Bacteria
4 to 4.5 billion	Pre-Archean Eon		Formation of Earth and solar system	None identified	None identified

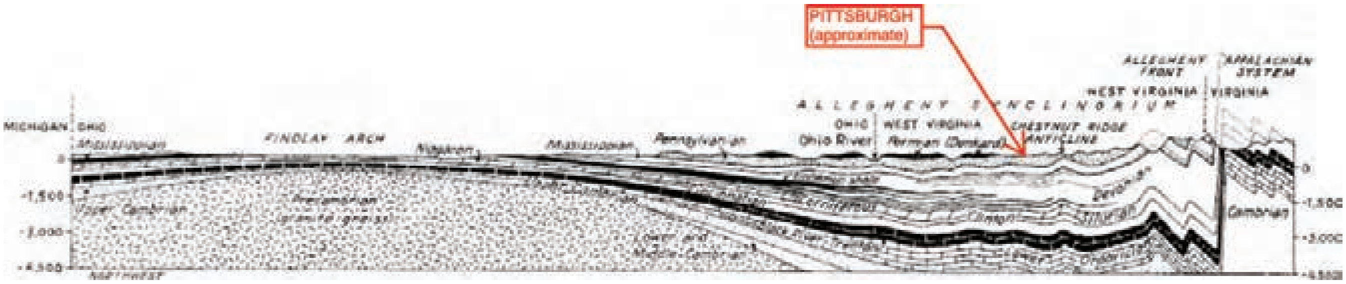

Figure 5. Cross section of the geologic structure of the Allegheny Plateau (King, 1977).

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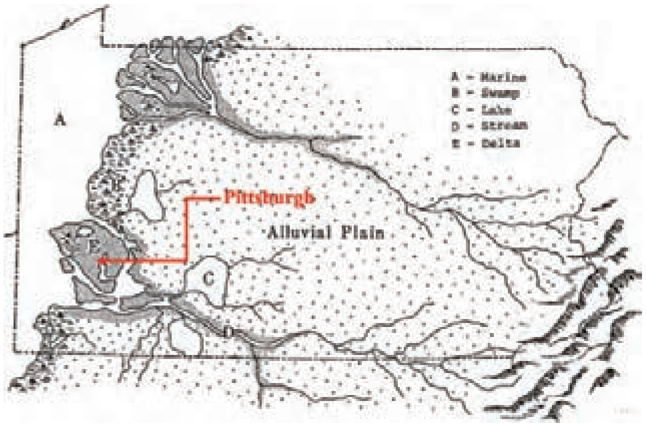

Figure 6. Inferred paleogeography of Pennsylvania during the Late Pennsylvanian when the rocks of Pittsburgh were being deposited (Wagner et al., 1970).

- Upper Ordovician clastic sequence of coarse shales, siltstones, sandstones, and quartz pebble conglomerates associated with the Taconic Orogeny;
- Silurian thin clastic seams with generally sandy limestones, dolostones, and evaporites.
- Silurian–Devonian carbonate sequence of limestone and dolostones;
- Devonian clastic wedge sequence of mostly gray fluvial and coastal shales, siltstones, and sandstones with a few mudstones, all associated with the Acadian Orogeny;
- Mississippian clastic wedge mainly composed of sandstone and shale, with a few conglomerates and limestones and sandy limestone; and
- Pennsylvanian into the Permian clastic sequence consisting primarily of sandstone, shale, mudstone, and coal from the Alleghany Orogeny with multiple delta complexes in southwestern Pennsylvania.

The surficial bedrock of southwestern Pennsylvania shows characteristics associated with deltaic depositional environments with a cyclical nature, indicating a fluctuating sea level resulting from glaciation in the Southern Hemisphere. Figure 7 illustrates a generalized depositional cycle for southwestern Pennsylvania along with the types of depositional environments associated with some of the rock units.

Geologic Setting

Rock strata cropping out in the Appalachian Plateau vary in age from Devonian to Permian, as shown on Figure 8. Mississippian- and Devonian-age rocks crop out north of Pittsburgh, as well as on the ridges to the east. Rocks of Pennsylvanian age form the surface strata within the Pittsburgh area. Permian-age rock crops out southwest of Pittsburgh.

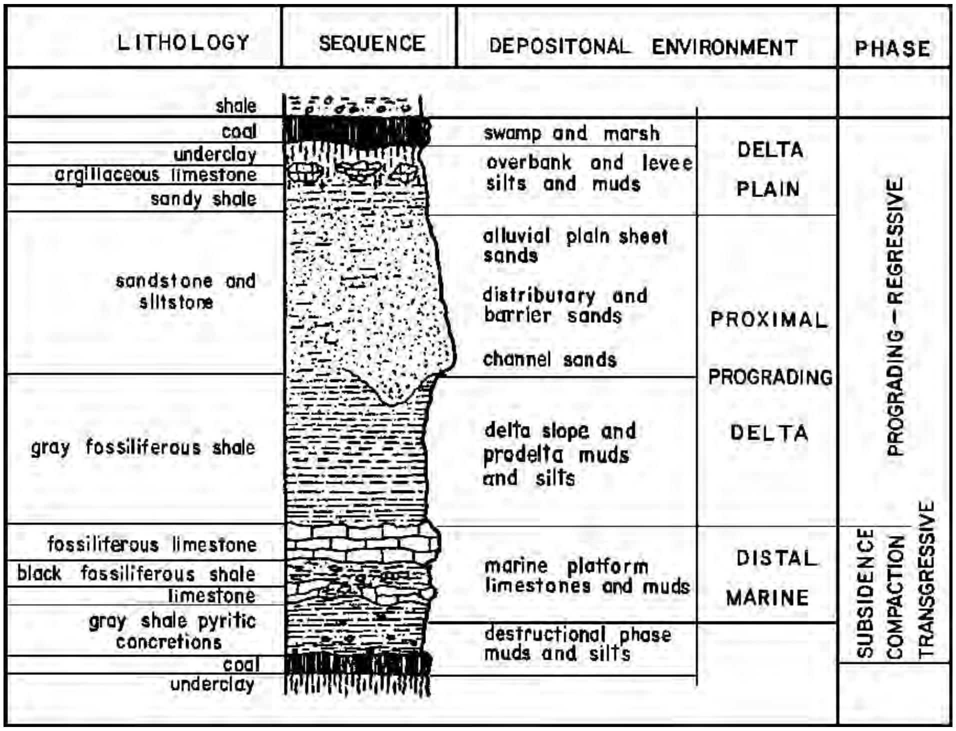

Figure 7. Generalized depositional cycle of southwestern Pennsylvania (Pryor and Sable, 1974).

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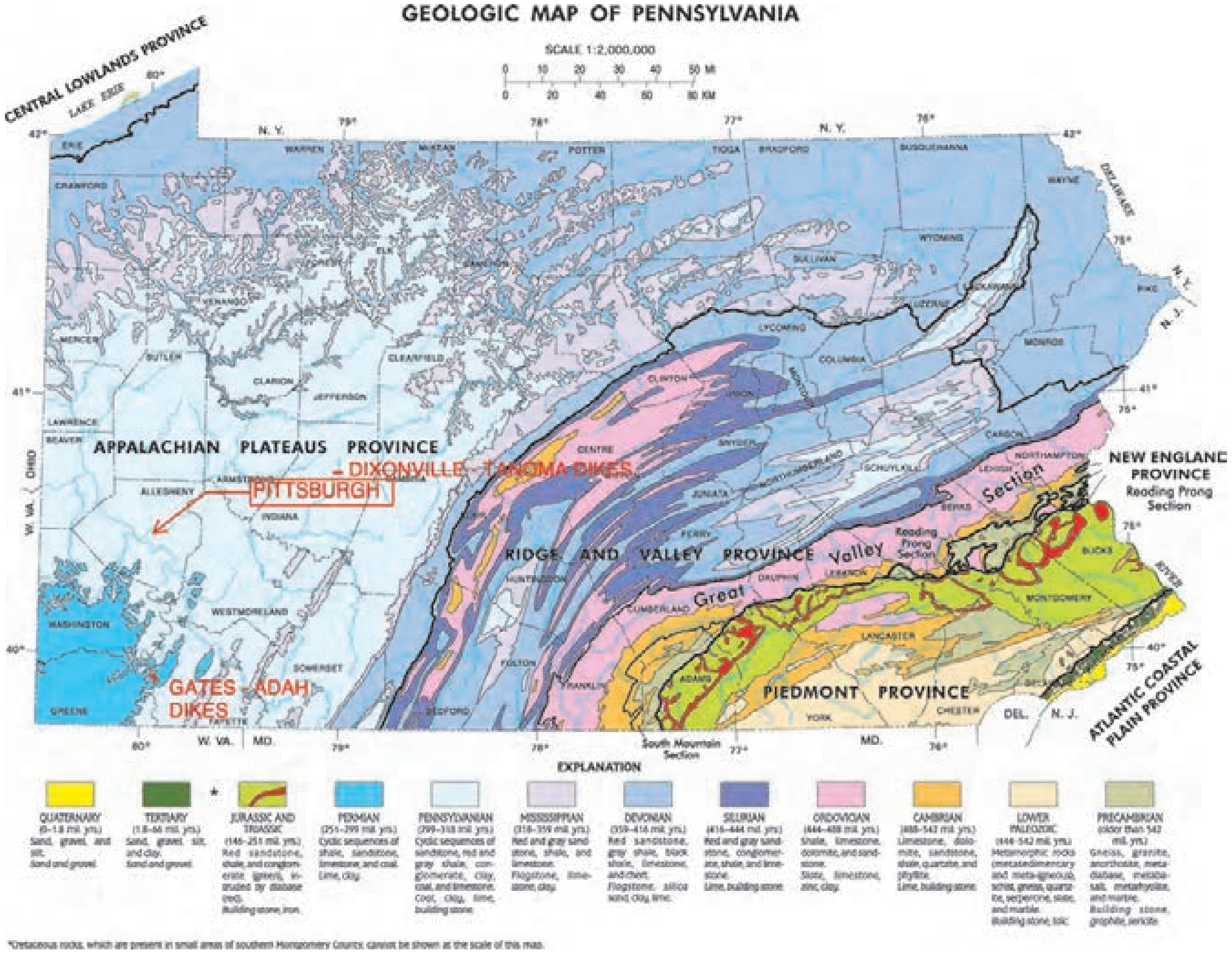

Figure 8. Geologic map of Pennsylvania (Pennsylvania Geological Survey, 2007).

The structural trend of the Appalachian Plateau ranges from N30E to N70E (Amdt et al., 1969). The lengths of the anticlines and synclines vary significantly, as shown in Figure 9. The dip associated with these folded structures is generally no more than a few degrees. The most readily identifiable and consistent rock strata are the coal beds and some limestone beds. Faulting is not common, but some minor localized vertical displacements are present.

Stratigraphy

Sedimentary Rocks

The surface and near-surface rocks in the greater Pittsburgh area belong to the Permian- to Pennsylvanian-age Dunkard Group and the Pennsylvanian-age Monongahela, Conemaugh, and Allegheny Groups. A generalized stratigraphic column of the Pittsburgh region is presented in Figure 10. A generalized summary of these rock types follows. Locations of mentioned counties are identified on the *Geologic Map of Pennsylvania* in Figure 8.

Dunkard Group (Permian and Pennsylvanian)—This group occurs at or near the surface in southern Allegheny County and in central and southern Washington County, which is southwest of the city of Pittsburgh (see Figure 8). The Dunkard unit reaches a maximum thickness of about 1,120 ft (341 m) (Berryhill et al., 1971) in Greene County. It is generally considered non-marine, composed mostly of fine-grained clastics, which frequently are calcareous. However, some findings of linguloid brachiopods in the Washington coal bed in nearby southeastern Ohio and the northern West Virginia panhandle may suggest possible marine brackish conditions extending into the

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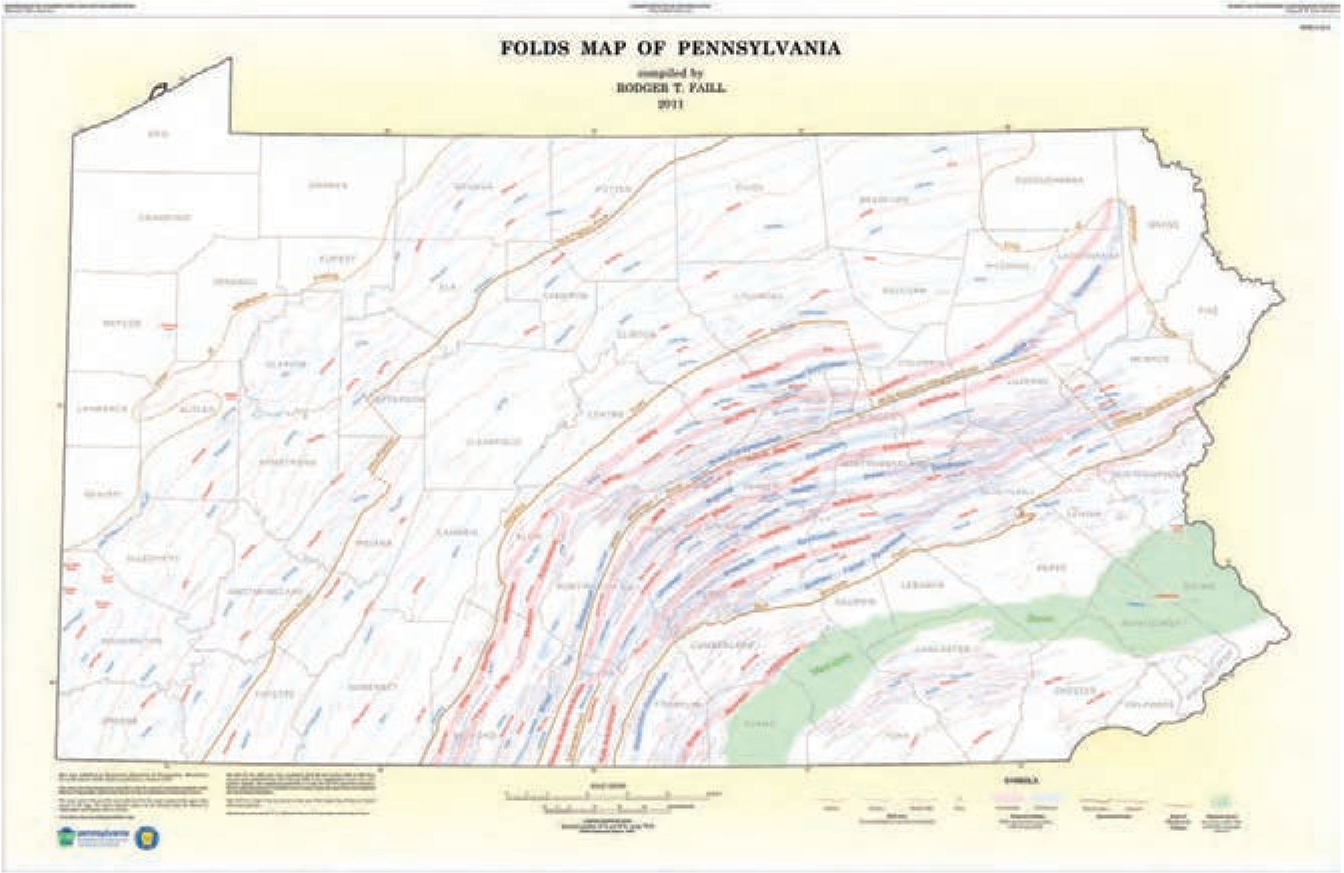

Figure 9. Structural folds map of Pennsylvania (Faill, 2011).

Dunkard Group (Cross and Schemel, 1956; Berryhill, 1963). The Dunkard Group consists of the Waynesburg, Washington, and Greene Formations (Berryhill et al., 1971). The lower boundary is defined as the base of the Waynesburg Coal, which is the only coal routinely mined in the Dunkard Group, and the upper boundary is the modern-day erosional surface (Berryhill et al., 1971). The basal Waynesburg Formation consists of shale, sandstone, siltstone, and coal. The overlying Washington Formation outcrops in valley bottoms in the northwest corner of Greene County and consists of limestone, claystone, siltstone, sandstone, carbonaceous shale, and coal. Thick lacustrine limestones are especially prevalent in the Washington Formation. The uppermost Greene Formation, which covers the western half of Greene County and caps the tops of ridges in the eastern part of the county, consists mostly of shale, sandstone, siltstone, and limestone.

Monongahela Group (Pennsylvanian)—The Monongahela Group underlies the Waynesburg Group, extending from the base of the Waynesburg Coal to the base of the Pittsburgh Coal, as shown in Figure 10. The group includes the Uniontown and Pittsburgh Formations. It is a non-marine sedimentary sequence. Coal seams, including the Uniontown, Sewickley, Redstone, and the Pittsburgh Coals, are persistent and are the primary marker beds in the area. This group ranges in thickness between 275 and 290 ft (84 and 88 m) (Berryhill et al., 1971). It consists of cyclic sedimentary sequences formed in a relatively low-energy, marginal upper delta plain having extensive lake and swamp development (Berryhill et al., 1971; Donaldson, 1974). The depositional environments of the coals are identified as tropical swamps in anaerobic conditions.

The Uniontown Formation contains both an upper and lower member separated by the Little Waynesburg Coal. The Upper Member is shale or very thinly bedded sandstone. The Lower Member is mostly sandstone with interbedded coal lenses near its base.

The Pittsburgh Formation contains several coal seams, including the laterally extensive Pittsburgh Coal, which is the basal member of the Pittsburgh Formation. The Pittsburgh Formation is divided into five members: the lower member; Redstone; Fishpot;

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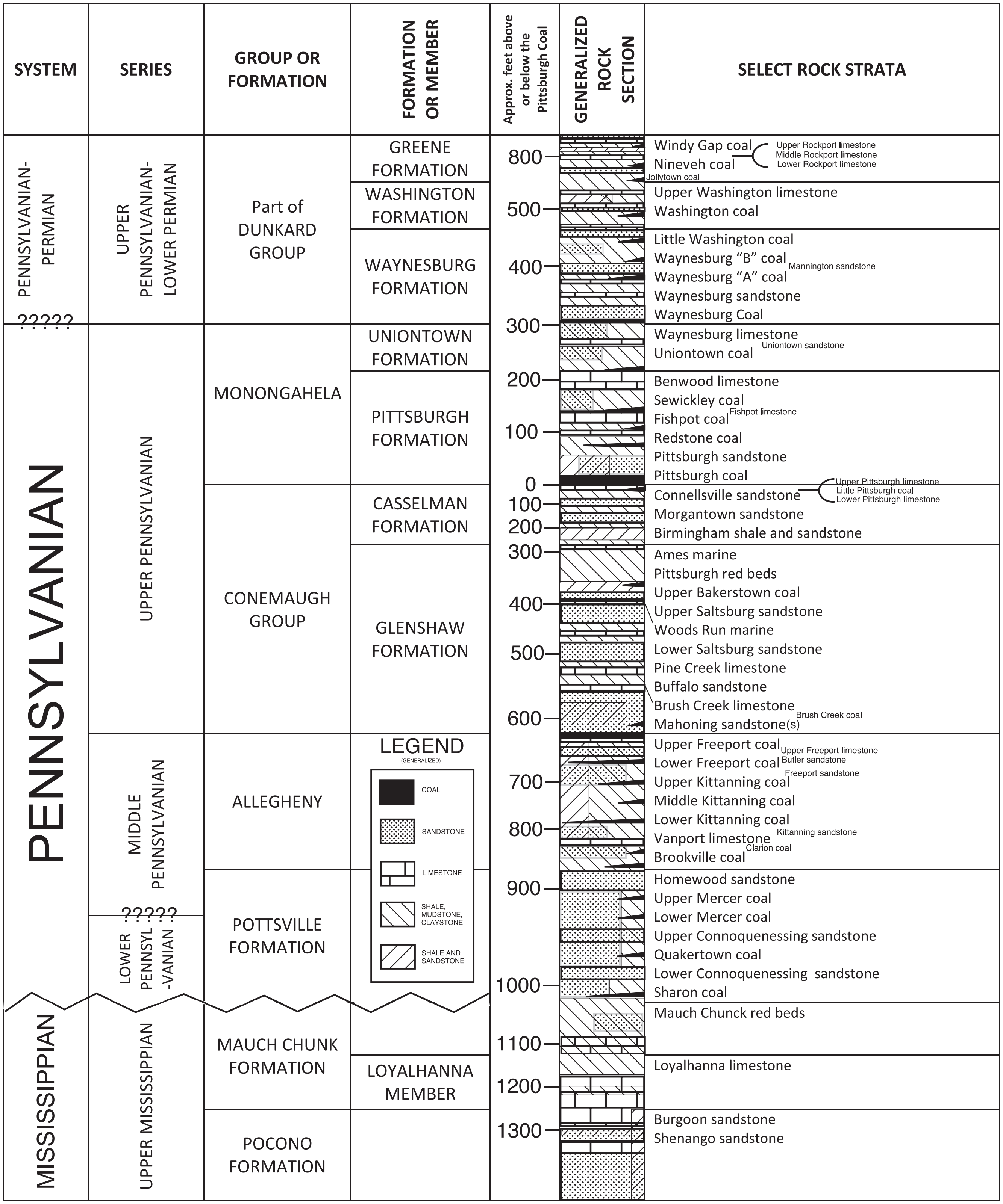

Figure 10. A generalized stratigraphic column of the Pittsburgh region (Harper, 1990).

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Sewickley; and the upper member. This formation consists of numerous relatively persistent limestone seams and lesser claystone beds in the upper portion, with the lower portion predominately composed of shale, sandstone, and coal seams.

The lower member includes the approximate 10 ft (3 m) thick and persistent Pittsburgh Coal, overlain by the only coarse clastic rock within the Pittsburgh Formation, the Pittsburgh sandstone. The Pittsburgh sandstone is a persistent fluvial unit that is generally thinly bedded to massive. A major fluvial channel system, flowing north to northwest through what is now Greene and Washington Counties, deposited this unit as an elongate sandstone body up to 80 ft (24 m) thick and several miles wide (Edmunds et al., 1999).

The Redstone member lies stratigraphically above the lower member and is characterized by siltstone and claystone, but it includes a persistent limestone unit. The division between the lower member and the Redstone member is typically marked by the Redstone Coal; however, the coal is laterally discontinuous.

The Fishpot member, the next stratigraphic unit within the Pittsburgh Formation, is the thinnest unit. The Fishpot member includes mainly siltstone and claystone, along with several thin sandstone bodies. This formation can be difficult to identify where the Fishpot Coal is absent because it marks the base of the Fishpot.

The Sewickley member represents the thickest limestone sequence, the Benwood Limestone. The Benwood Limestone is a relatively thick interbedded limestone and shale unit that is dolomitic in portions of the region.

The thick upper member of the Pittsburgh Formation contains four limestone units, designated in ascending order as “A,” “B,” “C,” and “D.” These rather persistent limestone seams are interbedded with siltstone and shale seams that are generally in proportion with the thickness of the limestone found above these fine-grained seams. Limestones of the Monongahela Group are freshwater limestones, deposited during highstands in the lakes of alluvial plains.

Conemaugh Group (Pennsylvanian)—The Conemaugh Group underlies the Monongahela Group in southwestern Pennsylvania. It includes the Glenshaw and Casselman Formations and is a clastic sequence dominated by siltstone, claystone, shale, and sandstone. The average thickness of this group is approximately 620 ft (189 m) (Shultz, 1999) in the Pittsburgh area and extends from the base of the Pittsburgh Coal to the top of the Upper Freeport Coal. Bedrock exposure of the Conemaugh Group is limited in southwestern Pennsylvania, with most exposures at and north of Pittsburgh.

Conemaugh stratigraphy is subdivided into two distinct formations based upon the presence or absence of marine units, with the boundary between them being the top of the persistent Ames Limestone (Flint, 1965). The upper unit, the Casselman Formation, is essentially devoid of marine units, while the lower unit, the Glenshaw Formation, contains widespread marine units (Shultz, 1999). Mineable coals are not common in the Conemaugh Group.

The Casselman Formation extends from the base of the Pittsburgh Coal to the top of the Ames Limestone and consists of a sequence of alternating layers of sandstone, shale, red beds (claystone), non-marine limestone, and thin discontinuous coal seams.

The Birmingham shale is a significant unit within the Casselman Formation. Numerous locations of this strata are exposed around the city. It is generally described as a dark, thinly laminated rock nearly 50 ft (15 m) thick that occurs below the Morgantown sandstone and about 30–60 ft (9–18 m) above the Ames Limestone in Pittsburgh. It consists mainly of fine-grained siltstone and shale overbank deposits. Marine fossils have been found in the shale at outcrops along Ohio River Boulevard, which is located just west of Pittsburgh. This transition zone contains marine to brackish fauna and suggests the last marine episode of the Paleozoic in the Pittsburgh area. The brachiopod findings identified in the earlier Dunkard Group suggest the last marine episode may be as late as the Washington Coal seam in areas further west of Pittsburgh.

The Glenshaw Formation extends from the top of the Ames Limestone to the top of the Upper Freeport Coal. The Ames Limestone is a laterally continuous fossiliferous limestone that is generally on the order of 2–4 ft (0.6–1.2 m) thick. It serves as the primary marker bed in the Conemaugh Group and identifies the last certain occurrence of marine conditions in Pittsburgh. The claystones and shales are the weaker units of the formation and are notorious for landslide potential. All of these rock units are commonly interbedded and tend to change lithologically over short lateral distances.

A primary source in the Pittsburgh area for landslides is the Pittsburgh red beds, which is near the top of the Glenshaw Formation. It is a 40–60 ft (12–18 m) series of mostly reddish, greenish, and grayish claystone and shale, with minor amounts of sandstone and siltstone, that tends to weather deeply on hillsides throughout southwestern Pennsylvania. Claystone is a low-permeability, low-strength rock with weakly connected pore space. Repeated weathering cycles and excessive pore pressure have a tendency to reduce the internal shear strength of this particular rock, leading to failure. In addition, Conemaugh claystones contain

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minerals that tend to expand in the presence of water (Pomeroy, 1982).

These red shales have been interpreted as a paleosol horizon (ancient soil zone) on the Pennsylvanian delta by Donahue and Rollins (1974). They suggested that the red color and the claystone texture are similar to that of a laterite soil weathering profile, with some channel-form structures indicating that these shales may be composed of multiple paleosols. It also has features that may indicate repeated and prolonged subaerial exposure and pedogenesis (Cecil and Dulong, 2004). The pedogenic origin is identified by good exposures of the series displaying evidence of an ancient soil development, with some occasional root casts, slickensides, and calcite-rich nodules.

Allegheny Group (Pennsylvanian)—The Allegheny Group underlies the Conemaugh with a thickness between 270–330 ft (82–100 m) in western Pennsylvania (Edmunds et al, 1999). It begins at the top of the Upper Freeport Coal and extends to the base of the Brookville Coal. This group consists largely of marine units and contains six mineable coals, referred to as the Upper Freeport Coal, Lower Freeport Coal, Upper Kittanning Coal, Middle Kittanning Coal, Lower Kittanning Coal, and the Brookville Coal. These coals crop out north of the Pittsburgh area. Coals and associated strata of the lower Allegheny Group (Brookville through Middle Kittanning Coals) were deposited during a general eastward marine transgression. The setting was a shifting complex of marine to brackish embayments, lower-delta-plain distributaries, and inter-distributary to coastal margin swamps, grading inland to an upper-delta-plain fluvial and interfluvial swamp system (Williams, 1960; Williams and Ferm, 1964; Ferm and Williams, 1965; Ferm and Cavaroc, 1969; and Ferm, 1970, 1974). The upper Allegheny Group (Upper Kittanning through Upper Freeport Coals) was deposited in a relatively high energy, upper-delta-plain fluvial and interfluvial lake and swamp environment during a period of general marine regression (Sholes et al., 1979; Skema et al., 1982).

The Allegheny Group contains a repeating succession of coal, limestone, and clastics, ranging from claystone to coarse sandstone. Most beds exhibit lithologic change both vertically and laterally over short distances, but some coals, and a few marine shales and limestones are continuous over large areas.

Pottsville Group (Pennsylvanian)—The Pennsylvanian-age Pottsville Group is a ridge-forming unit in parts of the Ridge and Valley Province in Pennsylvania and in the Allegheny Mountain section of the Appalachian Plateau Province. The group ranges in thickness from 100 ft (30 m) in western Pennsylvania to 1,600 ft (488 m) in northeastern Pennsylvania (Edmunds et al., 1999). Because it contains resistant rock units, it tends to form ridges and cap most of the highpoints, including Mount Davis in Somerset County, the highest point in Pennsylvania at 3,213 ft (980 m) in elevation.

The Pottsville Group consists predominately of a well-cemented pebble conglomerate with some sandstones and finer clastics and coal (Edmunds et al., 1999) that range in thickness from about 10 to 70 ft (3 to 21 m). It extends upward from the top of the Mississippian Mauch Chunk Formation to the base of the underclay beneath the Brookville Coal of the Allegheny Group. Abrupt variations in the thickness of the Pottsville Group of up to 100 ft (30 m) have been observed over short distances. The formation has minor marine limestones in northern Pennsylvania. Mining of coal in the Pottsville Group is limited, mainly occurring in the basal part of the formation (McElroy, 2000).

Igneous and Metamorphic Rocks

Precambrian basement rock (see Figure 11) underlies all of Pennsylvania, but it is only exposed in the southeastern part of the state. A thick Paleozoic sequence overlies the basement for all of southwestern Pennsylvania. The basement rocks directly under the Pittsburgh region are inferred from limited data found mainly in deep wells located in northwestern Pennsylvania, eastern Ohio, and northwestern West Virginia, as well as from geophysical surveys.

The basement in the Pittsburgh region is at a depth ranging from 14,700 to 16,400 ft (4,480 to 5,000 m), according to the Saylor (1999), and it is believed to have lithologies similar to the Canadian Grenville Belt. The most common lithologies identified are granite, gneiss, biotite granite, and biotite schist (Saylor, 1999), and all of these lithologies have been metamorphosed to the greenschist or amphibole facies (Bass, 1959, 1960; Saylor, 1968).

Some indirect evidence has been found that deformation of the basement exists; however, little physical information is available. Direct investigation and research into the basement are prohibited by depth, and most modern remote-sensing data remain confidential as a result of the increasing gas exploration from the recent Middle Devonian shale gas boom. Other than some glacial erratics derived from Canada, there are no surface metamorphic rocks in western Pennsylvania.

The only known near-surface igneous rock in western Pennsylvania are two separate single-fissure Jurassic kimberlite dikes. The first is the Gates-Adah Dikes, which outcrop near the Monongahela River on the border of Fayette and Greene Counties (south of Pitts-

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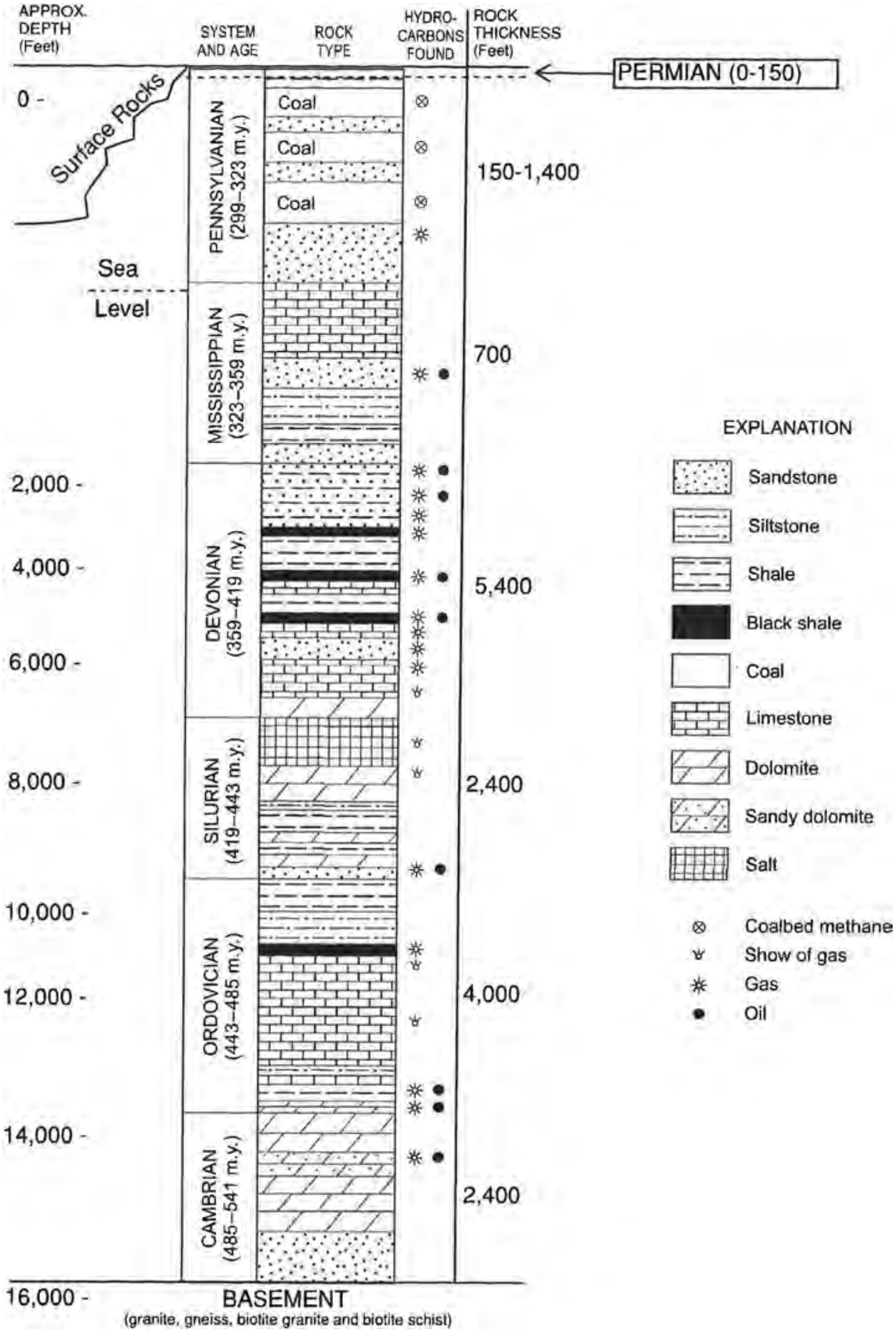

Figure 11. Subsurface rocks below western Pennsylvania (Adapted from Flaherty and Flaherty, 2014; and Wagner et al., 1970).

burgh), shown on Figure 8. The Gates-Adah kimberlite intruded approximately 170 million years ago (Bikerman et al., 1997), appears to have formed at a relatively shallow depth, and contains mostly pyrope garnets and Alexandrite-effect pyropes.

