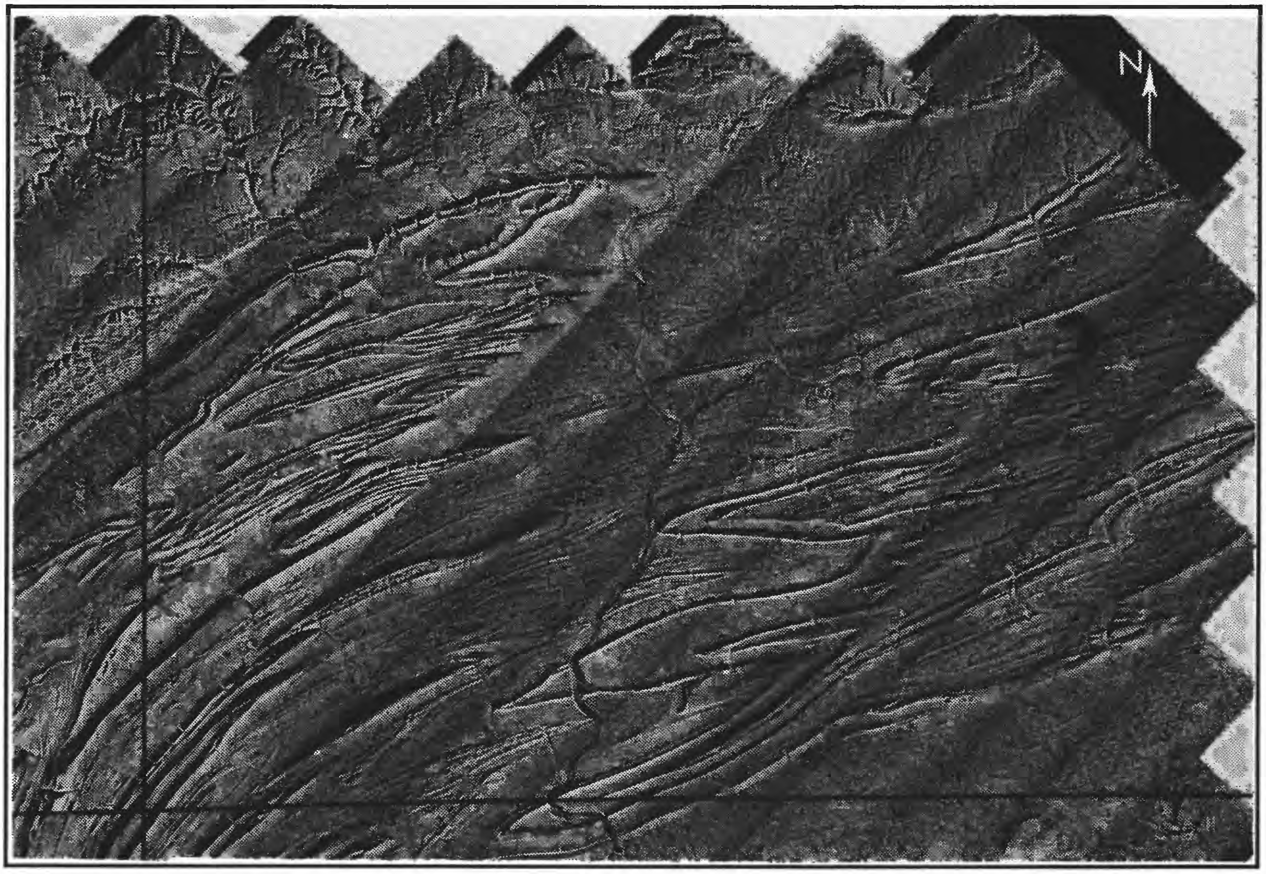
U.S. Geological Survey Open-File Report # 92-568

Field Trip Guidebook:

The Anthracite Basins of Eastern Pennsylvania



by:

Jeffrey R. Levine and Jane R. Eggleston

for the

1992 Joint Meeting of the

International Committee for Coal and Organic Petrology (44th) & The Society for Organic Petrology (9th)

The Pennsylvania State University
University Park, Pennsylvania
July 25, 1992

Field Trip Guidebook:

The Anthracite Basins of Eastern Pennsylvania

U.S. Geological Survey Open-File Report #92-568

by:

Jeffrey R. Levine
The University of Alabama, Tuscaloosa

and

Jane R. Eggleston
United Stated Geological Survey, Reston

with contributions by:

Eric Daniels, Chevron Oilfield Research, La Habra, CA
David C. Glick, Penn State University, University Park, PA
and Christopher Wnuk, U.S. Geological Survey, Reston, VA

for the

1992 Joint Meeting of the

International Committee for
Coal and Organic Petrology (44th)

& The Society for Organic Petrology (9th)

Cover Photo: Side-looking airborne radar mosaic of central Pennsylvania, encompassing the field trip route and most of the Pennsylvania Anthracite region. The Susquehanna River flows from north to south across the center of the photo. To the east of the river lie the anthracite basins, delineated by the bounding sandstone ridges of the Pennsylvanian-aged Pottsville Formation (inner ridge) and the Mississippian-aged Pocono Formation (outer ridge). Visible in the photo are the southwestern corner of the Northern field (upper right), the Eastern and Western Middle fields (center right) and the Southern field (lower right), with its characteristic "fishtail". To the west of the river, the predominant ridges are formed by the Ordovician Bald Eagle and Silurian Tuscarora Formations. The town of State College and the campus of Penn State University lie immediately southwest of the nose one of these folds (Mt. Nittany), which stands prominently above the carbonate valley floor near the center-left edge of the photo. The Tuscarora fold trend plunges eastward into the subsurface along a tectonic boundary that roughly parallels the Susquehanna River. In the extreme northern and northwestern are the comparatively flat-lying Upper Paleozoic strata of the Allegheny Plateau, with their characteristic dendritic drainage pattern. (Photo courtesy of H. Pohn, U.S. Geological Survey).

ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance, logistical support, and financial support for this field trip provided by Alan Davis, General Chairman of the 44th Meeting of the International Committee for Coal Petrology, along with his co-workers at The Pennsylvania State University.

C. Wnuk would like to thank Robert C. Smith of the Topographic and Geologic Survey of Pennsylvania and George Myer of the Geology Department at Temple University for the information that they provided about the Saint Clair fossil locality, and Hermann W. Pfefferkorn for his comments about the general biostratigraphy in the Anthracite region.

J.R. Eggleston would like to thank colleague William Edmunds, Consulting Coal Geologist (Harrisburg, PA), for his valuable insights into interpretation of depositional environments in the Anthracite region.

KOHINOOR COLLIERY

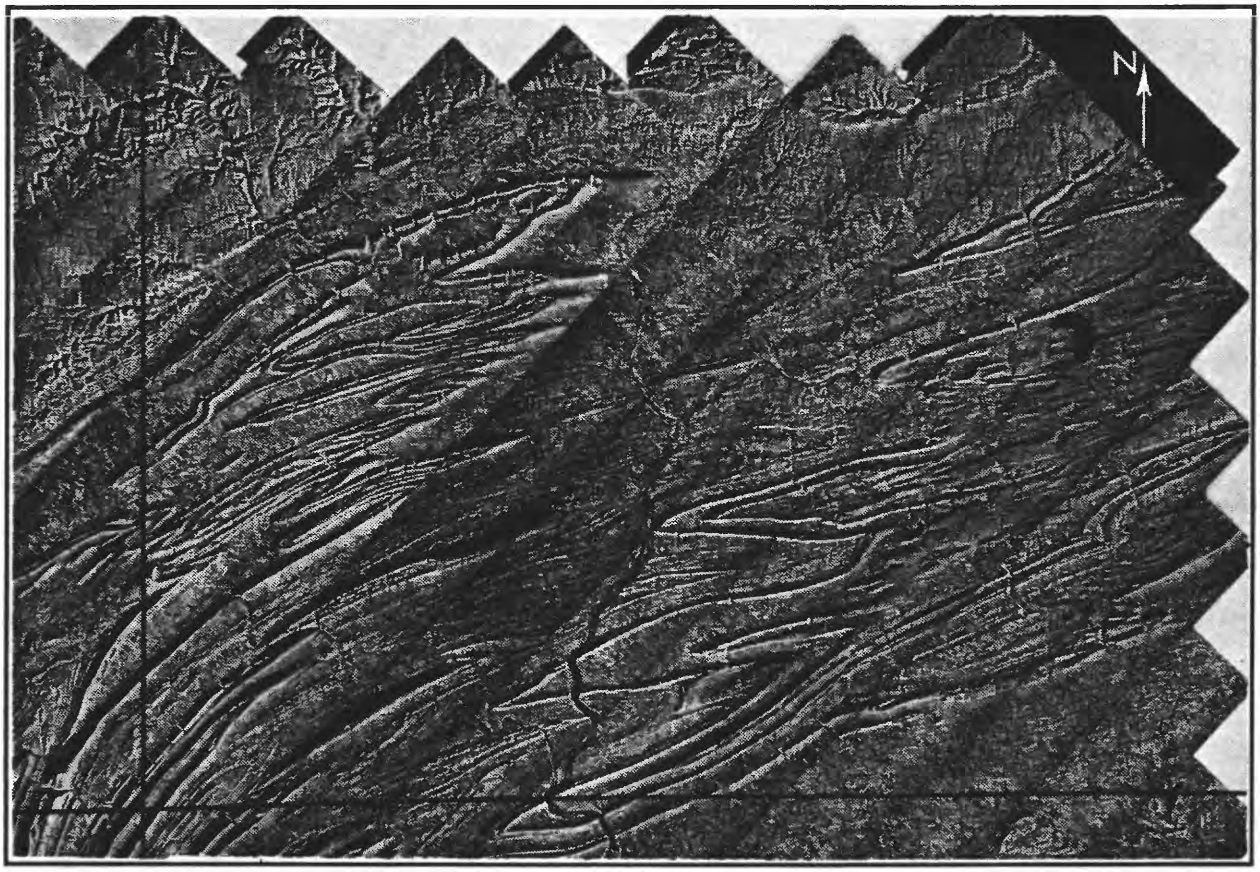
Kohinoor Colliery, Shenandoah, Pennsylvania, as it appeared in the 1880s, located in the eastern end of the Western Middle Anthracite field, owned and operated by Philadelphia and Reading Coal and Iron Company, predecessor to the Reading Anthracite Coal Company. (Courtesy of the George Bretz Collection, Albin O. Kuhn Library, University of Maryland, Baltimore County)

[Note: This and other historical photos appearing througout this guidebook are the work of George Bretz, taken for the most part during the 1880s. Bretz was a professional photographer based in Pottsville, PA, who worked extensively in the Anthracite fields. A collection of his photos has been published by Beck (1977); and selected Bretz photos also appear in Miller and Sharpless (1985).

U.S. Geological Survey Open-File Report # 92-568

Field Trip Guidebook:

The Anthracite Basins of Eastern Pennsylvania



by:

Jeffrey R. Levine and Jane R. Eggleston

for the

1992 Joint Meeting of the

International Committee for Coal and Organic Petrology (44th) & The Society for Organic Petrology (9th)

The Pennsylvania State University
University Park, Pennsylvania
July 25, 1992

Field Trip Guidebook:

The Anthracite Basins of Eastern Pennsylvania

U.S. Geological Survey Open-File Report #92-568

by:

Jeffrey R. Levine
The University of Alabama, Tuscaloosa

and

Jane R. Eggleston
United Stated Geological Survey, Reston

with contributions by:

Eric Daniels, Chevron Oilfield Research, La Habra, CA
David C. Glick, Penn State University, University Park, PA
and Christopher Wnuk, U.S. Geological Survey, Reston, VA

for the

1992 Joint Meeting of the

International Committee for
Coal and Organic Petrology (44th)

& The Society for Organic Petrology (9th)

Cover Photo: Side-looking airborne radar mosaic of central Pennsylvania, encompassing the field trip route and most of the Pennsylvania Anthracite region. The Susquehanna River flows from north to south across the center of the photo. To the east of the river lie the anthracite basins, delineated by the bounding sandstone ridges of the Pennsylvanian-aged Pottsville Formation (inner ridge) and the Mississippian-aged Pocono Formation (outer ridge). Visible in the photo are the southwestern corner of the Northern field (upper right), the Eastern and Western Middle fields (center right) and the Southern field (lower right), with its characteristic "fishtail". To the west of the river, the predominant ridges are formed by the Ordovician Bald Eagle and Silurian Tuscarora Formations. The town of State College and the campus of Penn State University lie immediately southwest of the nose one of these folds (Mt. Nittany), which stands prominently above the carbonate valley floor near the center-left edge of the photo. The Tuscarora fold trend plunges eastward into the subsurface along a tectonic boundary that roughly parallels the Susquehanna River. In the extreme northern and northwestern are the comparatively flat-lying Upper Paleozoic strata of the Allegheny Plateau, with their characteristic dendritic drainage pattern. (Photo courtesy of H. Pohn, U.S. Geological Survey).

ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance, logistical support, and financial support for this field trip provided by Alan Davis, General Chairman of the 44th Meeting of the International Committee for Coal Petrology, along with his co-workers at The Pennsylvania State University.

C. Wnuk would like to thank Robert C. Smith of the Topographic and Geologic Survey of Pennsylvania and George Myer of the Geology Department at Temple University for the information that they provided about the Saint Clair fossil locality, and Hermann W. Pfefferkorn for his comments about the general biostratigraphy in the Anthracite region.

J.R. Eggleston would like to thank colleague William Edmunds, Consulting Coal Geologist (Harrisburg, PA), for his valuable insights into interpretation of depositional environments in the Anthracite region.

KOHINOOR COLLIERY

Kohinoor Colliery, Shenandoah, Pennsylvania, as it appeared in the 1880s, located in the eastern end of the Western Middle Anthracite field, owned and operated by Philadelphia and Reading Coal and Iron Company, predecessor to the Reading Anthracite Coal Company. (Courtesy of the George Bretz Collection, Albin O. Kuhn Library, University of Maryland, Baltimore County)

(Note: This and other historical photos appearing througout this guidebook are the work of George Bretz, taken for the most part during the 1880s. Bretz was a professional photographer based in Pottsville, PA, who worked extensively in the Anthracite fields. A collection of his photos has been published by Beck (1977); and selected Bretz photos also appear in Miller and Sharpless (1985).

Table of Contents

Welcome!!

Dear TSOP & ICCP Colleagues,

Welcome to the field excursion to the Pennsylvania Anthracite region, held in conjunction with the 1992 joint meeting of The Society for Organic Petrology and the International Committee for Coal and Organic Petrology.

The Anthracite region of eastern Pennsylvania is a fascinating area, both from a scientific and historical perspective. Our trip today is intended to expose you to as many of its unique aspects as possible. Both of your field trip leaders have had the opportunity to work in the Pennsylvania anthracite region over the course of many years and we're very pleased to have the chance to share it with you today.

From a geological perspective, the most remarkable aspect of the Anthracite region is the large anthracite resource itself. One of the peculiarities of sedimentary basins is that coal-bearing strata are only rarely subjected to the conditions required for coalification to anthracite rank. Whereas anthracites represent no more than 1% or so of total U.S. coal resources, over 90% of the (original) anthracite reserves in the U.S. were located here in eastern Pennsylvania!

There are many other geological "superlatives" about the region as well. The Pennsylvania Anthracite fields contain the thickest Carboniferous coal beds in the eastern U.S., with as much as 15 m of coal occurring as a single bed in the Mammoth coal zone. Where the coals have been structurally thickened, individual beds may locally exceed 65 meters. The coal-bearing sequence in the Anthracite region also represents the thickest extant section of Carboniferous molasse in the central Appalachians, with as much as 1.5 kilometers of strata preserved. By virtue of structural downwarping, the coals are also extremely deep, extending well below sea level in the Southern field.

In the mid- to late 1800s, the Pennsylvania anthracite fields were the first area where large-scale coal mining operations were undertaken in the Americas, when anthracite became a highly desirable fuel for home heating and industrial applications. The intensive mining gave rise to terrible working and living conditions for the miners and their families which, in turn, gave rise to the birth of the organized labor movement in the U.S. with the clandestine activities of the "Molly Maguires".

Although the mining "boom" has long since passed, there are still many colorful (and painful) reminders of by-gone days. Our excursion today is intended to introduce you to as many interesting aspects of the Anthracite region as possible within the context of a one-day trip, including facets of the structural geology and tectonics, stratigraphy, sedimentary depositional environments, paleobotany, diagenesis and coalification, metamorphic petrology, and organic petrology, plus mining methods, labor history, and cultural history. During our travels we will pass through beautiful countryside and charming towns of central Pennsylvania. We will also see landscape devastated by strip mining and typical anthracite mining communities, most of which have seen "better days" economically. All in all, there should be something for everyone.

We hope you enjoy your visit.

--Jeff Levine and Jane Eggleston

REGIONAL PHYSIOGRAPHY AND GEOLOGY

Jeffrey R. Levine

Pennsylvania's anthracite basins (Figs. 1 & 2) lie within the Valley and Ridge physiographic province, which is characterized by long, narrow, sinuous ridges (generally 380 to 580 m elevation) and broad, (comparatively) flat valleys (150 to 500 m). These physiographic features are the erosional manifestation of the structural geology and stratigraphy of the central Appalachian foreland basin fold-and-thrust belt. Ridges have formed where resistant sandstones intersect the present-day topographic surface, while the valleys represent the outcrop of erosionally-incompetent limestones and finer-grained clastics.

The Allegheny Plateau, lying to the north of the Anthracite region is characterized by flat-lying to slightly dipping strata, while the Blue Ridge and Piedmont provinces to the southeast represent the crystalline core rocks of the Appalachian orogen.

The major ridge-forming sandstones in the central Appalachians are the Bald Eagle Fm. (Ordovician), the Tuscarora Fm. (basal Silurian), the Pocono Fm. (Mississippian), and the Pottsville Fm. (Pennsylvanian). Each of these sandstones represents a part of a major Paleozoic alluvial/deltaic system, with paleosource terrane(s) situated in the southeast and sediment transport direction(s) toward the west and northwest. Each influx of clastic materials can be linked to the erosional unroofing of orogenic source terrane occurring either concurrent with or subsequent to orogenesis

In west-central Pennsylvania immediately to the west of the Susquehanna River, where Lower Paleozoic strata are exposed at the surface, Tuscarora sandstone ridges are predominant. To the east of the river, major Alleghanian fold trains developed in the Tuscarora Fm. plunge eastward and disappear beneath younger upper Paleozoic strata along a NNE-SSW-oriented line referred to as the "Pennsylvania Culmination". Thus, in the east-central part of the state, Pocono and Pottsville ridges are predominant.

The typical fold geometry of the region, characterized by long relatively straight fold limbs, narrow hinge zones, and gently plunging fold axes, gives the anthracite basins their characteristic "canoe-shaped" configuration. The basal coal-bearing Pottsville Fm. forms prominent ridges which enclose the coal-rich, more easily eroded Llewellyn Fm. The "tip" of each canoe represents the area where the axial zone in the Pottsville Formation intersects the topographic surface. In the Southern field, where the three members of the Pottsville Formation are each thick and well developed, the southern bounding ridge (Sharp Mountain) is "double-crested", (as seen at stop #4). Here, the Sharp Mountain and Tumbling Run members form ridges, while the intervening Schuylkill member forms a narrow intervening valley.

The coal fields of the Anthracite region are the erosional remnants of a once much more extensive tract of coal-bearing strata. In all likelihood, these strata were at their time of deposition contiguous with time-equivalent strata of the bituminous coal fields of the Allegheny Plateau in western Pennsylvania. The Southern Anthracite field is the largest of the basins, followed by the Northern, Western Middle field, and Eastern Middle Anthracite fields.

Two aspects of the present day alluvial drainage patterns in central Pennsylvania are particularly interesting. First, drainage and sediment transport directions in the present day river systems in the region are opposite to the ones which operated during the Paleozoic and which deposited the coal-bearing Pottsville and Llewellyn strata (Meckel, 1967). Whereas the former orogenic source terrane was once a high standing mountain belt (Slingerland and Beaumont, 1989), it is now a topographical lowland, represented by the present-day Piedmont and Coastal Plain. The former foreland basin, the axis of which lay in central and western Pennsylvania, is now a topographical high region, by virtue of its erosionally-resistant quartzose sandstones.

The second interesting aspect of the present-day river drainage is that, with a few exceptions, the major rivers in the region (Susquehanna, Schylkill, and Lehigh), cut transversely across the major ridges, rather than being deflected around them. This phenomenon has long attracted the interest of geomorphologists, who have interpreted that the locus for the major river valleys was established long before erosional processes intersected the present-day ridge-forming sandstones. According to this model, once the location of the major river valleys was established, they continued to maintain roughly their present course, even as they progressively cut down into the underlying strata. The resultant narrow river "gaps", such as the where the Schuylkill River cuts across Sharp Mountain at Stop 4, have served as major transportation conduits from the earliest days of human habitation in the Anthracite region.

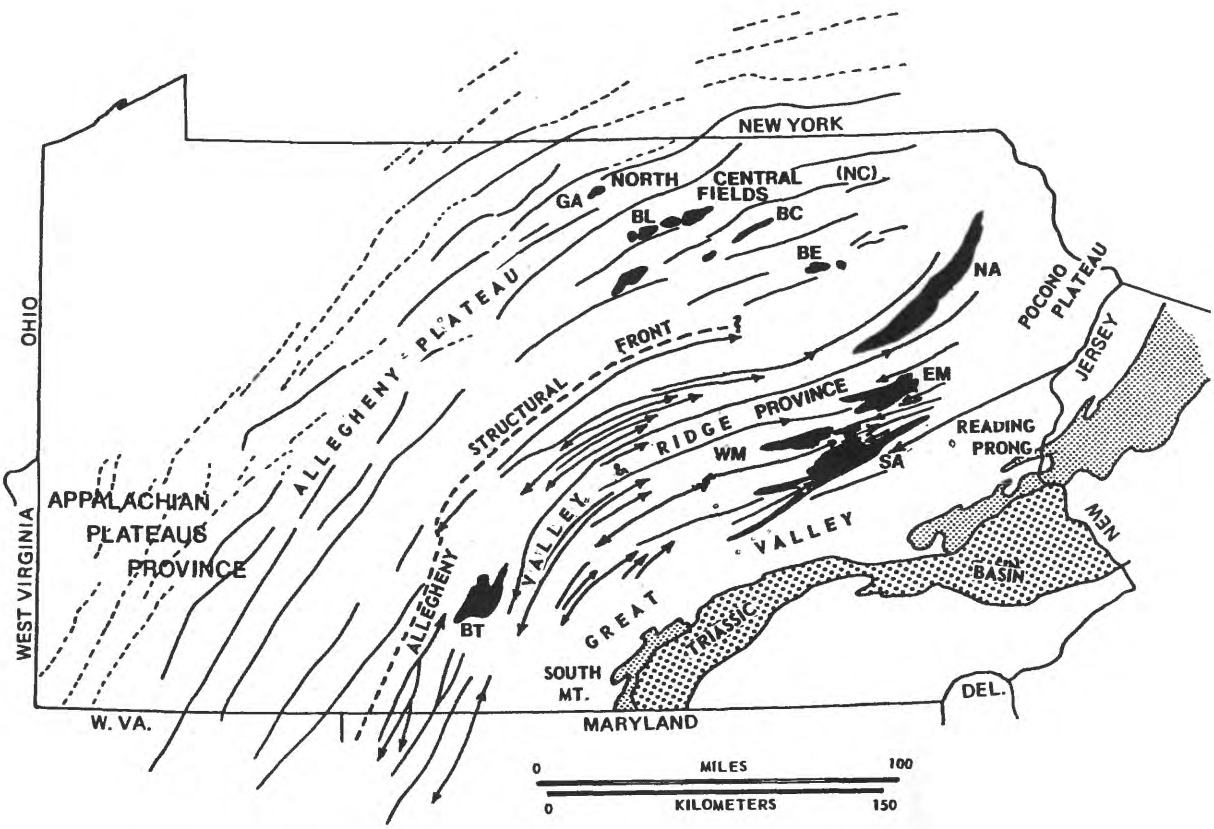


Figure 1. Map of the geology of the Appalachian basin in Pennsylvania and adjoining areas. Solid black represents areas where Upper Carboniferous coal-bearing strata have been preserved in 1st-order Alleghanian synclinoria. Coal-bearing rocks also outcrop over most of the Allegheny Plateau in western Pennsylvania, but are not depicted in black here. Principal coal basins are (from west to east): the Allegheny Plateau, Broad Top (BT), the North-Central fields, which include the Bernice (BE), Barclay (BC), Blossburg (BL), and Gaines (GA) basins, Western Middle Anthracite (WM), Southern Anthracite (SA), Eastern Middle Anthracite (EM), and Northern Anthracite (NA). Latest Carboniferous (?) to early Permian Alleghanian tectonism is evidenced by the major (1st-order) anticlinal axes, shown by solid lines (> 91 m vertical relief) and dashed lines (< 91 m relief). Data compiled from Gwinn (1964), Rodgers (1970), Pennsylvania Bureau of Topographic and Geologic Survey (1980), and Engelder and Engelder (1977).

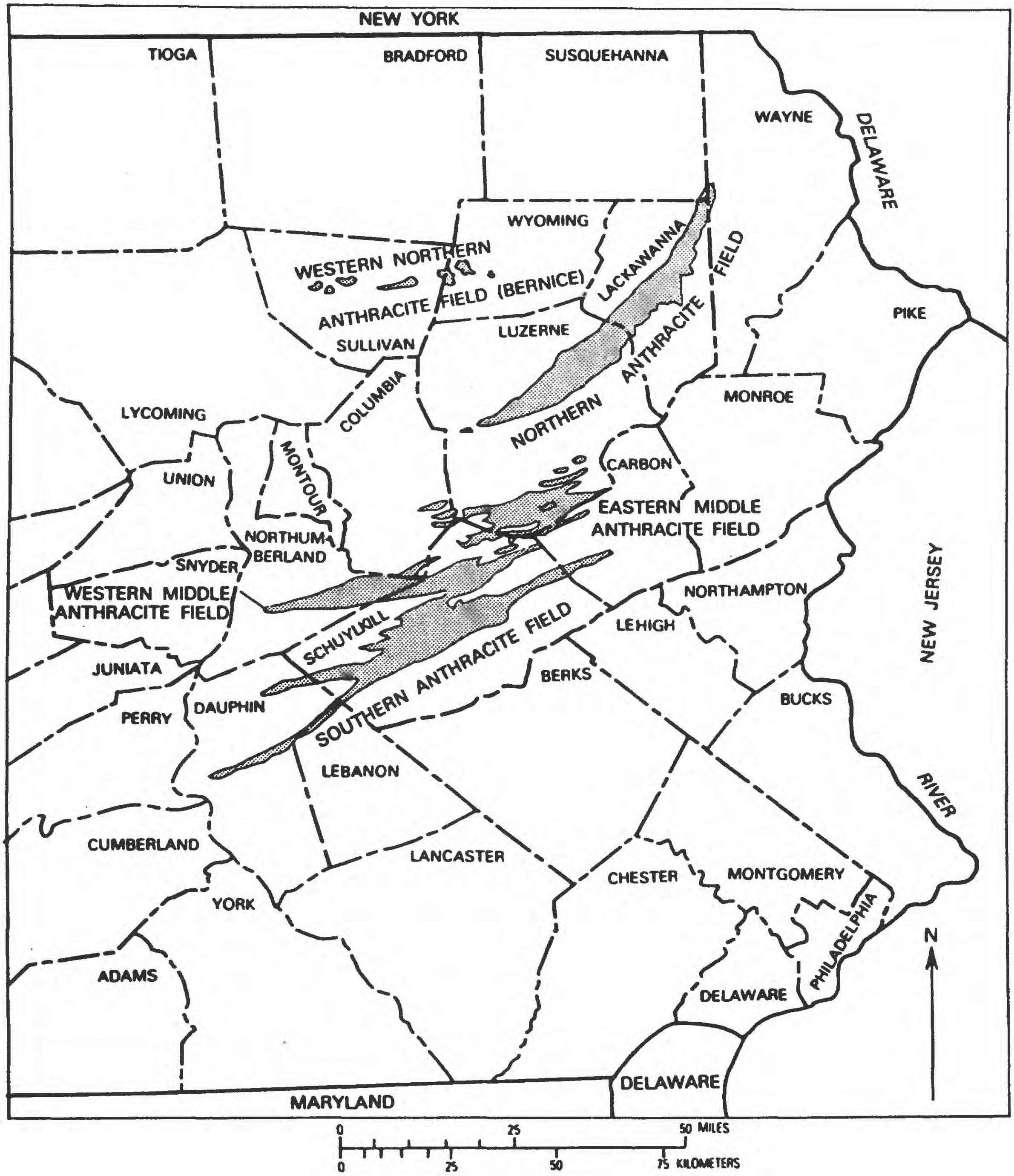


Figure 2. Map showing the locations of the anthracite fields in eastern Pennsylvania.

STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS

Jane R. Eggleston

Stratigraphy

All stops on this trip will deal with rocks of Late Mississippian through Middle Pennsylvanian age equivalent to the Chesterian through Desmoinesian of mid-continent chronostratigraphy and the Namurian B through Westphalian D of the European chronostratigraphy. The stratigraphically highest Pennsylvanian rocks present in this area are of Late Pennsylvanian (Virgilian) age (Fig. 3).