The other kimberlite intrusion is the Dixonville-Tanoma Dike in central Indiana County (northeast of Pittsburgh), as shown on Figure 8. The intrusions are carbonatized hypabyssal kimberlites (Gold et al., 2016). The Dixonville Dike and Tanoma Dike represent the same intrusion, and neither is exposed on the surface; they were initially discovered in the Tanoma Coal Mine while mining the Lower Kittanning Coal. They extend almost continuously from the Lower Kittanning Coal to the Lower Freeport Coal through a vertical distance of approximately 180 ft (55 m). The

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dike is 1–18 in. (2.54–45.72 cm) wide and extends some 7,200 ft (2.19 km) laterally through the mine workings (Gold et al., 2016). The coal mine has closed, and the dike is no longer accessible.

Surficial Geologic and Soil Features

Existing and past climatic conditions have resulted in substantial mechanical and chemical weathering, which has produced a residual or colluvial soil mantle over the rocks of the Pittsburgh region. The sedimentary rock strata are normally not exposed, other than in valley walls and excavations into rock. There is considerable evidence that rocks of this region remain highly stressed, and subsequent stress relief due to valley cutting aids in the physical breakup of rock and enhances its susceptibility to chemical weathering (Ferguson, 1967, 1974; Voight, 1974). The most important discontinuities within the surficial rock are joints. Both tectonic jointing and stress-relief jointing are recognized. Both systematic jointing and non-systematic jointing occur, with the majority of non-systematic joints in the weaker, fine-grained rock.

Joints caused by the local release of residual stress are closely spaced (up to 10 ft [3 m]), whereas joints caused by tectonic stresses exhibit a spacing of many feet (Nickelsen and Hough, 1967). The finer-grained rocks have more closely spaced joints. Nickelsen and Hough (1967) presented details of joint patterns, trends, and spacing in the Appalachian Plateau of Pennsylvania.

Southwestern Pennsylvania is dominated by soil derived from acidic shales and sandstones consisting of clay-sized particles with moderate to substantial amounts of rock fragments. The surficial soils are predominantly silty loams, which are usually well drained. This region has relatively steep slopes, making erosion a major concern. The available water-holding capacity (i.e., porosity) of many soils in the region is relatively moderate. Residual soils are characteristic of the flat upland surfaces and flat surfaces of larger benches, with colluvial soils forming the slopes. In general, the thickness of residual or colluvial soils in the Pittsburgh region is on the order of 10–30 ft (3–9 m). Alluvial soils fill stream and river valleys and reach thicknesses of up to 100 ft (30 m).

Pleistocene Glaciation

The closest extent of continental ice to Pittsburgh was approximately 30–40 mi (48–64 km) northwest. However, the periglacial activity and sand and gravel outwash are two major results of glaciation that impacted Pittsburgh. Figure 12 shows the limit of glaciation in western Pennsylvania and the present river systems. Extensive periglacial activity south of the glacial limits, consisting of cold wet weather and frequent freeze-thaw cycles, impacted the Pittsburgh area. This severe climate caused extensive mass wasting through rock breakup and downslope movement of broken material. Peltier (1950) and Denny (1956) found fossil periglacial features close to the front of the maximum advance of Wisconsinan glaciations in Pennsylvania, which strongly support influence of Pleistocene periglacial processes on the development of slopes.

Radiocarbon dating of wood from several large colluvial slide masses in western Pennsylvania and West Virginia indicate a Pleistocene age, and thus a periglacial origin, for these deposits (Gray et al., 1979).

Wisconsinan glaciation significantly altered the courses of the Allegheny and Ohio Rivers, and glacial outwash filled the valleys with sand and gravel. Erosion subsequently removed approximately 80 ft (24 m) of the sand and gravel, leaving about 50 ft (15 m) of alluvium, which created a significant aquifer in the river valleys. The alluvium consists of hard, dense sand and gravel, which provide excellent foundation conditions for large buildings and heavy structures along with a high-quality source of durable sand and gravel.

Pittsburgh's Three Rivers

Prior to the Pleistocene glaciation, which began approximately 800,000 to 1,000,000 years ago, the Pittsburgh River was the dominant river in southwestern Pennsylvania (Figure 13). It flowed north to the site of Pittsburgh in a channel approximately coincident with its present channel. From Pittsburgh, it followed the channel of the present Ohio River to Beaver, PA, where it turned north up the present Beaver River Valley and flowed north into the Erigan River or the former "Ancestral Erie Basin," as shown on Figure 13 (Harper, 1997). The Monongahela River system drained about three fourths of the area in Pennsylvania that is presently drained by the combined Ohio, Monongahela, and Allegheny Rivers and their tributaries (Harper, 2002). The Ohio River was a tributary of the Monongahela. It originated south of Moundsville, WV, and flowed north, joining the Monongahela River just south of New Castle, PA. The Allegheny River was three separate rivers that drained different parts of Pennsylvania (Figure 13). The "Lower Allegheny" originated in Elk, Forest, and Jefferson Counties, followed the course of the present Clarion River, and then flowed south to join the Monongahela River at what is now Pittsburgh. The "Middle Allegheny" started in Warren County and

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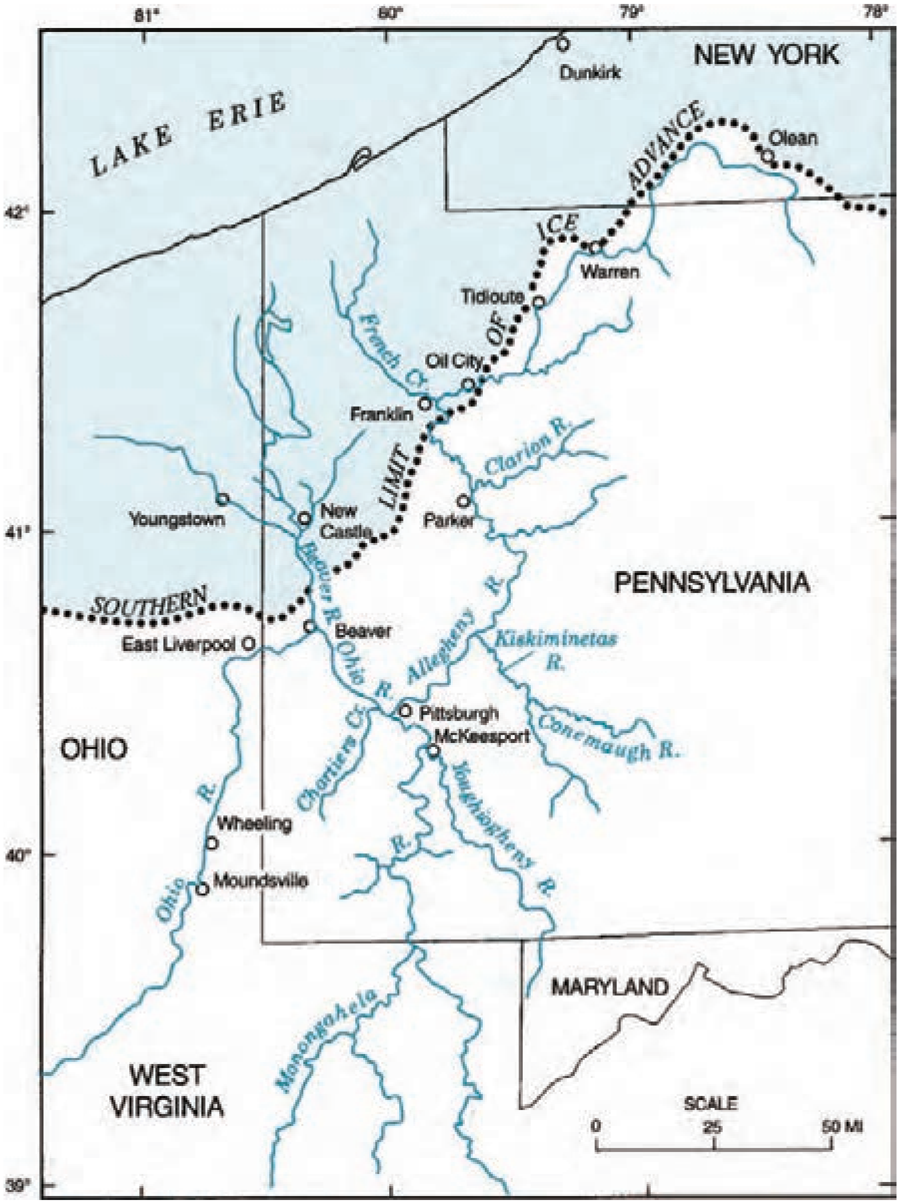

Figure 12. Limit of glaciation in western Pennsylvania and present river systems (Harper, 1997).

followed a course through Oil City to Franklin, where it turned northwest along what is now French Creek and flowed across Crawford and Erie Counties into the Erigan River. The "Upper Allegheny" began in northern Pennsylvania and southern New York and flowed from Olean to Dunkirk, NY, into the Erigan River (Harper, 1997).

During the last ice age (Wisconsinan), there were four major advances and retreats of continental ice sheets in North America. At least three of these ice sheets, the pre-Illinoian, Illinoian, and Wisconsinan, extended into western Pennsylvania and disrupted drainage patterns, forming the present drainages (see Figure 12). None of the continental glaciers reached Pittsburgh. The advancing ice sheets blocked the northwest-flowing streams, creating lakes within the existing drainage areas. As the ponded waters rose, they eventually crested and eroded notches in their drainage divides. The escaping waters formed new drainage channels that flowed southwestward, closely paralleling the front of the glaciers. The three Allegheny Rivers coalesced to form one, and the Ohio River became the major drainage system of western Pennsylvania, flowing south and then west along the boundary of the ice to the Mississippi River (Harper, 2002). The Allegheny and Ohio Rivers subsequently

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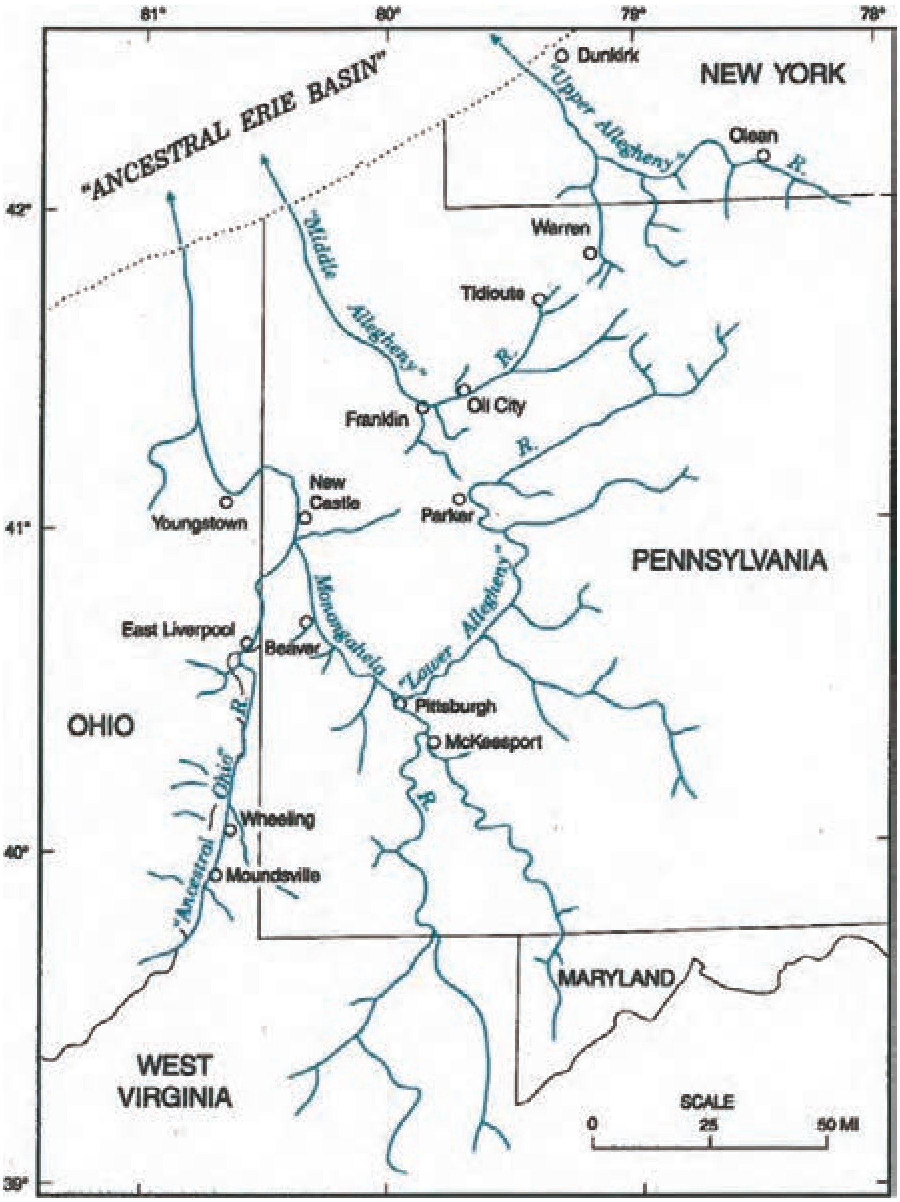

Figure 13. Western Pennsylvania stream patterns before glaciation (Harper, 1997).

served as the major channels for the flow of glacial meltwaters.

The relatively flat hilltops in the Pittsburgh area are 500–600 ft (152–183 m) above river levels. In Tertiary time, downcutting of streams produced a system of broad valleys 350–400 ft (107–122 m) below the hilltops and 200 ft (61 m) above present river levels. This pre-glacial erosional stage produced valley levels known as the Parker Strath (a Scottish word meaning a wide flat valley) (Heyman, 1970) (Figure 14).

During some pre-Illinoian glaciation, the ancestral Allegheny River was choked with glacial outwash, resulting in the ponding of tributary streams. The alluvium of the Monongahela and Youghiogheny River basins is known as the Carmichaels Formation. The Carmichaels Formation is a periglacial alluvial deposit found on multiple terraces generally south and east of Pittsburgh. The deposits typically contain clays, silts, and sands, with some deposit locations containing more cobbles and boulders generally from local sources. Some of the clays are high quality and were once a good source for the early pottery industry in the Pittsburgh area. Figure 14 presents idealized valley cross sections showing erosion levels and valley-fill deposits in Allegheny County. Following the Wisconsinan glaciation, active stream erosion cut down 250

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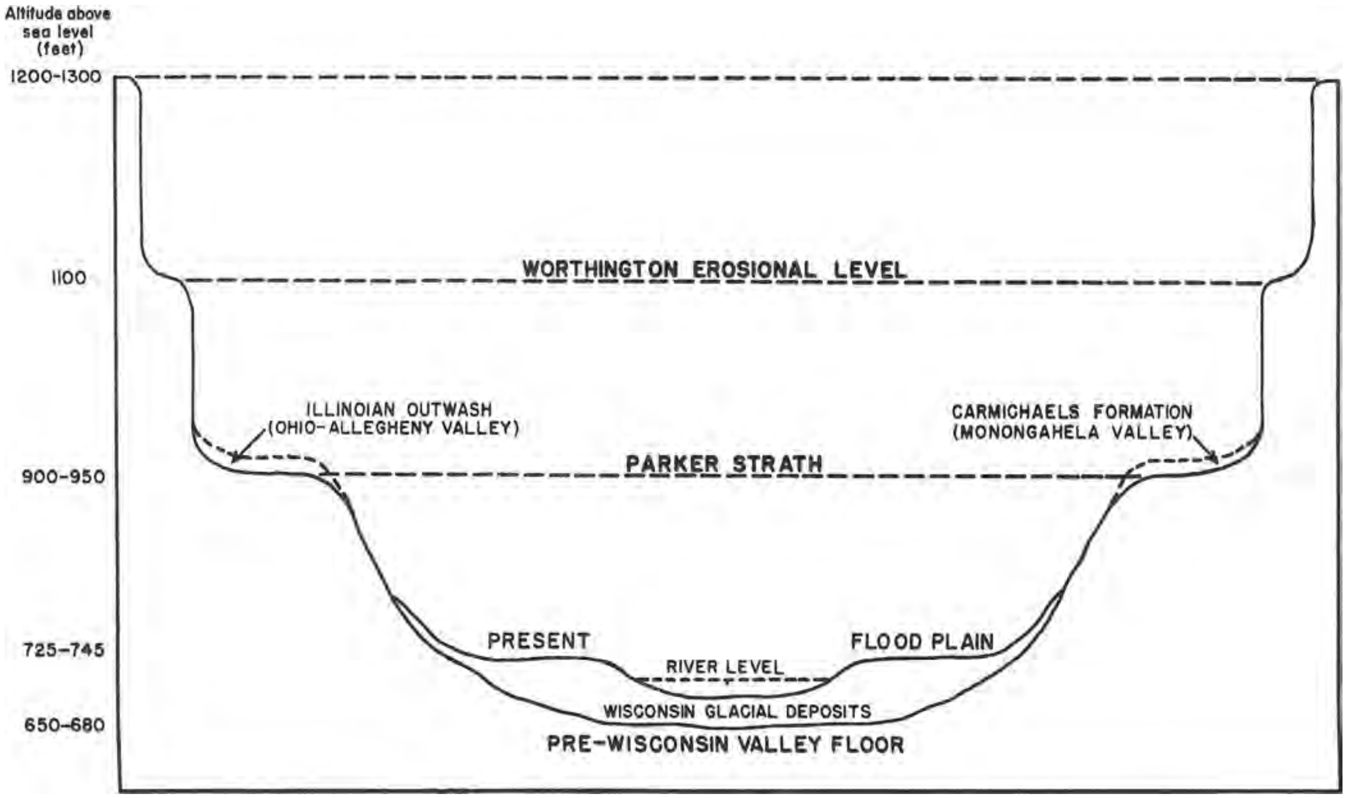

Figure 14. Idealized valley cross section showing erosion levels and the position of valley-fill deposits in Allegheny County (Adamson et al., 1949).

ft (76 m) below the gravel-covered Parker Strath, excavating channels to a depth of 50 ft (15 m) or more below present stream levels (Figure 14). Figure 15 shows the development of the Allegheny and Monongahela River valleys in the last 1 million years.

In cutting new channels, the streams locally took completely new courses, leaving behind great channel loops and meander cut-offs, which cross and re-cross the present valleys high above present stream level. Today, these wide valleys do not contain major streams.

Abandoned channels and terraces occur along all the rivers and larger creeks in the Pittsburgh region that existed during the Pleistocene. Some of these abandoned channels and high-level terraces in the immediate vicinity of Pittsburgh are shown by Figure 16. One major abandoned channel (1 mi [1.6 km] wide) leaves the Monongahela Valley between Braddock and Swissvale and extends through Swissvale, Wilkinsburg, East Liberty, and the Oakland section of Pittsburgh before rejoining the Monongahela River valley. Today, this abandoned channel is occupied by the Norfolk Southern Railroad main line and the east busway. Excavations anywhere in this valley reveal layers of silt and sand deposited by the "Old Monongahela." Excavations for the University of Pittsburgh's Cathedral of Learning (skyscraper) in this valley exposed up to 40 ft (12 m) of sand, gravel, and boulders, along with laminated plastic clay (Leighton, 1947).

As noted previously, the alluvium of the Allegheny and Ohio River valleys, in Allegheny County, consists largely of glacial outwash gravel and sand and is the primary source of groundwater in Allegheny County. Pebbles of crystalline rock transported from as far north as Canada are found included with pebbles of resistant sandstone of local origin and some material from further north in these valley deposits. The finer material is likewise of both remote and local origin. Most of the commercial gravel deposits in the vicinity of Pittsburgh will pass a 2 in. (5 cm) screen, but boulders are not uncommon. The material is well sorted in some places, but more commonly the grain size varies considerably. Figure 17 presents 12 large bulk grain size distribution curves for the glacial gravels from a deep excavation on the north side of the Ohio River in Pittsburgh. On average, gravel constitutes over 60 percent (by weight) of the glacial outwash.

The average maximum thickness of the valley alluvium is about 60 ft (18 m). Normally, glacial sand and gravel constitute the basal part of the alluvium,

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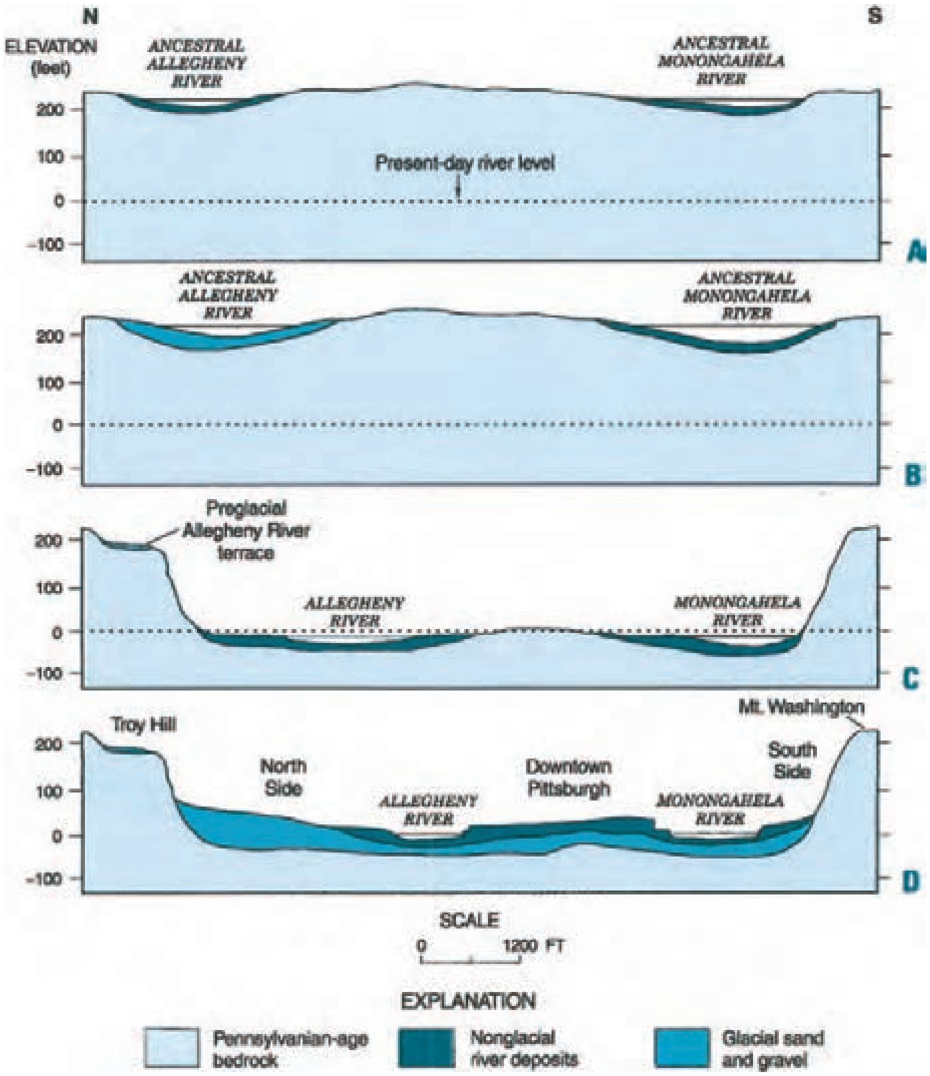

Figure 15. Development of Allegheny and Monongahela River valleys in the past 1 million years (Harper, 1997).

which is overlain by recent floodplain deposits ranging in thickness from 0 to 25 ft (0 to 7 m). In parts of the present stream bed, the topmost member of the alluvium is a layer of very fine silt, which to some extent is transitory and is probably scoured during floods and re-deposited as high-water stages decline. Characteristic sections across the Allegheny and Ohio River valleys are shown in Figure 18. Laterally, these alluvial deposits extend the width of the pre-Wisconsinan stream valleys, which are wider than the present streams. Generally, the bedrock floor of the valleys is relatively flat, except in a few areas along the upper Ohio River, where shallow channels were cut into the bedrock floor before the valley aggraded. In Allegheny County, the thickness of water-bearing sand and gravel remains fairly constant across the valleys; however, the sediments thin rapidly near the valley walls (Adamson et al., 1949). Figure 19 shows contours of the rock surface below Pittsburgh's downtown area, and the approximate eastern limit of water-bearing glacial gravel.

The old valley bedrock floor on the Allegheny River, which declines from an elevation of 682 ft (208 m) above sea level at Tarentum to 661.5 ft (201.6 m) immediately above the junction of the Allegheny and Monongahela Rivers (Pittsburgh's Point), averages a gradient of 1 ft per mile (30 cm per kilometer). Continuing down the Ohio 13 mi (21 km) from the Point, the ancient valley floor is found at an elevation of 651 ft (198 m), and the average gradient is 0.8 ft per mile (20 cm per kilometer) in this distance. At no place in the Allegheny and Ohio valleys in the county has bedrock been recorded at a depth in excess of 85 ft (25 m) below the average river level.

Within Allegheny County, the maximum thickness of the Monongahela valley alluvium is 65 ft (20 m). The Monongahela valley floor with a pre-Wisconsinan

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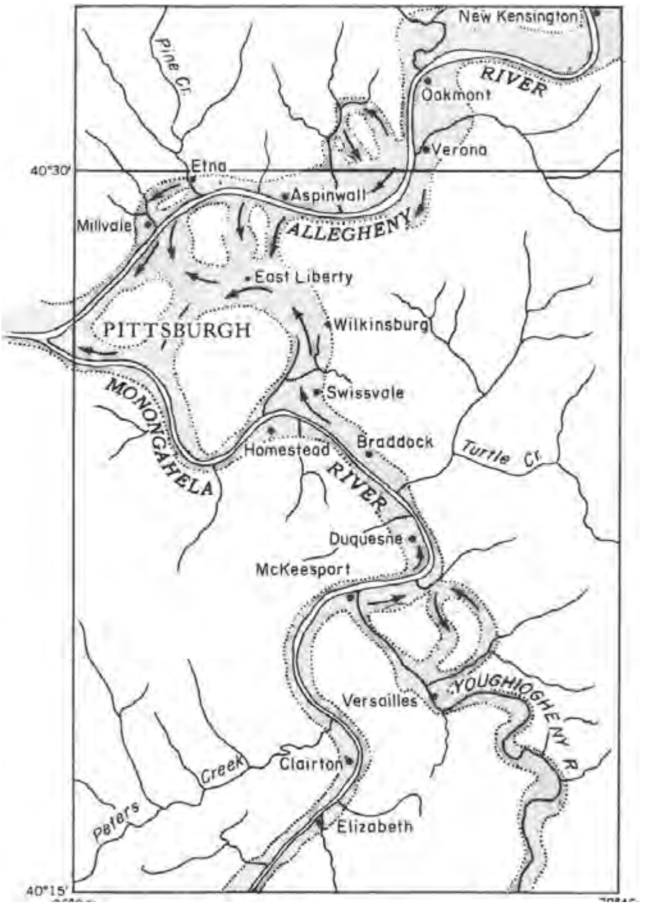

Figure 16. Abandoned channels and high-level terraces in immediate vicinity of Pittsburgh (Heyman, 1970).

age has a gradient of about 0.8 ft per mile (20 cm per km) from Elizabeth, PA, to the Point, which is a distance of about 23 mi (37 km) (Adamson et al., 1949).

NATURAL RESOURCES

Salt, Oil, and Natural Gas

Salt was an early high-value mineral and was much sought after on the frontier. It was expensive to haul over the mountains from the east coast, and therefore local sources were sought and established. It was originally obtained by boil-evaporating naturally occurring saline brine discharges in springs in the area. The process was simple; settlers would dig holes, and the holes would fill with brine, which was collected and kettle-evaporated to obtain the crystalline salt residue. Later, wells were drilled for salt, which frequently tapped the sandstones in the Pottsville Group, which in turn became known as "salt sands."

Crude oil was occasionally found in conjunction with the brine in the salt wells and was originally considered a nuisance to be discarded. Samuel Kier (ExplorePAhistory, 2014, Kier Refinery Historical Marker), an American inventor and business man, operated salt wells on his family property located in Tarentum, to the northeast of Pittsburgh. He noticed that the crude oil in the salt wells was similar to what was being prescribed for homeopathic cures for various illnesses and began collecting and bottling the oil and selling it as a "cure-all." In 1849, he opened a bottling and merchandising house in Pittsburgh, and his "Kiers Rock Oil" was sold throughout the northeastern United States (Figure 20). The oil was sold at the pricey rate of 50 cents (a day's wages) for a half pint bottle, and the label read "Kiers petroleum or rock oil. Celebrated for its wonderful curative powers. A natural remedy. Procured from a well in Allegheny (County), Pa. Four hundred feet below the earth's surface." (Richardson, 1932, p. 55). He also began to experiment with the crude oil as an illuminant and sold the "carbon oil" from a warehouse in Pittsburgh. In order to capitalize on his discovery, he built the first commercial petroleum refinery in Pittsburgh in 1854 to produce illuminating oil from the crude oil he obtained from the family salt wells. Kier was forced to move his refinery operation out of the city because of local residents' fear of fire and explosions.

Once it was determined that the "rock oil" had a use, it was collected from the salt wells and from crude oil seeps. In those areas, pits were dug to collect the oil, which was removed and containerized for subsequent sale. Commercial oil production began in Pennsylvania with the drilling of the Drake Well in 1859 (see Figure 21). The well was drilled near Titusville, Venango County, PA, which is located about 100 mi (161 km) north of Pittsburgh, and this was the first internationally economic well drilled intentionally to produce commercially valuable crude oil (Carter and Flaherty, 2011). Oil exploration slowly moved south, and in 1886, the Mount Nebo Field was discovered in nearby Ohio Township, Allegheny County. The slow southward movement of oil recovery activity was due primarily to the increasing depths of the oil-bearing Venango sandstones. The Drake Well was drilled in an area of known oil seeps and had a final depth of about 69 ft (21 m). Oil-bearing Venango sandstones were targeted in that area and were generally deeper, with depths ranging from 300 to 700 ft (91 to 213 m) deep. Similar strata in the Pittsburgh area are at depths between 1,200 and 2,800 ft (366 and 853 m). Such depths required the development of new exploratory and developmental drilling equipment and techniques. Between 1886 and 1904, almost all of the shallow oil fields in Allegheny County had been found and exploited, and the local oil industry started to decline.

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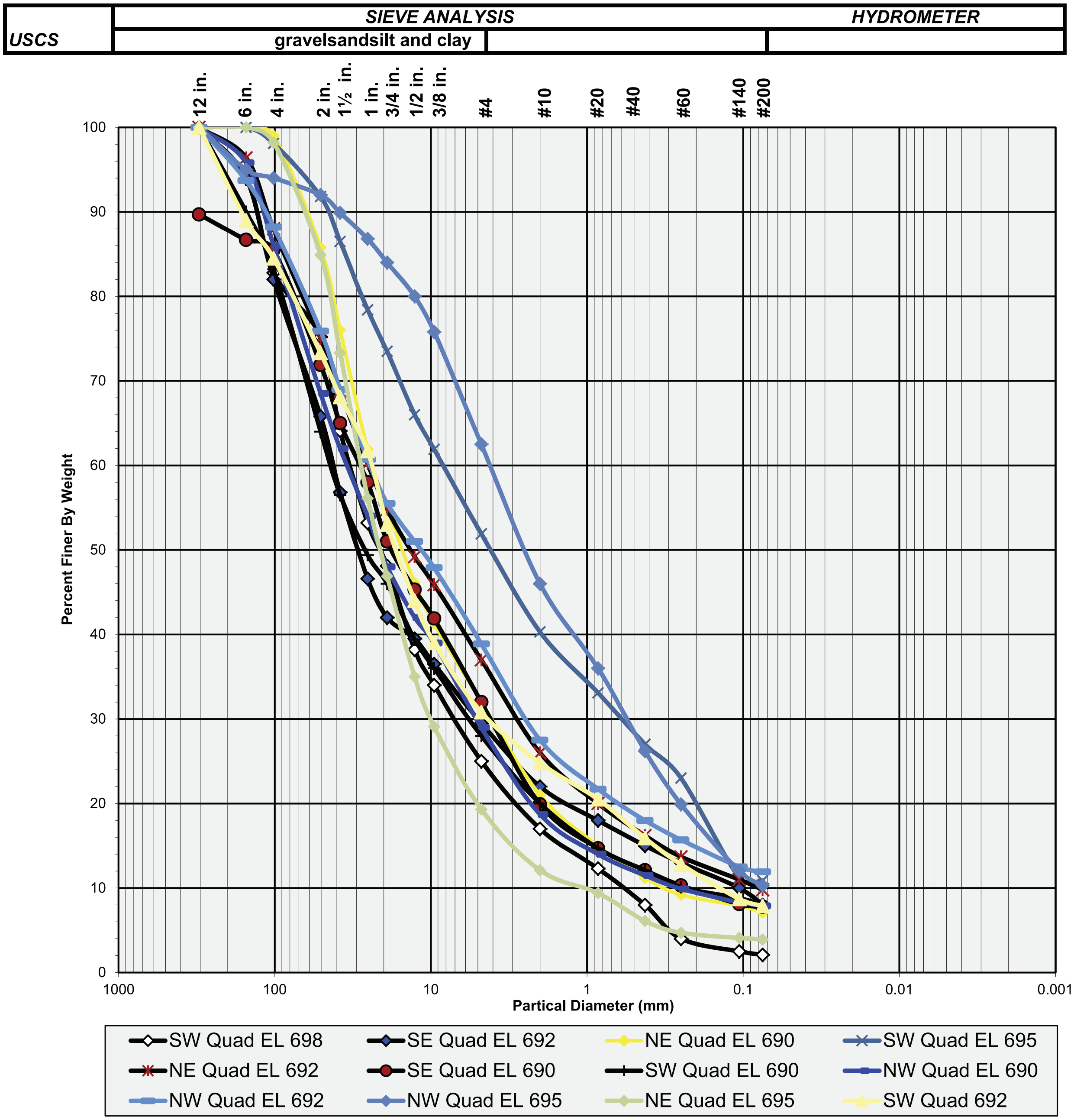

Figure 17. Twelve large bulk grain-size distributions for glacial gravels (DiGioia, Gray & Associates, 2007).

Pittsburgh profited by more than just the oil from the wells, because it was the largest industrialized city near the new oil fields. By the 1870s, there were more than 50 oil refineries operating in the area, with a total production of more than 35,000 barrels of oil per day (Gardner, 1980).

The nation's first commercial gas well, the Haymaker well in Murrysville, PA, about 20 mi (32 km) east of Pittsburgh, was drilled in 1878. Gas from that well was piped into Pittsburgh in 1883, which was at the technical limit of such pipelines for that time.

Figure 22 is a map showing the oil and gas fields of Pennsylvania (McCoy and Schmitt, 2007). Limited amounts of gas and oil from "shallow" Mississippian and Devonian sandstones are still produced in the area from some of the early wells. Several of the depleted gas and oil fields in the area are now utilized as gas storage fields by some of the regional gas companies.

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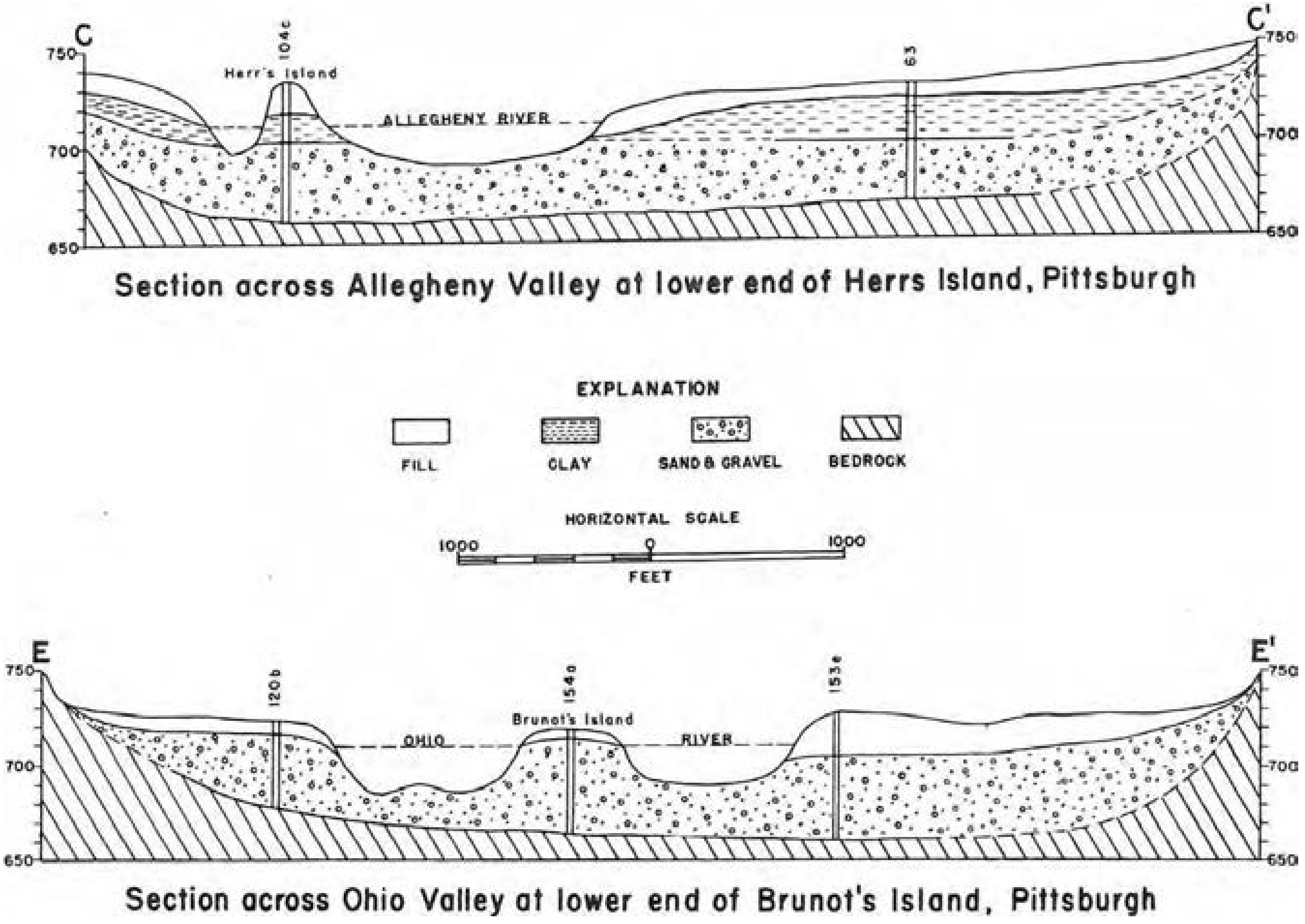

Section across Allegheny Valley at lower end of Herrs Island, Pittsburgh

Section across Ohio Valley at lower end of Brunot's Island, Pittsburgh

Figure 18. Sections across Allegheny and Ohio River valleys (Adamson et al., 1949).

In recent years, the industry has seen a rebirth with the development of natural gas with the Middle Devonian Marcellus Shale, which is at a depth of around 6,000 ft (1.8 km) in the Pittsburgh area. Much news attention is given to the Marcellus Shale, because it is thought to contain about 50 trillion cubic feet (1.4 trillion cubic meters) of natural gas and is recovered using fracking techniques, which are being widely debated in regard to possible environmental impacts associated with development. Another identified natural gas source in the area is the Upper Ordovician Utica Shale, which underlies the Marcellus Shale and has a correspondingly larger lateral extent. The Utica Shale in the Pittsburgh area lies at a depth of about 10,000–12,000 ft (3–3.6 km). It is estimated to contain about 38 trillion cubic feet (1.07 trillion cubic meters) of yet-undiscovered, technically recoverable natural gas (at the mean estimate), according to the first assessment of this continuous (unconventional) natural gas accumulation by the U.S. Geological Survey (Schenk et al., 2012). The Utica Shale has a corresponding mean estimate of 940 million barrels of unconventional oil resources and a mean estimate of 208 million barrels of unconventional natural gas liquids. The Marcellus and Utica Shales are the current big plays in western Pennsylvania, but other shale formations are also being developed. Some of these other Upper Devonian formations include the Burket-Geneseo, Middlesex, Pipe Creek, and Rhinestreet Shales. This group of Upper Devonian shales could have substantial potential for western Pennsylvania.

Coal

Pennsylvania is located at the northern end of the Appalachian Coal Basin. Coal beds underlie about 15,000 mi^2 (38,850 km^2) of the state (see Figure 23). All significant coal beds in Pennsylvania are Pennsylvanian or Permian in age. Prior to any mining, Pennsylvania contained over 75 billion tons of bituminous coal and almost 23 billion tons of anthracite and semianthracite coal (Edmunds, 2002).

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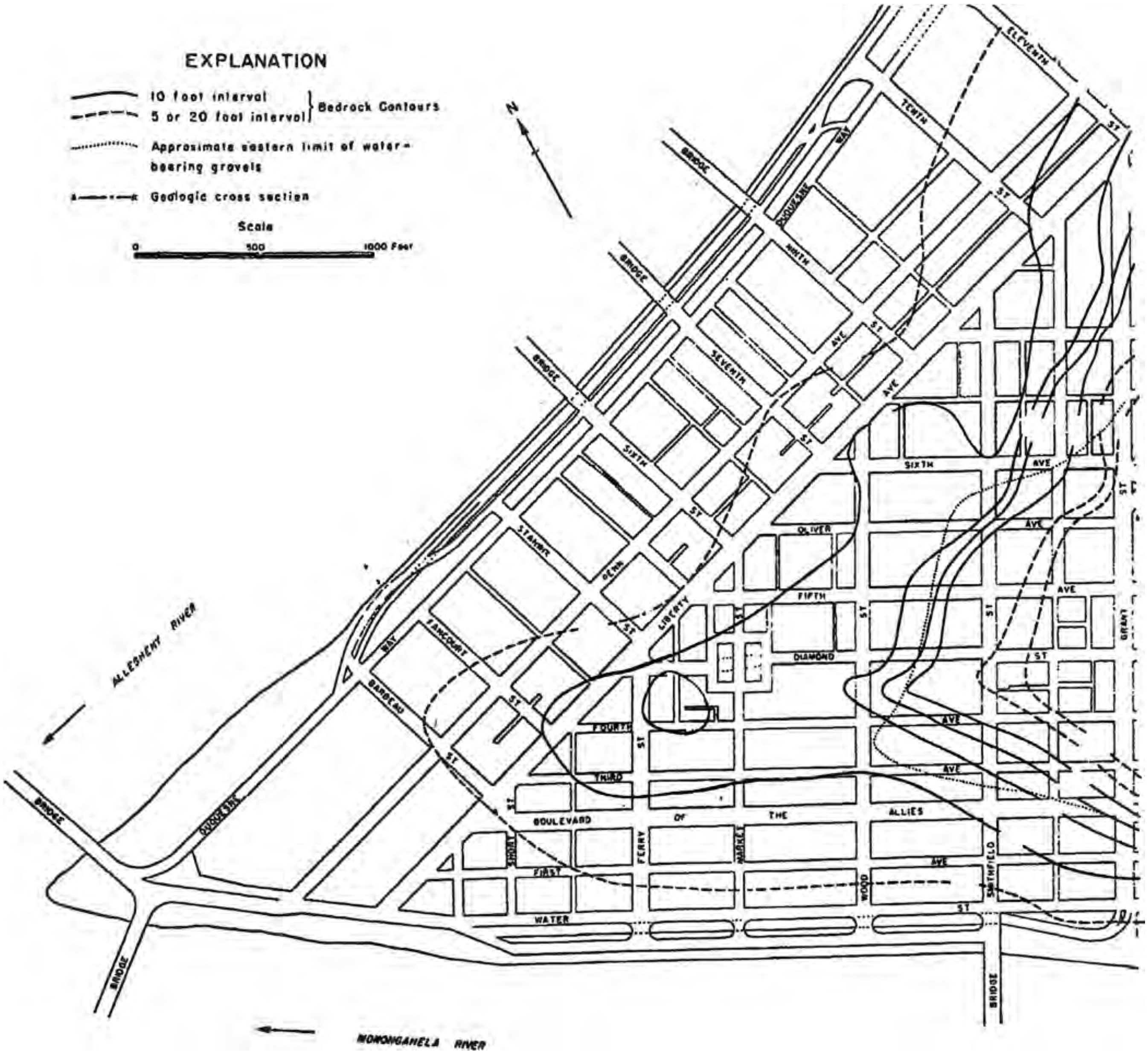

Figure 19. Contours of the rock surface below downtown Pittsburgh and the eastern limit of water-bearing glacial gravel (Van Tuyl, 1951).

Early Coal Mining

Coal was first mined commercially in the United States in 1745 near Richmond, VA. In 1760, British soldiers started mining the Pittsburgh Coal seam on Coal Hill (now Mount Washington) across the Monongahela River from Fort Pitt (Figure 3). By 1800, only Pittsburgh and Richmond, VA, were using coal to any extent for domestic purposes. In early 1807, a Mr. Cuming, traveling from Philadelphia to Pittsburgh, upon reaching Greensburg, PA, wrote:

> "On entering Habach's tavern, I was no little surprised to see a fine coal fire, and I was informed that coal is the principal fuel of the country, fifty or sixty miles 'round Pittsburgh'. It is laid down at the doors here for six cents a bushel." (Eavenson, 1939, p. 39)

In Pittsburgh, 10 collieries (e.g., a coal mine with connected coal-processing structures) were working in Coal Hill in 1837 (Eavenson, 1939). By 1865, coke produced from coal was increasingly important in iron processing (Gregory, 1980). There are few reports on

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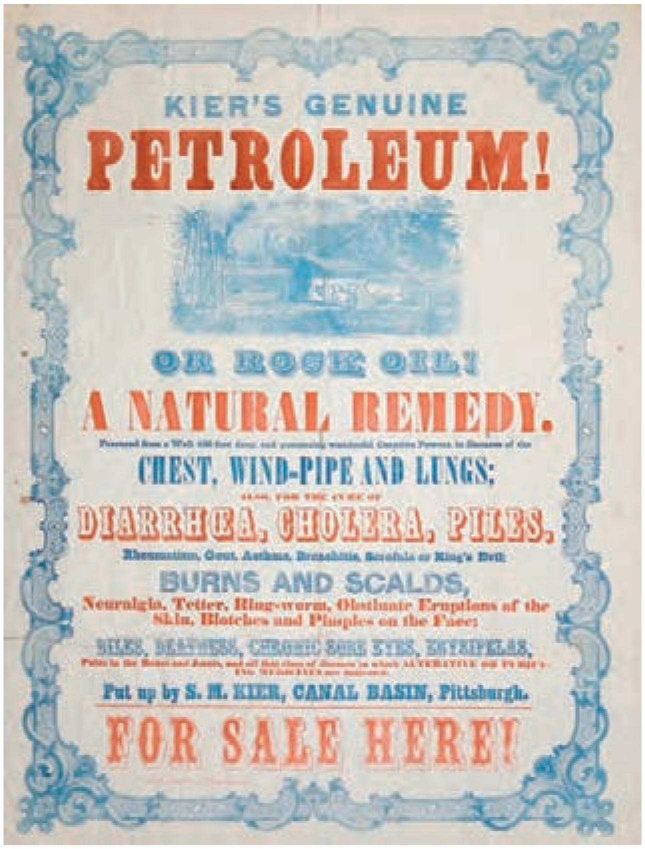

Figure 20. Kier's rock oil advertising poster (Flaherty and Flaherty, 2014).

coal and coke production before 1870 and no accurate records until 1885 (Eavenson, 1942).

Mining Methods

Room-and-pillar mining originated as a method of extracting as much coal as possible while still providing roof control by means of coal pillars. During the 18th and 19th centuries, mines were small, hand-excavated operations under shallow cover using hillside adits to enter the coal seam. Coal was cheap, and the spacing, size, and regularity of pillars were somewhat arbitrary (Figure 24). Coal pillars were left in place as a matter of convenience and safety to the miners. Increased production by the mid- to late 19th century brought mechanization and ventilation requirements to mines that necessitated a systematic arrangement of pillars, but it still resulted in considerable coal being left underground. Mining often extended to where the overburden was only 25 ft (7.6 m) thick. Early extraction ratios, i.e., the proportion of coal removed, averaged 30 to 40 percent. Since coal deposits were widespread and accessible, little effort was made to improve extraction ratios.

Figure 21. Replica of Drake Well, Titusville, PA (Flaherty and Flaherty, 2014).

In the latter part of the 19th century, total-extraction mining was initiated to achieve greater production of the coal, which was becoming increasingly valued for its coking properties by the steel industry and as the preferred feedstock for manufactured gas plants. Total-extraction mining was first implemented in existing partial-extraction mines of the day. The distinction from partial-extraction mines was that the long, narrow pillars left between rooms during the initial mining were now being extracted in a second stage of mining. Subsidence of the ground surface in a properly executed operation took place contemporaneously with pillar extraction (Gray and Bruhn, 1984).

Wide rooms and narrow pillars (10–15 ft [3–4.5 m] wide) continued in total-extraction mines because it was believed that more lump coal could be produced by room mining than by extracting the pillars left between rooms. However, by the 1920s, block systems of mining came into favor (see Figure 25), wherein square or rectangular pillars 50–100 ft (15–30 m) on a side were separated by narrow rooms and entries, reducing roof deterioration, roof falls, and support problems during pillar extraction (Paul and Plein, 1935). From 1948 to 1952, most remaining mines of the old pattern were converted to the block system as continuous mining machines were introduced on a large scale. Subsequently, as break lines controlling failure of the mine roof parallel to the pillar faces replaced angled break lines, the transition to the relatively efficient pillar extraction methods of today was essentially complete (Gray and Bruhn, 1984).

Longwall mining is another total-extraction technique. Entries for access and ventilation are very similar to those for room-and-pillar mining. The extraction face of a mine panel is equipped with a row of hydraulic roof supports, a coal conveyor, and a machine to break the coal from the panel face. The system (see Figure 26) is designed to support only the area at the

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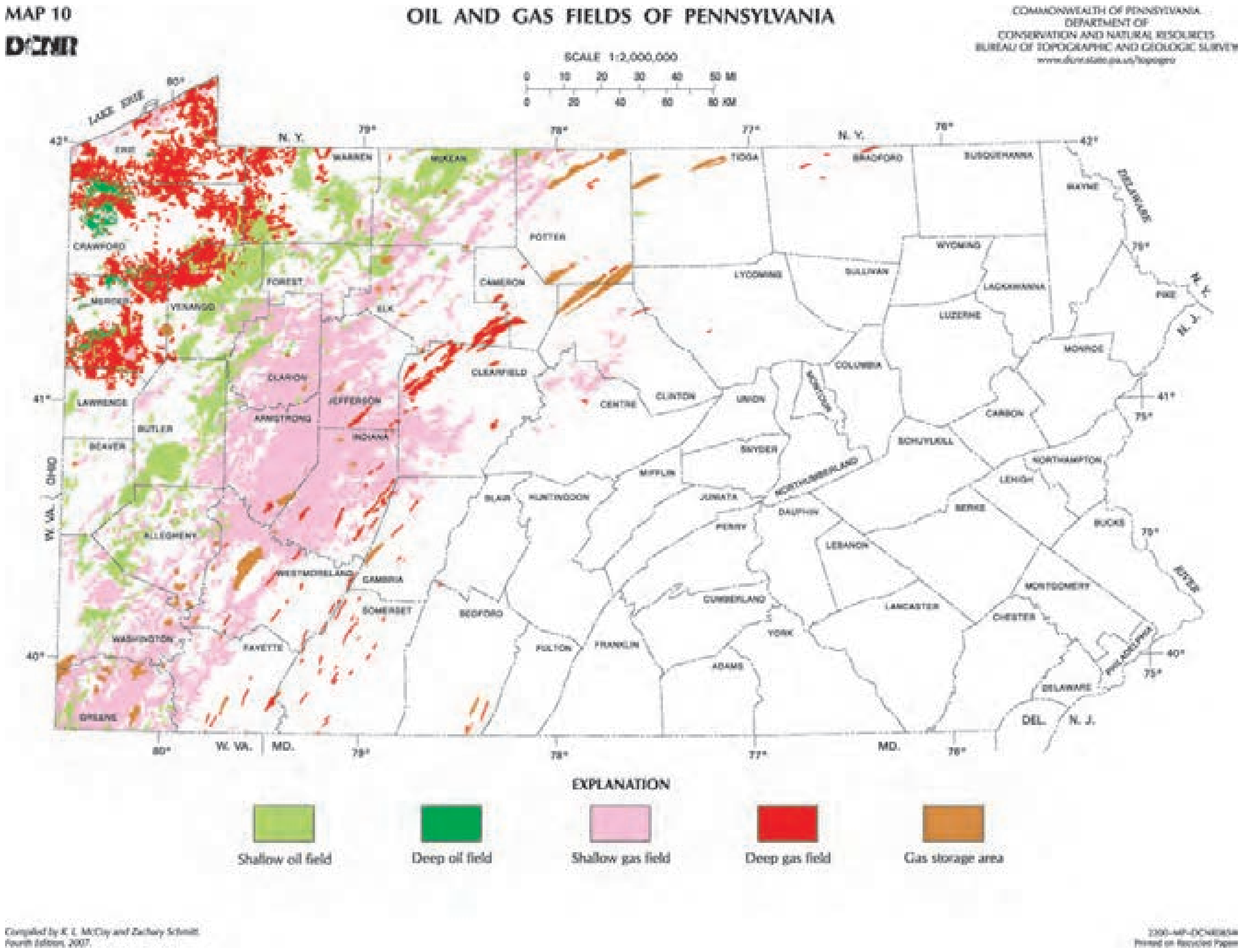

Figure 22. Oil and gas fields near Pittsburgh (Flaherty and Flaherty, 2014).

coal panel face and allow caving of the mine roof behind the support system, with the roof support system and conveyor automatically advanced as mining proceeds. Coal pillars supporting the entries are generally not recoverable (Gray and Bruhn, 1984). In longwall mining, the width of mined panels can exceed 1,200 ft (366 m), and the length of the panels can be 1 mi (1.6 km) or more. The advantage is that it is a one-stage operation. It was tried in the United States prior to 1900, but it was not found to be economical here until 1960, after development of self-advancing roof supports (Poad, 1977).

Virtually all of the economically minable bituminous coal resources of Pennsylvania are confined to 10 important coal beds in the Allegheny, Monongahela, and Dunkard Groups.

The Pittsburgh Coal is the most important seam in Pennsylvania. In 2010, 16 longwalls (41 percent of the U.S. total) under operation in the Pittsburgh Coal, including seven in Pennsylvania and 12 in West Virginia (Fiscor, 2011). In spite of extensive mining, it still represents one third of the recoverable reserves over 36 in. (1 m) thick and almost all of the reserves over 60 in. (1.5 m) thick. Most of the remaining Pittsburgh Coal is in Washington and Greene Counties south of Pittsburgh. It is a single, very persistent bed, generally between 4 and 10 ft (1.2 and 3 m) thick, and it is absent only in relatively limited areas (McCulloch et al., 1975; Socolow et al., 1980). The Pittsburgh Coal is of excellent quality overall and has been widely used for metallurgical-grade coke. Except in northwestern Washington County and eastern Greene County, its sulfur content is less than 2 percent (Socolow et al., 1980). Almost all production of the Pittsburgh Coal, past and present, is from underground mines.

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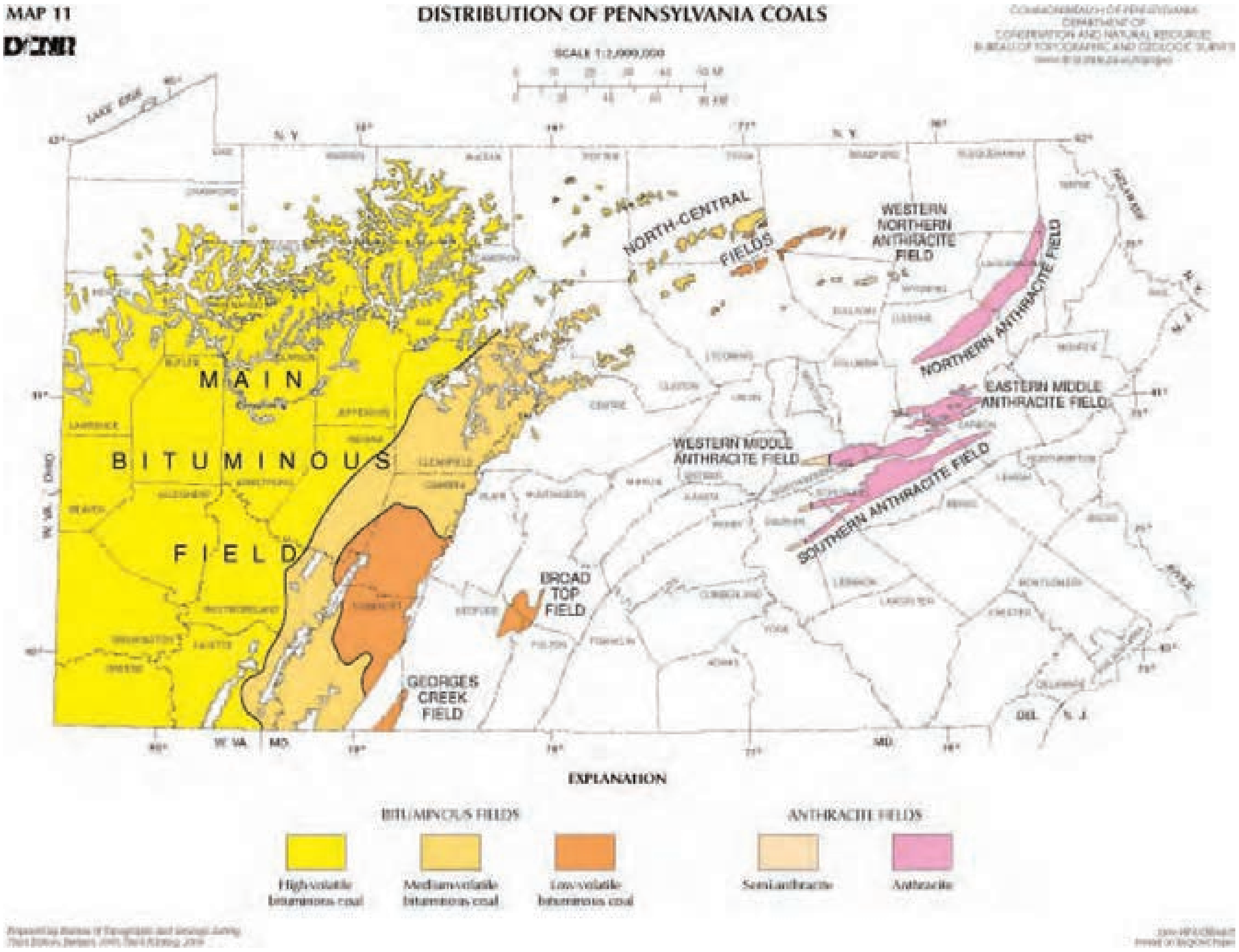

Figure 23. Distribution of Pennsylvania coals (Pennsylvania Department of Conservation and Natural Resources, 2000).

In the Pittsburgh area, the Upper Freeport Coal is the second most important bed in terms of mining and reserves (see Figure 10).

Pennsylvania bituminous coal (41,303 short tons in 20015) is mined for three markets: electric power generation, industrial use, and foreign export. The domestic distribution varies, but in 2015, electric utilities consumed 93 percent, and industrial use, including coke, consumed 6 percent. Foreign exports were approximately 7,298 short tons (U.S. Energy Information Administration, 2015).

Aggregates

Major sources of construction aggregates in the Pittsburgh area are sand and gravel, crushed stone, and repurposed steel mill slag (O'Neil, 1974). Sand and gravel are primarily glacially derived material, while the crushed stone is manufactured from local limestones and sandstones, and slag is a man-made byproduct resulting from iron and steel production.

As noted earlier, multiple periods of continental glaciation occurred to the north of Pennsylvania and into northwestern Pennsylvania. Much of the material deposited by the glaciers is located in the northern portion of the state, along the borders of the ice advance or behind them as surficial features (moraines, eskers, kames, etc.). However, with the melting of the glaciers, larger amounts of sand and gravel were transported to the south by the meltwater and were deposited in the valleys of the Allegheny, Ohio, and Beaver Rivers and their tributaries. The repetitive advance and retreat of the ice sheets resulted in multiple periods of sand and gravel deposition in the river valleys. During periods of significant deposition, the river valleys would fill with outwash deposits and aggrade. During the periods

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Figure 24. Old room-and-pillar mine (Gray and Meyers, 1970).

between the deposition events, the rivers would down cut, leaving behind outwash terraces along the banks of the rivers and in the surrounding upland areas. By the end of continental glaciation, the outwash deposits had been reworked numerous times by the glacial meltwaters, which had cleaned and sorted the sands and gravels and also tended to break down the softer materials, leaving hard, sound fragments. The end result is that significant deposits of sand and gravel can be found within the riverbeds, their floodplains, and the higher river terraces.

Original bodies of pre-Illinoian-age glacial outwash sand and gravel deposits were estimated to have exceeded 120 ft (37 m) in places and were generally found to be 90 ft (27 m) thick or less. Many of the gravels derived from less resistant rocks tend to be weathered, owing to the older age of the deposits, but the sand generally remains hard, being derived primarily from quartz-rich crystalline source rocks. The younger Wisconsinan-age sands and gravels were estimated to have been at least 150 ft (45 m) thick in places, but they are generally found to be somewhat thinner, with measured sections generally about 70–80 ft (21–24 m) thick or less. The gravel in these deposits is relatively unweathered, so the deposits tend to be excellent sources of high-quality sand and gravel.

Limestone is the primary source for crushed stone aggregate in the Pittsburgh region, followed by sandstone, which in the 1970s accounted for less than 10 percent of the overall crushed stone market (O’Neil, 1974). The most important sources of limestone in the area are the Loyalhanna and Vanport Limestones. The Loyalhanna Limestone is Mississippian in age and is a massive fine-grained siliceous carbonate composed of quartz grains in a limestone matrix. The bed varies from 40 to 70 ft (12 to 21 m) thick and is considered a good-quality coarse aggregate. Nearby occurrences are in the ridges to the east of Pittsburgh; however, the currently operating quarries are 50 mi (80 km) or more from Pittsburgh (Barnes, 2011), somewhat limiting the marketability of the stone because of the associated transportation costs. Uses today include coarse aggregate for concrete, base and sub-base roadway material, roadway surface treatment, riprap, and railroad ballast. An important past use of the Loyalhanna Limestone was in the old Belgium block street-paving industry. These blocks were used in the 1800s and early 1900s on many inclined streets of Pittsburgh and surrounding areas, in higher-volume traffic areas, and in the more wealthy areas as an upgrade to wood and cobblestone. Few of these surface roads remain, but some persist as sub-base to today’s asphalt road surfaces.

The Vanport Limestone, which is located in the Pennsylvanian-age Allegheny Group, is generally a massive, dense, fossiliferous, marine limestone. The thickness of the Vanport unit is quite variable. It is generally on the order of 15–20 ft (4.5–6 m) thick, but it has been found to be absent in some areas. The greatest measured bed thickness ranges from 40 to 45 ft (12 to 14 m). It is not an exceptionally high-grade stone. It is used as flux for iron and steel production, for cement and agricultural limestone, and for flue-gas scrubbing lime, as well as for coarse aggregate. The Vanport Limestone is not used for highway surface treatment because it polishes with traffic wear and develops a high skid characteristic (i.e., it becomes slick). Although there are significant reserves in the counties to the north of Pittsburgh, the operating quarries are 35 mi (56 km) or more (Barnes, 2011) from the city, resulting in transportation costs that limit its marketability.

Slag piles are concentrated in Pittsburgh and surrounding areas generally close to the historic and existing iron and steel mill facilities. In the region, there are two types of slag: (1) slag from open hearth, basic oxygen, and electric furnaces used in steel production, and (2) blast furnace slag from the production of iron. The steel-making operations produce one basic type of slag, but the blast furnace slag can be any of three different, but basically chemically

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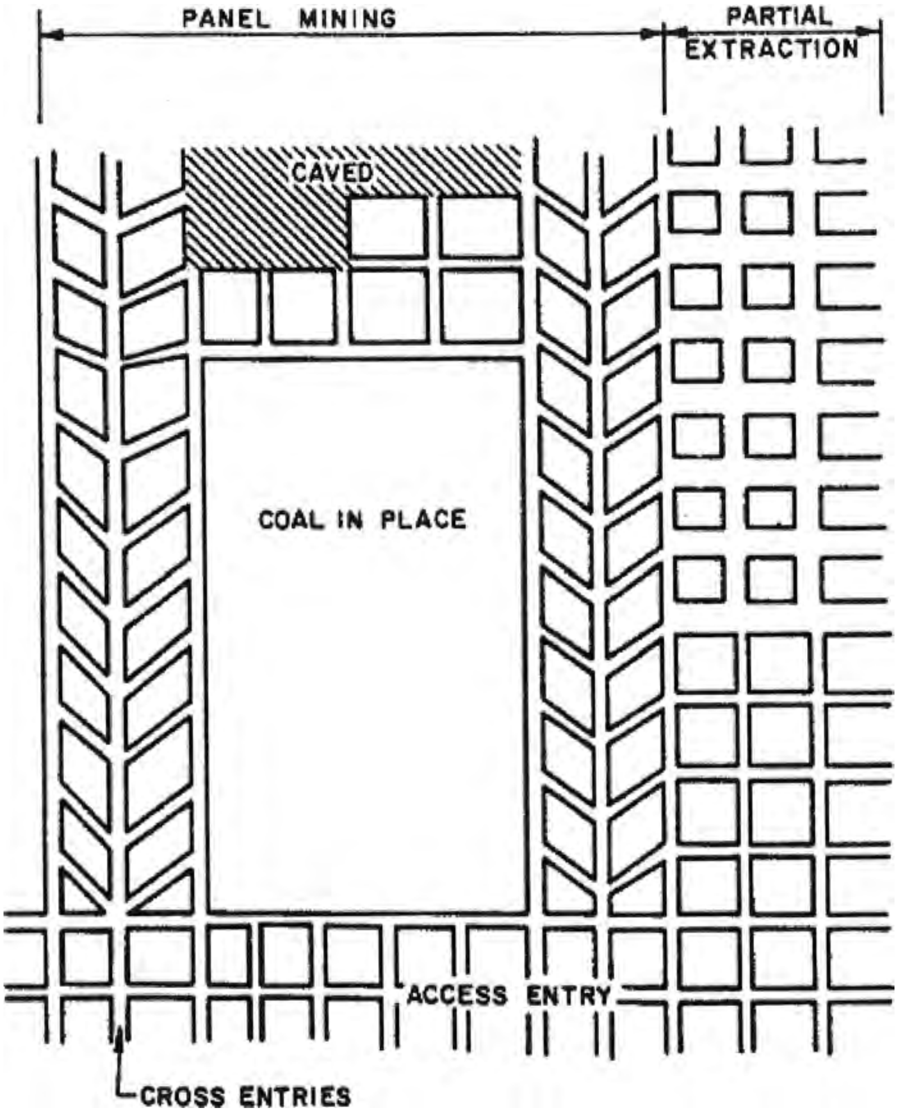

Figure 25. Example of room-and-pillar mining (Gray et al., 1974).

identical materials, depending on how the hot slag was when tipped and cooled: (1) air-cooled slag, which is cooled naturally and is crushed and screened to produce a coarse aggregate that is used in concrete and road base; (2) granulated slag, which is formed when slag is quickly quenched in water, creating a glassy, sand-sized granular product that is used in many applications for which sand is used, and for agricultural liming; and (3) lightweight or expanded slag, which is created by the controlled processing of molten slag with water, forming a lightweight material with a bulk relative density of about 70 percent that of air-cooled slag (FHA, 2012). Open hearth slag is used primarily as railroad ballast and has been used in the past as a base or sub-base material in highway construction. Open hearth slag and other slag from steelmaking furnaces can be expansive when exposed to water and should not be used in confined areas without laboratory confirmation testing. More detailed information is provided in the section on expansive slags.

There are other potential but minor aggregate sources in the area, including other limestones, a number of sandstone units, sintered fly ash, and expanded clays and shales.