Mauch Chunk Formation

The Mauch Chunk Formation in this area is generally poorly exposed, but, where unaffected by faulting, measures about 1100 to 1500 m (3700 to 5000 ft) thick. The essential characteristic defining the Mauch Chunk is its dominant red coloration. It is divided into three members, of which only the upper two will be considered on this trip.

The upper member of the Mauch Chunk is an interbedded transition between finer grained red claystone, shale, and sandstone of the underlying middle member, and coarser grained gray and olive-gray sandstone and conglomerates of the overlying Pottsville Formation. Wood *et al.* (1969, p. 67) report that the upper member ranges from 0 to 275 m (0 to 900 ft) thick and averages about 180 m (600 ft).

The base of the Mauch Chunk upper member is placed at the stratigraphically lowest occurrence of Pottsville-type (i.e. non-red) sandstone or conglomerate. The upper contact with the Pottsville Formation is placed at the stratigraphically highest occurrence of Mauch Chunk-type red beds.

In as much as the Mauch Chunk Formation along the southern edge of the Southern Anthracite field directly underlies the type section for the Pottsville Formation, and hence by definition the base of the Pennsylvanian System, the Mauch Chunk is, at that point, entirely Mississippian in age. The time-transgressive nature of the formational boundary to the north (Wood et al., 1969a) implies that at least a small part of the upper member of the Mauch Chunk becomes Pennsylvanian in age in that direction.

Pottsville Formation

The Pottsville Formation is about 70 to 80 percent conglomerate, conglomeratic sandstone, and sandstone with the remainder consisting of shale, siltstone, and coal. At any given locale, the base is placed at the stratigraphically highest occurrence of Mauch Chunk Formation red lithology and the top is at the base of the shale below the Buck Mountain coal bed (Fig. 3). The Pottsville Formation at Pottsville, PA is by definition the base of the Pennsylvanian System.

The Pottsville is as much as 460 m (1500 ft) thick along the south edge of the Southern Anthracite field, but thins rapidly to the north. It is less than 60 m (197 ft) thick in parts of the Eastern Middle Anthracite and Northern Anthracite fields. There are four apparent causes of Pottsville thinning: (1) increasing distance from source areas, (2) thinning as deposition passes from the rapidly subsiding trough in the south to the more stable craton edge in the north, (3) loss of section at the base by facies change to the Mauch Chunk Formation, and (4) loss to an internal disconformity at the base of the Sharp Mountain Member.

The Pottsville Formation is divided into the Tumbling Run, Schuylkill, and Sharp Mountain Members in ascending order (Wood *et al.*, 1956). The members are separated by conglomerates at the base of the Schuylkill and Sharp Mountain, although the former seems difficult to recognize in many areas. The base of the Sharp Mountain is a very substantial disconformity.

The Pottsville conglomerates contain pebbles and cobbles as much as 17 cm (8 in.), but average between 1.25 and 3.0 cm (0.5 to 0.75 in.). Most clasts are vein quartz or quartzite and shale fragments, although the lower two-thirds of the Tumbling Run contains a notable fraction of schist, gneiss, chert, sandstone, and siltstone pebbles.

The lower two-thirds of the Tumbling Run Member (below the position of the Lykens Valley No. 5 coal bed) is distinguishable from the rest of the formation by its being olive or greenish gray as opposed to various degrees of dark gray to light gray, the presence of a small but persistent fraction of metamorphic and chert clasts in the conglomerate, the absence of coal beds, and very limited occurrences of plant fragments and carbonaceous material.

The Pottsville Formation contains 13 coal beds which are locally persistent enough to be named in the Southern field (Fig. 3). None are of persistently mineable thickness and only a few are found in the Western Middle field and only one occurs in the Eastern Middle field. Based upon fossil flora (Read and Mamay, 1964), the age of the Pottsville extends from Morrowan into early Desmoinesian time (late Namurian into Westphalian C or D).

Llewellyn Formation

The Llewellyn Formation (Wood *et al.*, 1962) includes all rocks, exclusive of Quarternary deposits, above the Pottsville Formation in the Anthracite region. It is thought to be entirely Pennsylvanian in age, although the uppermost stratigraphic part could be Permian. The formation base is the base of the shale below the Buck Mountain (No.5) coal bed (Fig. 3). The thickest preserved section of strata is about 1070 m (3400 ft).

Lithologically, the Llewellyn Formation is a complex heterogeneous mixture of clastic rock types ranging from conglomerate to clay shale and includes numerous coal beds. The upper one-third of the formation is present only in a limited area of the Southern field and is so poorly exposed that little detail is available. The lower two-thirds is characterized by continuous, rapid vertical and lateral variability. Llewellyn rocks range in color from light gray to dark gray, gray-black, black, yellow-gray, and some green-gray and brown-gray. Fossilized plant material is common throughout. Most Llewellyn clastics may be classified as subgraywackes.

Conglomerate and conglomeratic sandstone in the Llewellyn are much less common than in the underlying Pottsville Formation. Pebbles may be as much as 7.5 cm (3 in.) in diameter, but are usually about 1.25 cm (0.5 in.). Most conglomerate clasts are vein quartz with a small fraction of sedimentary and other metamorphic rocks. The percentage of metamorphic rock clasts increases stratigraphically upward, suggesting that the metamorphic terrain in of the source area was being more widely exposed and deeply eroded.

Sandstones are fine grained to coarse grained and usually occur as tabular beds; cross bedding is common. Shales and siltstones are usually in beds less than 1 m (3 ft) thick, but may reach up to 15 m (50 ft) in thickness locally. Many shales and siltstones contain carbonaceous plant debris and coaly stringers.

The Llewellyn contains 40 anthracite beds that are sufficiently persistent or mineable to warrant assignment of a name and/or a number (Fig. 3). The degree of coal bed continuity implied by the bed nomenclature should not be taken too literally. Few, if any, beds are continuous sheet deposits. The thickest and most persistent anthracite beds are confined to the lower 450 m (1500 ft) of the formation and most to the lowest 200 m (650 ft). Numerous unnamed local beds and splits of the major beds are scattered throughout the stratigraphic sequence. The usual thickness of individual anthracite beds probably does not exceed 18 m (60 ft) measured normal to the bedding and most are much thinner. Locally, however, where folding and faulting has induced mass flow of coal much greater thicknesses have been reported.

Based upon paleobotanical studies (Read and Mamay, 1960 and 1964; Darrah, 1969), the lower part of the Llewellyn Formation is Desmoinesian and Missourian in age. The upper Llewellyn is at least early Virgilian (Stephanian B) (Eggleston *et al.*, 1988). Possibly the stratigraphically highest beds of the formation are Permian.

Depositional Environments

In general, the Mauch Chunk red beds and the Pottsville conglomerates and sandstones are the delta plain and alluvial phases, respectively, of the Mauch Chunk delta complex. Located in the confined northern end of the Appalachian basin in northeastern Pennsylvania, the delta had no marine facies and its development was restricted by the upwarped and eroding positive area to the north and northwest.

The sediment source lay to the south and southeast in the orogenic highlands along the impact zone at the edge of the North American plate where it was in collision with the African plate; a closer source also may have been in the Reading prong area, in Berks County (Figs. 1 & 2).

The prograding Mauch Chunk delta of the Late Mississippian age (Fig. 4a) followed a long, quiescent period in Middle Mississippian time when relatively little sediment was accumulating. Whether increased orogenic activity or wetter climate or both caused the renewed sedimentary activity, is unclear. Very late in the Mississippian renewed orogenic activity or increased rainfall allowed the coarse Pottsville alluvial clastics to build northward, first interfingering with the delta plain red beds and then overtopping and burying them (Fig. 4b,c).

Pottsville sediments accumulated on a broad, flat flood plain locally containing marshes and swamps. Most of the time, the environment was probably relatively placid, but, periodically, high-energy flood torrents spread coarse clastics across the plain. The Lykens Valley No. 5 coal bed in the Tumbling Run Member, marks an approximate time when larger and more persistent swamps began to develop and when large quantities of organic carbon were introduced throughout the sedimentary sequence.

The transition from the caliche-bearing red beds of the Mauch Chunk Formation, through the sandstones and conglomerates of the Pottsville

Formation, to the widespread coal beds of the Llewellyn seems to indicate a progressive change from a semi-arid climate to a moist, humid setting. White (1913), came to a similar conclusion in comparing the impoverished Late Mississippian flora with the lush flora of the Middle Pennsylvanian.

Although the general depositional environment of the lower part of the Llewellyn Formation (Fig. 4d) is similar to that of the Pottsville, the sediments are finer and the coals thicker and more persistent, indicating a somewhat more stable condition and a less rugged source area.

The swamps where plant material collected to form several of the more persistent coal beds must have been fairly widespread. Especially noteable is the remarkable Mammoth coal zone. In the Eastern Middle field and the eastern end of the Southern field, the Mammoth is virtually a single bed up to 12-15 m (40-50 ft) thick. West of these areas the Mammoth swamp fluctuated in response to two or more periods of clastic sedimentation; plant growth resumed between these periods that produced the three major splits of coal and some thin coal lenses in the Mammoth Zone.

In the Late Pennsylvanian, a series of marine transgressions from the west deposited several marine limestones and shales in western Pennsylvania. One of these marine transgressions extended eastward as far as Wilkes-Barre, in the Northern Anthracite field (Fig. 4e), depositing the estuarine Mill Creek Limestone of Ashburner (1886) (Eggleston and Edmunds, 1991). This is the only known marine occurrence in the entire Carboniferous of the Pennsylvania Anthracite region.

Strata in the upper part of the Llewellyn Formation, particularly above the position of the Peach Mountain (No. 18) coal bed, become distinctly more coarse-grained and contain numerous beds of conglomeratic sandstone and conglomerate, suggesting renewed uplift and/or a change to more severe climatic conditions in the source area (Fig.4f).

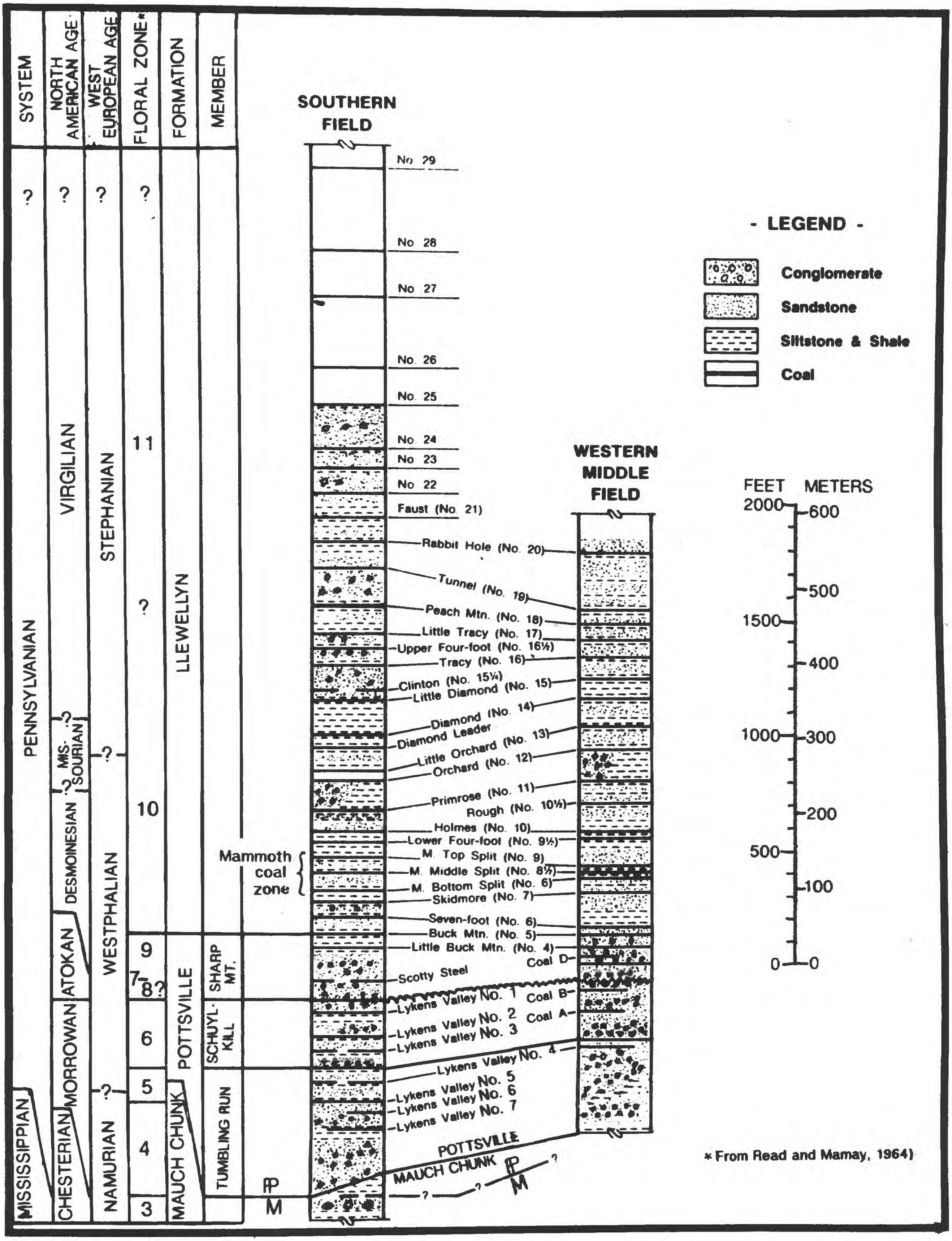


Figure 3. Generalized stratigraphic sections of the Southern and Western Middle Anthracite fields (modified from Eggleston and Edmunds, 1989). Abbreviations: Mt., Mountain; M, Mississippian; P, Pennsylvanian.