Glass

Pittsburgh was once recognized as the center of glassmaking. The first two glass factories west of the Appalachian Mountains were opened in 1797 in the Pittsburgh area (Fleming, 1922). Both made window glass and bottles. The success of these glassmaking facilities encouraged development of additional

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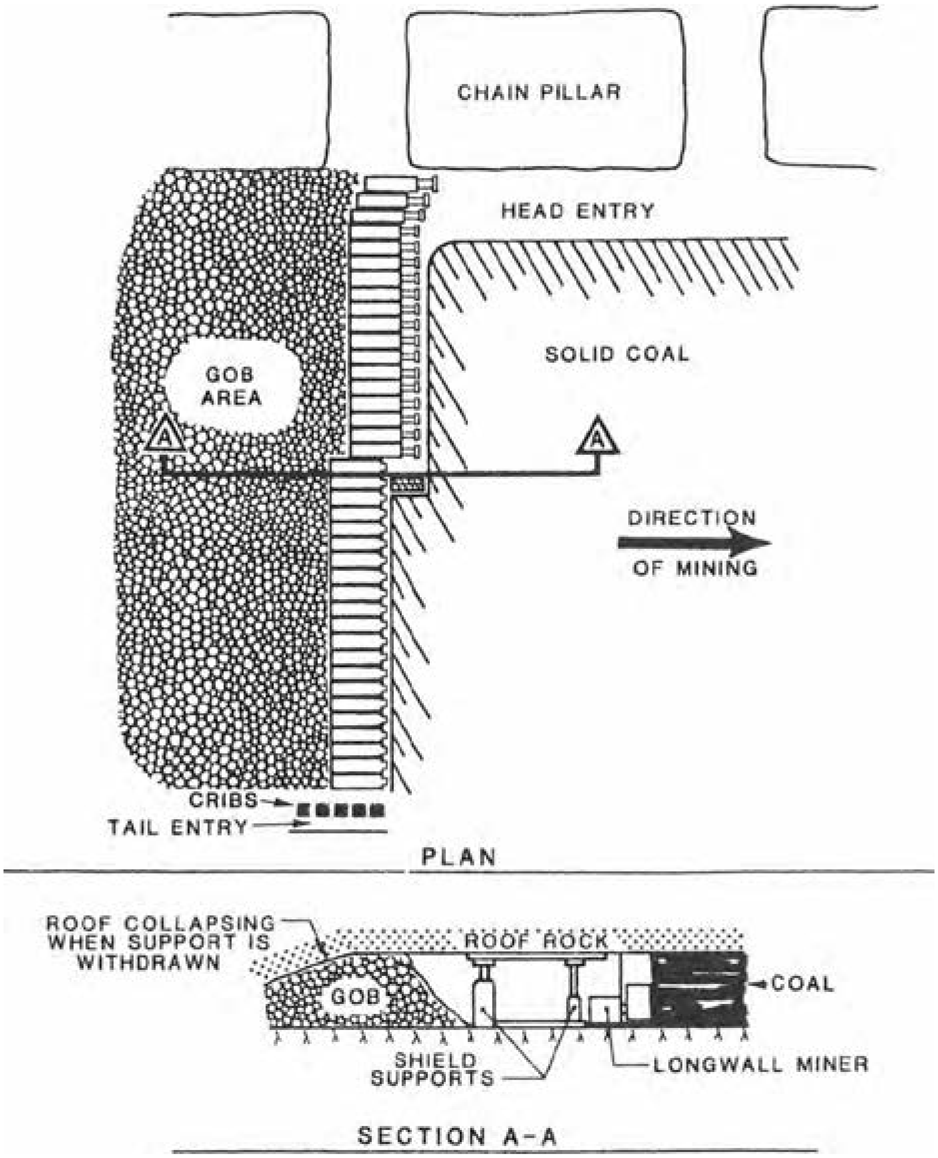

Figure 26. Longwall mine (Turka and Gray, 2005).

glassmaking facilities in and around Pittsburgh. Some specialized in particular glassmaking areas, while others continued with more residential commodities. An embargo in the early 1800s and the War of 1812 prevented foreign glass from entering the United States, thus catapulting domestic glass manufacturing to fill the demand (Flannery, 2009). By the Civil War, the Pittsburgh region reigned as the center of the nation's glass industry.

The reason for the regions' glassmaking success was the abundance of coal for the furnaces, facility space, nearby raw materials, available crafters of the products, and the ability to transport the materials along the rivers (Fleming, 1922). The main raw materials used to make glass are quartz sand or silica, potash (or soda) as a flux, and lime as a stabilizer (Fleming, 1922). The sand initially came from sand bars and longitudinal bars from the nearby major rivers and later from the larger tributaries of the region. Potash was generally obtained from the ashes left after wood burning or other plant material, which was an abundant waste product in the Pittsburgh area at that time. Soda was crushed carbonate material from nearby rock formations in the Pittsburgh area, as well as the lime from nearby limestone quarries.

The successful run of glassmaking in Pittsburgh ended by the 1920s, when most of the glass factories had moved from the region due to high taxation,

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decline of natural resources, and lack of available real estate for expansion (Hawkins, 2009). Very few remnants of these facilities remain today.

Iron Ore

Although Allegheny County, which eventually became the steel capital of the world, does not contain significant iron ore, siderite ores are present in Pennsylvanian-age rocks in adjacent counties.

Most of the siderite ores are nodular or concretionary. Enriched, secondary limonite deposits commonly developed from weathering of the carbonate nodules. Siderite ores generally ranged from 30 to 40 percent iron, whereas the enriched limonitic derivatives averaged about 50 percent. In the early charcoal-iron furnaces, the lower-grade unaltered siderite ores were mixed with limonitic ores from the same mine. The last extensive mining of carbonate ore took place in Fayette and Westmoreland Counties prior to 1900 (Inners, 1999). The great era of carbonate-charcoal iron production in western Pennsylvania lasted from the late 1700s to 1855. As the original hardwood forests were cleared, fuel for the iron furnaces switched in the 1850s to coal. About 1875, coal was replaced by coke (White, 1979) from local coal. Limestone flux was added to the furnaces to bond with molten iron-ore impurities, creating a glassy slag.

The early Pittsburgh region furnaces produced cast iron, which has a high carbon content (3–4.5 percent), making it brittle after casting. This cast iron was either cast directly into goods or into ingots for transport to iron foundries, where the ingots were converted into a more workable form, wrought iron (Hannibal et al., 2011).

Pennsylvania's first iron furnace began production in 1692 (Hannibal et al., 2011). By the time of the American Revolution, there were nearly 60 iron furnaces in Pennsylvania, and by 1841, there were well over 200 (Moldenke, 1920). Pittsburgh's first iron furnace was erected in 1792, but it eventually failed due to the absence of local resources. In the first half of the 19th century, Pittsburgh was not known for its cast iron production, but for the foundries that converted the cast iron into wrought iron (Moldenke, 1920).

Development of the Superior ore province in the Great Lakes region eventually put the iron mining industry of western Pennsylvania out of business. However, the iron and steel industry in Pittsburgh continued to grow because bituminous coal (and its coke) became an important ingredient in the process by the mid-1800s, and Pittsburgh was the hub of coal production. The large, high-quality iron ore deposits of Minnesota were mined and carried on the Great Lakes by freighters, which transferred the ore to trains and then transported the ore to Pittsburgh. These trains also transported coal north from the Pittsburgh area. The Great Lakes freighters then distributed the coal to the states adjoining the Great Lakes. Over time, loading and unloading facilities for the freighters and the trains significantly grew in size and efficiency. The freighters also increased dramatically in size, the largest being 1,013.5 ft (308.91 m) in length with a capacity near 70,000 gross tons (Bawal, 2011). Eventually, Pittsburgh became the largest iron- and steel-producing center in the world (Gardner, 1980).

Water Supply

Water has always been readily available to Pittsburgh and the surrounding communities from the abundance of surface water in the Allegheny, Monongahela, and Ohio Rivers. Annual mean discharge data, based on nearby long-term USGS stream gauging stations, show the Allegheny River (USGS, 2015a, Allegheny River) at 19,750 cubic feet per second (cfs) (559 cubic meters per second [cms]) and the Monongahela River (USGS, 2015b, Monongahela River) at 12,650 cfs (358 cms), resulting in flow at the head of the Ohio River (at Pittsburgh; USGS, 2011) of about 32,400 cfs (917 cms).

The most plentiful groundwater source is from the glacial outwash alluvium that overlies the bedrock of the major stream valleys of the Allegheny, Ohio, and Beaver Rivers (Gallaher, 1973). This alluvial aquifer generally consists of an older, basal portion that overlies bedrock and an upper portion that was recently deposited. Groundwater is derived primarily from the basal portion of the alluvium, and the relative groundwater yield from it depends upon the river system in which it is located. The Allegheny River valley generally has the coarsest basal alluvium, composed primarily of sand and gravel derived from melting glaciers to the north, while the Monongahela River valley contains finer-grained silts, sands, and clays derived from erosion of the local argillaceous rock lying east and south of Pittsburgh. Alluvium in the Ohio River is a mixture of alluvium from the two rivers. The permeability can change significantly over short distances within the alluvium, but for comparative purposes, well yields in the Ohio and Allegheny valleys average about 350 gallons per minute (gpm) (1,325 liters per minute [lpm]), while yields from the Monongahela valley wells average about 125 gpm (473 lpm).

Groundwater is available from the Pennsylvanian-age rocks nearly everywhere in the Pittsburgh area, but the yields from wells tend to be significantly lower than from the alluvial deposits. The well yields from rock wells tend to be highly variable, with many of the yields being less than 5 gpm (19 lpm), but some wells

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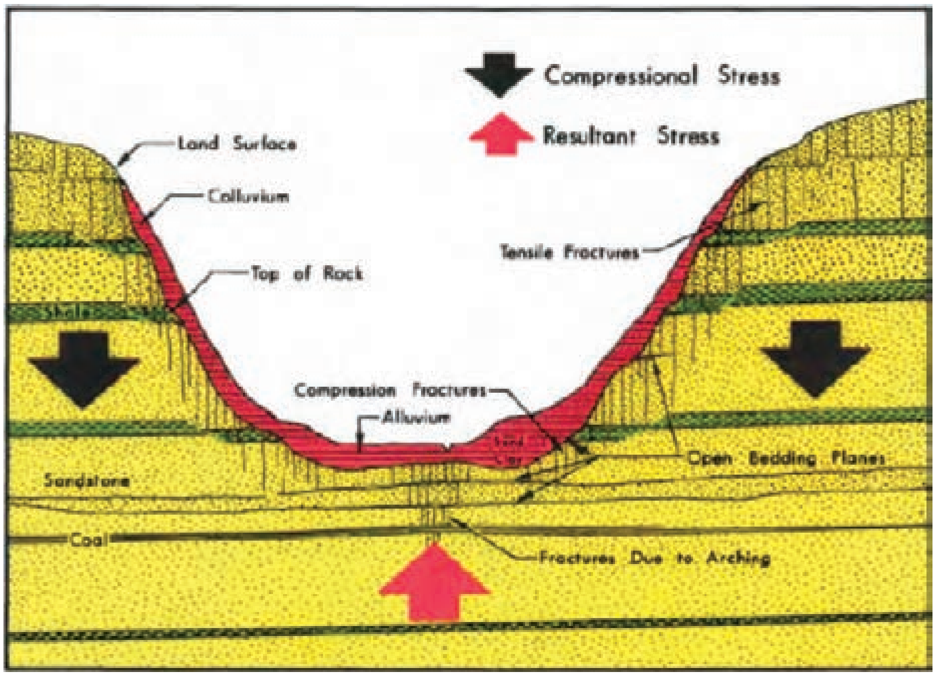

Figure 27. Stress-relief fractures (Wyrick and Borchers, 1981).

reach yields of 75 to 100 gpm (284–379 lpm) (Gallaher, 1973).

The primary aquifers are the harder rocks (sandstones, limestones), which have minimal primary permeability, but which tend to be highly fractured, resulting in significant, natural secondary permeability. Much of the secondary permeability in the sandstones and limestones is created by stress-relief fracturing (Ferguson, 1967) caused by erosion and unloading of the rock units along stream valleys, along with tensional and compressional fracturing along the axes of the structural folds in the area. Valley stress relief, discovered and described by Ferguson (1967) and further described by Ferguson and Hamel (1981), involves physical stress release changes to the physical integrity of the flat-lying sedimentary rock layers as a valley is cut through the layers by erosion. As overburden is removed, stresses contained within the rocks are released. This generally manifests itself as open, tension-related near-vertical features in valley walls and compression features taking the form of low-angle thrust faults in the valley floors. Harry Ferguson and his U.S. Army Corps of Engineers colleagues observed this phenomenon in numerous excavations into Pittsburgh area river bottoms during construction of the series of Ohio River navigation locks and dams. Figure 27 illustrates the process of valley stress relief.

There are 78 public water supply systems in Allegheny County that service 99 percent of the almost 1,225,000 county residents. The systems, including the system for the City of Pittsburgh, are overseen by the Allegheny County Health Department. Pittsburgh neighborhoods north of the Monongahela River are serviced by the Pittsburgh Water and Sewer Authority (PWSA, 2014), which serves 196,000 water and sewer customers within the city.

The first documented public water supply system in Pittsburgh was constructed in 1802 and consisted of four wells serving a population of about 1,600 residents. By 1828, the rapid growth of the city resulted in water shortages that eventually required construction of a river pumping station along the Allegheny River. The station supplied 40,000 gallons (151,416 liters) of water per day. The systems were expanded and updated as the population grew and the city expanded, reaching 9 million gallons per day (mgd) (34 million liters per day [lpd]) by 1884 and 15 mgd (57 lpd) by 1878, to service a population of 106,000 people. Water treatment was initiated in 1902 using primarily filtration. The first complete chemical treatment system of the water was installed in the 1960s, followed by replacement of slow sand filters with a dual-media, rapid sand filter system in 1969 (PWSA, 2014).

Groundwater wells continued to be used in the city but were not the primary source of drinking water. In 1927, beginning with a well for the Stanley Theater, several of the water wells in the city were drilled strictly for air-conditioning purposes (Van Tuyl, 1951). By 1950, the volume of groundwater utilized for air conditioning had increased to about 500 million gal-

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Figure 28. Aerial view of Allegheny Dam 5 and hydropower plant.

lons (1.8 billion liters) per year, or about 25 percent of the total groundwater usage per year. On a daily rate basis, during the average air-conditioning season (100–120 days), the air-conditioning use in 1950 was about 50 percent of the total groundwater use per day. Utilizing the alluvial aquifer under the city for air-conditioning purposes has continued into the 21st century, as evidenced by the 2007 installation of a subsurface geothermal heat pump system into the alluvium underlying Point State Park (at the confluence of the three rivers) to heat, as well as cool, the blockhouse museum of Fort Pitt.

Hydropower

Hydropower has been a part of the Pittsburgh region for many years. Four of the U.S. Army Corps of Engineers Pittsburgh District reservoirs currently generate hydropower: Kinzua Dam and Reservoir, Youghiogheny Dam and Reservoir, and Conemaugh Dam and Reservoir, and a fourth, Mahoning Dam, recently started generating hydropower (Kurka et al., 2014). Kinzua Dam and Reservoir is located on the Allegheny River near Warren, PA. At this location, the electric utility First Energy (contemporary survivor of Associated Gas & Electric Co. [AGECO], 1906–1946) draws water both from the U.S. Corps of Engineers' Allegheny Reservoir and also from a pumped storage reservoir located high above the left abutment of the dam. The project is a peaking plant, which means that it pumps water up to the storage reservoir at night when electric rates are low, and then it sends the water down an inclined power tunnel to the power plant during the day when power demand is high. As mentioned, two other U.S. Corps of Engineers' reservoirs also have hydropower generation: Youghiogheny Dam located south of Pittsburgh, and Conemaugh Dam located northeast of Pittsburgh. Mahoning Dam is a concrete gravity structure, also located northeast of Pittsburgh, that was built originally with a penstock, allowing the project to be fitted for future power generation. The penstock has been retrofitted with a turbine and downstream power plant to generate hydropower. Construction of the power plant at Mahoning Dam has been completed.

There are five low-head hydroelectric plants currently in place at existing locks and dams (L/D) near Pittsburgh. Four are located on the Allegheny River above Pittsburgh at L/D 5 (at Freeport, PA); L/D 6 (at Clinton, PA); L/D 8 (at Templeton, PA); and L/D 9 (at Rimer, PA). The fifth is at Hannibal Locks and Dam, located on the Ohio River close to Wheeling, WV. The four low-head hydroelectric plants located on the Allegheny River were built in the late 1980s. Figure 28 provides an aerial view of the plant at Allegheny Dam 5 (Freeport, PA). At each of these five sites, the generating plant is located on the side of the river opposite the navigation lock. Federal tax credits have stimulated private electric power developers to file power-generation permits for many of the remaining navigation structures and flood-control reservoirs. The Federal Energy Regulatory Commission licensing process, however, is rigorous and lengthy, and, therefore, at this time, further hydropower development in the region will occur only gradually, consistent with the response of the government.

GEOLOGIC CONSTRAINTS

Seismicity and Earthquake Hazard

Southwestern Pennsylvania, including Pittsburgh, is a relatively inactive seismic area. Earthquake activity in surrounding areas is somewhat more intense. These areas include the Piedmont Province in eastern Pennsylvania, northwestern Ohio, and New York State immediately east of Buffalo at Attica, NY, and in the St. Lawrence River Valley.

Pennsylvania earthquakes are generally small. The largest earthquake-of-record in Pennsylvania, a magnitude 5.2 (mbLg), occurred on September 25, 1998, in northwestern Pennsylvania near the Ohio border (Fleeger et al., 1999). Only twice per decade, on average, is an earthquake epicentered within Pennsylvania that is large enough (Richter magnitude 3 or greater) to be felt in an area of several hundred square kilometers (Gordon and Dewey, 1999). The Pennsylvania Geologic Survey's Map 69, *Earthquake Catalog and Epicenter Map of Pennsylvania* (Faill, 2004), is the basic reference document showing the locations of, and listing, all recorded seismic events since 1724 in

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Figure 29. Small-offset normal fault near Pittsburgh (photo courtesy John Harper, Pennsylvania Geological Survey).

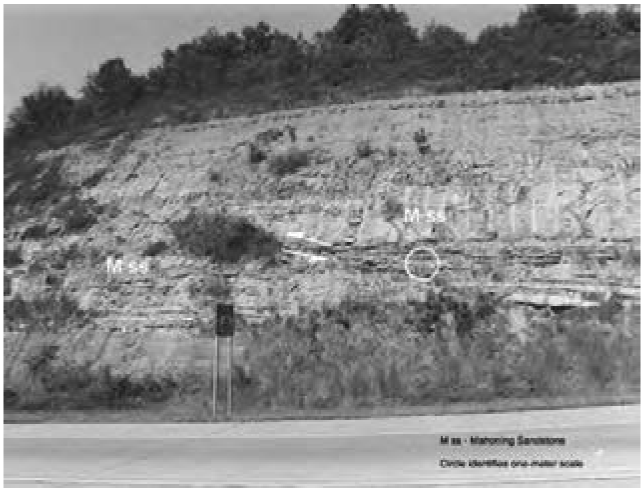

Figure 30. Typical low-angle thrust fault near Pittsburgh (photo courtesy John Harper, Pennsylvania Geological Survey).

Pennsylvania and surrounding areas. Some of the events that have been cataloged as "earthquakes" in the greater Ridge and Valley or Appalachian Plateau Provinces were not tectonic earthquakes but mine explosions or related to mine subsidence (Gordon and Dewey, 1999).

About 35 earthquakes have caused slight damage in Pennsylvania since the beginning of the American Colonial period. Occasional broken windows, cracked plaster, and glassware toppled from shelves are characteristic of this type of damage. Nearly one half of these damaging events had out-of-state epicenters. Foremost among this class of distant earthquakes that were felt strongly in Pennsylvania were a trio of major earthquakes near New Madrid, MO, in 1811–1812, and the Charleston, SC, earthquake in 1886. Most earthquakes with epicenters inside the state have been located in southeastern Pennsylvania (Gordon and Dewey, 1999). Scharnberger (2003) provided general information on the nature, occurrence, history, and earthquake hazards in Pennsylvania.

Faults

Bedrock faults in the Pittsburgh region exhibit relatively small displacements. These include normal faults and thrust faults. The faults that have been identified to date are not capable of generating significant earthquakes. An example of a small listric normal fault resulting from rotational slump near Pittsburgh is depicted in Figure 29, and a typical low-angle thrust fault is shown in Figure 30. A key process in the development of small faults of importance to the region is valley stress relief, as previously described in the section on water supply.

One of the most structurally complex areas, typical of the relative importance of faults to the design and construction of engineered works, is located about 16 mi (26 km) north of the city, and it is a faulted-rock zone observable along the CSX Railroad tracks at the Bakerstown Station rock cut. Figure 31 is a representation of the west wall of the cut, depicting high-angle faulting within the Casselman Formation shales and claystones. Faulting is present within these fine-grained rocks of lower mass shear strength, but it does not penetrate the overlying Morgantown sandstone. This has been interpreted to indicate that the faulting ceased before deposition of the overlying stratum, the Morgantown sandstone (Wagner et al., 1970).

Several normal faults cut the Ames Limestone near Creighton, PA, located about 15 mi (24 km) northeast of the city, creating a block of rock that has dropped down between the faults, forming a classic graben structure. Reverse faults are far less common in Allegheny County than are normal faults (J. A. Harper, personal communication, 2012). One of the better examples can be seen in a road cut along PA Route 28 at Tarentum, PA. At this location, a portion of the lighter-colored Mahoning sandstone can be seen thrust upwards over and into darker-colored shales.

A suspected strike-slip fault, representing the least common of fault orientations around Pittsburgh, is inferred from displacement of the crystalline basement rocks at some 16,000 ft (4.9 km) beneath Pittsburgh detected by magnetic geophysical surveys (Harper, 2012).

In 2010, construction at a sewage treatment plant in Sewickley Township, 18 mi (29 km) southeast of downtown Pittsburgh, revealed an ancient, but locally significant fault. At this location, the Pennsylvanian-

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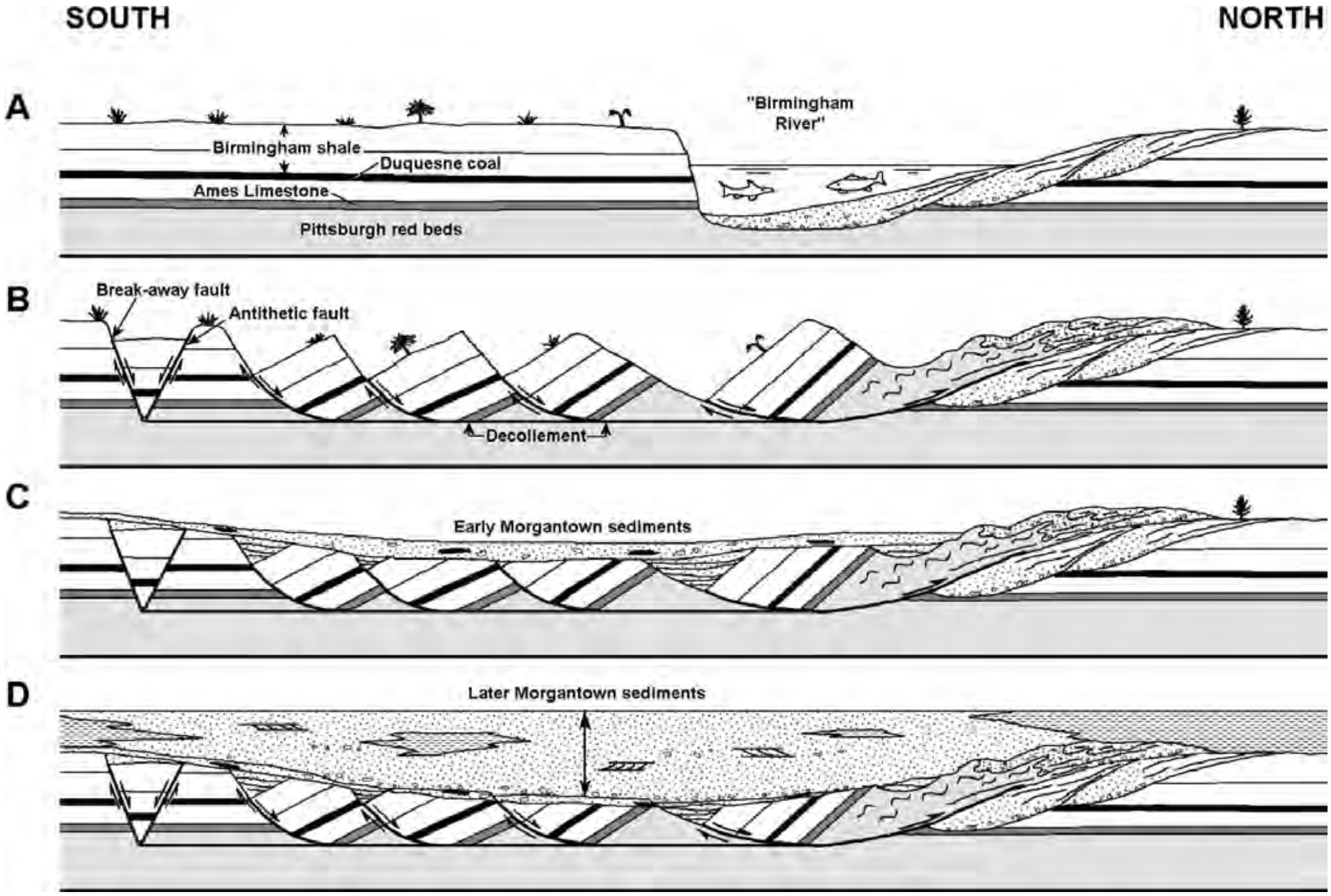

Figure 31. High-angle faulting within the Casselman Formation shales and claystones north of Pittsburgh (Shultz and Harper, 1996).

aged sedimentary strata exhibit gentle northeast-southwest–trending folds, the dip of the beds is very slight (1–2 degrees), and tectonic faults are rare (Hamel, 2011). Available mine maps for the area indicate the plant is underlain by abandoned room-and-pillar workings within the Pittsburgh Coal. The floor of the mined seam is at a depth of approximately 90 ft (27 m). Excavation for a raw sewage pump station exposed a major tectonic fault zone at least 500 ft (152 m) wide and 20 ft (6 m) thick with a brecciated zone containing sandstone blocks up to 15 ft (4.6 m) in diameter in a matrix of finer breccia and fault gouge (Hamel, 2011). The fault was mapped as having both thrust and transverse components and appears to have been related to the brittle response of the gentle folding of interbedded stronger and weaker sedimentary rocks during the Alleghanian Orogeny. Hamel (2011) indicated that faulting of this type should be routinely expected and considered for site investigations related to foundation and other load-sensitive future engineering projects in the Pittsburgh region.

Landslides

The Allegheny Plateau has long been recognized as an area of major landslide severity, with its steep hillsides, thick soil cover, and precipitation of 35–45 in. (89–114 cm) per year (Figure 32). It is a naturally dissected upland surface developed on gently folded but essentially flat-lying sedimentary rocks.

Slope Formation

Current slope development in the unglaciated portion of the Appalachian Plateau is consistent with flat-lying sedimentary rocks in a temperate, humid climate. The occurrence of alternating weak and resistant rock strata is reflected topographically by breaks in slope and somewhat subdued to well-developed erosional benches (Gray and Gardner, 1977; Gray et al., 1979).

Existing and past climatic conditions, including periglacial effects, have resulted in substantial mechanical and chemical weathering, which produced a

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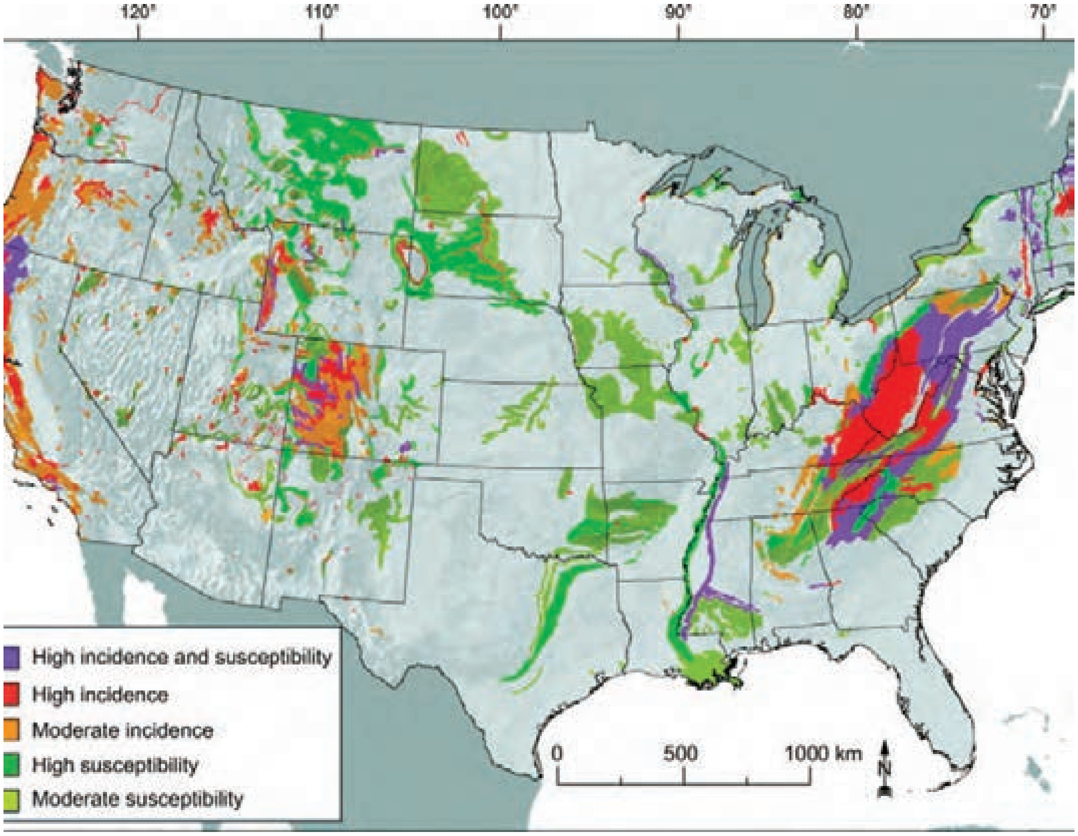

Figure 32. Landslide incidence map of the United States (Radbruch-Hall et al., 1978).

residual or colluvial soil mantle over almost the entire rock surface. The most significant periglacial effects were the greater rates of weathering, increased soil formation, and subsequent mass wasting (Denny, 1956; Philbrick, 1961; and Rapp, 1967).

Downslope movement of the soil results in its accumulation at the toes of slopes in colluvial masses. These colluvial soils tend to be 5–30 ft (1.5–9 m) thick on slopes and generally increase in thickness (to a maximum of about 100 ft [30 m]) near the toes of slopes, unless there is active stream erosion (see Figure 33). Colluvial soils are generally stiff to hard, and individual samples have relatively high shear strengths. However, creep or sliding processes (or both) during slope development generally reduce the shear strength along movement surfaces to residual or near-residual levels (Gray et al., 1979). These low-shear-strength surfaces can occur at several levels within the colluvial mass, but there is always a low-shear-strength surface at the soil-rock interface (Deere and Patton, 1971). As the slope materials seek equilibrium between stress and strength, the soil mantle moves downslope, and the mean slope angle decreases until a state of marginal equilibrium is achieved. This natural slope-flattening process accounts for the relatively thick soil cover on mature colluvial slopes, particularly at the base of slopes. Deere and Patton (1971) suggested that there are no stable natural slopes in the Appalachian Plateau, where the slope inclination exceeds 12–14 degrees. Terzaghi and Peck (1948) reported movements on slopes as flat as 10 degrees, whereas Gray and Donovan (1971) demonstrated that several mature colluvial slopes, with evidence of pre-existing failure surfaces, had slope angles ranging from 7 to 10 degrees. Gray and Gardner (1977) presented observations on the development of colluvial slopes.

Numerous field observations suggest that colluvial slopes, which may creep at rates of a few centimeters per year, visually appear stable unless disturbed by cutting, filling, drainage changes, or extreme precipitation events (Gray et al., 2011).

Landsliding

As stated above, the Allegheny Plateau is recognized as having some of the most severe landsliding in the United States (Ladd, 1927–1928; Sharpe and

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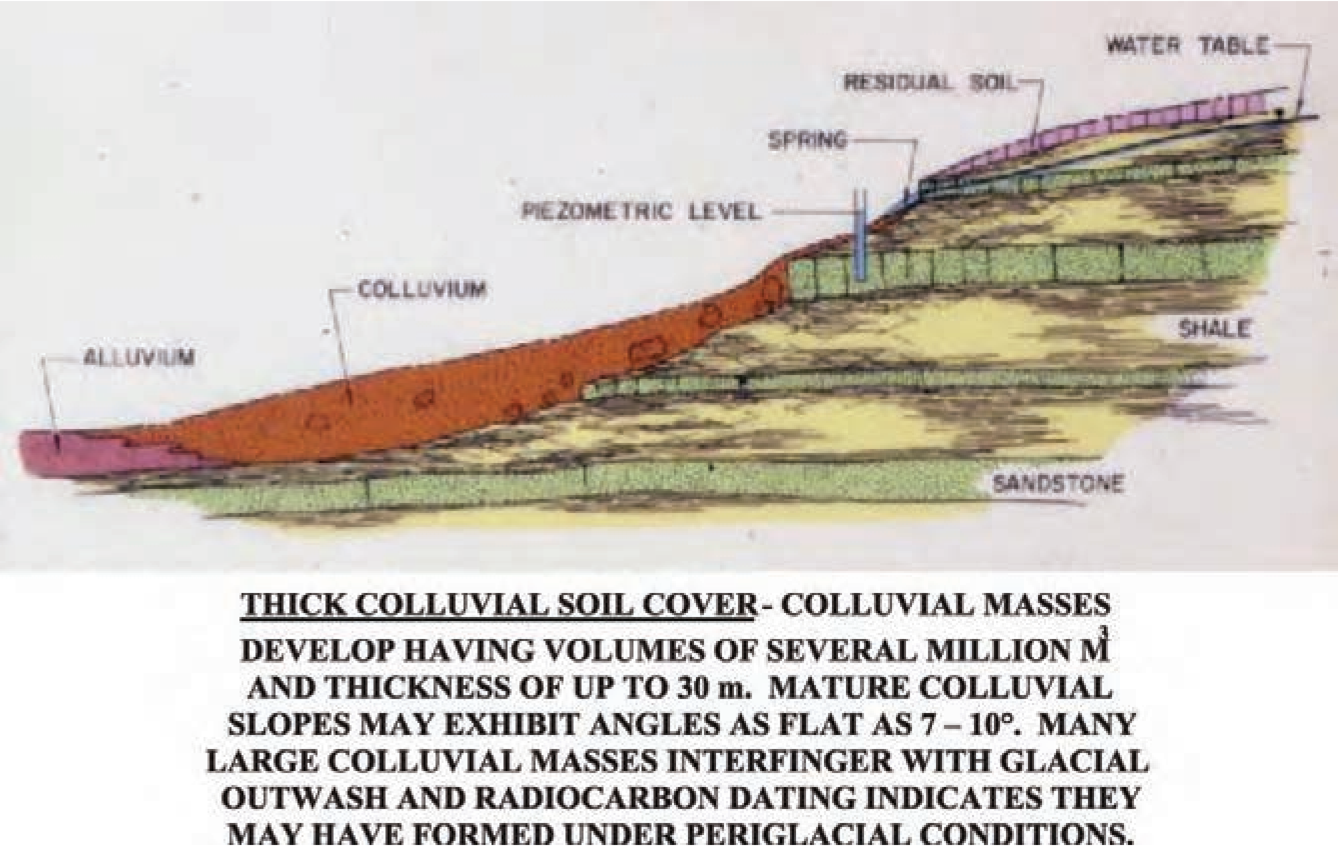

<u>THICK COLLUVIAL SOIL COVER</u> - COLLUVIAL MASSES DEVELOP HAVING VOLUMES OF SEVERAL MILLION M^3 AND THICKNESS OF UP TO 30 m. MATURE COLLUVIAL SLOPES MAY EXHIBIT ANGLES AS FLAT AS 7 – 10°. MANY LARGE COLLUVIAL MASSES INTERFINGER WITH GLACIAL OUTWASH AND RADIOCARBON DATING INDICATES THEY MAY HAVE FORMED UNDER PERIGLACIAL CONDITIONS.

Figure 33. Thick colluvial soil cover.

Dosch, 1942; Ackenheil, 1954; Eckel, 1958; and Baker and Chieruzzi, 1959). Most landslides in the Allegheny Plateau occur in hillside soil masses, with the most common being slump-type slides or slow earth flows, which range in size up to several million cubic yards. Rockfalls, the next most common type of slide in the area, are typically much smaller, with maximum volumes on the order of a few hundred cubic yards. The best-documented rockslide occurred at the Brilliant Cut in Pittsburgh in 1941 (Hamel, 1972) (see landslide case histories in the following section). At present, deep-seated rockslides are uncommon in the area. However, during the Pleistocene Epoch, when climate was more severe and rivers were rapidly downcutting their valleys, this type of slide is believed to have been common. Other types of slide movements are relatively rare. Injuries and fatalities due to landslides are rare and result mainly from rockfalls on highway slopes and soil failure in construction trench excavations.

Residual strength values play an important role in the evaluation of landslides and the design of remedial measures in the area. The colluvium generally exhibits strain-softening behavior (Skempton, 1964), and its residual (large-displacement) shear strength is generally less than half its peak (small-displacement) strength at a given effective normal stress. For effective normal stresses of less than about 50 psi (345 kPa), the peak strength of claystone colluvium is commonly characterized by cohesion intercepts of 1 to 5 psi (7 to 34 kPa) and friction angles of 20 to 25 degrees, while the residual strength is usually characterized by negligible cohesion intercepts and friction angles of 8 to 20 degrees. Measured residual friction angles for most claystone-derived colluvium are on the order of 11 to 16 degrees (Gray et al., 1979). Experience in calculation of strength data from colluvial slide masses (Hamel, 1969, 1980, 2004; Hamel and Flint, 1969, 1972; and Gray and Donovan, 1971) indicates that in-place shear strengths are characterized by residual friction angles of 13 to 16 degrees, with a zero cohesion intercept.

The largest slides usually result from disturbance of ancient landslide masses in soils and/or rock. These ancient landslides appear to have occurred mainly in moister periglacial conditions (Gray et al., 1979; Hamel, 1998). Limited radiocarbon dating of wood in the colluvium (Philbrick, 1961; D'Appolonia et al., 1967) suggested a Pleistocene age for some of these

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deposits. Peltier (1950) and Denny (1956) found fossil periglacial features close to the front of the maximum advance of the Wisconsin glaciation in Pennsylvania that strongly supported the influence of Pleistocene periglacial processes on slopes.

Rockfalls result from differential weathering that creates unsupported, resistant rock overhangs. Rates of undercutting have been observed that vary from 1 to 7 in. (2.5 to 17.8 cm) per year, based on measurements conducted over a period of several years (Philbrick, 1959; Bonk, 1964).

Fleming and Taylor (1980) published landslide damage estimates for Allegheny County (Pittsburgh and suburbs) from 1970 to 1976. Annual costs ranged from $1.2 to $4.0 million over this 7 year period and averaged $2.2 million per year. The maximum annual cost of $4 million was for 1972, the year of Tropical Storm Agnes.

Landslide Case Histories

Brilliant Cut Rockslide—Several rockfalls and landslides in the Pittsburgh, PA, area, have been costly in terms of lives and money. An historic case involved the failure of 110,000 cubic yards (84,101 m^3) of rock that broke away from a large railroad cut in Pittsburgh on March 20, 1941 (Hamel, 1972). The area of the catastrophic rockslide is known as the Brilliant Cut. The rock cut was located on the nose of a hill at the junction of an abandoned tributary valley and the Allegheny River valley. The hill consists of nearly horizontal beds of sandstone, shale, siltstone, claystone, limestone, and coal. The cut was originally excavated in the early 1900s, and it experienced its first rockslide in 1904. In 1930, the railroad tracks were relocated farther into the rock slope, triggering two additional slope failures (Xanthakos et al., 1994). In addition, in the 1930s, a 1 ft (0.3 m) wide joint opened in the rock mass that extended to the crest of the hill. The joint was persistent, extending through the rock layers, and it has been interpreted to be a valley stress relief joint (Hamel, 1972).

The March 1941 rockslide displaced multiple sets of railroad tracks and derailed an operating train. The remedial rock excavation cost was about $100,000. Analyses conducted subsequent to the slope failure indicated that the rockslide was triggered by cleft water pressure that had built up within the master rock joint, primarily because natural drainage from within the slope had been blocked by large buildups of ice.

Aliquippa Rockslide—On December 22, 1942, about 150 cubic yards (115 m^3) of rock plunged off a highway cut on the west bank of the Ohio River about 16 mi (26 km) downstream of Pittsburgh, killing many factory workers riding in a bus (Gray et al., 1979). On that day, at 5:03 p.m., an Ohio Valley Motor Coach bus left from Aliquippa (the site of an operating steel plant) for Pittsburgh. The bus was filled with wartime steel workers on their way home following completion of a work shift. At 5:12 p.m., the time that victim's watches stopped, the bus was demolished by an avalanche of rock, which had been loosened by freezing and thawing, falling 75 ft (23 m) down the hillside and crushing the bus. Two of the largest blocks were estimated to be in the range of 100 tons each. The accident killed 22 passengers and injured three.

The valley wall at the location of the rockslide was approximately 360 ft (110 m) high with a mean inclination of 30 to 35 degrees (Gray et al., 1979). Adjustments to the slope were made in 1922 with the excavation of a 45 ft (14 m) sidehill cut. At the road level, an ~15 ft (4.5 m) section of erodible clay shale was exposed and overlain by 6 ft (1.8 m) of soft claystone. These weak rock layers were overlain by about 18 ft (5.4 m) of hard sandy shale with numerous joints oriented parallel to the valley wall. The clayshale and claystone units rapidly weathered, undercutting the hard sandy shale above. Records supplied by Ackenheil (1954) indicate that at least nine major rockfalls occurred on this section of road between 1932 and 1954. This event remains the worst rockslide to occur in the Pittsburgh region. This slope was later redesigned to minimize rockfalls, and reconstruction of the slope was completed in 1956.

Route 51 Rockfall of 1983—On February 16, 1983, two persons were killed as an estimated 400 tons of rock had fallen to the road surface below in an area locally known as Saw Mill Run Boulevard. The rockslide occurred several minutes after explosives had been used to free unstable, overhanging rock on part of the cliff face located above Route 51 during a construction project that was under way. A contractor at the site was working to stabilize a rock overhang, and they had released stopped traffic, which they had been holding back during periods of blasting. Within several minutes after traffic was permitted to flow after the last blasting operation, the rockfall occurred without warning.

Expansive Shales and Slags

Expansive Shales

Structural damage due to heaving caused by expansive sulfide minerals in shales was first recorded in western Pennsylvania in 1950 (Dougherty and Barsotti, 1972). Heaving of the ground results from oxidation of sulfide minerals such as pyrite and marcasite. Finely divided, black, amorphous sulfide minerals are very susceptible to oxidation due to their relatively

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large surface area. These expansive rocks are created in depositional environments where large volumes of decomposing organic material are exposed to low-oxygen and low-energy conditions, such as in swamps or lagoons. When freshly exposed by excavation, such as in a rock cut or a foundation excavation, they rapidly oxidize, and the sulfide minerals change into new minerals with greater volume, creating rock expansion that damages overlying or adjacent structures.

These expansive shale (and coal) seams are found throughout the stratigraphy in the Pittsburgh area, so avoidance can be difficult. Also, Pittsburgh's topography of steep hills and narrow valleys can typically require rock cuts and excavation to prepare sites for construction, so building in freshly exposed rock in building sites is very common.

The iron sulfide content of the expansive shales usually exceeds 1 percent by weight. However, damaging heave is reported for sulfide contents as low as 0.1 percent. Many of the expansive shales, although not all, are dark in color. These dark shales are often called carbonaceous shale, which implies the shale's dark color is due to high carbon content. Often, the dark color is due to black amorphous sulfide minerals rather than carbon.

Researchers report that weathering of the shale is partly biochemical and caused by autotrophic bacteria belonging to the *Thiobacillus-Ferrobacillus* group. The preferred environment for this expansion process seems to be warm and relatively dry, with a plentiful supply of air (Penner et al., 1973). No clear relationship has been identified between the amount of heaving and iron sulfide content or thickness of the shale (Dougherty and Barsotti, 1972). When identified in the planning stage of a project, the common avoidance methods in the Pittsburgh area include: (1) over-excavation of the shale by some interval (dependent on specific location and building loads) and backfill with inert, non-expansive fill such as slag or gravel; (2) installation of deep foundations (drilled piers, drilled-in piles) to extend below the expansive shale and properly base the structure on load-bearing beams above the shale, avoiding contact; (3) grading of the site to remove the potentially expansive shale; or (4) construction of the building grade so that inert fill is placed over the top of the shale without exposing the shale, with the fill being of sufficient thickness to attenuate heave and minimize any heave that may occur. If none of these alternatives can be done, the expansive shales are sealed with concrete or bitumastic materials in an attempt to prevent oxidation. However, there remains some risk of heave, because sealing is not a long-term solution since most seals eventually leak.

Although no correlations have been identified that relate maximum heave to thickness of the expansive shale or percent of sulfide content (Dougherty and Barsotti, 1972), heave is a process that can continue for many years. Heave can be substantial because the oxidized iron sulfides occupy ten times more space than un-oxidized material, and the splitting of the shale causes it to occupy a greater volume (ENR, 1960). The ENR article indicates structures continued to heave 25 to 40 years after their construction. In one case, a lightly loaded column was raised 4 in. (10 cm) by the heave of the expansive shale (ENR, 1960). Spanovich and Fewell (1969) reported their observations verifying heave pressures exceeding 6,000 pounds per square foot (psf) (29,295 kg/m^2).

A prime example of expansive shale in the Pittsburgh area is the Queen of Angels (originally named St. Agnes) School in North Huntingdon, PA (15 mi [24 km] east of Pittsburgh). It was built in 1961 as a one-story, slab-on-grade building with the walls supported on grade beams that spanned between spread footing foundations. The walls and floors began to crack shortly after the school opened. The building continued to heave, and engineering studies in 1989, 1992, 1994, and 1997 found the damage was becoming progressively worse. In 1999, it was concluded the school's main structural support system had failed and that repairs estimated at more than $2.5 million were required. The 39 year old building was closed, and it was demolished in 2000 (Reeger, 2012).

Expansive Slags

Again, because of Pittsburgh's steep hills and narrow valleys and the minimal flat-land available, large development areas throughout the region were dependent upon fill. A by-product of all the once-numerous large steel making facilities in Pittsburgh was slag. Much of the slag was used in continued development of the steel-making facilities along waterways, and much was discarded. However, because of its abundance and low cost, it was made commercially available. The problem with using some forms of the material was the tendency for it to expand when it was used beneath foundations, structures, and roadways, which caused excessive heaving and buckling damage. The slag would continue to expand until all of the reactive calcium oxide was hydrated, which could take several months or years. The number of damage cases due to expansive slags is relatively few because producers of potentially expansive slag learned not to use it in their own plants and generally placed such slag in waste dumps, and also because the material is no longer readily available as the steel industry is essentially depleted. Most of the damage in the Pittsburgh area occurred in the 1960s and 1970s, when steel pro-

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duction was at its highest and the effects were less known.

The iron and steel industry produces a variety of slags as by-products of its operations. Iron blast furnace slag, both air cooled and granulated, has a long history of use. However, steel slags from open hearth, basic oxygen, and electric furnaces have exhibited these expansive properties (Crawford and Burn, 1969). Expansion of slags occurs when free calcium and magnesium oxides (CaO and MgO) take on water. Particle size is an important factor controlling the rate of expansion, since the smaller the size, the greater is the surface area and the greater is the exposure to moisture.

Flooding

Pittsburgh has experienced a wide range of flood hazards, including hurricane-related rainfall events, spring snowmelt, and releases related to ice-jam flooding. Due to its location at the headwaters of the Ohio River, the region is historically susceptible to flooding. In the headwaters region of the Ohio Basin, slopes are often steep, and runoff into tributaries and rivers occurs rapidly. As in other intensely urbanized areas with moderately high precipitation and ground that prevents potential infiltration, the transfer from rainfall to flood management is nearly instantaneous, and stream surges can mount significantly within 24 hours.

The headwaters region of the Ohio River receives one of the highest annual rainfall amounts in the country and also has one of the lowest evaporation rates (W. C. Loehlein, personal communication, 2010). The region also has one of the highest reliabilities of receiving its annual rainfall in the world. Unlike most regions, the area surrounding Pittsburgh has historically had flooding from every direction, for example, from storms that cross over the Great Lakes to the northwest, from thunderstorm activity originating in the Gulf of Mexico, and from hurricanes that form in the Atlantic Ocean. The distinctive four seasons that are present in the region include average winter snow accumulations of 40–60 in. (101–152 cm) per year that contribute to the area's flood-prone nature. Because of the area's significant relief, flooding of Pittsburgh can occur within 24 hours after the initiation of a storm event.

Flooding in Pittsburgh has occurred historically dating back to the early settlement of the region (see Figure 34). One of the earliest recorded floods was at Fort Pitt in January 1762. Many homes were filled with water, and the village surrounding the fort was covered in mud. No one, however, drowned by what was then reported as "ye Deluge or Inundation" (Johnson, 1978, p. 8).

Figure 34. Historical flood levels at the Point (photo courtesy of the U.S. Army Corps of Engineers).

Many devastating floods have impacted Pittsburgh. On April 6 and April 19, 1852, floodwaters reached 28 ft (8.5 m) and 34.9 ft (10.6 m), respectively, on the Pittsburgh river gauge. Normal river stage at Pittsburgh is ~16 ft (4.9 m), and flood stage at the Point has been established as being any level above 24 ft (7.3 m). On the Allegheny River just above Pittsburgh, many residents were routinely prepared to take to standby rafts for protection from the rising waters. The "St. Valentine's Day Flood" of 1884 peaked in the city at a stage of 36.3 ft (11 m), leaving at least 10,000 Pittsburghers homeless and some 15,000 out of work (Johnson, 1978). Farther down the Ohio River, conditions were even more serious where private and municipal levees were overtopped.

Devastating flooding again plagued Pittsburgh in 1907, leading to the formation of a Pittsburgh Flood Commission to evaluate flooding in the city. It was the first of its kind. The voluminous commission report, which was released in 1912, predicted that Pittsburgh would someday experience a 40 ft (12 m) flood stage and recommended construction of a system of reservoirs and levees to protect the city (Johnson, 1978). Several surveys were undertaken to determine the optimal sites for dams that would impound reservoirs and act to attenuate flooding downstream. Some of the major river systems evaluated for such projects were the Allegheny, Mahoning, and Shenango Rivers. Following a flood in 1913, the U.S. Army Corps of Engineers took a more aggressive approach to flooding problems. This was likely a direct reaction to the strong opinions of President Theodore Roosevelt. Roosevelt declared that it was imperative for the federal government to build multipurpose dams and reservoirs to conserve flood waters for later use in irrigation, hy-

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droelectric power generation, and improving dry season flows (Johnson, 1978). In direct response to this national attention, the Ohio River Flood Board was formed to initiate America's first regional flood mitigation planning. Additional floods impacted Pittsburgh, with the most significant one occurring in March 1936. That flood peaked at over 30 ft (9.1 m) above normal river level (46.4 ft [14.1 m] actual water depth). This event was then calculated to represent a record-setting 500 year flood, and it is considered as the worst flood to impact the Pittsburgh region and the city to date. Subsequent engineered flood control was constructed by the U.S. Corps of Engineers in 1938. The severity of the flooding in Pittsburgh was demonstrated to be greatly reduced during the more recent floods that occurred in 1972, associated with Hurricane Agnes, and in 1996, by the system of upstream flood-control reservoirs.

The Great Flood of 1889

On May 31, 1889, approximately 60 mi (97 km) east of Pittsburgh, a man-made disaster of unrivaled proportions took place in the city of Johnstown, PA. It was the Johnstown Flood (or the "Great Flood of 1889" as it became known locally). Although not directly associated with the Pittsburgh region, the flows from the watershed in Johnstown end up in the Allegheny River and ultimately pass the Point at Pittsburgh. Heavy rains poured down over this direct upper sub-basin of the Ohio River for several days (Law, 1997). The area surrounding Johnstown remains naturally prone to flooding due to its position at the confluence of the Little Conemaugh River and Stony Creek, which combine to form the Conemaugh River. The area above Johnstown consists of a 657 mi^2 (1,701 km^2) watershed within the Allegheny Plateau. Adding to these factors, artificial narrowing of the riverbed because of early industrial development made the city even more flood-prone. The Conemaugh River immediately downstream of Johnstown is hemmed in by steep mountain slopes.

Upstream of Johnstown, near the small town of South Fork, the South Fork Dam was built between 1838 and 1853 by the Commonwealth of Pennsylvania as part of a canal water delivery system to be used as a source of water for a canal basin in Johnstown (McCullough, 1968). With railroads superseding canal barge transport, the obsolete South Fork Lake was sold to the Pennsylvania Railroad, and later sold again to private interests. A group of notable Pittsburgh businessmen, including coal and coke magnate Henry Clay Frick and steel magnate Andrew Carnegie, led the group to purchase the reservoir, modify it, and convert it into a private resort lake for wealthy industrialists of Pittsburgh. They built cottages and a clubhouse to create the South Fork Fishing and Hunting Club, an exclusive mountain retreat. Membership grew to include over 50 wealthy Pittsburgh steel, coal, and railroad industrialists. Changes to the lake, which was renamed Lake Conemaugh, included lowering the dam that impounded the lake to make its top wide enough to hold a road, and putting a fish screen in the spillway, which unfortunately could also trap debris. These alterations increased the vulnerability of the dam to overtopping.

Figure 35. Artist's depiction of South Fork Dam prior to its 1889 failure (National Park Service, 2008).

Lake Conemaugh sat at 450 ft (137 m) in elevation above Johnstown. The lake was about 2 mi (3.2 km) long, approximately 1 mi (1.6 km) wide, and 60 ft (18 m) deep near the dam. The lake had a perimeter of 7 mi (11.2 km) and held 20 million tons of water. When the water was at its highest point in the spring, the lake covered over 400 acres (1.6 km^2). The dam was 72 ft (22 m) high and 931 ft (284 m) long. Between 1881, when the club was opened, and 1889, the dam frequently leaked and was patched, mostly with mud and straw. Additionally, a previous owner removed and sold for scrap the three cast iron discharge pipes that had allowed a controlled release of water, as a form of safety-related control of the impounded water level. There had been some speculation as to the dam's integrity, raised by the head of the Cambria Iron Works, which was located directly downstream in Johnstown. Cambria Iron Works, which was Carnegie Steel's chief competitor, at that time boasted the world's largest annual steel production. Despite these concerns, no major corrective action was taken, and the flawed dam continued to impound Lake Conemaugh (McCullough, 1968) as depicted on Figure 35.

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Figure 36. Flood aftermath in Johnstown (National Park Service, 2008).

In late May 1889, a major storm formed over the Midwest, moving east. When the storm struck the Johnstown–South Fork area 2 days later, it was the largest recorded rain event in that part of the country (Law, 1997). The U.S. Army Signal Corps estimated that 6–10 in. (15–25 cm) of rain fell within 24 hours over the entire region of west-central Pennsylvania. During the night, small creeks became roaring torrents, ripping out trees and carrying significant amounts of debris. Most telegraph lines were struck down, and rail lines were washed away. Before long, the Conemaugh River overflowed its banks. At around 3:10 p.m. on May 31, 1889, the South Fork Dam failed, allowing the 20 million tons of Lake Conemaugh to cascade down the narrowly channeled Little Conemaugh River. It took about 40 minutes for the entire lake to drain. As the flood wave made its way to Johnstown, it picked up and carried an immense amount of debris, and there was total devastation in the city (see Figure 36). In some areas of the Little Conemaugh River, the narrowly constrained river transferred the flood at high velocity, and its own valley bottom was eroded down to bedrock. The death and destruction in Johnstown were nothing less than a total catastrophe. The total death toll was 2,209, making the disaster the largest loss of civilian life in the United States at the time, and South Fork the worst dam failure in United States history when measured in terms of loss of life. The remnants of the failed dam can be seen in place today as depicted on Figure 37. Following the tragic failure of the South Fork Dam in 1889 and the subsequent failure of Austin Dam in north-central Pennsylvania in 1911 (Greene and Christ, 1998), Pennsylvania instituted one of the first state dam safety commissions in the nation in 1913.

Figure 37. Current photograph of South Fork Dam depicting abutment remnants (National Park Service, 2008).

The Pittsburgh Flood of 1936

The March 1936 St. Patrick's Day Flood was the largest flood of record in the Upper Ohio River valley. This flood prompted the passage of the Flood Control Act of 1936 by Congress. Following record floods along the middle Ohio River in January 1937 and the lower Ohio River in March 1937, the 1936 act was amended with more projects and funded in 1938 for the construction of most of the flood protection projects east of the Mississippi River. The result in the Upper Ohio River Basin was a system that currently consists of 16 federally built flood-control and multiple-purpose dams. This reservoir system has proven to have substantially reduced flood damages in Pittsburgh and communities downstream of the city. For example, these projects combined to reduce the 1972 Hurricane Agnes flood by an estimated 12 ft (3.6 m) at Pittsburgh. Without the upstream reservoirs, this flood would have been 2 ft (0.6 m) higher than the record flood level recorded in March 1936. The January 1996 flood was reduced by 10 ft (3 m) at Pittsburgh; otherwise, it would have equaled the flood elevations recorded during the March 1936 flood.

Coal Mine Subsidence

Historical Background

Mining in western Pennsylvania was concentrated in the Pittsburgh Coal seam, which was accessed by

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adits driven into hillsides. From Coal Hill, mining progressed up the Monongahela River valley and over time moved inland away from the river, which was still extensively used for transportation of coal to markets. The land surface above the mines was largely used for pasture or agriculture. In the late 1940s and the 1950s, rapidly expanding suburbs were constructed over both abandoned and active mines. Over the abandoned mines, most problems were related to sinkhole formation in areas of shallow mining.

In abandoned mine areas, concerns for subsidence damage due to pillar failure were mainly limited to schools and large commercial developments. Most active mines, by this time, were using full-extraction room-and-pillar mining. The mining companies had purchased the coal many years before, generally with a waiver of surface damage or the right to legally subside the land surface. However, many coal-mining companies, recognizing social problems, offered protection to surface landowners, and starting in 1957, one company even guaranteed safety from subsidence if approximately 50 percent of the coal was purchased by homeowners and left in place by the mining company. The extent of support for a home was usually determined by providing a zone 15 ft (4.5 m) in width around the periphery of the home. This area was then projected downward and outward at an angle of 15 degrees from the vertical to the level of the mine and referred to by the industry as the angle of draw. This projected area became the recommended area of support defined as the limits of subsidence over a particular mined-out area. Unmined pillars of coal equivalent in area to 50 percent of the support area were left in place to prevent subsidence, as indicated in Figure 38. For an average coal-seam thickness of 6 ft (1.8 m), which is typical of the Pittsburgh Coal, approximately 10,000 tons of coal per acre are present. The cost to purchase support for a single dwelling located a significant distance above a mine was often prohibitive to homeowners. For groups of homes where the support areas overlapped, the shared cost was greatly reduced. In 10 years, one company that guaranteed surface protection provided support for 635 homes and had to make repairs on approximately 2 percent of the homes (Gray and Meyers, 1970).

The Bituminous Mine Subsidence and Land Conservation Act of 1966 was enacted by the Commonwealth of Pennsylvania to prevent undermining that would damage any public buildings or any noncommercial structures customarily used by the public, such as churches, schools, hospitals, and municipal utilities or municipal public services operations, homes, and cemeteries. This law covered only structures existing at the time of enactment. For new structures, the mining law required subsequent property-ownership deeds to indicate the existence or lack of existence of subsurface support. Prior to mining, the coal company was required to contact property owners and assign a price for leaving coal pillar support as previously described. If the price was not agreeable to the property owner, then the Secretary of the State Department of Mines and Mineral Industries (now the Pennsylvania Department of Environmental Protection [PADEP], 2014) assigned a mediator to determine just compensation for the coal to be left in place for surface support (Gray and Meyers, 1970). The Surface Mining Control and Reclamation Act of 1977 imposed land-use controls on active mines. This law requires an evaluation of whether subsidence can occur and cause material damage or diminution of use of structures or renewable resource lands. If a potential for damage is present, a plan to prevent or mitigate the damage is required.

Coal Extraction and Subsidence

Subsidence does not occur until mining removes a significant amount of coal. Significant factors are related to the geometry of the mine, its depth, and the physical characteristics of the coal and overlying rock strata. In many ways, all interests are met if complete extraction occurs in a large part of the mine that results in subsidence of the ground surface concurrent with mining. Many mines in operation today utilize longwall mining, which removes all coal from large areas, or total-extraction room-and-pillar mining, which systematically removes the coal pillars from one end of a large panel to the other. Total extraction in room-and-pillar mines has been practiced in the Pittsburgh region since the latter part of the 19th century.

Subsidence contemporaneous with longwall or total-extraction room-and-pillar mining is similar and ceases in a few months to a few years after mining. However, other mines only remove a portion of the coal, leaving pillars of coal in place. Uniformly spaced pillars, if of sufficient size relative to the strength of the mine roof, floor, and coal itself, can support the overlying rock strata without subsidence. If the coal pillars are too weak, subsidence will eventually occur. This is the case with many old mines. Subsidence over abandoned mines may continue for many years and is often sporadic.

The availability and quality of mine maps varies throughout the United States. In the Pittsburgh region, mine maps are usually available for all but the earliest or very small mines. Large mining companies became common after the Civil War, resulting in excellent maps. Turka et al. (1996) discussed mine map accuracy.

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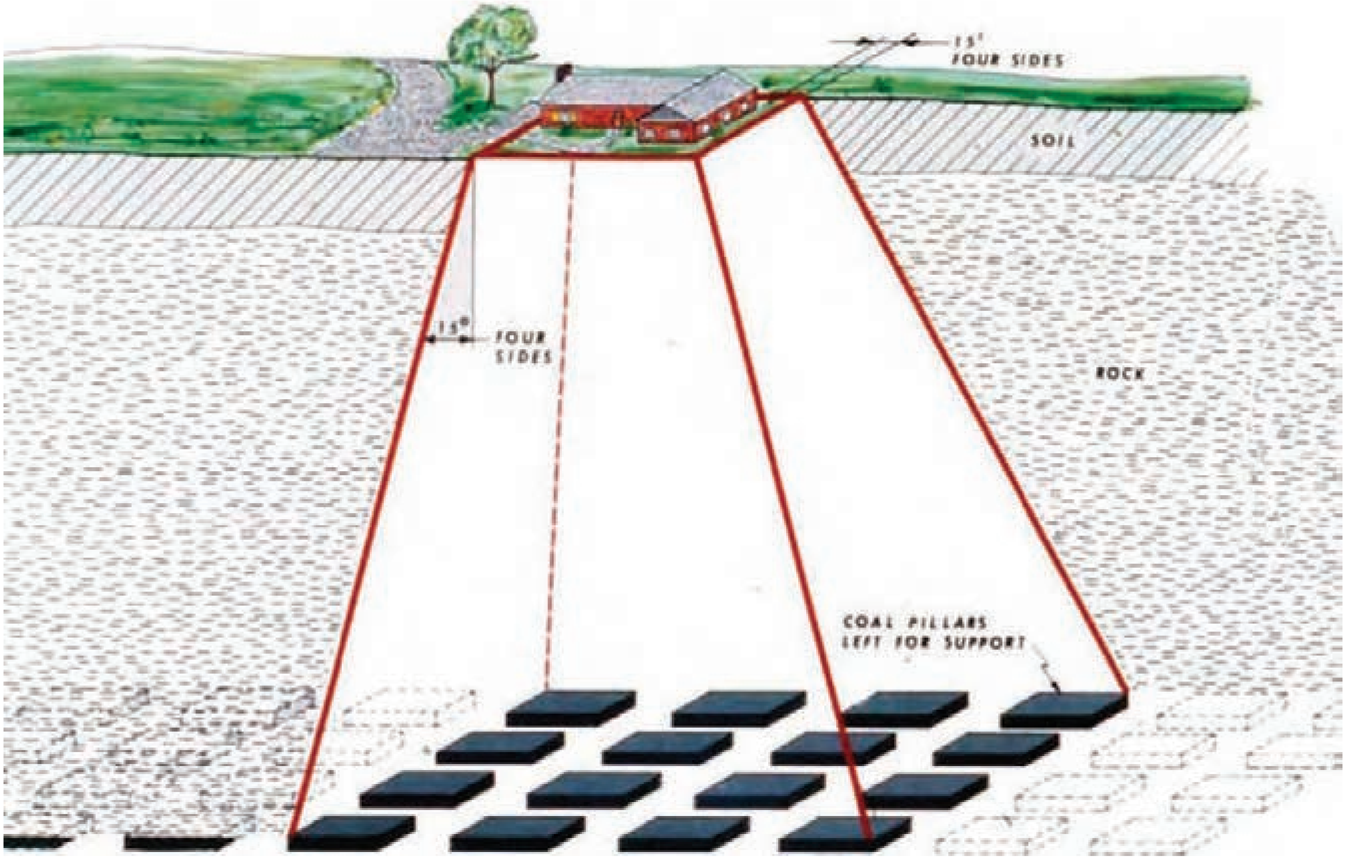

Figure 38. Coal pillar support (Gray and Meyers, 1970).

Ground Movements over Longwall Mines

The angle-of-draw previously defined the limits of subsidence over a particular mined-out area. However, small movements outside the angle of draw associated with longwall mining were recognized about 20 years ago in Australia (Hebblewhite, 2001). Although the mechanism of these movements remains uncertain, possible explanations include one, or a combination of factors such as post-mining stress relaxation, valley bulging, regional joint patterns, shearing of valley walls, and bedding-plane shear failure (Hebblewhite, 2001). These movements, sometimes described as far-field movements, may occur over a mile from the longwall panel and, thus, well outside the angle of draw (Hebblewhite, 2001; Waddington and Associates, 2002).

Similar movements have been recently recognized in southwestern Pennsylvania in studies of longwall mining under Interstate 70 in Washington County, PA, near the split between Interstate 70 and 79 (GeoTDR, Inc., 2001) and in the remedial investigation of leakage from Ryerson Station State Park Dam, located in northwestern Greene County, in 2005 (Hebblewhite and Gray, 2014). In monitoring the mining under Interstate 70, time domain reflectometry (TDR) cables, installed in deep boreholes, recorded deformation over 1,000 ft (305 m) in front of the advancing mine panel, well beyond the limits of theoretically anticipated movement around the active mine panel (GeoTDR, Inc., 2001). Mining of a longwall panel 2,500 ft (762 m) south of Ryerson Station State Park Dam is the only apparent concurrent cause of bedding-plane slip in rock beneath the dam that was recorded by slope inclinometers (Hebblewhite and Gray, 2014).

Subsidence Modes

Topographic ground surface subsidence features over mines are classified as *sinkholes* or *troughs* (Figure 39). A *sinkhole* is a depression in the ground surface that occurs from collapse of the overburden into a mine opening (a room or an entry). A *trough* is a shallow, commonly broad, dish-shaped depression that develops when the overburden sags downward into a mine opening in response to coal extraction, crushing of mine pillars, or punching of pillars into the mine floor. Troughs develop over both active and

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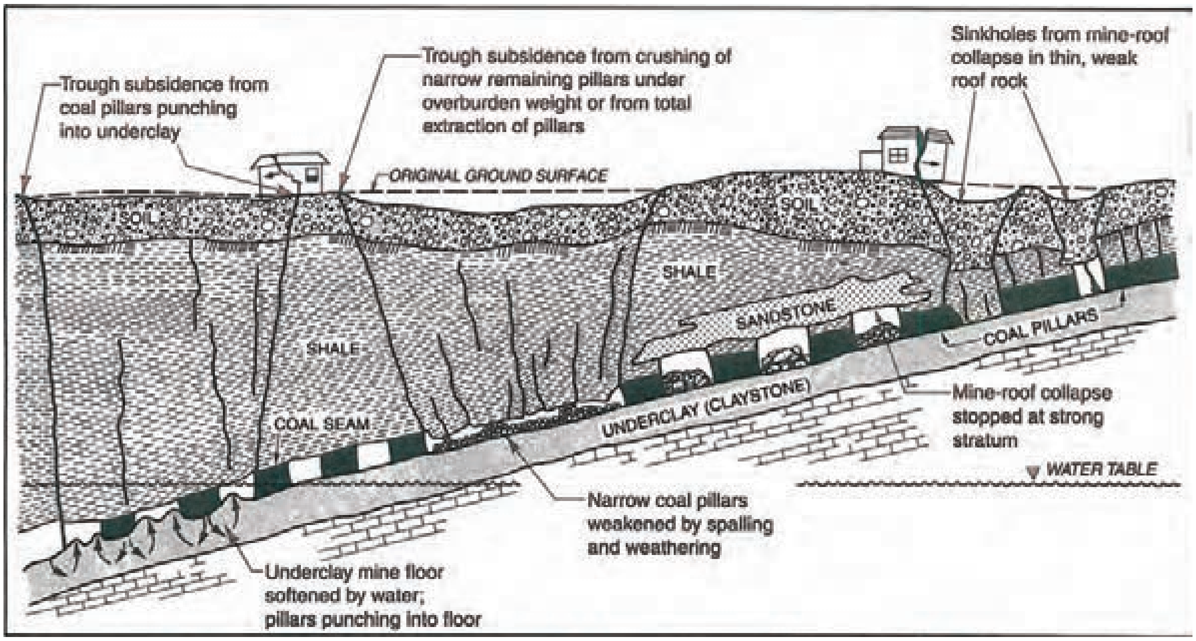

Figure 39. Modes of mine subsidence (Gray, 1999).

abandoned mines. There appears to be no safe depth of mining that prevents trough development.

Sinkholes generally develop where the cover above a mine is relatively thin (Figure 40). Competent strata above the coal limit sinkhole development (Figure 39). Piggott and Eynon (1978) indicated that sinkhole development normally occurs where the interval to the ground surface is less than three to five times the thickness of the extracted seam and that the maximum overburden interval is up to 10 times the thickness of the extracted seam. In western Pennsylvania, most sinkholes develop where the soil and rock above a mine are less than 50 ft (15 m) thick (Bruhn et al., 1978). A study of subsidence in the Pittsburgh area revealed that the majority of sinkholes, which constituted about 95 percent of all reported subsidence incidents, occurred on sites located less than 60 ft (18 m) above mine level (Bruhn et al., 1981).

Abandoned Mines

Figures 41 and 42 show subsidence damage over abandoned mines. It appears that:

Figure 40. Coal mine sinkhole (photo by S. English, 1969).

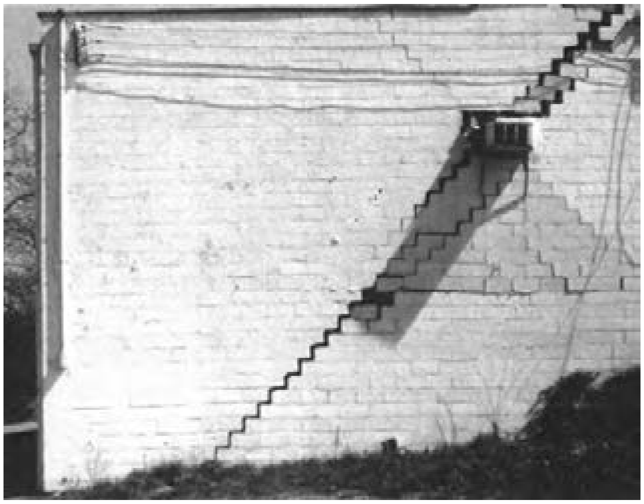

Figure 41. Building damage caused by subsidence, with coal at 175 ft (53 m) depth (Gray, 1999).