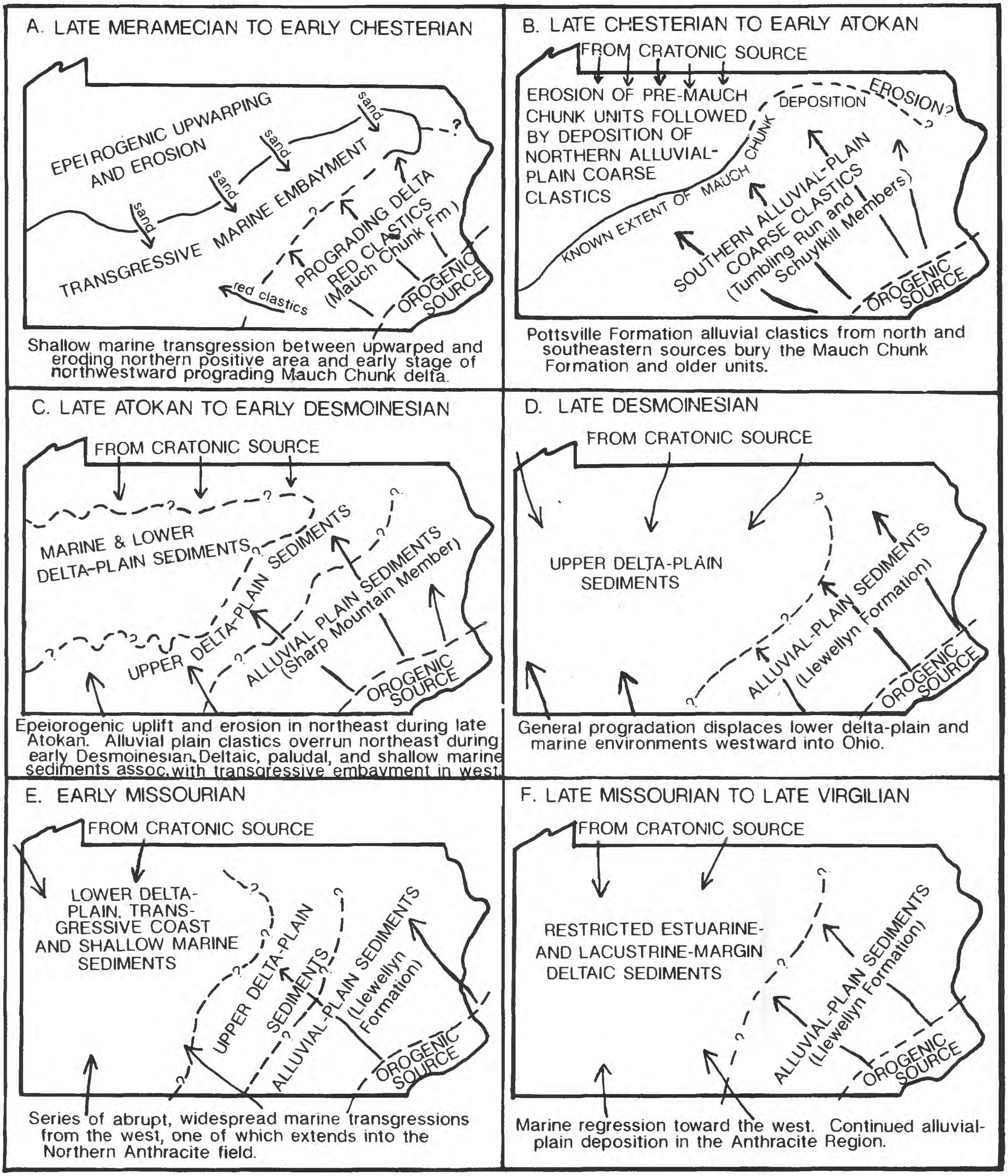


Figure 4. Late Mississippian through Late Pennsylvanian paleotopography and depositional environments (modified from Eggleston and Edmunds, 1989). Fm, Formation

STRUCTURAL GEOLOGY AND TECTONICS

Jane R. Eggleston
Jeffrey R. Levine
Eric Daniels

Orogenic History.

The continental margin of North America was initially created as a result of rifting of Gondwana (Africa and South America) from Laurentia (proto North America) during the Late Proterozoic (610-630 Ma) (Cook *et al.*, 1983; Cook and Oliver, 1981). This rifting took place along a trend approximately coincident with the present-day Appalachians. Throughout the Paleozoic this margin would become the locus of three successive collisional orogenic events of varying intensity: the Taconian, commencing around Middle Ordovician, the Acadian, commencing around Early Devonian, and the Alleghanian (actually representing a continuation of Acadian deformation), commencing around Lower Pennsylvanian.

Each tectonic episode was accompanied by an influx of clastic materials onto the otherwise quiescent continental margin, as orogenic source terranes became uplifted to the east and southeast. The Taconic Orogeny produced the Middle Ordovician shales through Lower Silurian Tuscarora Sandstone. The Acadian Orogeny produced the Early Devonian through Early Mississippian Catskill-Pocono clastic wedge. Then, after only a minor hiatus, the Alleghanian Orogeny produced the extant Pennsylvanian coal-bearing section, plus a large thickness of additional sediments, now removed by erosion. Ultimately, during later stages of the Alleghanian event, dramatic folding and faulting influence the strata previously deposited in the Appalachian foreland basin.

The coal-bearing strata comprising the anthracite fields of eastern Pennsylvania were deposited during the early stages of the Alleghanian Orogeny--the third and most intense orogenic event to influence the Central Appalachians durng the Paleozoic. Based upon plate reconstructions the Alleghany Orogeny developed as a consequence of the plate collision between the northwest margin of African and the eastern margin of North America. Compressive forces arising from this collision produced crustal thickening and concomitant uplift of a high mountain range to the southeast of the present Anthracite region. The Carboniferous clastic depositional systems, which included extensive peat-forming swamps, were deposited in the adjacent foreland basin, to the northwest.

Subsidence and uplift history of the Appalachian foreland basin have been effectively modeled as relating to thickening of the lithosphere due to orogenic activity along the eastern continental margin of North America (Quinlan and Beaumont, 1984; Beaumont *et al.*, 1987; Slingerland and Beaumont, 1989). In a convergent margin setting, lithospheric thickening produces uplift in the hinterland due to the buoyancy of the low density upper crustal rocks. Supracrustal loading, however, produces downwarping of the adjacent foreland, providing a coupled source terrane/sedimentary basin (Fig. 6a). A peripheral bulge forms along the external margin of the foreland basin as a mechanical consequence of the loading, providing both a barrier to the dispersal of sediments and a minor source terrane for additional sediment input (Fig. 6b & d). The Alleghanian foreland basin received sediment influx from the source terrane throughout much of the time interval extending from the Middle Devonian through Lower Permian. The rate of sediment influx is variable during this interval, presumably reflecting variable rates of uplift and erosion of the hinterland (Slingerland and Beaumont, 1989).

Structural Geology.

The Mississippian and Pennsylvanian rocks of the Southern, Western Middle, and Eastern Middle Anthracite fields are preserved in downfolds within the deep sag that makes up the northeastern end of the folded Appalachians. Each of the three fields is a complexly folded and faulted synclinorium. The general structural trend is between N55°E and N85°E, generally rotating counterclockwise toward the northeast (Fig. 1).

The synclinoria forming the Western Middle and Eastern Middle Anthracite fields carry the same name as do the fields. The Southern field is formed by the Minersville synclinorium, which to the west splits into north and south branches around the New Bloomfield anticlinorium to form the Southern Anthracite "fishtails".

Folds

Within the synclinoria (1st-order folds) that form the three fields are a multitude of subordinate (2nd- 3rd-, and higher order) folds in a wide variety of scales and sizes. Considering only the prominent larger folds, most synclines are tightly folded, whereas the anticlines tend to be broader, more open structures in many, though not all, cases. Most of the secondary and smaller scale anticlines and synclines are tightly closed. Most folds follow a parallel style up to the point that mechanical limits are exceeded, whereupon severe disharmonic folding takes place locally. Disharmonic folding is almost always confined to the incompetent coal and shale beds. Northward overturning of fold limbs and high-angle thrust faulting are common occurrences.

Faults

Each of the three Anthracite fields is widely and intricately faulted. High-angle and low-angle thrust faults, bedding-plane faults, underthrust faults and tear faults are present throughout the area (Wood *et al.*, 1969a). Many of the low-angle thrusts and bedding-plane faults also are folded. Except for the tear faults, most faults are oriented approximately parallel to the structural grain of the area.

The low-angle thrusts and underthrusts are large scale planes of detachment underlying large parts of the Anthracite region. Most formed early in structural history and were subsequently folded. A few low-angle thrusts along the southern edge of the Southern field were late features and are unfolded. The larger folded low-angle thrusts are limited to the Pottsville Formation and older formations.

High-angle thrust faults are very common throughout the area. Most appear to be associated with mechanical failure in the more tightly folded synclines or in some cases they are rooted in underlying low-angle thrusts. Most high-angle thrusts dip to the south. Those associated with synclinal folding usually originate in the core and, rising to the north, cut the north limb of the syncline. In the case of some especially deep synclines the thrust slices through the axis and north limb of the adjacent anticline. Bedding plane faults are very common, but usually difficult to recognize. It is probable that in may cases bedding plane faults pass into other types of faults.

Most tear faults seem to be limited to the Southern field and are associated with the later stage unfolded low-angle thrusts found there.

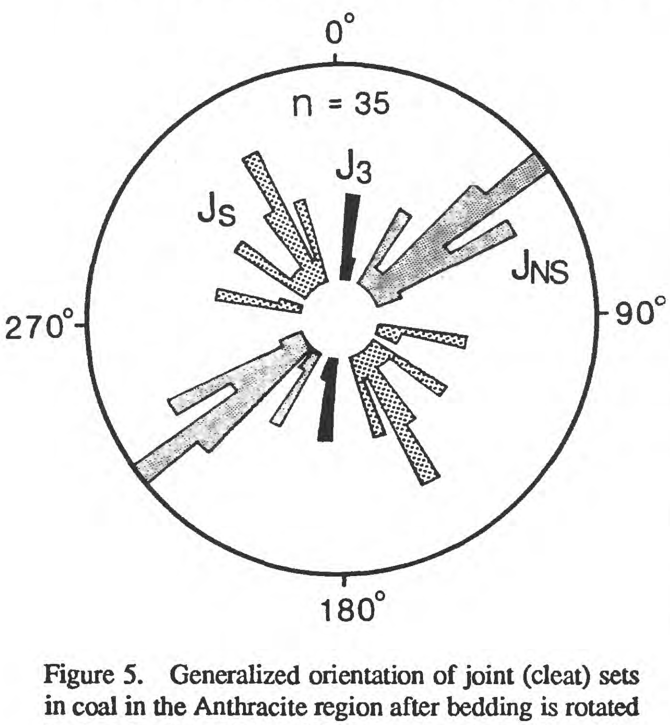


Figure 5. Generalized orientation of joint (cleat) sets in coal in the Anthracite region after bedding is rotated back to horizontal (pre-folding) orientation. Most joint sets are interpreted to have formed prior to significant folding of the stata.

Joints and Other Fractures in Anthracite

Coal beds in the Appalachian basin commonly contain numerous joint and fracture surfaces. Most coalbeds contain a cleat system (cleat is a term used to describe joints that are restricted to coal beds) comprised of two cleat sets that intersect at 70° - 90° (Nickelsen and Hough, 1967; Wood *et al.*, 1969b; Daniels, 1992). One set (termed the systematic cleat) is usually well-developed and relatively planar and continuous, whereas the other (non-systematic) cleat set is usually poorly developed, discontinuous, and terminates at intersections with systematic cleat. Systematic cleat (J_S) and non-systematic cleat (J_{NS}) are equivalent to cross-fold and fold-parallel cleat, respectively, of Geiser and Engelder (1983) and dip and strike cleat, respectively, of Wood *et al.* (1969b). Another type of joint set commonly observed in coal beds from the Anthracite region are quartz veins (J_3), whch tend to be systematic, planar, and penetrate adjacent lithologies. All joints are oriented approximately perpendicular to bedding, although J_{NS} exhibit much greater orientational deviations than other joints. When beds are rotated back to a horizontal (pre-folded) orientation, J_S generally strikes northwest, J_{NS} strikes northeast and J_3 strikes north-northeast (Fig. 5). The cleat system probably formed prior to or during the earliest stages of Alleghanian deformation, whereas J_3 probably formed in both the coal and adjacent shale during a later, more intense deformational stage of the Alleghanian orogeny (Wood *et al.*, 1969b; Nickelsen, 1979; Geiser and Engelder, 1983).

Cleat is not nearly as well developed in coals of the Anthracite region as in stratigraphically equivalent coals of lower rank from the bituminous fields in north-central Pennsylvania. While cleat planes can be vaguely discerned in most anthracites, the coal does not readily break across them; and the coal is generally much harder and more resistant to breakage than lower rank low volatile bituminous coals. Applying the concepts of progressive structural deformation (Arndt and Wood, 1960; Nickelsen, 1979) and progressive regional coalification (White, 1925), it can be inferred that cleat fractures were at one time well-developed in these anthracites, but have been "rehealed" by coalification processes associated with their transition to anthracite rank. Polymerization of proto-graphitic aromatic structures in the coal matrix would provide a viable mechanism for such a rehealing process.

Owing to the intensive structural deformation, and their relative mechanical incompetance, coal beds in the Anthracite region have commonly served as the loci for much of the bedding-parallel slip, and inhomogeneous deformation associated with folding and faulting. Accordingly, anthracite beds (or subdivisions of beds) are commonly intensely sheared, giving them a polished, slickenensided appearance. Lithotype banding and jointing has been destroyed by shearing in such cases.

Structural History

Alleghanian tectonic deformation followed a sequence of progressive structural stages which migrated across the foreland basin in a northwesterly direction (Arndt and Wood, 1960; Nickelsen, 1979), described as follows:

"1) Folding of horizontal strata into broad anticlines and synclines.
2) Low-angle thrusting and imbricate faulting, followed by formation of subsidiary folds on the larger folds to develop anticlinoria and synclinoria. Additional low-angle thrusting followed by high-angle thrusting accompanied the subsidiary folding.
3) Folding of low-angle and high-angle thrusts, and offsetting of pre-existing structural features by high-angle thrusts.
4) Development of overturned folds and offsetting of overturned folds by tear faults and high-angle [changed to low-angle in Wood *et al.* (1969a, p. 114)] thrusts."

The deformational effects of each successive stage were overprinted on the one(s) that preceded it. The North-Central fields, in the more external parts of the basin, exhibit evidence of only the incipient phases of tectonic deformation, including layer-parallel shortening (estimated 10-15%; Nickelsen, 1966, 1979; Engelder, 1979), incipient bedding plane faults (Nickelsen, 1979), and 1st-order folds having limb dips of only a few degrees and amplitudes on the order of a few hundred meters (Nickelsen, 1963; Gwinn, 1964). Further to the southeast, in the Western Middle Anthracite field, these early-formed features have been overprinted by additional shortening of the 1st-order folds, high-angle reverse faulting and tight 2nd- and 3rd-order folding (Nickelsen, 1979) indicating a much greater amount of tectonic shortening (estimated 25-35%; Root, 1973). All four structural stages are superimposed only along the southern edge of the Southern field.