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Figure 42. House damaged by sinkhole subsidence, Connellsville, PA (photo by R. Turka, 1979).

(1) unless total extraction has occurred, there is no overburden interval above an abandoned mine that is safe from subsidence, nor is there necessarily a reduction in severity of damage with an increased overburden interval;
(2) subsidence occurs at reduced frequency with increasing overburden thickness; and
(3) unless total extraction has been achieved, subsidence may occur long after mining and may not be limited to a single episode (Gray, 1988).

Item (3) implies that the possibility of future subsidence at a site cannot be ruled out merely because subsidence has not occurred in the first 50 to 100 years after mining. If abandoned mine openings beneath a site have not been designed for long-term stability, the potential for subsidence remains until the openings collapse, or until they are stabilized by backfilling, grout columns, or some other means of engineered remedial ground support (Gray et al., 1974). Precisely when collapse might take place in the absence of stabilization is not predictable. Even after subsidence has taken place at a particular site, the possibility of future additional subsidence may remain. Multiple episodes of subsidence have been documented at many sites in the Pittsburgh region (Gray et al., 1977). Pillar failure can fall into three general categories: delayed, progressive, or sporadic (Abel and Lee, 1980). Site surveillance programs of a few months' duration or, in fact, indefinite duration cannot provide definitive evidence that a site overlying a mine with open voids will not experience future subsidence (Bruhn et al., 1981).

Insurance programs to provide assistance if and when subsidence occurs appear to be desirable (DuMontelle et al., 1981). Pennsylvania and other states have mine-subsidence insurance programs. Such an approach appears to be more desirable than large-scale urban stabilization programs for residential areas (Gray, 1983).

Volcanism

The Pittsburgh region contains no volcanoes or volcanic deposits. The closest volcano to Pittsburgh, Mount Tremblant, is almost 500 mi (800 km) north in Quebec Province, Canada. However, in 1766, Reverend Charles Beatty, a well-educated English Presbyterian minister, visited Pittsburgh and climbed Coal Hill where British Soldiers were mining the Pittsburgh Coal. Reverend Beatty wrote in his journal:

> "In the afternoon we cross the Mocconghehela River accompanied by two gentlemen, and went up the hill opposite the fort, but a very difficult ascent, in order to take a view of that part of it more particularly from which the garrison is supplied with coals, which is not far from the top. A fire being made by the workmen not far from the place where they dug the coal, and left burning when they went away, by the small dust communicated itself to the body of the coals and set it on fire, and has now been burning almost a twelve month entirely underground, for the space of twenty yards or more along the face of the hill or rock, the way the vein of coal extends, the smoke ascending up through the chinks of the rocks. The earth in some places is so warm that we could hardly bear to stand upon it: at one place where the smoke came up we opened a hole in the earth till it was so hot as to burn paper thrown into it; the steam that came out was so strong of sulphur that we could scare bear it. We found pieces of matter there, some of which appeared to be sulphur, other nitre, and some a mixture of both. If these strata be large in this mountain it may become a volcano. The smoke arising out of this mountain appears to be much greater in rainy weather than at other times. The fire has already undermined some part of the mountain so that great fragments of it, and trees with their roots are fallen down its face. On the top of the Mountain is a very rich soil covered with fine verdure, and has a very easy slope on the other side, so that it may be easily cultivated." (Eavenson, 1942, p. 25)

Although, today such a ridiculous idea is amusing, at that time it was the accepted wisdom in Europe. Abraham Werner, the most renowned geologist in Europe, believed coal was the fuel of volcanoes into the 1800s (Adams, 1938).

Acid Rock

Acid rock drainage is the water-quality hazard resulting from the oxidation of iron sulfide minerals (Nordstrom and Alpers, 1999). In the Pittsburgh area and elsewhere in the coal-bearing Pennsylvanian-age rocks, it is common to encounter acid mine drainage generated by coal and pyritic shale.

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However, acid rock drainage resulting from other sources was virtually unknown in the area until 2003. At that time, an excavation for Interstate 99 (I-99) at the Skytop site on Bald Eagle Mountain, located to the west of State College in Centre County, PA, exposed pyrite-rich rocks associated with a zinc-lead deposit within a sandstone ridge. As part of the I-99 work, this sandstone was excavated, crushed, and used locally as road base and fill. Within months, acidic (pH <3), metal-laden seeps and surface runoff were generated from the crushed rock fill and the exposed pyritic deposits in the road cut. This raised concerns about surface water and groundwater contamination and prompted a halt in road construction and the beginning of a costly program of environmental remediation. The Skytop site posed a reclamation challenge because the road base and fills were deposited over a large area, there was a lack of neutralizing minerals in the host rock, and the acidic drainage exhibited low pH and a complex chemistry. The situation at Skytop was more extreme than situations involving acid mine drainage from coal mines and is comparable to environmental problems that develop at abandoned metal mines (Hammarstrom et al., 2005). Pennsylvania had developed special handling techniques for coal surface mines spoil and for acid-producing materials in highway construction prior to the Skytop incident. However, pyrite-rich sandstones such as those encountered at Skytop had not been identified prior to the highway excavation, and, therefore, no plans were prepared for handling the acid rock. The potential for situations similar to what had happened at Skytop, where unexpected acid rock might be encountered, prompted the Pennsylvania Geological Survey to prepare a publication on acid rock in the commonwealth. The resultant open-file publication (Pennsylvania Geological Survey, 2005) includes a map showing the formations that may contain acid-forming minerals (primarily pyrite). The publication also includes text describing each of the formations. In the Pittsburgh area, the identified areas correspond with the coal-bearing formations.

TRANSPORTATION

The regional topography, consisting of major rivers, steep hillsides, and flat hilltops, resulting from the underlying geology required a unique transportation infrastructure in Pittsburgh that included roads, tunnels, bridges, railroads, inclines, bike paths, and stairways. Most of the transportation methods were used to move resources to local and distant markets. Pittsburgh's strategic location as a "gateway to the West" resulted in use of the river valleys as the primary transportation corridors, as they still are today.

Canals

Philadelphia had been the leading seaport on the Atlantic Coast in the 1700s, but in the early 1800s, completion of the Erie Canal to the north, connecting New York City to the Great Lakes via the Hudson and Mohawk Rivers, and Maryland's National Road to the south, connecting Baltimore to the Ohio River at Wheeling, WV (Shank, 1981), resulted in the growth of those two seaports as the emergent gateways to the great American West. People and goods transported through Pennsylvania from the east coast to Pittsburgh were moved primarily by coaches and wagons via a system of locally owned and constructed turnpikes. Movement of people and freight by this pioneer system was slow and of limited capacity, resulting in high transportation costs. Conestoga wagons were used to carry freight over the roads and took about 23 days to go from Philadelphia to Pittsburgh.

Pennsylvania constructed a system of canals in order to improve the transportation from Philadelphia and the east coast to Pittsburgh and to compete with New York City and Baltimore. The trunk section of the Pennsylvania Canal system, referred to as the Main Line of Public Works, ran from Philadelphia to Pittsburgh and covered a distance of 395 mi (636 km). Construction began in 1826, and the final link, the Allegheny Portage Railroad, was completed in 1834.

The canal boats moved at an average of about 4 mi per hour (mph) (6.4 kilometers per hour). The canals were generally 40 ft (12 m) wide and 4 ft (1.2 m) deep with locks to change elevation. There were towpaths on either side of the canals for the animals pulling the canal boats. The canal boats could carry the same loads as the Conestoga wagons and shortened the trip from Philadelphia to Pittsburgh to about 4.5 days and later to 3.5 days when steam locomotives replaced animals on the canal towpaths. The boats varied in size, with the largest being 79 ft (23 m) long and capable of carrying 25 passengers and 30 tons (27 metric tons) of freight (Shank, 1981).

The canal approached Pittsburgh along the north side of the Allegheny River and then split; one branch extended to the north shore of the Allegheny River for access to the Ohio River, and the other branch passed over the Allegheny River and into Pittsburgh via an aqueduct that was 1,100 ft (335 m) long (Figure 43).

From the aqueduct, the canal passed to the main terminal and turning basin. The canal continued to the south through a tunnel completed in 1828 and ended on the south side of the city at a lock structure providing access to the Monongahela River. Originally, the plan had been to extend the Chesapeake and Ohio (C&O) Canal to Pittsburgh and connect the two canal systems at the lock structure, but the C&O canal was

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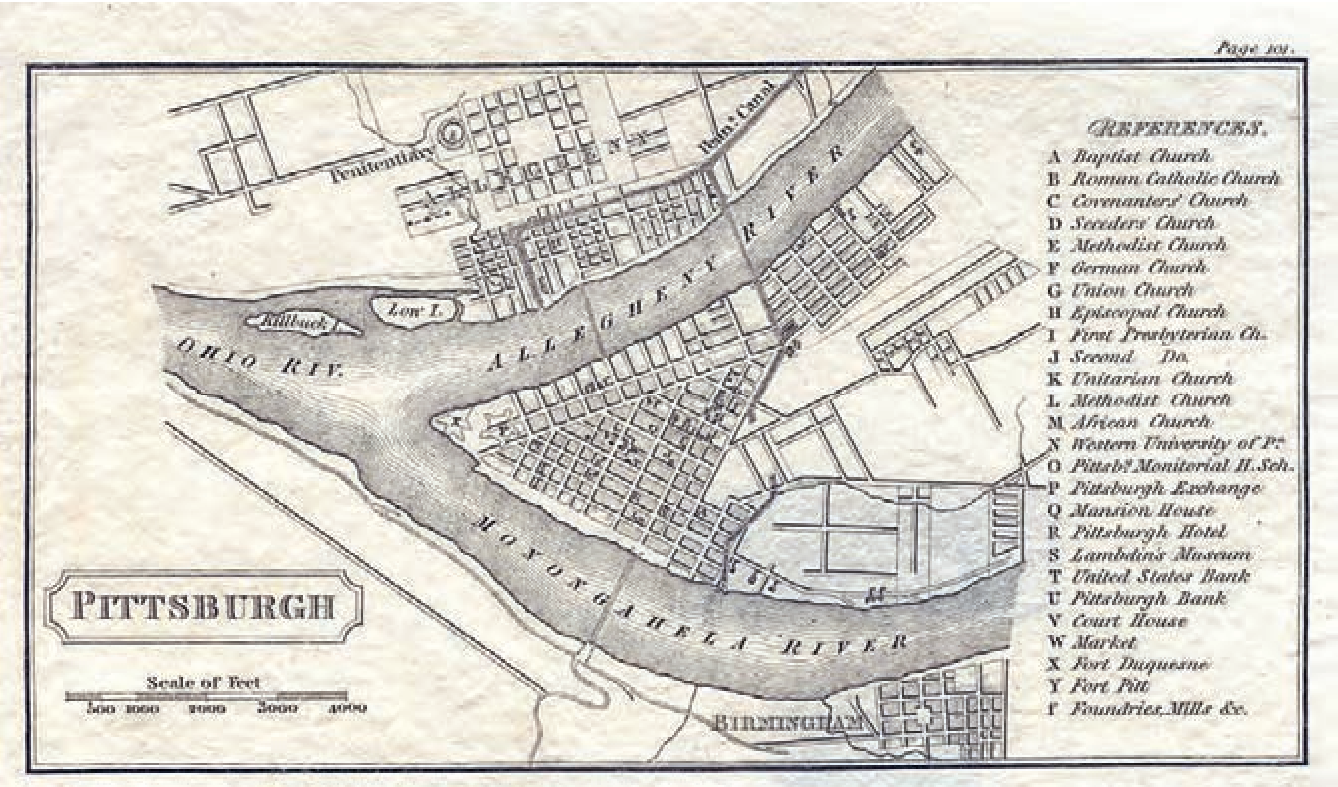

Figure 43. Pittsburgh map showing canal (Darby, 1828).

never extended that far. The original aqueduct over the Allegheny River was replaced in 1844 by John A. Roebling's first wire cable suspension bridge, the Allegheny Aqueduct (ExplorePAHistory, 2014, Roeblings). Mr. Roebling lived at that time in Saxonburg, PA, about an hour north of Pittsburgh, where he was attempting to establish a settlement of German immigrants. In 1841, he also obtained a contract to replace the hemp ropes used to pull the boats on the Portage Railroad with wire rope, and he built a factory at Saxonburg to make the needed cable. Aside from the Allegheny Aqueduct, he also designed two other suspension bridges in the city, the Smithfield Street Bridge over the Monongahela River in 1846, which was replaced in 1883, and the Sixth Street Bridge over the Allegheny River in 1859, which was also replaced multiple times and now has a different name.

In 1854, the Pennsylvania Railroad initiated rail service between Philadelphia and Pittsburgh, reducing the travel time to only 13 hours. The railroads quickly made the canals obsolete, and the canal system was eventually sold at a loss to the Pennsylvania Railroad in 1857. They briefly ran the system and then shut it down, using some sections for rail lines and continuing to operate other sections. The last canal section near Harrisburg was shut down in 1901.

The canal tunnel that carried the canal from the Allegheny to the Monongahela River was uncovered during the foundation excavation for the USX Tower (built as the headquarters office of U.S. Steel) in 1967 (now UPMC Building). Figure 44 shows the tunnel

Figure 44. Tunnels exposed during USX Tower construction (Rathke, 1968).

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as it was exposed during construction, along with a nearby rail tunnel.

River Navigation Structures

Since early settlement of western Pennsylvania, the three rivers have served the region for basic transportation and shipment of goods and cargo by barges. As pushed by towboats, this transport mode continues, commonly referred to as "tows." The amount of coal transported down river from Pittsburgh jumped greatly following the Civil War (Johnson, 1978). The size of the tows also grew with the amount of coal hauled for its increasing down-river demand.

Due to the escalating coal trade, the U.S. Army Corps of Engineers began studying methods to produce a reliable navigation depth on the Ohio River. The U.S. Army Corps of Engineers launched an international study to analyze other navigation projects worldwide. The study led to the determination that construction of an integrated system of locks and dams, each forming a downstream pool (defined as a reach of artificially deepened river) was the best solution to meet the demands of growing navigation industry. The increased storage capacity of each "pool" increased the amount of river water that could be managed by sequential release from each pool proceeding down river.

Opening of the first lock and dam on the Ohio at Davis Island in 1885, located downstream of Pittsburgh, proved to be a significant technologic advance for the civil engineering profession at large. At Davis Island Lock and Dam, the wooden timber wicket dam was almost 1,900 ft (579 m) long, and the dimension-stone masonry lock, at 600 ft (183 m) long and 110 ft (36 m) wide, was the world's largest river navigation structure at that time. Even then, the stone-masonry lock at Davis Island was wider than the reinforced concrete locks built in 1914 at the Panama Canal (Johnson, 1978).

In 1910, the Rivers and Harbors Act was authorized by Congress, providing for the systematic construction of a system of locks and dams along the Ohio River, and this project was completed in 1929. The project produced 51 wooden wicket dams and typical lock chambers 600 ft (183 m) long by 110 ft (36 m) wide lock chambers along the length of the river starting at Pittsburgh. Wicket dams were composed of moveable slab sections that were hinged at the bottom and held upright by adjustable props. Wicket dams in the Pittsburgh region were the earliest to be replaced by mass concrete dams.

Taken together, the systems of locks and dams on the three rivers of the Pittsburgh region have been described as "rivers that are highways." Even today, they are the most efficient means by which to move bulk commodities such as coal and construction aggregates and, as such, are more cost effective than rail or truck transport. Throughout the late 19th and early 20th centuries, the Monongahela River has carried a greater tonnage than any other inland river in America (Johnson, 1978). In comparison with the mighty Ohio and Mississippi Rivers, the Monongahela River was called the "Little Giant" because of the tonnage it transported annually. Moving coal to steel mills in the western Pennsylvania towns upstream and downstream of Pittsburgh was of great importance, especially to the war effort in the late 1930s and early 1940s.

During the 1940s, a shift from steam-propelled to diesel-powered towboats allowed for larger tows on the river. However, this meant that tows had to be disassembled, in order to lock all the barges through in multiple lockages, and then reassembled before continuing. This functional inconvenience backed up river traffic and increased expenses for the river towboat industry. Even as modernization of locks in the lower Ohio River was initiated in the 1950s to handle the larger tows, the locks in the Pittsburgh region remained unchanged. In the upper Ohio River, nearest Pittsburgh, each river navigation dam was a gated type or a simple concrete weir, which had two parallel, adjoining locks: one 600 ft (183 m) by 110 ft (36 m) main chamber and a 360 ft (110 m) long by 56 ft (17 m) wide auxiliary chamber.

The Pittsburgh District of the U.S. Corps of Engineers currently operates and maintains 23 locks and dams on the three rivers (see Figure 45). This represents the largest number of navigation projects in any district of the corps, and it systematically provides a 9 ft (2.6 m) minimum navigation "pool" depth. In the 1990s, a new lock and dam project was built on the Monongahela River south of Pittsburgh. The project was Grays Landing Locks and Dam, and it involved traditional cofferdam construction. Steel sheet piles were used to form a series of interconnecting coffer cells. Once completed, the inner cofferdam area was pumped dry. Excavation of alluvial sediments was carried down to "top of bedrock." At these variable depths, additional rock removal was continued in order to establish a foundation within competent bedrock. Once the final excavation was performed, concrete was placed on the prepared rock foundation.

Recent construction involved the 2004 completion of a new gated dam on the Monongahela River, known as Braddock Locks and Dam, located 11 mi (18 km) upstream of Pittsburgh. This project employed innovative float-in construction techniques,

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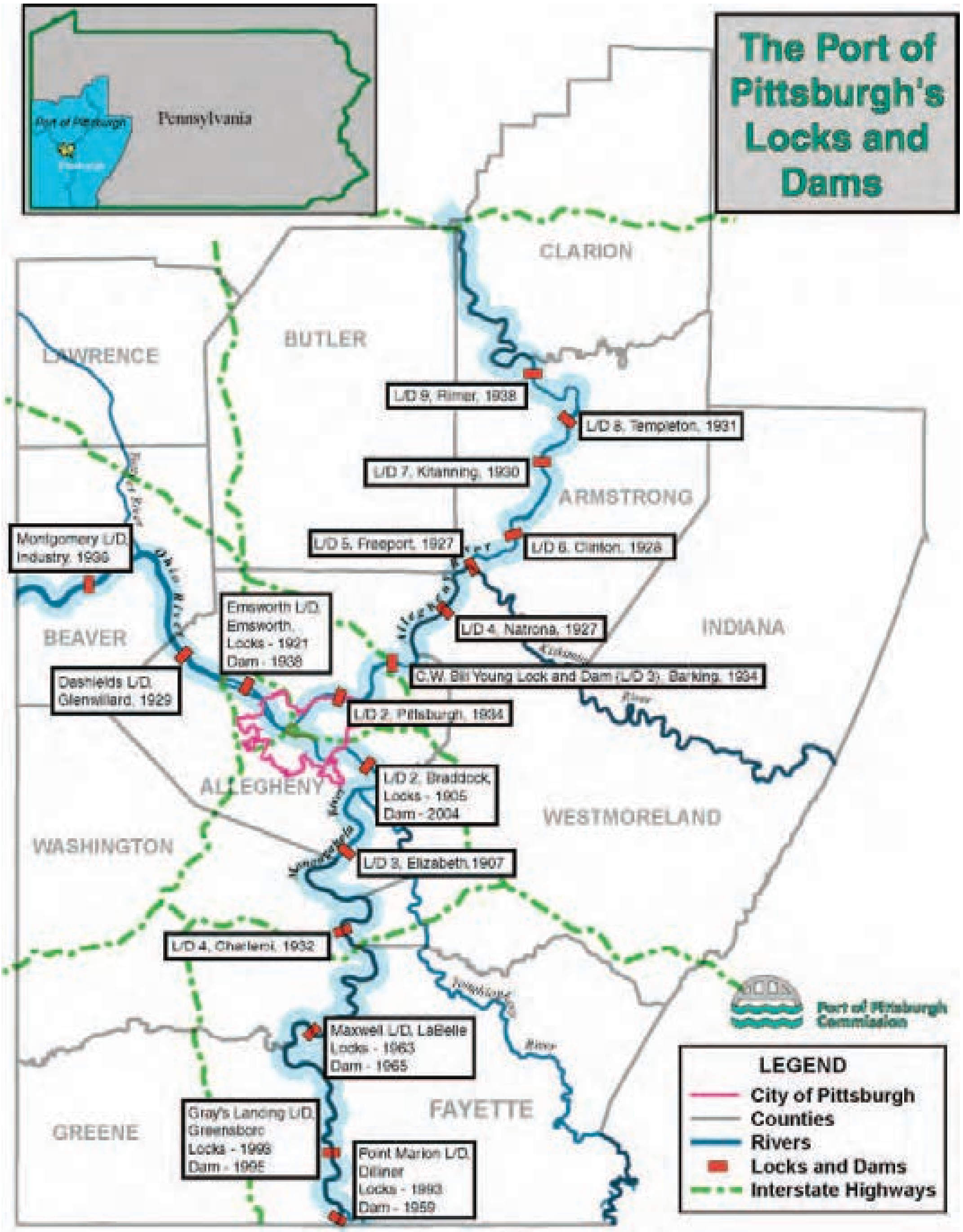

Figure 45. Location of locks and dams on Pittsburgh's three rivers (photo courtesy of the Port of Pittsburgh Commission).

which involved two large precast segments set down on nearly 90 reinforced concrete drilled shafts embedded 16 ft (4.9 m) into bedrock (Edwardo et al., 2002). In addition, construction is currently under way at Charleroi Locks and Dam, located 40 mi (64 km) upstream of Pittsburgh, which will provide two new lock chambers 720 ft (220 m) long by 84 ft (26 m) wide.

Rail Systems

When Pittsburgh was incorporated as a city in 1816, it was the major center for commerce in the west, and most travel from the east coast went through it. Around 1830, the commerce aspect of Pittsburgh's economy was surpassed by its manufacturing base. To transport bulk goods, including coal, an economical

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and reliable mode of transportation was needed. The first rationally designed transportation network was the local railroad. This system was intended to transfer coal and goods to the industries within and surrounding Pittsburgh. Topography initially restricted population growth to the city and railroad corridor expansion to the river valleys. However, with the development of the abundant Pittsburgh Coal seam, which resulted in newly established farm roads and communities in these mining areas, the railroad lines began following the contours of the nearly flat-lying Pittsburgh Coal seam. Bridge structures developed as the railroads required "jumping" from one hillside to another to be in close contact with the mining areas. Like all other railroads of that time, they relied on horses or mules for power. Not much faster than wagons or canal boats, their main advantage was smooth-running rails.

The transition to the widespread interstate railroad system was a long battle. Pennsylvania had no urgent reason to invest in railroad technology until 1825, when the Erie Canal linked New York City's ports to Midwest markets (Finch, 1988). Once the Erie Canal opened, shipping costs from New York to the Midwest dropped significantly, and the time it took to ship the goods was cut significantly. This greatly increased trade for New York City businesses while bypassing Pittsburgh and Philadelphia.

Shipping by water was still cheaper than by rail, but the railroads did have the advantage of traveling where rivers didn't flow. A result was the combined use of trains and rivers together (Fleming, 1916). Started in 1834, the state-owned Main Line of Public Works used canal boats where possible on relatively level ground and a combination of gravity and stationary steam engines where necessary in the mountains (Baer, 1996). This patchwork of canals, railroads, and inclined planes offered a 3 to 4 day journey from Philadelphia to Pittsburgh. However, it was soon ended by the cheaper, all-purpose, all-weather railroads. The interstate railroads entered the area in the 1850s. In 1852, the Ohio and Pennsylvania Railroad began service between Cleveland and Allegheny City (present-day North Side), and in 1854, the Pennsylvania Railroad began service between Pittsburgh and Philadelphia. An historical map of the Pittsburgh railroads is shown on Figure 46. A journey between Philadelphia and Pittsburgh now took only 13 hours. The Pennsylvania Railroad was the largest railroad in the world for much of its 121 year life span, absorbing many other railroads as it grew. It hauled more freight and passengers than any other railroad in the world during that time (Baer, 1996).

The railroad system in Pittsburgh flourished for many years. From the beginning of the industrial era through its collapse in the 1980s, Pittsburgh was always a key market for the nation's largest and most important railroads. At one time, up to 22 railroads, including main lines and branches, entered Pittsburgh (Fleming, 1916). They comprised the lines of the Pennsylvania System, the New York Central Lines, the Baltimore and Ohio, the Buffalo, Rochester and Pittsburgh, the Pittsburgh, Bessemer and Lake Erie (the Carnegie Road), and the Wabash. However, with the coming of publicly funded highways and the availability of automobiles after World War II, railroads began a long downward slide. Despite the near collapse of heavy industry in the northeast, Pittsburgh still remains an important link in the nation's rail network. Current railroads in Pittsburgh include: Norfolk Southern, CSX, Amtrak, Wheeling & Lake Erie, and the Allegheny Valley Railroad.

Another rail system that once existed in Pittsburgh was the inter-city trolley car. It started in the late 1800s and early 1900s and followed the farm roads lying at the ridge tops, the alignments of the railroad network, and many abandoned railroad corridors. They became most popular in the 1940s and 1950s as an economical mass-transit solution for the expanding city of Pittsburgh (see Figure 47). A fleet of more than 600 trolleys was in use in 1948 (Bennear, 1995). The demise of the trolley was due to the speed and flexibility of gasoline-powered buses. By the early 1970s, the fleet had dwindled to 95 cars and 4 lines. By 1985, almost all trolley rails were overlain by asphalt, with few cars and lines existing. Today, a light rail system in Pittsburgh known as the "T" has replaced remnants of the trolley lines. These lines run between downtown Pittsburgh and the South Hills suburbs. In town, these lines become Pittsburgh's subway. The most recent addition included a tunnel under the Allegheny River to the north side of Pittsburgh, as described in the section of this paper on tunnels.

Inclines

In the mid- to late 1800s, the land on the floodplains within and surrounding Pittsburgh had become crowded by industrial and commercial development. Land for residential housing was available on the tops of the surrounding bluffs, such as on Mount Washington (Coal Hill), but traversing the 300–400 ft (91–122 m) of elevation change was arduous. The answer to this situation was inclined railways or funiculars, which are referred to as inclines in the Pittsburgh area. The inclines are composed of two parallel sets of railway tracks with a car on each track. The cars are connected by a single cable that passes through a pulley at the top of the incline. The cars counterbalance one another so that the engine that moves the

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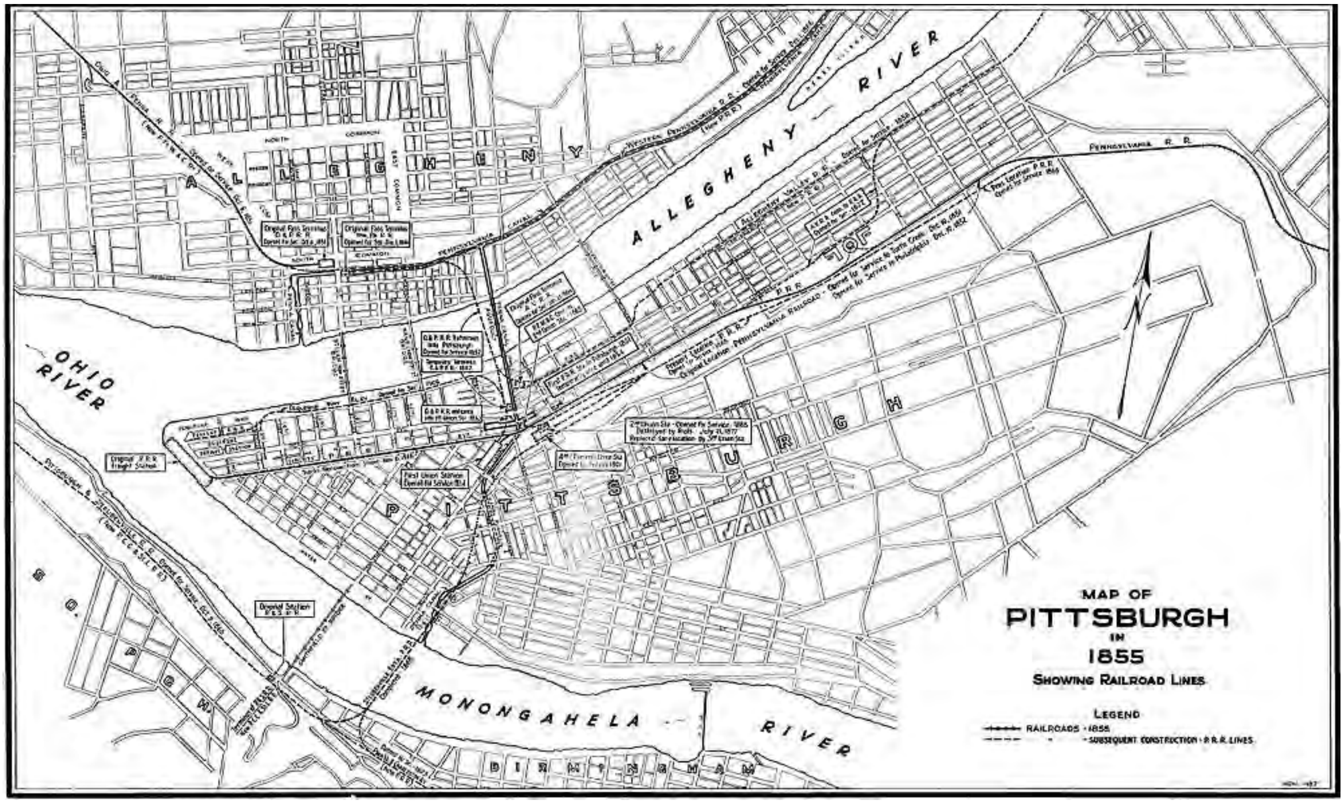

Figure 46. Map of Pittsburgh railroads in 1855 (Pennsylvania Railroad, 1948).

cars only needs to overcome the weight difference in the cars plus any frictional forces.

The first incline built in Pittsburgh, the Monongahela Incline, opened on May 28, 1870. From that time until the opening of the last incline in 1901, between 15 and 20 inclines were built in Pittsburgh (Old Pittsburgh Maps, 2012). Most of the inclines were built to negotiate the steep bluffs on the south side of the Monongahela River, but a few were built on the north side of the city to the north of the Allegheny River. Most of the inclines were built solely for passengers, but some were built for freight. The Monongahela passenger incline had a companion freight incline that was built and remained in service until 1935.

Figure 47. August 1964 photo taken along the P&WVRR tracks looking down at a Pittsburgh Railways inbound Shannon trolley.

The inclines fell out of use as personal vehicles became common, and most of them were closed during the first half of the twentieth century. Only two, the Monongahela and the Duquesne Inclines, remain in operation. Both are located on the south side of the city.

The Monongahela Incline, shown in Figure 48, is 635 ft (194 m) long with a grade of 78 percent (38 degrees) and an elevation change of just over 367 ft (112 km). It is owned and operated by the Port Authority of Allegheny County and has been in constant operation since it was constructed. It has undergone major renovations and upgrades.

The Duquesne Incline is located opposite the Point. It is 793 ft (242 m) long with a grade of 58 percent (30 degrees) and an elevation change of 400 ft (122 m). The Society for the Preservation of the Duquesne Heights Incline raised money in 1963 to save the incline. It still

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Figure 48. Monongahela Incline.

has the same Victorian cars with the original woodwork. The engines have been converted from steam to electric power.

Bridges (by Thomas Leech, professional engineer [P.E.], Gannett Fleming, Inc.)

> "There is something intensely dramatic and fanciful in the appeal of the bridge to all classes of people, under all conditions of nature. All traffic converges and concentrates on the bridges. They become a daily necessity and a familiar benefactor, giving convenient passage over some natural obstruction." (Kidney, 1999, p. 29)

In Pittsburgh, bridges are all around us. They cross mighty rivers, small streams, and deep chasms. Allegheny County, including the city of Pittsburgh, includes over 2,000 bridges of varying types, materials, and sizes. Some bridges are quite new; others are quite old. Some are distinct and magnificent; others are quite ordinary. Many bridges have seen a service life well over 100 years. Many replace one or even two earlier bridges at the same site. Each bridge records in its composition, in essence, a genetic code of its era of construction. This genetic code records both an engineering and architectural imprint of the age in which it was built. All of these bridges have been distinctly shaped by both the geography and geology of the area.

River Crossings

The Monongahela River (i.e., *river with sliding banks*, Delaware Native American) and the Allegheny River (i.e., *river of the Alligewi*, Delaware Native American) form the Ohio River (i.e., *the good river*, Seneca Native American) at the "Point" in Pittsburgh (Bright, 2004). At present, there are 30 river crossings in the city of Pittsburgh and another 29 river crossings in other communities within Allegheny County. Pittsburgh rivals other "bridge" cities of the world, including Paris with its 38 river crossings within the city proper, and Venice with its 409 bridges spanning 150 canals, but with only four bridges that cross the Grand Canal (Cridlebaugh, 2009).

Figure 49. Smithfield Street Bridge in downtown Pittsburgh: Historic American Engineering Record collection (Cridlebaugh, 1999).

As Pittsburgh emerged as a city in the early 1800s, the rivers were a formidable barrier to transportation. The first river crossings relied on geographic features, such as fords in the rivers by way of sand bar islands. These crossings were later replaced with ferry service near the fords. The locations of fords and subsequent ferries later became sites of the first river bridges constructed in Pittsburgh. The first established river crossing within Pittsburgh was the site of the present Smithfield Street Bridge over the Monongahela River, initially a river ford, which later was replaced with the nearby Jones Ferry (Cridlebaugh, 2009). The ferry service was subsequently replaced by a wooden covered bridge in 1818, which later was destroyed by the great fire of 1845 (Lorant, 1975). The present Smithfield Street Bridge, a third-generation replacement bridge, is an elegant lenticular steel truss and an American Society of Civil Engineers (ASCE) Civil Engineering Landmark. The present bridge was constructed in 1881 and is recognized as the oldest standing bridge in the city (Figure 49). The second established ferry, Robinson's Ferry, connected the North Side (previously Allegheny City) with downtown Pittsburgh in close proximity to the present Sixth Street Bridge. In 1819, the first span across the Allegheny River was a wooden covered bridge constructed at this site. It was ultimately replaced by the present third-generation Sixth

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Figure 50. Sixth Street Bridge in downtown Pittsburgh: Historic American Engineering Record collection (Cridlebaugh, 1999).