In addition to these progressive stages, detailed structural analysis in the region Geiser and Engelder, 1983) has revealed evidence of (at least) two major episodes of Alleghanian structural deformation, an earlier "Lackawanna" phase (so named for the synclinorium containing the Northern Anthracite field), which had a west to north-west vergence in the Anthracite region, followed by the "Main" phase, which had a more north to northwestward vergence in the Anthracite region. Irrespective of the specific details, structural and sedimentological evidence indicates that rather than occurring as a single "event" the Alleghanian Orogeny represents a poly-phase, ongoing episode that spanned an extended period of time--probably tens of millions of years in total. Although the tectonic forces which caused the deformation were generally directed toward the northwest, the direction of maximum compression may have rotated up to 30°

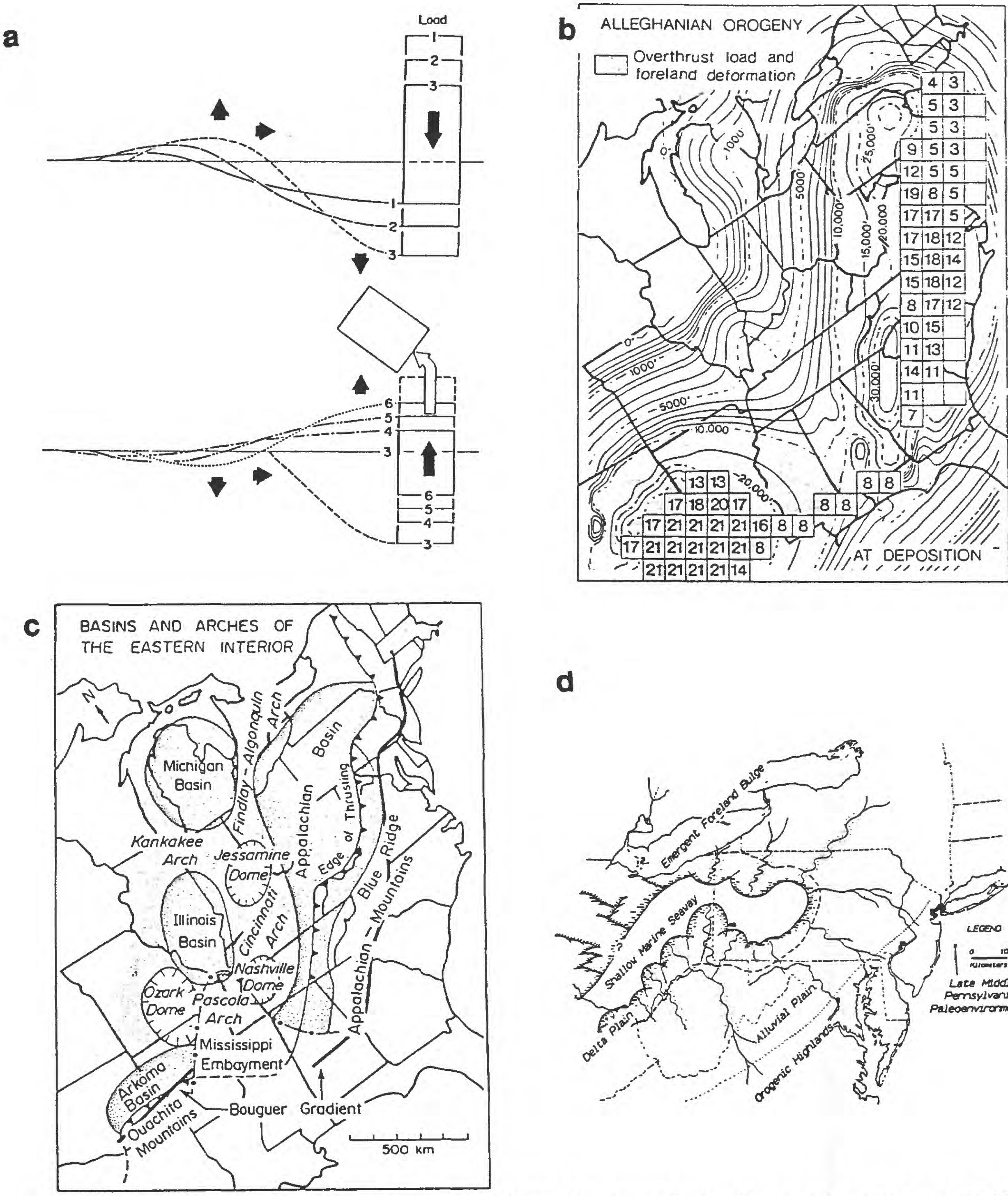


Figure 6. Geodynamic modeling of subsidence and uplift of Alleghanian foreland basin in the central Appalachians (from Slingerland and Beaumont, 1989). a) Qualitative representation of loading and unloading of a model lithosphere arising from tectonic activity, b) Isopach map of total Alleghanian sediment thickness (in feet) along with model prediction of cumulative load thickness for the Pennsylvanian and Permian (in kilometers), c) General basin configuration in the eastern U.S. depicting Appalachian foreland basin and adjacent peripheral basins. The Michigan, Illinois, and Arkoma basins were all sites of significant peat deposition during this time interval (modified from Beaumont *et al.*, 1988), d) More detailed paleogeography of the northern end of the Appalachian basin during late Middle Pennsylvanian depicting the depositional axis of the basin and emergent peripheral bulge to the northwest (modified from Donaldson and Shumaker, 1981).

MINERALOGY OF COAL AND SHALE IN THE ANTHRACITE REGION

Eric J. Daniels

Shale Mineralogy

The dominant minerals observed in shale (used here to describe fine-grained, clay-rich rock, including underclay) from the Anthracite region are illite, kaolinite, Fe-rich chlorite, pyrophyllite and quartz (Hosterman *et al.*, 1970; Paxton, 1983; Juster *et al.*, 1987; Daniels and Altaner, 1990). The latter three studies also show that some of the illite minerals in organic-rich shale in this region contain large amounts of NH_4^+ substituting for K^+ in the illite interlayer (20-80 mole% substitution). The amount of NH_4^+ substitution in shale appears to increase with increasing amount of organic matter and with decreasing distance from the coal seams, and does not appear to be related to diagenetic rank. Minor or trace amounts of Na-illite (brammallite), paragonite, pyrite, rutile, anatase, barite, gypsum, cerrusite ($PbCO_3$), lepidocrosite and goethite occur in many samples (Table 1). Some shale contain numerous microfractures filled with Fe-rich chlorite and mixed-layer chlorite/smectite and illite/smectite. In general, kaolinite contents decrease, and NH_4-rich illite and pyrophyllite contents increase with increasing coal rank in the Anthractite fields, whereas illite, quartz and chlorite contents do not vary systematically with rank.

Coal Mineralogy

Coal beds contain minerals dispersed in the dense organic matrix, as well as in various joints and other fractures, which are common in coal beds from this region. The mineralogy of the coal in the Anthracite region is extremely interesting and complex because mineral assemblages in the organic matrix may be distinctly different from mineral assemblages occurring in the coal fractures (Table 1). Such complexity in coal is often overlooked, however, because mineralogical analyses of coal are typically done on combusted (ashed) whole coal samples (e.g., Spackman and Moses, 1961), thus precluding separate analysis of mineral assemblages in the matrix and joints.

The coal matrix contains 4-25 wt% inorganic material and the mineral assemblages are similar to associated shale in the region. The dominant minerals are illite ($2M_1$ polytype), NH_4-rich illite (1M polytype), kaolinite and quartz. Minor minerals include Fe-rich chlorite, Na-bearing illite (brammallite), rutile, lepidocrocite, goethite and boehmite. Some of the highest rank anthracites contain paragonite, diaspore and siderite (Table 1). Kaolinite is the most abundant mineral in coal matrices of lower-rank anthracites, yet comprises < 2 wt% of the matrix mineralogy in higher-rank anthracites. NH_4-illite is present in nearly every anthracite-rank coal sample and its abundance in the coal matrix increases with increasing coal rank. NH_4-bearing illite in most high-rank coal samples contains relatively large amounts of NH_4^+ in the interlayer sites (67-76 mole% substitution for K^+), and lesser amounts in lower-rank anthracite samples (20-30 mole% substitution). The other minerals in the coal matrix show no significant trends with respect to coal rank.

All joints and slip surfaces may contain minerals. The cleat sets are partially filled with thin (30-120 μ), translucent flakes primarily composed of clay minerals, plus minor quantities of quartz and sulfides. These mineral flakes can comprise a significant portion of the total ash yield of the coal because these cleat can be well-mineralized and closely spaced (2-8 joints/cm). In addition to minerals, cleat flakes commonly contain large detrital grains of organic material.

Minerals observed in systematic cleat include kaolinite, tosudite, rectorite, berthierine, pyrophyllite, sudoite, quartz and lesser amounts of NH_4illite, pyrite, barite, and gysum. Rectorite (dioctahedral paragonite/smectite with ~50% paragonite and regular alternation of paragonite and smectite layers, or R1-order), tosudite (dioctahedral chlorite/smectite with 50% chlorite layers and R1-order) and sudoite (Mg-rich chlorite with 50% dioctahedral and 50% trioctahedral sheets) have not been previously identified in rocks from the central Appalachians, yet they are abundant in systematic cleat in all four Anthracite fields. These minerals are usually found only in hydrothermal veins (Miser and Milton, 1964; Fransolet and Bourguignon, 1978), hydrothermally altered rocks (Gradusov, 1971; Percival and Kodama, 1989) and Kuroku-type hydrothermal sulfide deposits (Shirozu, 1978).

In contrast with systematic cleat, non-systematic cleat are typically sparsely mineralized, more widely spaced (0.5-2 joints/cm) and contain mostly NH_4-illite or pyrophyllite, and minor amounts of kaolinite or quartz. Although present in the coal matrix, K-illite, Na-illite and rutile are not present in any of the coal joints.

The mineral assemblages in quartz veins are distinct from those in the cleat sets and are composed mainly of Fe-rich chlorite and quartz with minor amounts of kaolinite and pyrophyllite.

Clay Mineral Authigenesis

Minerals in the coal matrix and shale probably represent a mixture of detritus and low- and high-temperature authigenic phases. The origin of most minerals in shale and coal matrices is ambiguous because they may be detrital or authigenic (e.g., kaolinite, quartz, illite and chlorite). In addition, authigenic phase could have formed from a number of precursor phases (e.g., illite could have formed from precursor kaolinite or smectitic illite/smectite). In contrast, minerals within coal cleat must be authigenic because cleat necessarily form after lithification. By understanding mineral paragenesis in the coal, the origin of minerals in adjacent shale beds can be inferred.

Minerals in cleat from bituminous- and lower-rank coal deposits have been the subject of numerous studies. Kaolinite and quartz are the only silicates observed in cleat in Pennsylvania (Nickelsen and Hough, 1967), Illinois (Hatch *et al.*, 1976), England (Spears and Caswell, 1986) and Canada (Van der Flier-Keller and Fyfe, 1988). These silicates probably precipitated during early diagenesis (Spears and Caswell, 1986). Presumably, Al and Si migrate (in a gel or colloidal form) out of the organic matter, and eventually recrystallize in cleat as kaolinite and quartz. Al and Si are initially concentrated in the peat swamp due to intense cation leaching of detrital minerals caused by acidic conditions and the action of plants, which selectively absorb alkali elements for nutrition and which may secrete silica (Mackowsky, 1975). Other minerals observed in coal cleat include carbonates and sulfides in the Illinois Basin (Hatch *et al.*, 1976), and zeolites in the Colorado Plateau (Finkelman *et al.*, 1987).

The following paragenetic sequence is proposed for mineral authigenesis in coal cleat from the Anthracite region: Kaolinite and quartz are nearly always the only silicates observed in the cleat of low-rank coals and, hence, probably also formed in these cleat sets at relatively low temperatures (50°-100°C) during early diagenesis. Textural evidence suggests that all other fracture-filling clays directly replaced kaolinite (Figs. 7 & 8) via a variety of diagenetic reactions (Daniels, 1992).

Kaolinite replacement reactions probably occurred at T > 200°C during late-stage diagenesis because (1) these minerals are absent in lower-rank coal, (2) these phases usually occur naturally in low-grade metamorphic environments and (3) hydrothermal experiments suggest that pyrophyllite (Hemley *et al.*, 1980), NH_4-illite (Eugster and Munoz, 1966) and sudoite (Fransolet and Schreyer, 1984) are more stable than kaolinite only at T > 200°C.

Paragenesis in quartz veins does not follow the patterns observed in the cleat sets. Dense, anhedral masses of Fe-rich chlorite and quartz appear to be a result of precipitation from solution (crack-seal vein mineralization), rather than from replacement of an earlier kaolinite + quartz assemblage. In some areas, a minor amount of kaolinite also precipitated in these joints and, subsequently, was partially replaced by pyrophyllite. Chlorite, quartz and kaolinite precipitation in the quartz veins postdates cleat formation and early diagenesis because the quartz veins formed much later than the cleat sets (Nickelsen, 1979). Vein mineralization predates regional cooling because fluid inclusions in quartz are enriched in CH_4, and kaolinite has been partially replaced by pyrophyllite. Fluid inclusions in quartz (both H_2O-rich and CH_4-rich) are quite common and yield homogenization temperatures of 180-240 °C (Orkan, 1986; Kisch and van den Kerkhof, 1991).

State of Nitrogen in Anthracite

Previous studies have generally assumed that all N in coal resides in the organic matter, however, the results of recent studies show that anthracite-rank coal contains significant amounts of N in illite (Fig. 10). Up to 20% of the total N in coal from the Anthracite region resides in illite interlayers, based on both X-ray diffraction (XRD) and chemical analyses of mineral matter in coal. The total N content in coal decreases (1.4 to 0.7 wt.% N) with increasing coal rank across the region, whereas the amount of inorganic N in anthracite increases with increasing rank. Several bituminous and anthracite samples contain ~100-600 ppm inorganic N according to chemical analysis, but contain only K-illite according to XRD, suggesting that small amounts of NH_4^+ are present in K-rich illite within coal. Estimates of inorganic N are conservative because all of the mineral matter in the fractures was removed prior to chemical analysis. Minerals in fractures can consist primarily of NH_4-illite and comprise a significant percentage of the total mineral content of the coal. In addition, the low-temperature ashing procedure used to concentrate mineral matter can remove about 10 - 20% NH_4^+ from illite interlayers (Daniels, 1989).

MINERAL ABUNDANCES	SHALE	COAL				
		Organic-rich Matrix	Systematic Cleat	Non-Systematic Cleat	Quartz Veins	Slip Surfaces
Major	**Kaolinite Illite NH_4-rich Illite Pyrophyllite Quartz Fe-rich Chlorite**	**Kaolinite Illite NH_4-rich Illite Quartz**	**Kaolinite Sudoite Tosudite Rectorite Berthierine Pyrophyllite**	**Kaolinite NH_4-rich Illite Pyrophyllite**	**Quartz Fe-rich Chlorite**	**Kaolinite Pyrophyllite NH_4-rich Illite**
Minor/Trace	Brammallite Paragonite Pyrite Rutile Anatase Goethite Lepidocrocite	Fe-rich Chlorite Brammallite Rutile Goethite Paragonite Ankerite Lepidocrocite	NH_4-rich Illite Quartz Pyrite Fe-rich Chlorite	Tosudite Sudoite Rectorite	Kaolinite Pyrophyllite Rectorite	Tosudite Fe-rich Chlorite

Table 1 - Mineralogy of shale and coal in Anthracite region.