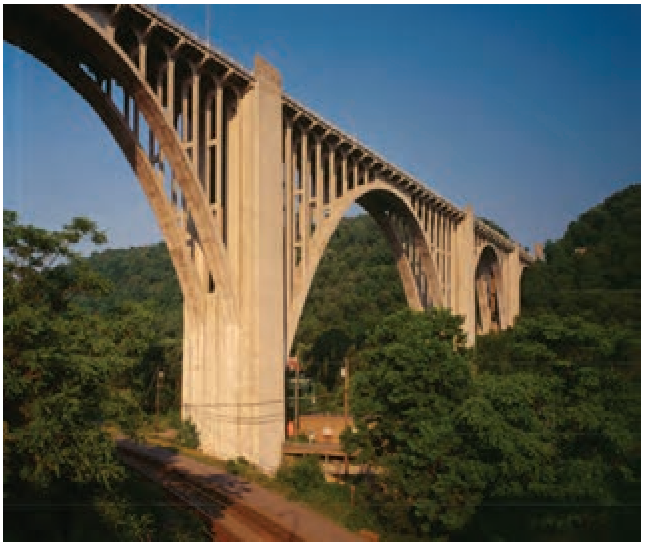

Figure 51. George Westinghouse Bridge: Historic American Engineering Record collection (Cridlebaugh, 1999).

Street Bridge, a self-anchored suspension span, one of the 1928 Three Sisters Bridges, which is recognized as the only surviving eyebar chain suspension bridge in America (Figure 50). Quickly, transportation routes developed around these ferry crossings, and the rivers of Pittsburgh now contain a myriad of bridges with unique structural form and complexity, all of which is a testament to Pittsburgh's prominence as an historic center of civil engineering practice. The main spans of the river crossings range from 400 ft (120 m) to 800 ft (240 m), consistent with navigation requirements, and the present 59 river crossings typically comprise various steel superstructures, egalitarian trusses, and plate girder bridges and visually appealing tied arch and suspension bridges.

As Pittsburgh grew to become an industrial power, the surface transportation routes shifted from town centric to bypass or through routes as the transportation routes ultimately shifted to interstate corridors, presently converging at the "Point" in Pittsburgh. Three generations of bridges have spanned the Monongahela River at the "Point," including the 1875 Point suspension bridge, the 1927 steel cantilever truss, and the current 1959 Fort Pitt (I-279/I-376) steel double-deck tied arch. Three generations of bridges also have spanned the Allegheny River at the "Point," including the 1874 Union, wooden covered bridge, the 1915 two-span steel trussed Manchester Bridge, and the current 1969 Fort Duquesne (I-279) steel double-deck tied arch.

The transportation networks within Pittsburgh and the surrounding communities in Allegheny County required an array of valley crossings that are supported by nearly 2,000 bridge structures. Many of the valleys are quite steep sided, and many interesting structures were designed with heights as much as 200 ft (60 m) above the valley floors and spans reaching 300 ft (90 m) and more. Structural forms include routine steel and concrete girders, steel box girders, steel trusses, steel viaducts, and high-level steel plate girders. Additionally, with competent bedrock so close to ground surface, even in the steepest of valley settings, there is ample opportunity to build structures that rely on lateral thrust principles. A wide variety of steel rigid frame, steel high-level arch, and concrete high-level arch bridges can be found in the Pittsburgh region. An example of a concrete high-level arch is the George Westinghouse Bridge, which is shown on Figure 51.

Tunnels

Western Pennsylvania has a place in tunnel history. The first railroad tunnel in the United States was the Staple Bend Tunnel, which is located about 60 mi (97 km) east of Pittsburgh along the Conemaugh River near Johnstown, PA (National Park Service, 2013). It was excavated between 1831 and 1833 as part of the Allegheny Portage Railroad, which was part of the Pennsylvania Canal that connected Philadelphia to Pittsburgh. The same Pennsylvania Canal also had a tunnel under downtown Pittsburgh. It is located under Grant's Hill, which is now Grant Street in the downtown area. The tunnel still exists, but it is sealed (see Figure 45). The Pennsylvania Canal Tunnel, which was constructed between 1827 and 1830, is considered to be Pittsburgh's oldest transportation tunnel.

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Today, Pittsburgh has 11 tunnels, according to the Pittsburgh Bridges and Tunnels website (Cridlebaugh, 1999). See Figure 52 for the tunnel locations.

- From Pittsburgh to the east, the tunnels include:
  - (1) Panhandle Railroad Tunnel runs under Grant's Hill in downtown Pittsburgh in rock belonging to the Glenshaw Formation of the Conemaugh Group, and it is now sealed.
  - (2) Armstrong Tunnel is an automobile tunnel under Duquesne University on the bluff just east of downtown Pittsburgh in rock of the Casselman Formation of the Conemaugh Group. It is a prominent tunnel in Pittsburgh known mostly for an approximate 45 degree bend. It was built in 1926–1927 with a length about 1,320 ft (402 m). The bend was created to avoid possible mines, some property rights (including Duquesne University), and to connect alignments with existing or proposed roads.
  - (3) LTV South Side Works Railroad Tunnel is owned by CSX and is a cut/cover tunnel with cut-stone side walls and a steel beam ceiling located under the South Side neighborhood of Pittsburgh.
  - (4) Neville Street Tunnel (or Schenley Railroad Tunnel) is used by CSX. It is located in the Oakland neighborhood of Pittsburgh and is a cut/cover tunnel about 70 ft (21 m) below the grade of Neville Street.
  - (5) Squirrel Hill Tunnel is an automobile tunnel under the Squirrel Hill neighborhood of Pittsburgh through rock of the Casselman Formation of the Conemaugh Group.
- From Pittsburgh to the west, the tunnels include:
  - (6) Corliss Street Tunnel is an automobile tunnel through the Norfolk Southern Railroad embankment, West End section of Pittsburgh.
  - (7) Fort Pitt Tunnel is an automobile tunnel through Mount Washington through rock of the Casselman Formation of the Conemaugh Group.
  - (8) Wabash Tunnel was built in 1902–1904 for the Wabash-Pittsburg Terminal Railroad through Mount Washington, now retrofitted for automobile traffic. It has a vertical-wall horseshoe profile and concrete lining, and it is 3,342 ft (1,019 m) long through rock of the Casselman Formation of the Conemaugh Group.
  - (9) Mount Washington Transit Tunnel hosts the Port Authority "T" and South Busway through Mount Washington, and it was built in 1904 with a concrete-lined vertical-wall horseshoe profile. It was excavated through rock of the Casselman Formation of the Conemaugh Group with an approximate length of 3,500 ft (1,067 m).
  - (10) The Port Authority North Shore Connector runs under the Allegheny River between downtown Pittsburgh and Pittsburgh's North Shore. It is the latest tunnel constructed in Pittsburgh as part of the "T" and subway system. Additional information is provided in the "Major Engineering Structures" section.
  - (11) Liberty Tunnel is an automobile tunnel through Mount Washington through rock of the Casselman Formation of the Conemaugh Group.

Much of the heaviest automobile traffic is associated with the tunnels, because motorists tend to slow down approaching and traveling through them, which is ironic because these structures were supposed to reduce driving time. Notable tunnels of the area include the Liberty Tunnel, which connects the south suburbs to the city, and the two interstate I-376 highway tunnels (Squirrel Hill and Fort Pitt), which connect the east and west suburbs to the city.

Mount Washington is nearly 400 ft (122 m) high along the length of Pittsburgh's downtown area, and it posed a barrier to the development of the South Hills. In order to provide access, the Liberty Tunnel, which is considered to be the first modern automobile tunnel in the United States, was excavated through Mount Washington. It consists of twin concrete-lined tunnels in a vertical-wall horseshoe profile. The county began construction of the tunnel in the winter of 1919, and the excavation was completed in July 1922. The rock excavated was mostly "green" and "red" claystone and soft laminated sandstone of the Casselman Formation of the Conemaugh Group, with a minor amount of more competent "blue" sandstone (Public Works, 1921). Most of the excavation was considered treacherous due to the poor condition of the soft rock. The tunnels are 5,889 ft (1,795 m) long and 28.6 ft (8.7 m) wide, with 20.75 ft (6.3 m) clearance in the arch portion of the tunnels and a 14.5 ft (4.4 m) vertical entrance clearance. It opened in 1924 with restricted use until the ventilation system was completed in 1925. The tunnel was owned by Allegheny County until it was transferred to the Pennsylvania Department of Transportation (PennDOT).

Construction of the Squirrel Hill Tunnel started prior to World War II, was delayed until after the war, and was completed in 1953. Figure 53 shows the tunnel excavation. It is the principal highway route from the eastern suburbs of Pittsburgh into the city. The cost to construct the tunnel was $18 million and was the most costly project by the State Highways Department at that time. The tunnel consists of twin

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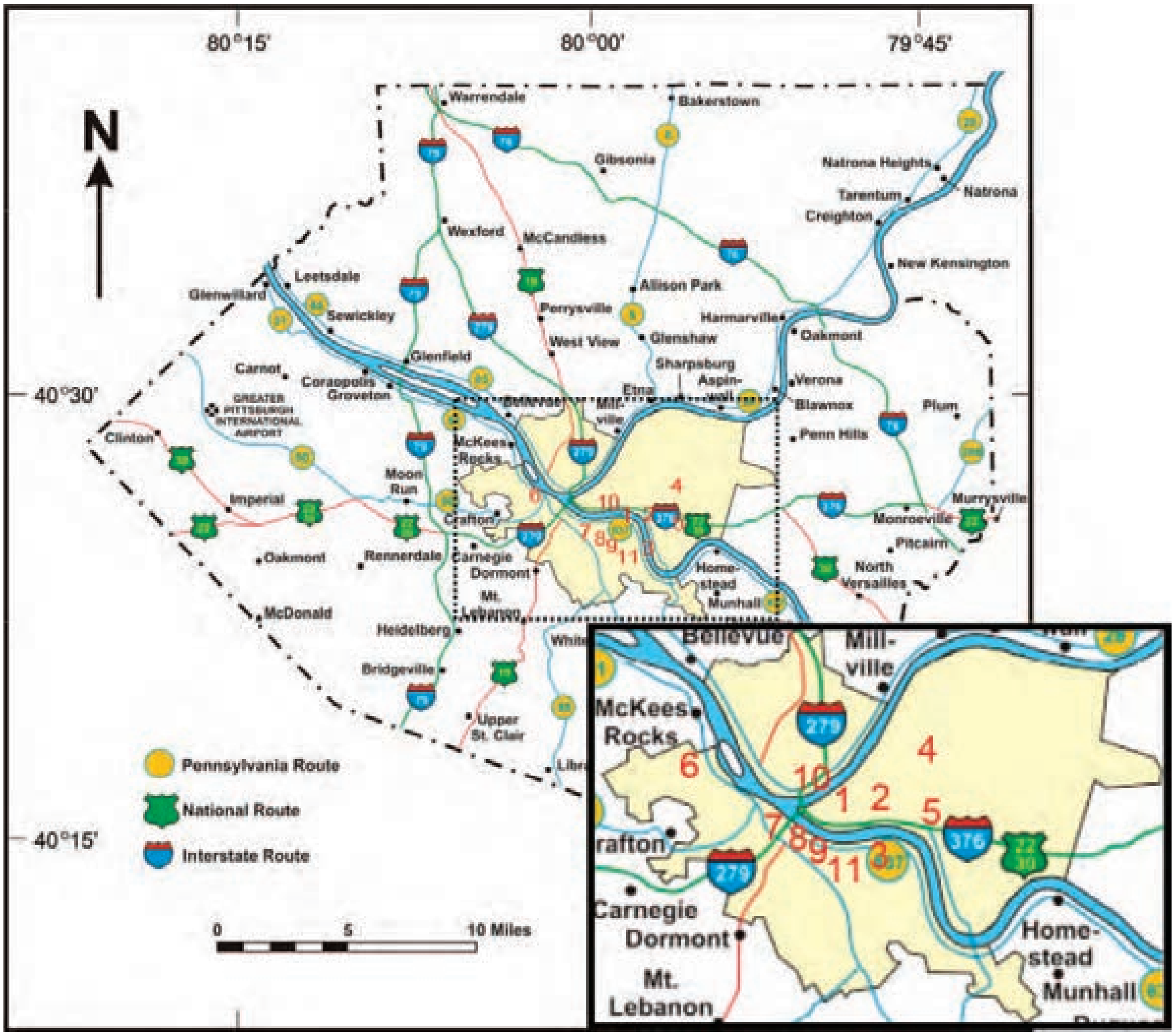

Figure 52. Tunnel locations in Pittsburgh (main map courtesy of John Harper, Pennsylvania Geological Survey).

Figure 53. Squirrel Hill Tunnel construction, 1953 (Collier, 2014; taken from Historical Society of Western Pennsylvania).

arch-shaped reinforced concrete bores that are 4,225 ft (1,288 m) long and approximately 29 ft (8.8 m) wide with a ceiling height of 13.5 ft (4.1 m). Vertical clearances are changing with the current rehabilitation project. The tunnel design was based on subsurface evaluations made from conventional borings, which revealed rather poor-quality rock would be encountered in excavating the tunnels. To adequately support the conditions, permanent steel supports were installed as the tunnel lining, and grout was placed outside of that lining. The grout was used to impregnate, strengthen, and seal the weak and shattered rock adjacent to the tunnel (Pennsylvania Department of Transportation, 2014, District 11 website, 2014 summary update).

The Fort Pitt Tunnel goes through Mount Washington, formerly Coal Hill. It is unique in that the outbound portal is lower than the inbound portal on the downtown side of the tunnel. The downtown por-

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tals are vertically offset to accommodate traffic of the stacked deck from the Fort Pitt Bridge, while the westbound portals are at the same elevation. The Fort Pitt Tunnel is similar in design to the Squirrel Hill Tunnel. Construction of the Fort Pitt Tunnel started in 1957 and was completed in 1960 by the Pennsylvania Department of Highways at a cost of $17 million. The total length of the tunnels is 3,614 ft (1,101 m), with an estimated opening of each portal at 28 ft (8.5 m) wide and a ceiling height of 13.5 ft (4.1 m). The Fort Pitt Tunnel is regarded as the "best way to enter an American city," because motorists emerging from the tunnel are suddenly presented with a dramatic view of Pittsburgh (Lorant, 1964, p. 395).

MAJOR ENGINEERING STRUCTURES

Foundations

The topography and geology of Pittsburgh result in many foundation types being used to support structures. The type and size of structure, site-specific conditions, local practice, and the designer's preference may influence the type of foundation selected as much as geology. There are areas where special foundation problems such as soft soils, subsidence due to mining, expansive shale, and landslides exist. In general, residual soils throughout Pittsburgh are adequate to support the foundations of homes and light-commercial buildings. For heavy foundation loads, rock normally provides adequate support, except where deeply weathered. Some local claystones and shales slake or dry out when exposed to the atmosphere and require immediate covering to avoid further deterioration and additional excavation. Pile driving can shatter these shales and claystones, and piles may have to be re-driven several times before deeper competent rock is encountered. A foundation designer must consider both surface and underground mining as potential sites for differential settlement, subsidence, slope instability, mine and refuse fires, and acidic soil, rock, and water. Shales should be considered a foundation problem until their potential for heaving is determined.

The alluvial soils in the Monongahela River drainage are generally soft, and large structures normally require foundations extending to or into rock to avoid excessive settlements. The glacial gravels in the Allegheny and Ohio River Valleys are generally dense and can carry significant foundation loads with only minor settlement. These dense glacial sand and gravel deposits occur in downtown Pittsburgh. In the area between the rivers, the contours of the top of rock rise away from the rivers, and the sand and gravel deposit ends around Smithfield Street between Fourth and Sixth Avenues, as shown on Figure 20 (Van Tuyl, 1951).

Various foundation types have been used to support buildings on the dense glacial gravel in downtown Pittsburgh. They include spread footings, a mat foundation, and friction piles. However, the three Gateway office buildings adjacent to Point State Park are an anomaly in that they are supported on H-piles driven through the glacial gravels to rock. Where the dense glacial gravel is not present, east of Smithfield Street, buildings are generally supported by spread footings or drilled piers bearing on rock.

In recent years, larger-scale projects, including the Braddock Dam, the PPG Paints Hockey Arena, the University of Pittsburgh Medical Center (UPMC) East Hospital, and the Pennsylvania Turnpike Bridge crossing the Allegheny River at Harmarville, 14 mi (22.5 km) north of downtown Pittsburgh, have been constructed. The size of the projects justified the use of Osterberg load cell tests to determine the bearing and side shear properties for optimizing the design of drilled piers in rock.

Some site and projects of interest are described as follows:

Point State Park

Point State Park comprises 36 acres (14.6 ha) at the confluence of the Allegheny and Monongahela Rivers. The park recognizes Pittsburgh's past and present, including the strategic importance and historic role that Pittsburgh's Point had in the development of the United States. The Ohio River afforded great influence over more than 200,000 mi^2 (517,998 km^2) of undeveloped territory downstream of the Point. In the early 1800s, swarms of settlers moved through Pittsburgh on their way west. Traffic down the Ohio reached a volume of more than 1,000 boats per year leaving Pittsburgh, with 20,000 people and more than 12,000 head of livestock, wagons, provisions, and household goods.

Following capture of the French Fort Duquesne in 1758, the English proceeded to construct the most impressive fort on the American Frontier, Fort Pitt. Point State Park includes parts of the Fort Pitt Bastions, and the original Fort Pitt Block House built in 1764. The Fort Pitt Blockhouse is the oldest architectural landmark in Pittsburgh and is the nation's only authenticated pre–Revolutionary War structure west of the Appalachian Mountains (Pennsylvania Department of Conservation and Natural Resources, 2015). Much of the structure is intact, including the stone foundation, brick, and timber elements that are largely original to its 1764 construction. The wall footing was uncovered in the early 1940s and found to be made of almost entirely of relatively small, light greenish-gray

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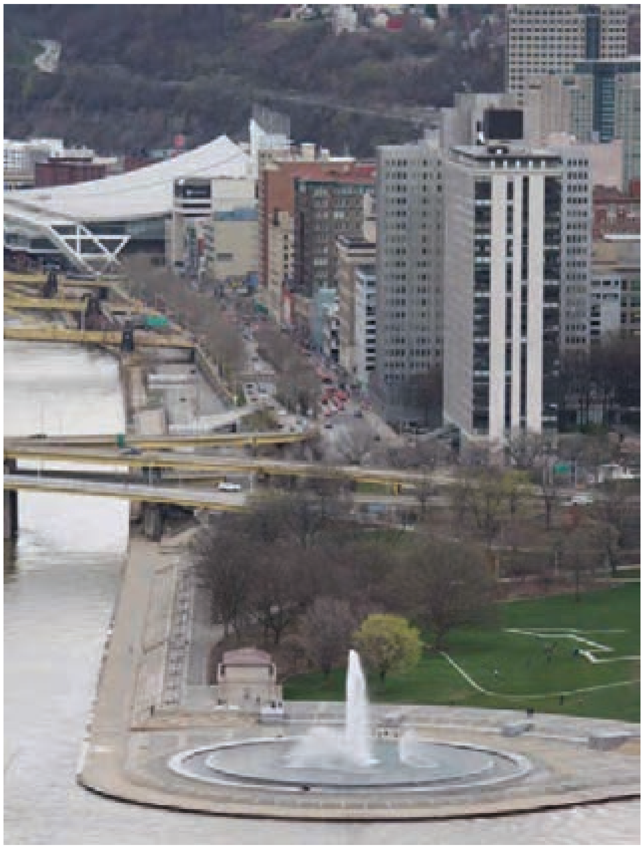

Figure 54. Fountain at Point State Park (photo courtesy of Linda Kaplan, Gannett Fleming, Inc.).

sandstone (possibly Connellsville Sandstone) blocks, with some locations consisting of glacially imported granitic blocks placed directly on glacial outwash material (Bliss, 1943). In addition, the park contains a fountain, dedicated in 1974, said to be the largest in the United States, which propels water upwards approximately 200 ft (61 m) (Figure 54). The 73,000 gallons of water in the closed-loop system are drawn from glacial gravels 50 ft (15 m) beneath the Point (Compressed Air Magazine, 1974).

U.S. Steel Tower (Formerly Known as USX Tower or U.S. Steel Building)

The U.S. Steel Tower, first known as the U.S. Steel Building and then the USX Tower, is a 64 story (841.0 ft or 256 m high) skyscraper located on Grant Street in downtown Pittsburgh. Construction started in March 1967 and was completed September 30, 1971. At 841 ft (256 m) above street level, the U.S. Steel Building was the tallest building between New York and Chicago until 1987. The building site occupies a portion of Grant's Hill, a prominent feature in the early history of Pittsburgh. In September 1758, Major James Grant led an advance column of 800 men of British General John Forbes' army against Fort Duquesne. The British force was repelled on a hill east of the Point, with 342 men killed, wounded, or captured. Major Grant was captured, but paroled soon after. When General Forbes occupied the abandoned Fort Duquesne on November 25, 1758, the nearby site of the battle was named Grant's Hill (Pittsburgh Post-Gazette, 2008).

Grant's Hill was leveled on several occasions, by a total of approximately 20 ft (6 m). Excavation for the U.S. Steel Building foundation extended up to 90 ft (27 m) below grade, bypassing previous fill material and poor rock conditions. A continuous concrete mat foundation with a thickness of up to 12 ft (3.7 m) was used for the structure and was placed on a competent shaly sandstone to reduce settlement issues (U.S. Steel Tower, 2015).

The excavation uncovered two tunnels that had been constructed through Grant's Hill (Figure 44). One was an 810 ft (247 m) Pennsylvania Canal tunnel constructed in 1834. The second was the Pittsburgh and Steubenville Extension Railroad tunnel. This railroad was a link between the Pennsylvania Railroad's western terminus and the eastern terminus of the Steubenville Railroad Company. When this rail link opened in 1865, it extended the Pennsylvania Railroad's trade and transportation network into Ohio, as far as Columbus. This tunnel was built using cut-and-cover techniques. A trench, approximately 35 ft (10.7 m) wide, was excavated from the ground surface to elevation 780 ft (238 m), and the tunnel was constructed within the trench, and then the excavation was backfilled. The average height of the tunnel side walls was 18 ft (5.5 m). A five-course brick arch was supported on the walls. The railroad tunnel was rehabilitated to serve as an underground right-of-way and station area (Midtown Station) for the Light Rail Transit Subway (HAER, 1985).

During the 1965–1967 construction of the U.S. Steel Building, a new single-track tunnel, measuring 409 ft (125 m) long and 17.4 ft (5.3 m) wide, was built within the subterranean levels of the building as part of Pittsburgh's Light Rail Subway. The support systems for the tunnel and the building were designed to be independent of each other, so that train vibrations would not disturb the building's structural integrity, and the weight of the building would not bear on the tunnel. The U.S. Steel Building tunnel begins 1,029.6 ft (314 m) from the south portal, is rectilinear in design, and has two safety bays measuring 1 ft (0.3 m) deep and approximately 5 ft (1.5 m) wide.

The U.S. Steel Building made history by being the first to use liquid-filled fireproofed columns. U.S. Steel deliberately placed the massive steel columns on the exterior of the building to showcase a new product

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called Cor-ten steel. Cor-ten resists the corrosive effects of rain, snow, ice, fog, and other meteorological conditions by forming a coating of dark brown oxidation over the metal, which inhibits deeper penetration and doesn't need painting and costly rust-prevention maintenance over the years. The initial weathering of the material resulted in a discoloration of the surrounding city sidewalks, as well as other nearby buildings. A cleanup effort was conducted by the corporation once weathering was complete to undo this damage, but the sidewalks still have a decidedly rusty tinge. The Cor-Ten steel for the building was made at the former U.S. Steel Homestead Works and contains over 44,000 tons (39,916 metric tons) of structural steel (U.S. Steel Tower, 2015).

Subway

Pittsburgh's subway system was constructed in the early 1980s. The project's goal was to upgrade the city's streetcar lines into a modern 10.5 mi (17 km) long light rail transit (LRT) system with two connecting exclusive bus roadways. Most of the rail system is in the suburbs south of the Monongahela River and is almost entirely on non-exclusive right of way at grade. After crossing the river into downtown Pittsburgh, the transit line dives into a 1.1 mi (1.8 km) long Y-shaped subway layout consisting of new and renovated two-track tunnels. This portion of the project accounted for only about one seventh of the project's $480 million cost.

The Port Authority of Allegheny County held the cost down by purchasing an old railroad bridge across the river along with a tunnel that ran north across the city. New subway work, all cut-and-cover, included building the large Midtown Station at the intersection of the subway Y and a line running east through Wood Street Station and terminating at Gateway Center.

One of the most challenging sections was the Wood Street Station, extending out below storage vaults under the sidewalks to adjacent building lines. Alluvial sand and gravel up to 40 ft (12 m) thick is found at this location, so some form of shoring of the excavation and nearby structures was necessary. Hayward Baker Co. conducted the work, and it represented the largest chemical grouting job ever performed in the United States to that date (Karol, 2003). This $2.5 million job was a showcase for non-destructive testing. Work was monitored by the cross-hole seismic method. Hayward Baker injected a 13,000 ft^2 (1,208 m^2) area beneath Sixth Avenue with 1 million gallons of chemical grout, turning the sand and gravel into a solid matrix that was excavated without danger while shoring up six adjacent buildings. The grout consisted of a proprietary formulation of sodium silicate and a number of reactants. The subway was completed in late 1984.

The North Shore Connector is a light rail extension that opened in 2012. The connector extends the Pittsburgh LRT system from its previous terminus at Gateway Center Station in the Central Business District to the new North Side Station and Allegheny Station on the North Shore by way of a tunnel under the Allegheny River.

The North Shore neighborhood of Pittsburgh evolved from a "sea of asphalt" in the 1990s to a bustling extension of the Central Business District, reflecting approximately $1 billion dollars of investment and construction in the first decade of the 2000s (O'Neill, 2008; Schmitz, 2010). The North Shore Connector links Pittsburgh's previously existing light rail network to the new businesses and attractions of the North Shore, serving commuters, visitors, and sports event attendees alike (Fontaine, 2012).

The North Side Station serves PNC Park (1.75 million annual baseball fans) and the Community College of Allegheny County (7,200 students). The Allegheny Station serves residents in Allegheny West and Manchester, as well as visitors to Heinz Field (500,000 annual Steeler fans, excluding concerts), the Carnegie Science Center (700,000 annual visitors), Children's Museum of Pittsburgh (250,000 annual visitors), and the Rivers Casino (Port Authority of Allegheny County, 2015, North Shore Connector). During weekdays, downtown-destined vehicle commuters utilize the connector by parking in one of the many North Shore parking facilities and completing their commute on the connector (Shumway, 2012). The North Shore lacks the parking capacity to serve additional sports fans, so the North Shore connector helps to alleviate the congestion by making it easier for fans to park downtown and travel to the North Shore stadiums (Lord, 2010).

The new subway section was constructed by cut-and-cover techniques from the Gateway Center 400 ft (122 m) to the Stanwix Street receiving pit. The subway construction consisted of twin bored tunnels, 22 ft (6.7 m) in diameter, from the Stanwix Street receiving pit to the West General Robinson launch pit, a length of 2,240 ft (683 m), including 875 ft (67 m) beneath the Allegheny River. From the General Robinson Street launch pit, the subway was constructed by cut-and-cover techniques for a distance of 1,200 ft (366 m). From this north portal, the line is elevated for 2,000 ft (610 m) to Allegheny Station. Figure 55 shows a map of the tunnel alignment and Pittsburgh's subway stations.

The top of the twin tunnels lies 20–25 ft (6–7.6 m) below the riverbed. The German tunnel-boring machine (TBM) assembly began in November 2007. The TBM, measuring 200 ft (61 m) long and weighing 500 tons (453 metric tons), was lowered into a 55 ft

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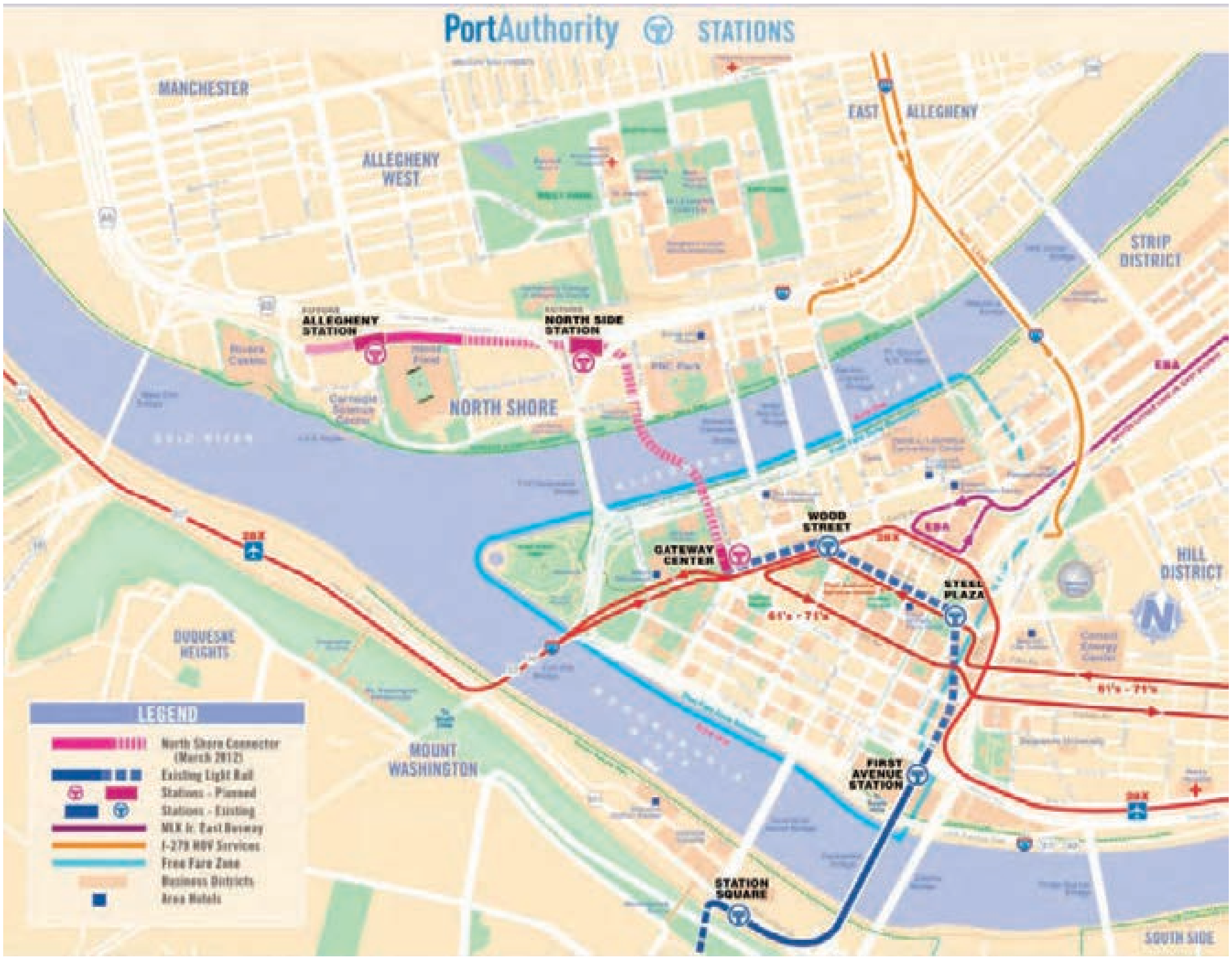

Figure 55. Map of the North Shore Connector Tunnel and subway stations (Port Authority of Allegheny County, 2012).

(16.8 m) deep launch pit excavated near the intersection of West General Robinson Street and Mazeroski Way near PNC Park. The TBM began work in January 2008 and completed the twin bores in January 2009 (Wargo et al., 2009).

In July 10, 2008, the TBM penetrated through into the receiving pit at Stanwix Street near Penn Avenue downtown. The machine was hoisted by crane, turned around and began digging the second parallel tunnel September 3, arriving back at the North Side launch pit January 15, 2009. Completing the second tunnel in 4.5 months showed the benefit from experiences gained; the second tunnel was a full month faster than the first.

The laser-guided, slurry-pressure-balanced, mixed-shield TBM had a 22 ft (6.7 m) diameter rotating head (typically 1 RPM), featuring 17 in. (43 cm) cutters, driven by electric motors. Digging through glacial/fluvial gravel and rock, the working face was stabilized with a pressurized bentonite-water slurry; the excavated material was transported by the clay slurry through pipes back to a separation plant aboveground. Excavated sand and gravel were separated from the slurry, allowing the slurry to be reused and the other materials to be reserved for future use elsewhere. The TBM's cutting face had a diameter that was 1 in. (2.5 cm) larger than the rest of the machine. This small annulus reduced side friction of the TBM shield, enabling it to move more easily, assisting in steering the machine, and thus controlling alignment (Wargo et al., 2009). The TBM was generally operated in two 12 hour shifts, five days a week, averaging 34 ft (10 m) per day. As the front of the TBM cut, a steel shield in the trailing section held the cavity open, and 4 ft (1.2 m) wide, pre-cast concrete segments were bolted together to form the tunnel liner (seven modules com-

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Figure 56. Interior of the completed North Shore Connector Tunnel (photo courtesy of Port Authority of Allegheny County, 2012).

Figure 57. 1936 flooding in downtown Pittsburgh (courtesy of Reddit, 2015).

pleted the circumference of a given ring). The TBM then used hydraulic legs to push off the placed concrete rings as it moved forward. The complete mining assembly measured approximately 150 ft (46 m) from the cutter head to the end of the trailing gantry system.

Paralleling the western side of Mazeroski Way, the 2,240 ft (683 m) TBM section of the tunnel passes below the Equitable Resources building. The tunnel descends on a 6.6 percent grade from the North Shore to a depth of 69 ft (21 m) (25 ft [7.6 m] river depth, 22 ft [6.7 m] further to top of 22 ft [6.7 m] diameter tunnel bore). Below the Allegheny River, the path turns left then right, about 45 degrees each time, to align with Stanwix Street. The tunnel ascends a 7.6 percent grade to arrive at the Gateway Station. Figure 56 shows a photograph of the completed North Shore Connector tunnel.

The key challenges of the North Shore Connector projects included the following: threading the tunnels through the pile-supported foundation of a downtown Pittsburgh landmark building; passing under the 25 ft (7.6 m) deep Allegheny River; and tunneling beneath a busy downtown street adjacent to Penn Avenue Place, and an historically important building founded on spread footings. In addition, controlling ground movement to mitigate the potential for damage to buildings was of paramount importance (Wargo et al., 2009).

The North Shore Connectors original budget was estimated at $350 million. The final cost was $523.4 million (Schmitz, 2010).

Dams

The Ohio River Flood Board, established by the federal government in 1912, examined many strategies for managing stream flow within the Ohio River Basin in terms of flood control, navigation, power, irrigation, and other possible uses. As a result of intense lobbying by the Ohio River Flood Board and with financial cooperation from the Commonwealth of Pennsylvania, the Pittsburgh District of the U.S. Army Corps of Engineers (Pittsburgh District) completed its first comprehensive River Basin Report in 1935. The report proposed a series of dams that would create reservoirs in the headwaters of the Ohio River Basin. This report represented the complete commitment by the Pittsburgh District to the concept of dams utilized for multipurpose water resource development in addition to flood control (Johnson, 1978). Multipurpose projects can include a combination of flood control, water flow for reliable navigation, water quality, recreation, and hydropower generation.