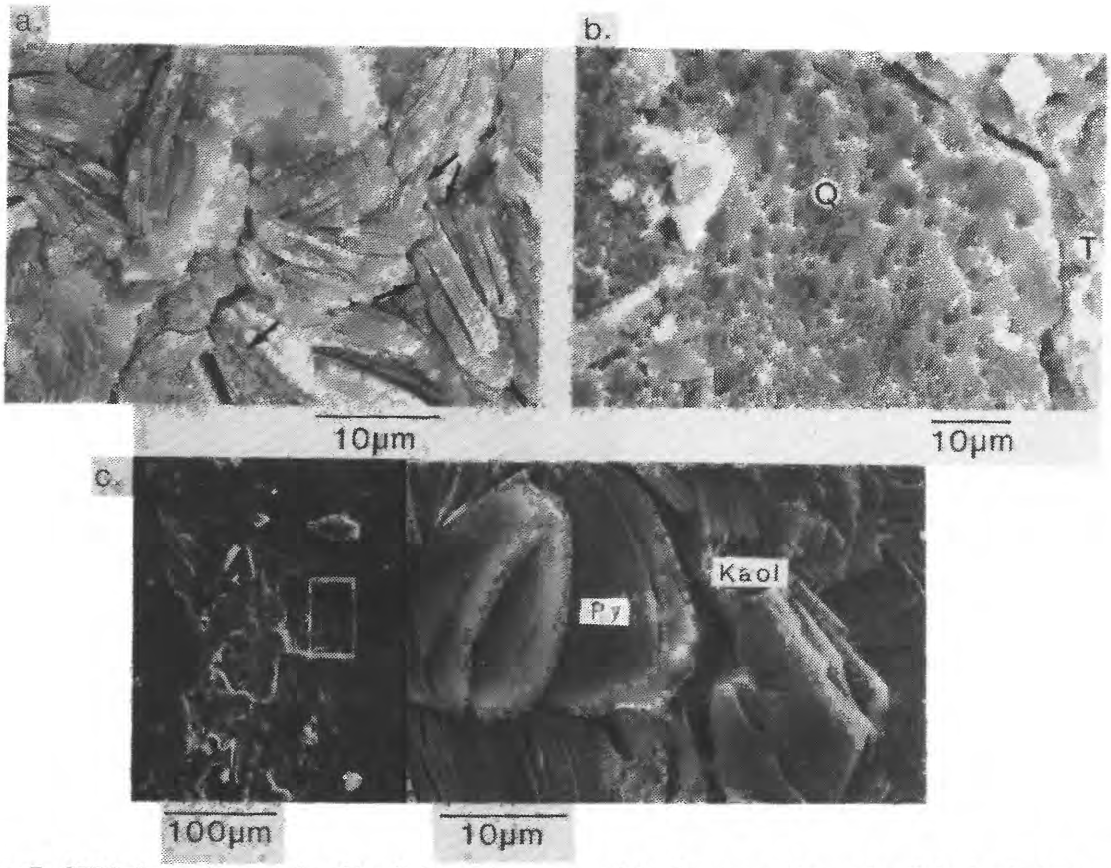


Figure 7. SEM photomicrographs of kaolinite replacement. a) Replacement of some kaolinite books by tosudite (arrows); b) Etched quartz grains; c) Pyrophyllite in quartz etch-pit on a kaolinite-dominated flake.

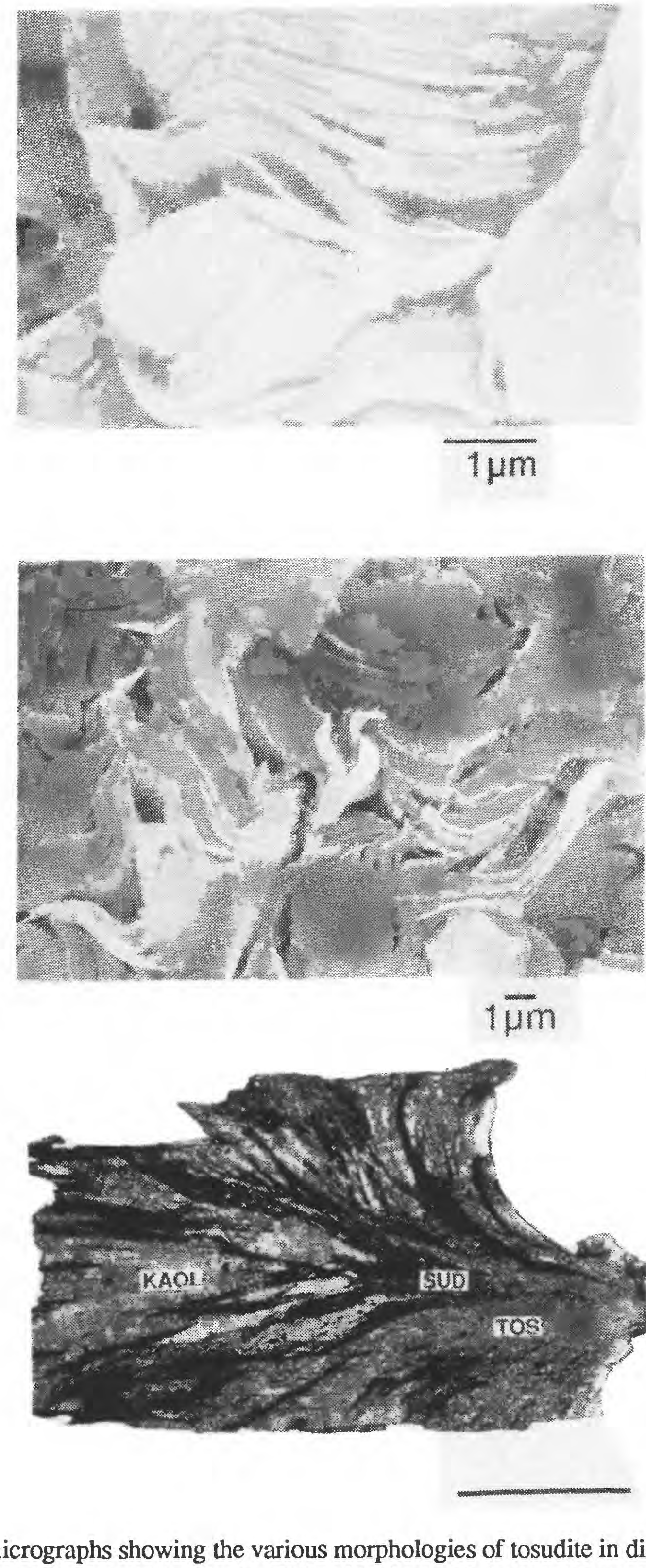


Figure 8. SEM photomicrographs showing the various morphologies of tosudite in different samples: a) initial stage of replacment: pseudomorphs after kaolinite; b) after complete replacment: densely-packed, wavy crystallites; c) Petrographic photo of kaolinite replacment by sudoite + tosudite in an authigenic mineral flake from J_S joint in coal. Sudoite (SUD; dark regions) occurs along the grooves of the hackles in the joint surface. Tosudite (TOS) occurs adjacent to sudoite replacment. Unreplaced kaolinite (KAOL) is lightest in color (Scale bar = 1 mm).

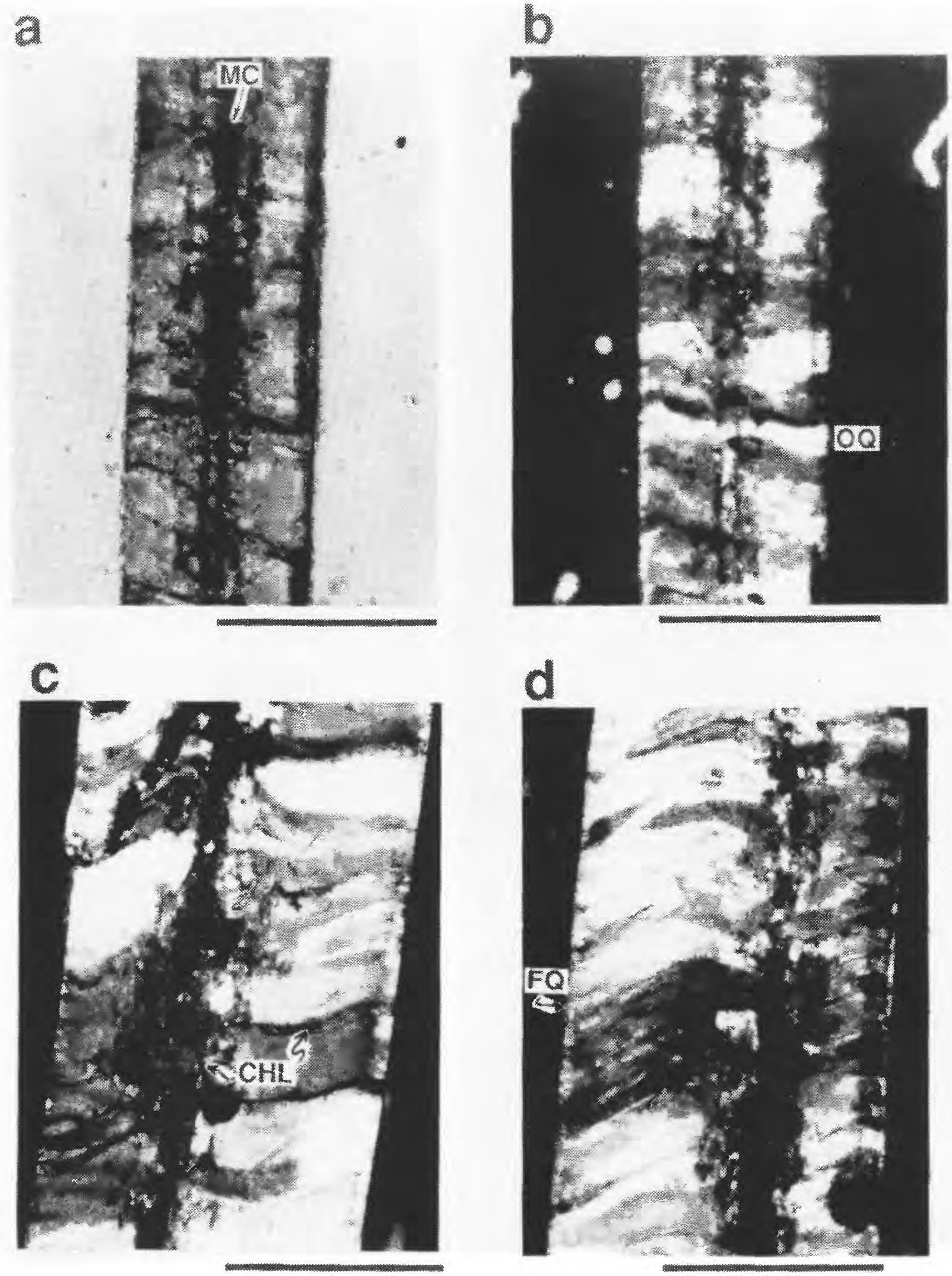


Figure 9. Petrographic photos of polished cross-sections of quartz-rich veins in J_3 joints in coal. a) view in plane-polarized light; b) same vein in crossed-polars showing optically continuous quartz fibre (OC) crossing median plane of coaly inclusions (MC) severed from joint surface during initial fracturing; c) chlorite fibres under crossed-polars; d) thin layer of quartz (FQ) occurring between initial quartz + chlorite mineralization and joint surface.

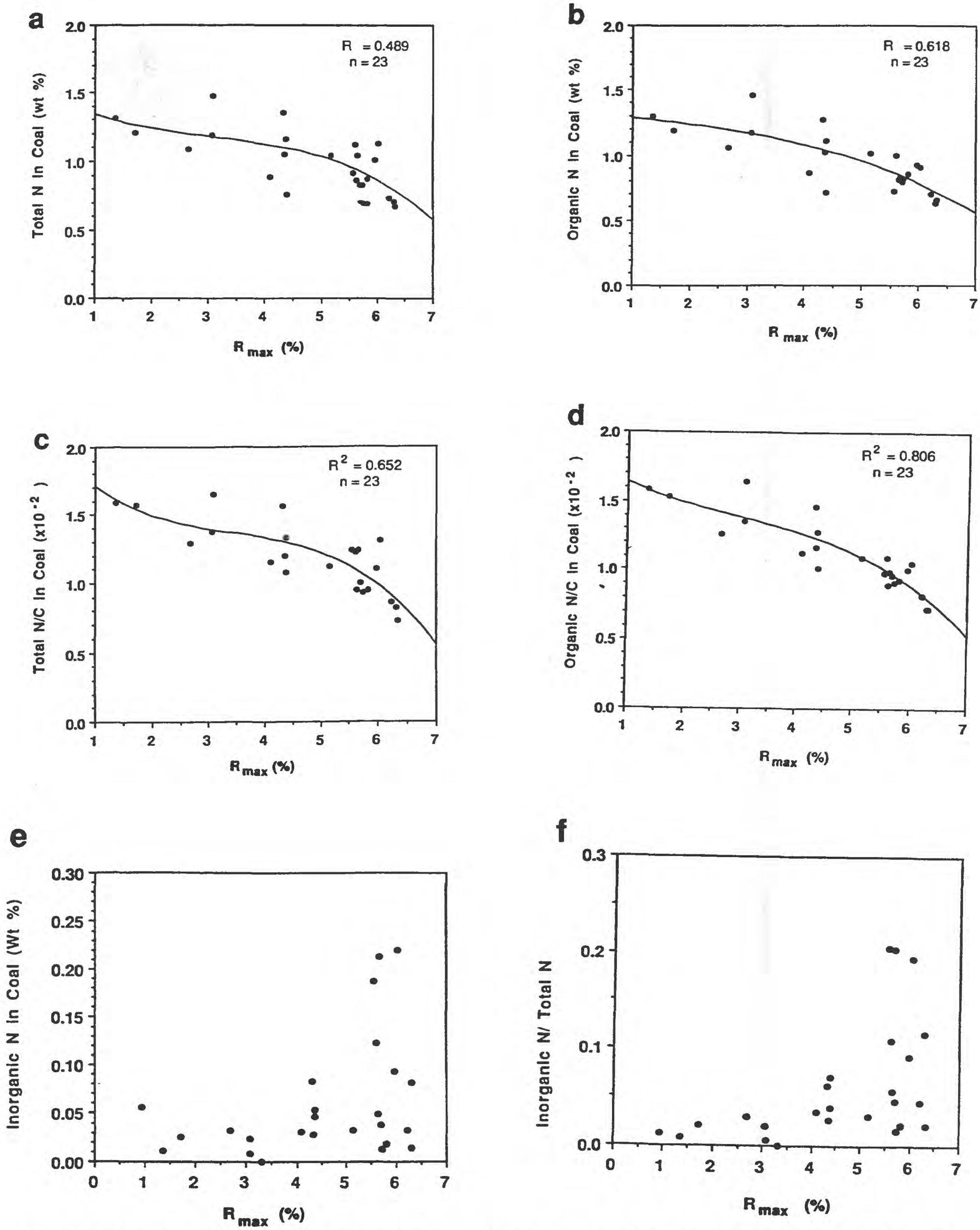


Figure 10. Cross-plots of nitrogen in coal vs. $R_{o,max}$: a) total N; b) organic N (d,mmf basis); c) total N/C in coal; d)organic N/C in coal; e) inorganic N, determined by chemical analysis; f) inorganic N/total N ratio.

COALIFICATION, DIAGENESIS, AND BURIAL/THERMAL HISTORY OF THE ANTHRACITE REGION

Jeffrey R. Levine

Introduction

Carboniferous coal-bearing strata of eastern Pennsylvania were deposited in the Appalachian foreland basin during the early stages of the Alleghanian orogeny. During succeeding Alleghanian stages these strata were buried by substantial thicknesses of additional overburden, diagenetically altered, structurally deformed, and uplifted. Former overburden has since been removed by erosion; and the coal measures, now present only within a series of isolated, elongate synclinoria, constitute the youngest Paleozoic strata preserved in the region (Fig. 1). The large thickness of rocks that once overlay them is evidenced by the almost negligible porosity of the clastic sediments and by the high regional coal rank, both of which indicate a systematic increase in diagenetic grade from northwest to southeast and from west to east.

The high regional rank attained by coals in the study area is very unusual. Only rarely are coal-bearing strata subjected to conditions of temperature and pressure required for their transformation into anthracite. The Pennsylvania Anthracite region consititutes less than 1% of identified coal resources in the U.S., but well over 90% of known anthracite resources.

The fundamental question regarding the coal rank patterns in the Pennsylvania Anthracite region is: What factor(s) account for upper Carboniferous coal-bearing strata having been metamorphosed to anthracite rank in eastern Pennsylvania, while stratigraphically equivalent coals in western Pennsylvania attained only high volatile A bituminous to low volatile bituminous rank. To answer this apparently simple question requires a thorough

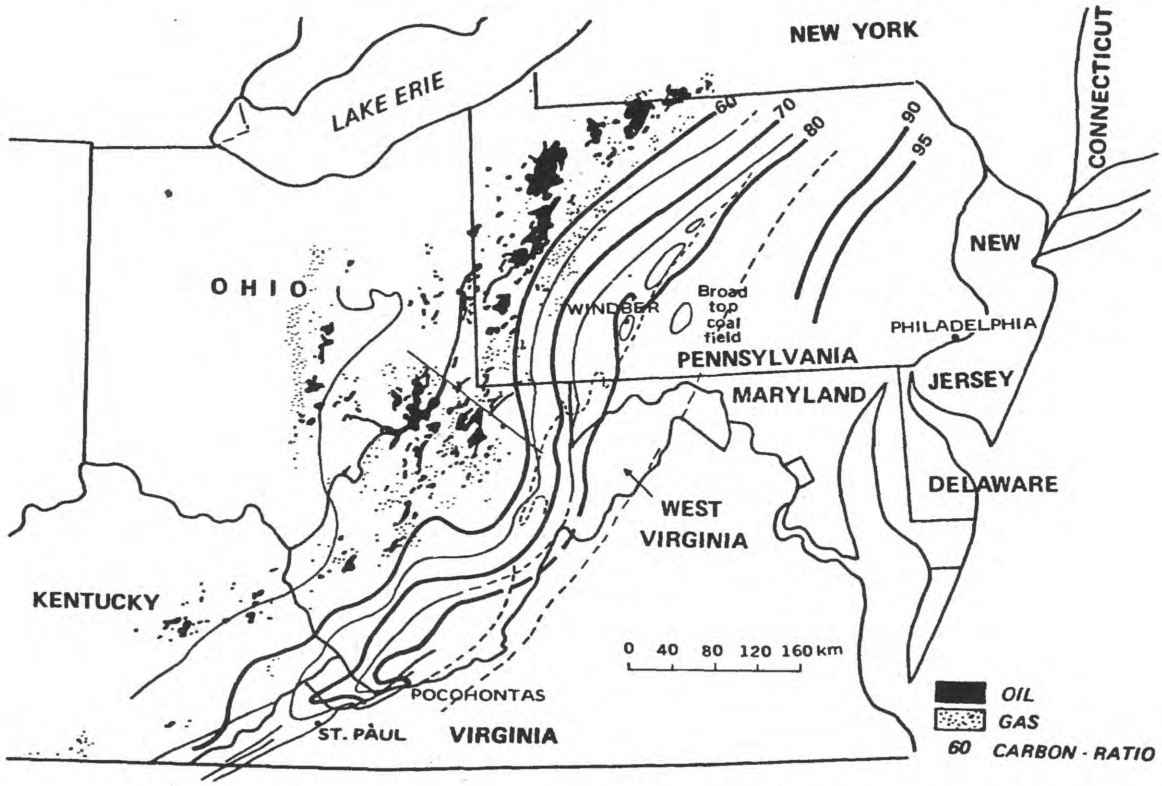


Figure 11. Regional coal rank patterns in Pennsylvania and surrounding portions of the Appalachian basin, as originally depicted by David White (Source: Robert, 1988). Rank is measured in units of "Carbon Ratio", which is the percentage of total carbon represented by "Fixed Carbon". Isorank contours lie generally parallel to the structural grain of the Appalachian fold-and-thrust belt.

understanding of the burial, thermal, and deformational history of these strata. Even with intensive study, however, interpretation of these ancient events remains enigmatic and subject to various interpretations.

Coal Rank Patterns

Regional and Local Rank Patterns

For many years, geologists have used systematic variations in coal rank as a tool to aid interpretation of diagenetic history of coal-bearing strata. Among the earliest (if not the earliest) such work was conducted by David White (1915, 1925) in the central Appalachian basin, including the Pennsylvania Anthracite region. White showed that coal rank in the Appalachian basin generally increases from west to east, from the external (foreland) side of the orogen toward the internal (hinterland) side (Fig. 11). Based upon the observation that the higher rank coals were, in general, associated with more intensely deformed strata, White developed his influential "dynamochemical" theory of coalification, which ascribed increases in coal rank to the combined effect of burial and tectonic compression.

A subsequent study by Turner (1934) elucidated the rank patterns in the Anthracite region more clearly by showing that isorank contours do not lie parallel the structural 'grain' of the Appalachian fold-and-thrust belt, but intersect it at nearly a 90^{o} angle (Fig. 12). This trend is especially well expressed in the Western Middle and Southern Anthracite fields where coal rank increases along the length of the basins from semianthracite in the west to high grade anthracite in the east. In spite of the apparent inconsistency with White's dynamochemical model, Turner remained faithful to the idea that tectonic compression caused coalfication, and concluded that two distinct deformational events must have influenced the region--an east-west directed event which caused the coal rank patterns, and a north-northwest directed event which later caused the tectonic deformation. In fact, White's interpretations remained widely accepted in North America well into the 60s, when compelling arguments were raised that temperature rather than pressure is the primary cause of coalification (Teichmüller and Teichmüller, 1966; Damberger, 1974).

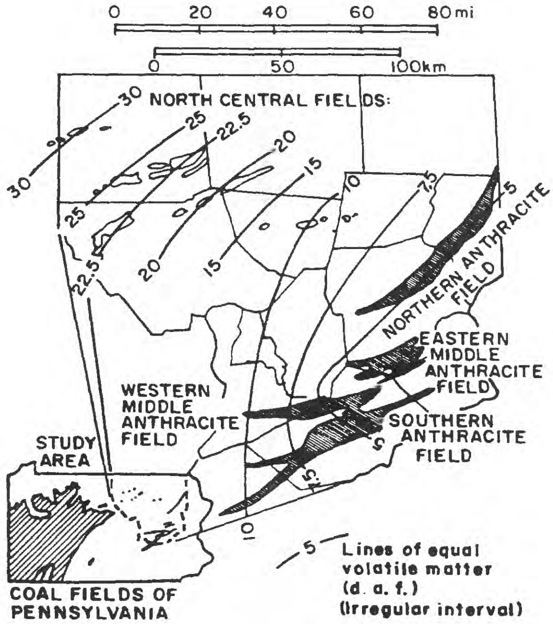


Figure 12. Regional coal rank trends in the study area exhibit increasing diagenetic grade toward the east and southeast (adapted from Turner (1934) and Edmunds et al. (1979)). The isorank lines transversely intersect the structural grain of the Alleghanian fold axes. In this diagram, the local rank perturbations in the Southern Anthracite and Western Middle Anthracite fields are not depicted (cf. Figs. 13 & 14).

Wood *et al.* (1969a) further refined the coal rank patterns in the region by demonstrating that coals outcropping along the axial zone of the Southern Anthracite field are of higher rank than coals outcropping along the adjacent basin margins (Fig. 13). This relationship is opposite to what would be intuitively expected in a synclinal structure. This localized rank pattern is more-or-less 'superimposed' upon the larger scale northwest-to-east increase in rank defined by White and by Turner, causing a slight westward deflection of isorank contours. Subsequent studies by Arndt (unpublished) and Levine (1983) have revealed a similar rank pattern in Western Middle Anthracite field, where coals in the central part of the basin have slightly higher rank than coals outcropping along the adjacent margins. The highest coal ranks occur along the axes of 2nd-order anticlines lying within the margins of the basin (Fig. 14).

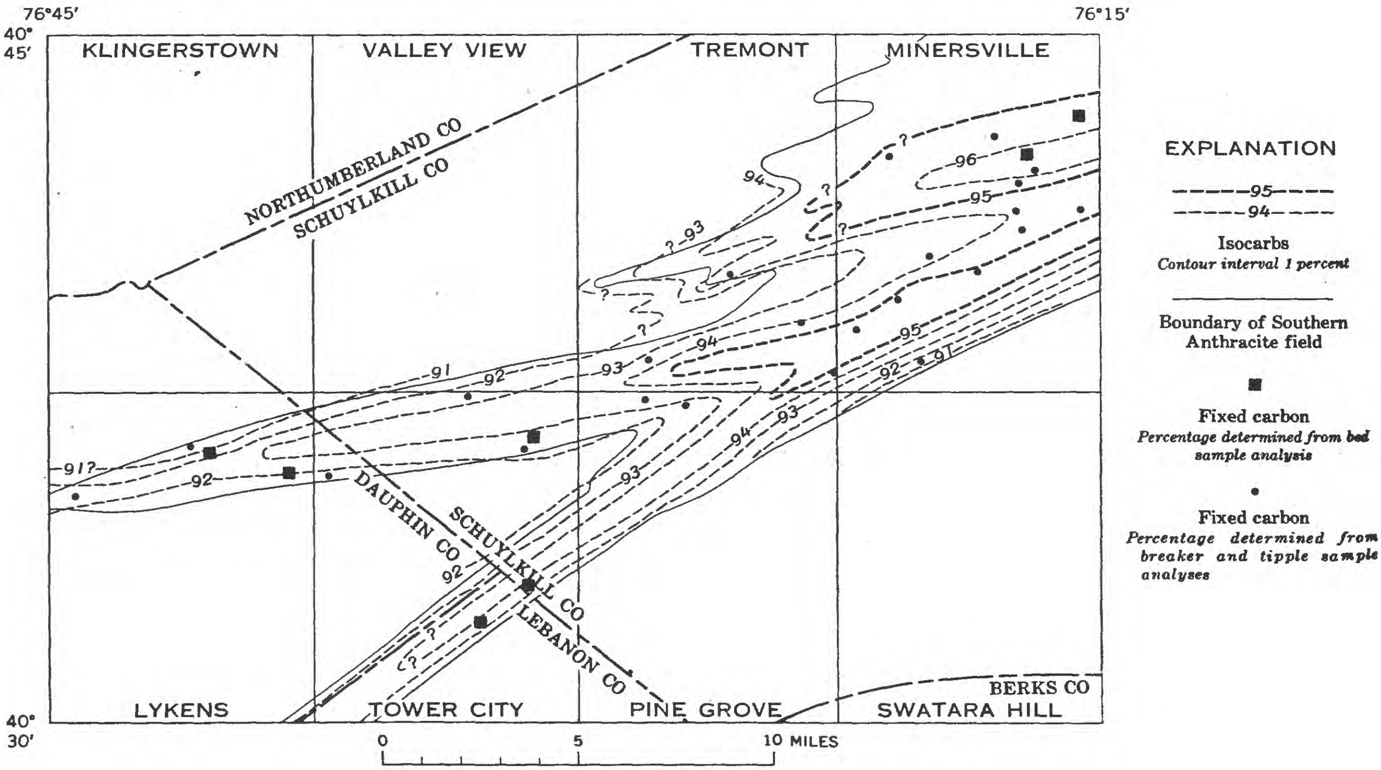


Figure 13. Coal rank patterns in the Southern anthracite field indicate that coal is of higher rank in the center of the basin than on the adjacent fold limbs (from Wood et al., 1969a).

In accordance with White's concept of dynamochemical metamorphism, Wood *et al.* (1969) proposed that high rank along the axis of the Southern Anthracite field was produced by a concentration of deformation in the hinge zone of the major synclinorium comprising the field. While this interpretation seems untenable in light of present day understanding of coalification, questions regarding the possible role of pressure have never been thoroughly resolved.

At several localities in the Anthracite region it has been possible to measure the coal rank gradients in uninterrupted stratigraphic sequences. These have invariably shown rank increasing down section, irrespective of the present day orientation of the strata. In the Pioneer Tunnel (Field Trip Stop #1), the rank increases along a horizontal transect (toward the south) from 4.25% in the Orchard (#12) seam near the mine entrance to 4.57% in the Buck Mountain (#5). Near Shamokin, along the northern margin of the Western Middle field, the reflectance increases in the opposite direction (toward the north) from 2.6-2.9% in the Mammoth (#8, #8, and #9) zone to 3.0% in the Lykens Valley #2 seam (Hower, 1978). Turner (1934) also noted that in 9 of 11 localities studied, volatile matter yield decreased with increasing stratigraphic depth. These relationships imply that a significant component of coalification occurred prior to folding, a conclusion consistent with sandstone diagenesis and coal reflectance anisotropy (discussed subsequently).

At one location it was possible to determine the vertical coal rank gradient for samples from a pair of drill holes near Minersville, Pennsylvania, in the Southern Anthracite field. These holes intersected approximately 600 m of slightly dipping coal-bearing strata in the Llewellyn Formation. The vitrinite reflectance from several coals and organic-rich shale horizons plotted versus depth shows an increase from 3.73% near the surface to 4.97% at 700 meters depth. These local trends imply that the coal rank patterns within the Pennsylvania Anthracite basins are much more complex than those depicted in Figures 11, 12, 13, and 14, and probably have many discontinuities and reversals of trends associated with structural deformation.