Historic flooding has been common in the Pittsburgh region. Towards noon on St. Patrick's Day in 1936, waters began to fill the valleys in Johnstown, PA. Much like the devastating flood of 1889, the narrow, natural, topographic channels of Stoney Creek and the Little Conemaugh River were incapable of passing much of the rising volume of flood waters through the City of Johnstown, resulting in major flooding. "A scene of inconceivable desolation, following devastation by a flood that rivaled the deluge caused by the historic dam break in 1889" was cited by a reporter from the *Engineering News-Record* in his description of Johnstown after the flood (Johnson, 1978, p. 24). The floodwater surges moved downstream to Pittsburgh, where water filled the downtown, and many residents took to boats to navigate the city streets (see Figure 57). The rivers crested at 46 ft (14 m), which is 30 ft (9 m) above normal river stage in Pittsburgh, on March

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18, 1936. This flooding surpassed prior record stages by more than 5 ft (1.5 m) and resulted in flooding of 62 percent of the downtown "Golden Triangle" area of the city.

It became clear following the March 1936 flood that series of dams and reservoirs were was needed to protect the city from a real and recurring topographically driven flood threat. Congress passed the federal Flood Water Control Act of 1936, authorizing and funding these secondary flood-control structures, including dams and levees, mostly located on tributaries to the three major rivers. Several of the dams built in the Upper Ohio River Basin that protect Pittsburgh today were authorized by this act. One of the most significant retention structures is Kinzua Dam, located on the Allegheny River near Warren, PA. Other flood-control structures authorized by this federal act include Tionesta Dam, Crooked Creek Dam, Conemaugh Dam, and Loyalhanna Dam, all located in the Allegheny River basin above Pittsburgh. In addition, Youghiogheny Dam, located on a tributary to the Monongahela River, was also authorized.

Tygart Dam, which also protects Pittsburgh, was under construction by the Pittsburgh District prior to the Flood Control Act of 1936. It is located on the Tygart River, a tributary to the Monongahela River, at Grafton, WV, and was completed in 1938 at cost of $18.5 million dollars. At the time it was built, Tygart Dam was the highest concrete gravity dam east of the Mississippi. Tygart Dam is a multipurpose project that provides significant flood and flow control to areas downstream, including Morgantown, WV, and ultimately Pittsburgh. Tygart Dam, in addition to the five dams built in response to the act, formed the mainstay of comprehensive surface-water management by the Pittsburgh District in the Upper Ohio River Basin.

Eventually, the total number of dam projects constructed and operated by the Pittsburgh District reached the current level of 16. The project that forms the largest single reservoir in the basin, at a length of over 26 mi. (42 km), is Kinzua Dam, located on the Allegheny River near the Pennsylvania–New York border. Kinzua Dam is the only dam on the mainstem Allegheny River that flows south to the city of Pittsburgh. It is a combination concrete gravity and earth-rock fill dam and is what many believe to be one of Dr. Shailer Philbrick's finest foundation designs. Dr. Philbrick was the Pittsburgh District geologist for the foundation of the dam. The original siting of the dam axis was more than 1 mi (1.6 km) upstream from its present-day location. On account of considerable depth to sound bedrock (silt-shale), the original design called for a rather deep excavation with cofferdam construction and construction of a concrete gravity dam. Dr. Philbrick conducted a detailed field investigation, which included studying the glacial history of the valley and then planning and conducting an extensive program of core borings and geophysical surveys in reaches downstream of the originally selected site. With these data in hand, he proposed an alternate location for the construction of the dam axis, so the dam was fit to the site geologic conditions and the cost estimate was reduced. The design modification was accomplished by constructing a concrete gravity dam section where bedrock was shallow on the left side of the valley and an earth-rock fill embankment on the right side of the valley where bedrock was much deeper. The concrete gravity dam was cast in progressive monolithic sections, so as to permit river flow to continue throughout construction. The embankment was constructed on alluvial soils with an upstream clay-soil blanket. The clay blanket was subsequently tied into a concrete cut-off wall taken to significant depths within the river valley alluvium. This was the first slurry cut-off wall constructed for a dam in the United States (Legget and Karrow, 1983). The earth-rock embankment has a wrap-around section that ties it into the concrete gravity section of the dam. Construction of the dam was completed in 1965. The project has a pumped storage hydropower unit that is operated by a private utility in cooperation with the Pittsburgh District.

The primary purpose of the project is flood mitigation, but the other uses, including water supply, recreation, and hydropower, are carefully balanced to optimize the use of the available water. The ASCE Pittsburgh Section bestowed its Outstanding Civil Engineering Award on the project, recognizing its innovation. The optimized foundation design saved several million dollars. Dr. Philbrick received the Association of Environmental & Engineering Geologists (AEG) Claire P. Holdredge Award in 1977 for his seminal paper "Kinzua Dam and the Glacial Foreland" (Philbrick, 1976). Two honorary members of AEG, Dr. Shailer Philbrick and Harry Ferguson, a coworker and successor as district geologist, were instrumental in developing efficient foundation designs for most of the flood-control dams located within the Pittsburgh District.

History of Cofferdam Construction

Cofferdams have a long history of use in the Pittsburgh region, in particular for concrete gravity dams and for the construction of navigation locks and dams founded on bedrock. The earliest local cofferdams date back to 1878, with federal government construction of the Davis Island Lock and Dam, the first navigation project to be constructed on the Ohio River. Davis Island is located downstream of Pittsburgh. Between

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1878, when construction began, and 1885, when completed, the Davis Island Lock and Dam project incorporated seven very rudimentary wooden but successful cofferdams. O'Bannon (2009) suggested that the cofferdams were designed and constructed in conformance with principles outlined in: *An Elementary Course of Civil Engineering, for Use of the Cadets of the United States Military Academy* (Mahan, 1837).

Cofferdam construction continued on the three rivers from the late 1800s to late 1900s and eventually transitioned from wood to steel sheet pile. From a geological standpoint, cofferdams permitted complete dewatering and then open excavation of river alluvial sediments to reach bedrock and into the rock until a suitable foundation level was encountered. Once uncovered, standard practice was to clean the exposed rock with brushes and high-pressure water jets, clean and treat rock defects with dental concrete, and then cast dam-base concrete on the prepared surface as soon as practical, as a means to avoid any deterioration by air or water slaking (in the case of fine-grained argillaceous bedrock).

In the later 1990s, a highly unique cofferdam was built on the Monongahela River near the Pennsylvania–West Virginia border. The old existing navigation lock at Point Marion, PA, built in 1926, had exceeded its design life. A new, larger lock was needed to improve both structure reliability and to ensure continuous river passage. The challenge for the U.S. Army Corps of Engineers was to build a larger lock chamber (84 ft [26 m] by 720 ft [219 m]) on the landward side of the existing lock chamber (56 ft [17 m] by 360 ft [110 m]). Construction of a lock landward of an existing lock had only been attempted once before in the United States, in 1961, at the General Joe Wheeler Lock and Dam on the Tennessee River in northern Alabama. Construction at the General Joe Wheeler Lock and Dam met with disaster when, during excavation for the new lock, the land wall of the existing lock slid into the excavation. This resulted in loss of life and closure of the river to navigation for several years. The sliding failure was determined to be related to weak clay shale seams in the underlying limestone, a condition that had not been identified during the site investigation (Terzaghi, 1962).

The Pittsburgh District undertook similar construction at Point Marion Lock and Dam with the experience of Wheeler Lock well in mind. This facility is located on the Monongahela River on the Pennsylvania–West Virginia border, about 70 mi. (113 km) upstream from Pittsburgh. Construction of the new lock chamber had to be accomplished while keeping the existing lock chamber in service to accommodate on-going river navigation (Greene et al., 1993). Three rows of high-capacity rock anchors (nearly 500 total) were installed through the landward wall of the existing lock and anchored into the underlying claystones, siltstones, and sandstones, so that the wall could be incorporated as a portion of the cofferdam for the new lock. One row of vertical anchors was installed prior to excavation, and two rows of inclined anchors were placed as the excavation was carried two lifts deeper (see Figure 58). A large portion of the land-wall foundation of the existing lock was on claystone, and therefore it was of the utmost importance that the sliding and overturning stability of the wall be improved (Greene et al., 1993). An extensive instrumentation program was installed to monitor movements and water levels; this program included shear strips, inclinometers, piezometers, and load cells placed on selected inclined rock anchors. The new lock was completed in the early 1990s, and in 1994, the ASCE Pittsburgh Section awarded Point Marion Lock and Dam the Outstanding Civil Engineering Achievement Award. This distinction was primarily due to the unique cofferdam design and construction.

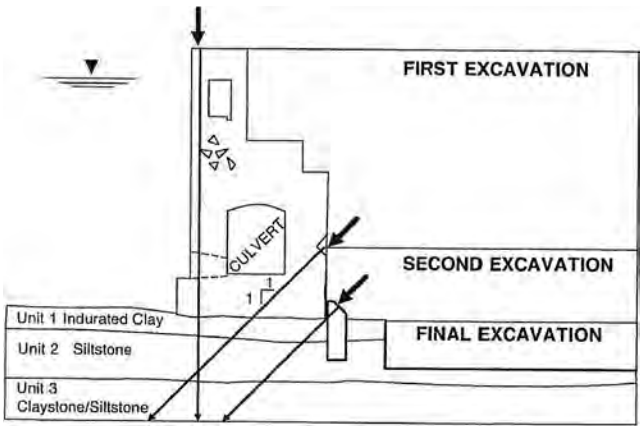

Figure 58. Rock anchor configuration for Point Marion Lock cofferdam (Greene et al., 1993).

Post Cofferdam In-the-Wet Construction

In the late 1990s, replacement of the 100 year old Braddock Dam became necessary. Braddock Dam was part of the Braddock Locks and Dam navigation project, located only 12 mi. (19 km) upstream from Pittsburgh, and it was the first lock and dam on the Monongahela River. Braddock Dam introduced a new type of in-river construction that did not employ the use of cofferdams. This project represented innovation and was a major departure from the proven methods that had been used for several decades. The Braddock Dam employed "float-in" or "in-the-wet construction." The project began in 1999 and was completed in 2004. It represented the first time in the his-

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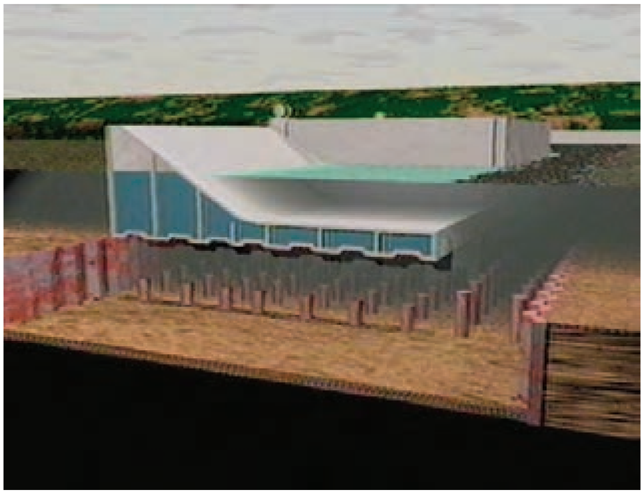

Figure 59. Braddock Dam segment–foundation interface (courtesy of the U.S. Army Corps of Engineers, Pittsburgh District).

Figure 60. Completed Braddock Dam in 2004 (courtesy of the U.S. Army Corps of Engineers, Pittsburgh District).

tory of an inland navigation system that a concrete dam had been floated into place (Edwardo et al., 2002).

As opposed to traditional "in-the-dry" methods of cofferdam construction, the "in-the-wet" method permitted drilled shaft foundations to be built at the site while the two dam segments, which were composed of a combination of pre-cast concrete panels and conventional concrete, were fabricated at an off-site casting basin located downstream of Pittsburgh. Eighty-nine reinforced concrete drilled shafts were installed within the footprint of the dam. Each shaft was 78 in. (2 m) in diameter and 40 ft (12 m) long, which included a 15–20 ft (4.5–6 m) long drilled rock socket. Approximately 20 percent of the drilled shafts were affixed with circular-form, hydraulic flat jacks, which were subsequently used to level the segments of the dam. Once the drilled shafts were completed, the concrete segments were floated upriver, passing through three locks, to the location of the new dam site (Edwardo et al., 2002).

Segment 1 was a 330 ft (100 m) long by 104 ft (32 m) wide concrete section of the dam, and it weighed nearly 11,600 tons (10,000 metric tons), (see Figure 59). The segment was lowered onto the drilled shaft foundations by filling the structure with water and sinking it. The segment-shaft connections were grouted under water, and the interior of the segment was filled with tremie concrete, thus displacing the water. A neat cement grout was used to fill the 1 ft (0.3 m) void that existed between the base of the dam and a pre-placed graded gravel base under the footprint of the dam. Steel sheet piles (Z-type) driven to rock at both the upstream and downstream limits of the dam served as an additional barrier to prevent seepage under the dam.

Segment 2, which measured 265 ft (81 m) by 104 ft (32 m) and weighed 9,000 tons (8,164 metric tons), was installed in the same manner as segment 1.

To complete the Braddock Dam project, the existing 100 year old fixed-crest dam, located approximately 600 ft (182 m) downstream, was completely removed to the riverbed, and the demolished concrete was used for creation of underwater simulated reefs to promote fish habitat. Another environmental aspect of the project was that the dredged material from the footprint of the new dam was tested and found to be suitable for riverside disposal. Some 400,000 yards (305,821 m^3) of dredged material provided cover for the restoration of a nearby brownfield site (an abandoned steel mill property). A photograph of the completed Braddock Dam is shown in Figure 60.

UNDERGROUND STORAGE

For over a century, there has been underground dimension-stone mining of the Vanport Limestone, near Pittsburgh. Several of these abandoned room-and-pillar limestone quarry mines are now used for office space, records storage, vehicle and recreational vehicle (RV) storage, growing mushrooms, manufacture of precision telescope lenses, and even the filming of movies (Kochanov and Bragonier, 2005).

The second largest employer in Butler County is the Boyers underground mine-storage facility, which is located approximately 40 mi. (64 km) north of Pittsburgh. This facility contains offices for six different agencies, including the Office of Personnel Management, Social Security Administration, and The Smithsonian Institution, with a combined on-state

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payroll of some 3,000 federal employees, and a private sector record storage firm as well.

The world's largest mushroom growing facility is in Worthington, which is located about 35 mi. (56 km) northeast of Pittsburgh. This re-purposed former limestone quarry mine features a controlled entry and egress at more than 300 ft (91 m) below the ground surface, and it has been stabilized and improved for production for as far as 0.75 mi (1.2 km) in from the entry portal. The entire original mined area consists of about 150 mi. (241 km) of through-pillar pair passageways that were created by the termination of the rock-production life, now more than 75 years ago. The mine environment, with its constant cool temperature (62°F) and high humidity, is ideal for growing mushrooms.

The Wampum Mine facility, which is also located north of Pittsburgh, is currently used for records storage and was the site for filming portions of the movie "The Zombies" (Kochanov and Bragonier, 2005). The mine had been used during the early years of the Atomic Age to store nuclear materials. The most unique use of the mine occurred in the late 1990s, when a telescope mirror, which at that time was the world's largest single-piece optical element, was manufactured within the Wampum Mine. The mirror blank, initially fabricated by Corning, Inc., measured over 27 ft (8 m) in diameter and was about 9 in. (23 cm) thick. A Pittsburgh firm, Contraves, converted a portion of the Wampum Mine into an optical fabrication facility where the mirror was ground, polished, and tested. The mirror was finished in 1997 and was installed in a telescope at the Mauna Kea Observatory in Hawaii.

In addition to converted mined areas, depleted gas and oil fields have been converted for current natural gas storage. One of more noted gas storage fields in the area is under the Oakford Natural Gas Storage facility about 25 mi. (40 km) east of Pittsburgh. It is one of the largest underground storage facilities in Pennsylvania, and it provides temporary storage for natural gas originating from the South and Midwest for markets in the Northeast and the Mid-Atlantic region. There are two separate storage zones. One is in the Lower Mississippian Murrysville Sand, and the other is in an Upper Devonian sandstone called the "Fifth Sand" (Enbridge, 2017). These storage fields are both geologically contained by stratigraphic and structural characteristics particular to this area.

ENVIRONMENTAL CONCERNS

Abandoned Mine Lands

One unintended and poorly considered legacy of the mining of the abundant coal resources in the Pittsburgh region is the mining-related problems that remain, problems that are generally referred to as abandoned mine lands or AML. AML problems include mine subsidence; unfilled or improperly filled shafts, slopes, and drifts; mine and spoil pile (culm bank) fires; unstable slopes; gas problems stemming from methane, carbon monoxide, carbon dioxide, or hydrogen sulfide; and acid mine drainage.

Coals was mined nearly everywhere in the Pittsburgh region, and now the AML problems are found nearly everywhere as well. The shallow depth to the Pittsburgh Coal, its significant thickness, and the early mining methods and laws, such as 50 percent mining for surface support, came together to create an almost ideal environment for mine subsidence. Much of the area to the east and south of the city is underlain by shallow, abandoned room-and-pillar mining where the overburden thickness is less than 100 ft (30 m), and often less than 50 ft (15 m). An engineering-based study of subsidence over the Pittsburgh Coal (Gray et al., 1977) that was completed in 1976 determined that 251 of the 352 documented incidents of subsidence (about 71 percent) occurred in Allegheny County. This was attributed in part to the area being one of the earliest mined and also to being one of the most densely populated sectors of the region.

There are over 34,000 documented AML features in the state and 296 documented AML sites in Allegheny County alone. Figure 61 shows the current number of AML sites by county in Pennsylvania. As can be seen from Figure 61, the problem is extensive, and the number of AML sites for all of the surrounding mined counties is similar. Figure 62 shows the distribution of individual AML sites in Allegheny County. The Federal Office of Surface Mining had defined three priority levels for pre-law AML sites under the Surface Mining Control and Reclamation Act of 1977 (SMCRA). They initiated an inventory of priority 1 (P1) and priority 2 (P2) AML sites, which are the sites that are counted and are shown on Figure 62, and now the state maintains the inventory (PADEP, 2014). Those sites are generally defined as requiring reclamation to protect the public health and safety from extreme danger of adverse effects (P1) or just from the adverse effects (P2) of coal-mining practices. Priority 3, the sites requiring restoration of land and water resources because of environmental degradation previously caused by the adverse effects of coal mining, are generally not included in the AML inventory list. These sites, which include mine water discharges, abandoned surface mines, and abandoned mine spoil dumps that are not included within P1 and P2 sites, are considered to have a very low priority for reclamation, even though they are as ubiquitous as the P1 and P2 sites.

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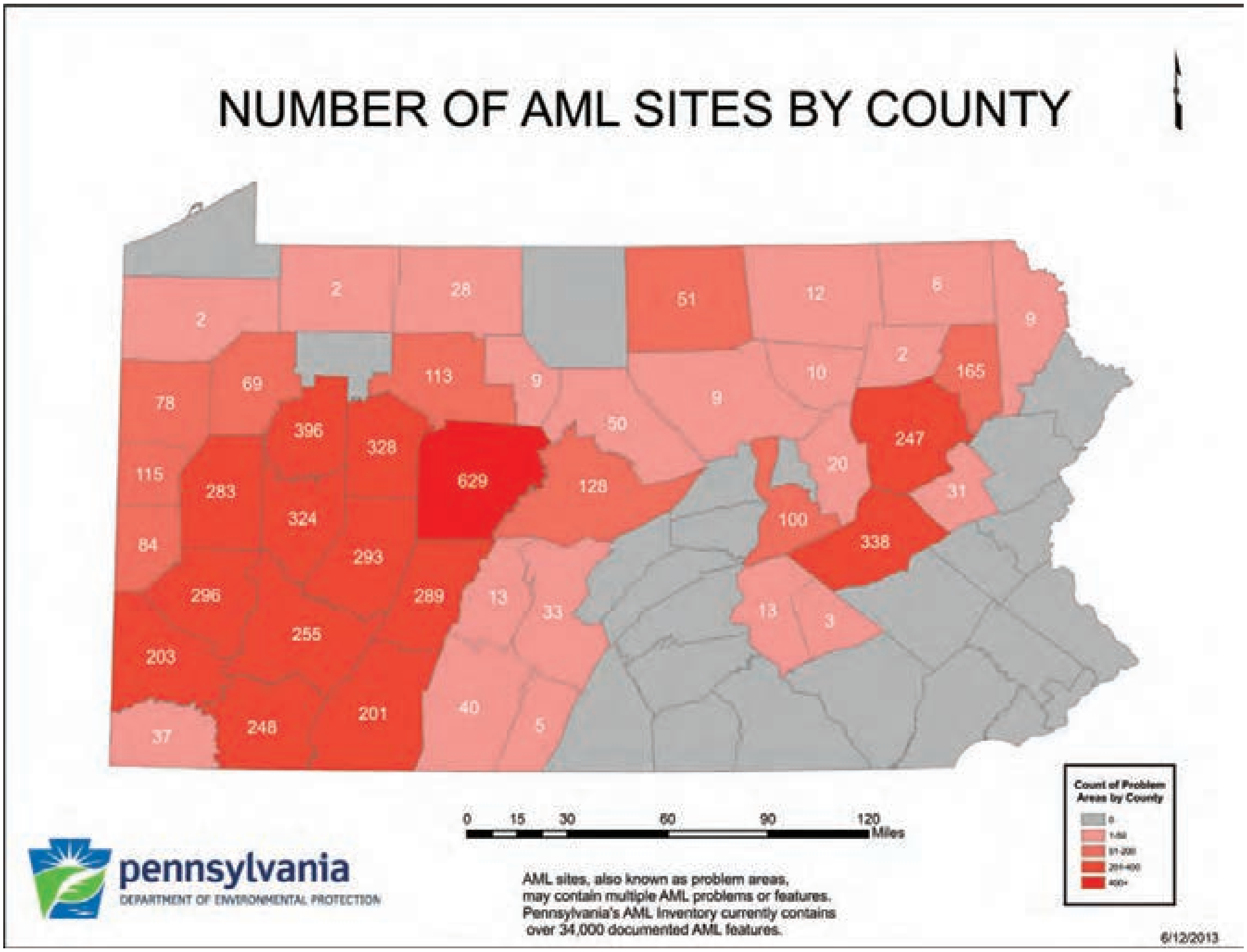

Figure 61. Abandoned mine lands (AML) sites in Pennsylvania by county (PADEP, 2014).

Hydraulic Fracturing Fluids Associated with Natural Gas

In recent years, there has been a boom in the exploration and production of natural gas and natural gas liquids associated with the Marcellus Shale Formation (Pennsylvania Department of Conservation and Natural Resources, 2014). Significant secondary natural gas recovery has resulted from physically improving the permeability of the host rock shale through the process of hydraulic fracturing (fracking) in conjunction with lateral drilling (Figure 63). However, there is controversy concerning the volume, chemical additives, and ultimate fate of fluids used in the hydraulic fracking process. Some 6 to 10 million gallons of freshwater combined with surfactants, chemical additives, and propping sand are used to frack a single well, and to keep the induced fractures open to radially inward flow of formation gas. The actual volume of water, sand, and chemicals used is largely dependent on the length of the lateral leg of the borehole. Fluids used in the hydrofracturing process return to the surface as flowback and produced water and must be recovered with the enhanced flow of natural gas and then treated appropriately and disposed in a regulatory/permitted manner. Major flowback constituents of regulatory concern are released chlorides and total dissolved solids, both which have been used to fingerprint the fluids, if and when they may be detected in surface water. Some of the drillers have elected to dispose of the recovered fluids in Class 2 deep injection wells in neighboring Ohio, and some operators are recycling their produced fluids for re-use in other fracking operations. Flowback is first treated in public and industrial wastewater treatment facilities. Prior studies by the U.S. Army Corps of Engineers (USACE,

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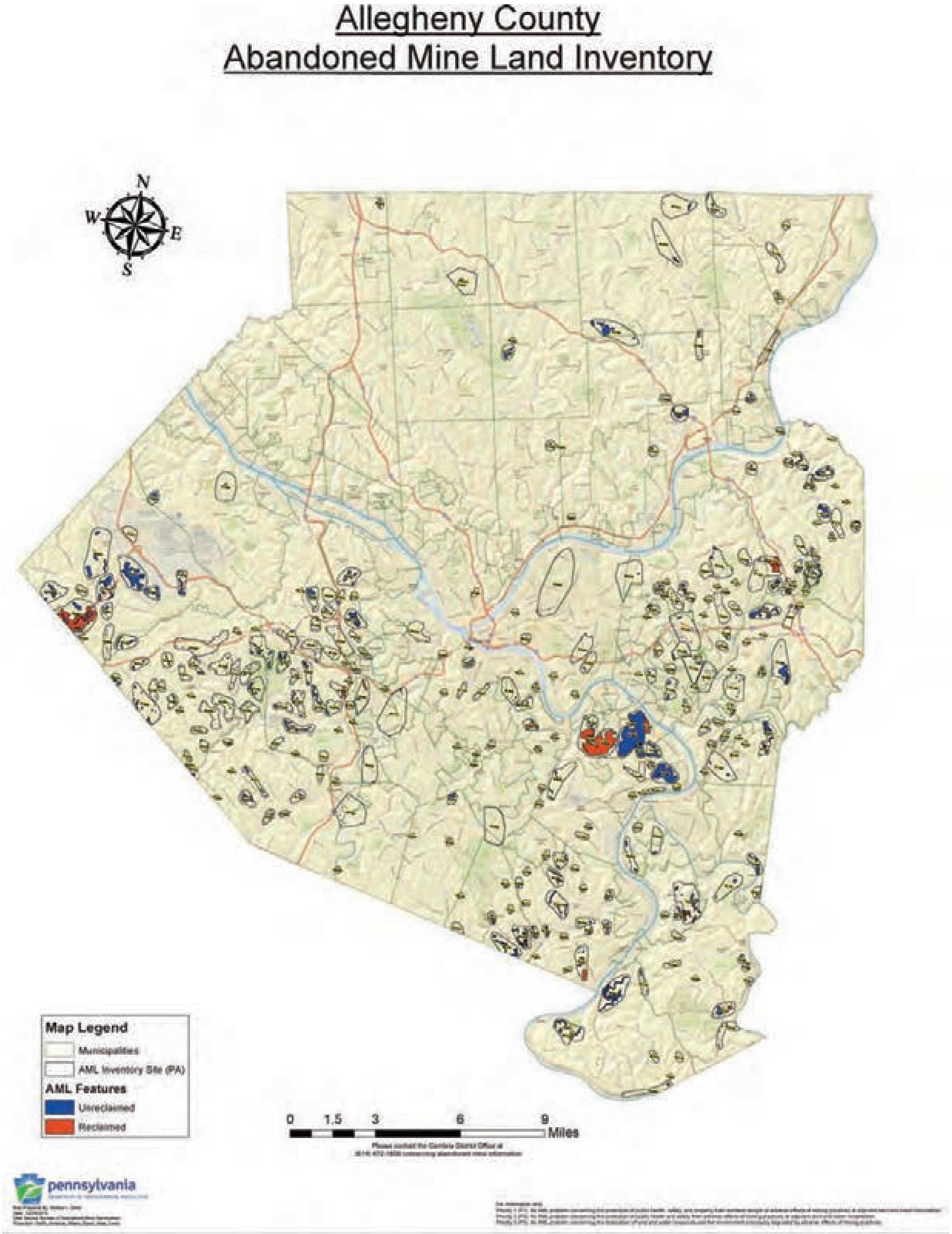

Figure 62. Abandoned mine lands (AML) inventory in Allegheny County (PADEP, 2014).

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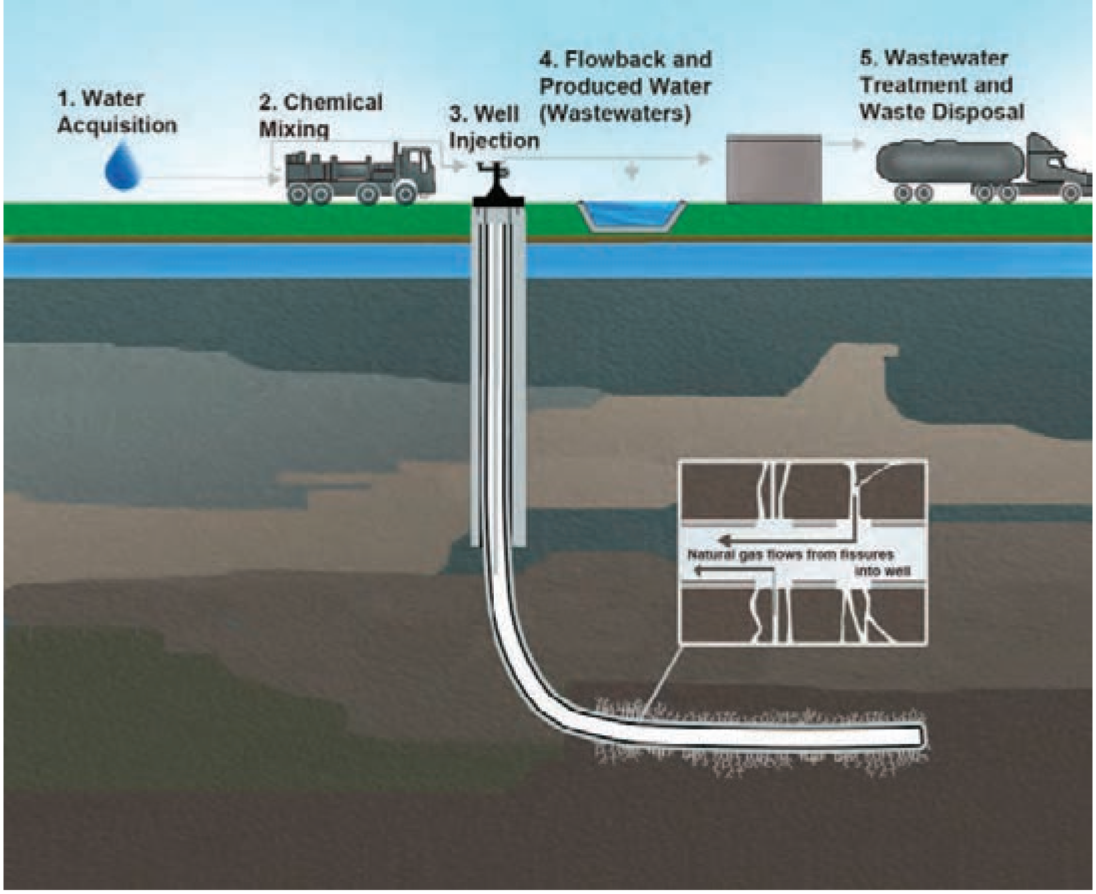

Figure 63. Schematic diagram of shale gas well hydrofracturing (US EPA, 2016).

2012) have shown that the quality of the Monongahela River water has been a concern in the sense of the Federal Clean Water Act (as amended). The U.S. Army Corps of Engineers has confirmed that the primary water-quality problems within the Monongahela River watershed are related to acid mine drainage, traditional gas drilling, industrial/municipal pollution, and in some cases Marcellus Shale gas production. State and federal environmental agencies are working with the gas drilling firms to ensure that fair but important environmental limits are placed on the disposal of gas-filled recovery fluids.

Low-Level Nuclear Waste—Shallow Land Disposal Area

The Parks Township Shallow Land Disposal Area (SLDA) site, located approximately 23 mi. (37 km) east-northeast of Pittsburgh, encompasses 44 acres (17.8 hectares) of private land presently owned by BWX Technologies. Land use within the vicinity of the SLDA site is mixed, consisting of small residential communities, individual rural residences, small farms with croplands and pastures, idle farmland, forested areas, and light industrial properties (USACE, 2002).

The Nuclear Materials and Equipment Corporation (NUMEC), which was a predecessor of BWX Technologies, disposed of low-level radioactive waste (LLW) materials, generated from national defense programs, on-site between 1961 and 1970 in accordance with Atomic Energy Commission regulations (predecessor to the present Nuclear Regulatory Commission). BWX Technologies presently is licensed by the Nuclear Regulatory Commission to properly maintain the site to ensure the protection of caretaker staff and of the general surrounding public. The SLDA site consists of 10 trenches containing contaminated soil and other waste materials. The estimated quantity of contaminated waste material from the trenches is approximately 24,300 yd^3 (688 m^3). This equates to the area of a football field 12 ft (3.6 m) deep. The contaminated waste included uranium, thorium, americium, and plutonium.

In the early 1900s, the Upper Freeport Coal was deep-mined at a depth of 60–100 ft (18–30 m) beneath the uphill portion of the site and surface mined later

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on the downhill portion (USACE, 2002). Nine of the trenches are on the uphill portion of the site in 11–16 ft (3.3–4.8 m) of Pleistocene terrace deposits that overlie 54–80 ft (16–24 m) of shale and sandstone, above the mined Upper Freeport Coal. The tenth trench, in the strip mine downhill of the other trenches, is located within the strip mine spoil, and it rests on a clay and shale layer below the Upper Freeport Coal.

In January 2002, Congress directed the U.S. Army Corps of Engineers to clean up radioactive waste at the SLDA site. At the time of this writing, all of the excavated contaminated material has been packaged and transported from the project site to a secure landfill meeting containment requirements of the federal Resource Conservation and Recovery Act of 1976 (as amended). The remedial action wastewater treatment plant (WWTP) has been disassembled and removed from the project site. The purpose of the WWTP was to capture, filter, and contain suspended waste particulates from remedial action wastewater used during remediation activities (USACE, 2007). A late 2014 contract was planned for construction of a new long-term wastewater treatment plant at the site.

CONCLUSION

Pittsburgh has a rich history, and its Three Rivers have always played a major role in the city's growth and development. No longer known as just "The Steel City," Pittsburgh is a major metropolitan area rich with mineral resources and abundant surface and groundwater supplies. The city is now vibrant, with a bright future, with new construction, and with a greatly improved natural environment. Air quality has improved, as has the quality of the region's three rivers, the Allegheny, Monongahela, and the Ohio.

Western Pennsylvania enjoys abundant natural resources. Coal and natural gas produced from shale formations are the significant energy resources of the area. Acid mine drainage remains a legacy environmental impact from past coal mining.

Geohazards are present in the Pittsburgh region, including slope instability, mine subsidence, expansive shales and slags, and pyritic acid rock. The local infrastructure is aging, and there is a need to repair major highways, including the Pennsylvania Turnpike, the oldest interstate in the nation. Pittsburgh is a city of bridges, and many are in need of repair or replacement. The river navigation system of locks and dams is aging, and one major replacement project is under way on the Monongahela River, with others being planned for the Ohio River.

Pittsburgh is a city with a bright future as its industrial base changes and the region's abundant natural resources are utilized. Water is plentiful and is used in many ways to benefit the citizens of the region.

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