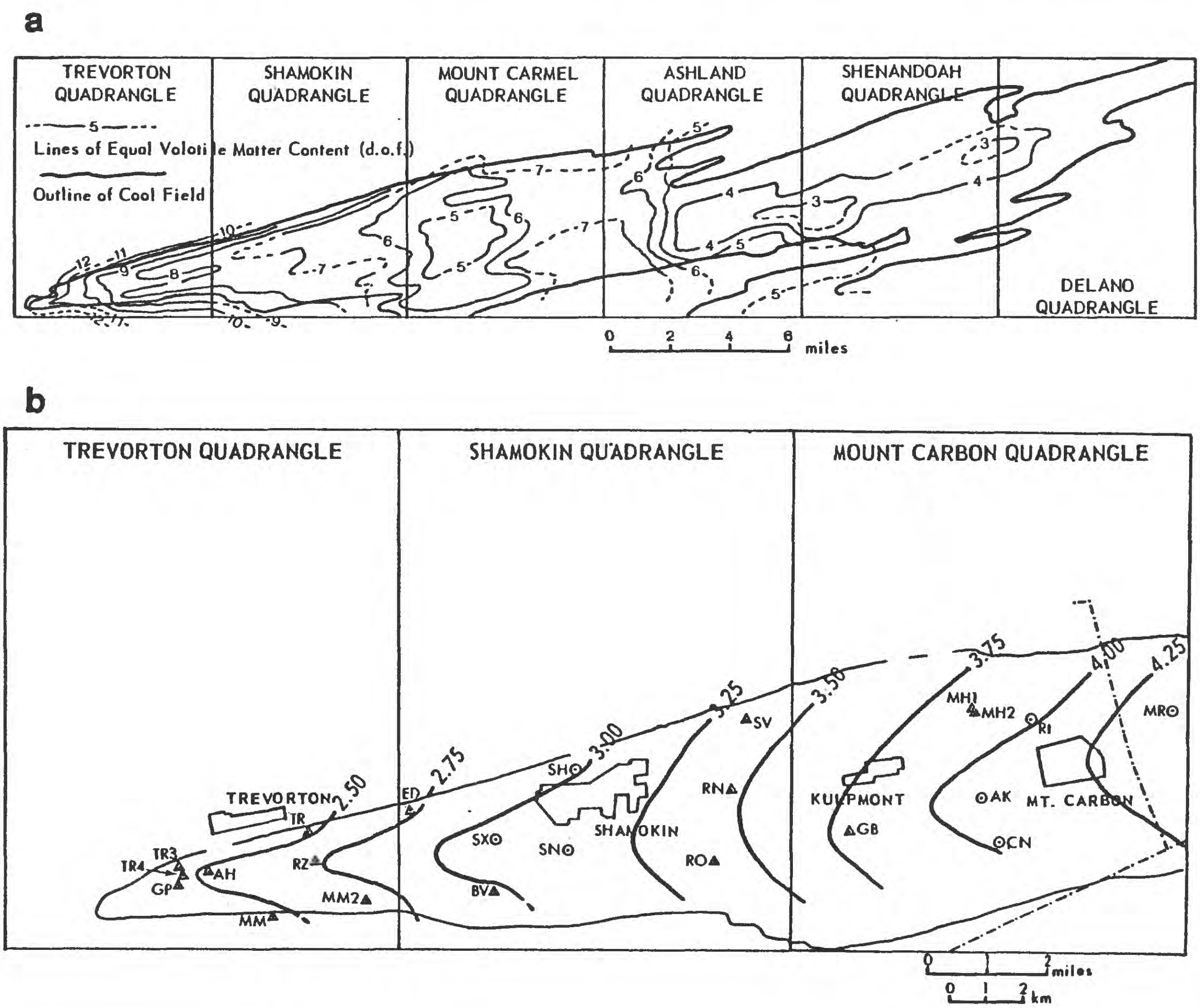


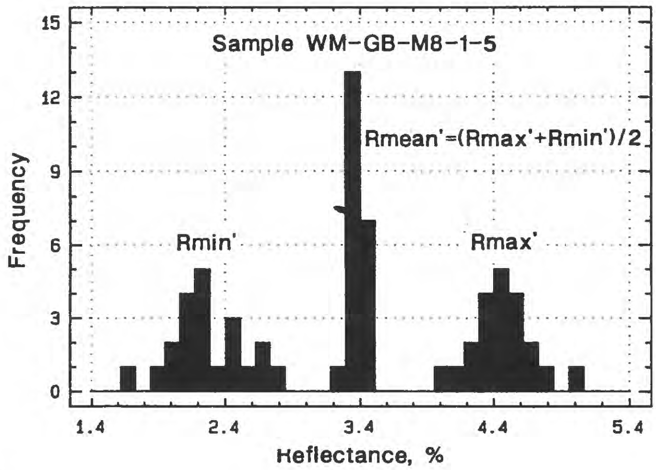
Figure 14. Coal rank patterns in the Western Middle Anthracite field reveal a pattern similar to the Southern Anthracite field. a.) The volatile matter content (d.a.f.) is lower for coals outcropping at the center of the basin than along the adjacent margins, (modified from unpublished map compiled by H. Arndt, U.S. Geological Survey, 1964). In the Trevorton quadrangle the highest rank coals are aligned along 2nd-order anticlinal axes. b.) Although comparitively few data are available, mean vitrinite reflectance expresses a trend similar to that of volatile matter for the western portion of the Western Middle field. Evidence indicates that rank patterns are actually more complex than depicted here.

Possible Influence of Stress and Strain on Rank Patterns

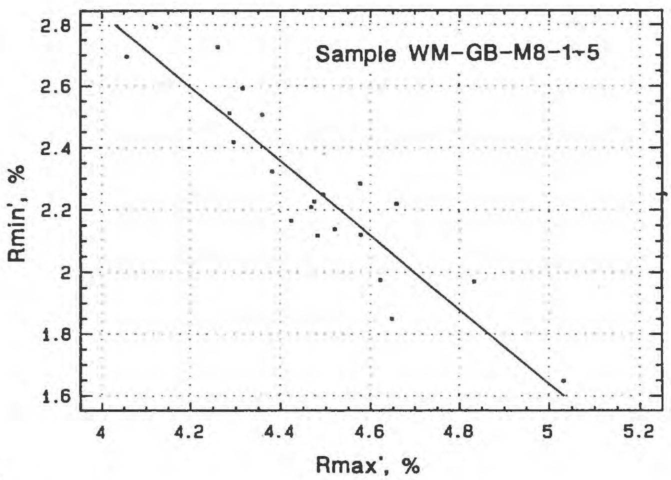
David White's theory of dynamochemical metamorphism has been largely supplanted in recent years by models which ascribe maturation solely to the influence of temperature. Pressure has been relegated to the subsidiary role of merely influencing the physical structure of the coal. Field evidence concerning the role of pressure on coalification within the Pennsylvania Anthracite region shows that the intensity of structural deformation does not correlate regionally with coal rank. Strata in the western end of the Western Middle field (for example at Stop #1-Bear Valley Mine) are much more intensively deformed than strata in the eastern portions of the Eastern Middle and Northern fields, which are of much higher rank

Oriented Pellet	Rmax'	S.D.	Rmin'	S.D.	Rmean
WM-GB-M8-1-5:	4.43	0.258	2.31	0.339	3.37
WM-GB-M8-1-6:	4.46	0.077	2.33	0.063	3.40

a.



b.



c.

Figure 15. Reflectances measured on two core specimens drilled from a single oriented block of coal, Western Middle field, show the effect of localized shear strain on vitrinite reflectance. a.) The apparent maximum (R_{max}'), apparent minimum (R_{min}'), and mean reflectance (R_{mean}) are essentially identical, on average, for the two cores. Core #6 contained no pyrite inclusions. The coal was homogeneously deformed, and R_{max}' and R_{min}' values were very uniform in magnitude Core #5 contained abundant rigid framboidal pyrite inclusions around which the vitrinite was inhomogeneously deformed. The reflectance magnitudes varied considerably, depending on the amount of shearing. b) In Core #5, regions having very high R_{max}' magnitudes had correspondingly low R_{min}' magnitudes, and vice versa. Therefore, R_{mean} varied very little from point to point, in spite of the shearing. c) Measurement points having high R_{max}' had correspondingly low R_{min}' values. This demonstrates that shear strain influences reflectance anisotropy, but not mean reflectance.

(Figs. 13 & 14). It must be emphasized, however, that: 1) deformation styles do not imply anything regarding stress magnitudes, 2) most coalification was completed prior to tectonic deformation, so rank is unlikely to be related to tectonic strain, and 3) neither the temperature nor the ambient pressure conditions during coalification are known, so little can be concluded with regarding the potential role of pressure.

Shear strain (i.e. deformation, rather than stress *per se*) may have a positive influence on some types of coalification reactions, but once again, the data are ambiguous. Field evidence has shown that coals which have been deformed by shearing in fault zones have equivalent average vitrinite reflectances as adjacent unsheared coals; but the strained coals have greater anisotropy of reflectance (Teichmüller and Teichmüller, 1966; Teichmüller, 1979; Levine and Davis, 1989a & b). This suggests that while shear strain may have a negligible influence on the rank attained, it may affect the degree of preferred orientation in the molecular structure. The same effect has been observed on a microscopic scale in a coal sample from the Western Middle Anthracite field (Levine, 1983; Fig. 15). In this case, reflectance properties were compared between two 2.5 cm diameter cores specimens, drilled within a few centimeters of one another from a single oriented block of coal. One core was characterized by internal deformation by 'flowage' around rigid pyrite inclusion, whereas the other core was relatively free of such pyrite inclusions and was more homogeneously deformed. The mean vitrinite reflectances of the two cores were nearly identical, but the optical anisotropy was much higher and much more variable in the sheared sample. In the deformed core, measurement points having low minimum reflectances had correspondingly high maximum reflectances (Fig. 15c), such that the mean reflectance was nearly invariant from point to point (Fig. 15b).

On the other hand, some studies have suggested a possible positive influence of shearing, particularly at anthracite rank. A study by Jüntgen and Karweil (cited by Teichmüller and Teichmüller, 1966), demonstrated that pulverizing coal in a grinding mill at room temperature produced no measurable effect on the rank; however, grinding at temperatures of 200-300^oC (similar to the temperatures interpreted for anthracitization) resulted in the release of gases such as CO, CO_2, H_2, CH_4, and higher hydrocarbons. Simple heating at these temperatures does not normally produce such products. It is possible that shear stress and/or strains may have promoted coalification-type reactions during grinding.

It has also been noted that graphitization of coal structure requires not just higher temperature but shear strain as well, (Bonijoly *et al.*, 1982; Deurbergue *et al.*, 1987; Ross *et al.*, 1991). Although graphitization in the strictest sense is a higher rank phenomenon, anthracites from the Pennsylvania Anthracite region show evidence of incipient graphitization in their x-ray diffraction peaks (Ergun, 1968). In other basins, incipient graphitization has been observed in anthracites that have clearly never been subjected to temperatures greater than 300-500^oC during their burial history; yet according to experimental studies, these temperatures are far too low to have produced graphite structure (Ross *et al.*, 1991). Shear strain is apparently also required to effect this transition at low temperatures. Evidence to be discussed subsequently, however, indicates that most coalification in the Pennsylvania Anthracite fields was already completed prior to most of the tectonic deformation. Therefore, the potential influence of shearing may have been muted.

In summary, it has become almost axiomatic to state that pressure serves no positive role in coalification, yet laboratory studies have proven that it is impossible to produce a coal-like product in an open, unconfined pyrolysis system. Moreover, shear stress and strain are known to facilitate the development of graphitic structure and may, therefore, have facilitated anthracitization to some degree. Although the high confining pressures ambient during anthracitization of coals in the study area must have exerted a substantial influence on the product coal, the precise effects remain uncertain.

Estimated Temperatures, Burial Depths, and Thermal Gradients

While there remains some uncertainty regarding the relative influence of temperature, pressure, and time on coalification, there is general agreement that maximum temperatures were in the range of 200-300^oC across the region. There has been considerable disagreement, however, regarding the depths at which these temperatures occurred.

A simplified estimate of coalification temperatures using Waples' (1980) correlation between $R_{o,vit}$ and Temperature-Time Index (TTI), suggests anthracitization temperatures around 200-225^oC for the Parker core holes in the Southern field. These temperatures (Levine, 1983, 1986) imply a paleogeothermal gradient of 33^oC/km over this stratigraphic interval. Based upon these temperature and gradient estimates, Levine (1983, 1986) interpreted maximum burial depths on the order of 7+ km for the Anthracite region.

Daniels *et al.* (1990) have pointed out that even if these estimated paleogeothermal gradients are accurate, they are not necessarily applicable to the entire stratigraphic section overlying the extant coal-bearing sequence. If gradients were steeper in the overlying strata, then temperatures required for anthracitization could be attained at shallower depths than would otherwise be the case.

At the Bear Valley mine, in the western end of the Western Middle field (Stop #1), fluid inclusions from quartz veins associated with the coals indicate average maximum filling temperature of 205^oC and pressure of 1150 bars (Orkan and Voight, 1983). Assuming that the fluid pressure was not greater than lithostatic, this would imply a minimum overburden thickness of 5 km, hence a maximum paleogeothermal gradient of 37^oC/km, assuming a mean surface temperature of 20^oC (ibid.). If fluid pressures were less than lithostatic, the estimated depth would be correspondingly greater and the geothermal gradient lower.

More recently, Kisch and van den Kerkhov (1991) interpreted coalification temperatures in Anthracite Region to have been in the range of 170-240^oC, but interpreted pressures to have been relatively low, based upon phase behavior of co-existing H_2O-rich and CH_4-rich fluid inclusions. Their pressure/temperature/depth estimates imply significantly higher geothermal gradients (ca. 50-55^oC/km) and shallower burial depths (<4.5 km) at the time of fluid inclusion entrapment than other previous interpretations. Formation of the quartz veins containing the fluid inclusions (set J_3) is interpreted to have occurred relatively late in the coalification sequence, perhaps at the onset of anthracitization. If so, the estimated depth from fluid inclusions may be approximately equal to or less than the maximum burial depth of the coal, depending on the mechanism of anthracite formation.

Estimated Burial Depths Based on Sandstone Diagenesis

Paxton (1983) undertook a detailed study of diagenetic characteristics of clastic sediments associated with the coals in the Anthracite Region and nearby parts of the North-Central (bituminous) fields. This study included estimates of former burial depths based upon regional changes in porosity and bulk density.

Porosities and bulk densities of the ductile grain sandstones both exhibit a systematic variation across the study area paralleling that of coal rank. In all basins there are some rocks with negligible porosity but the maximum porosity diminishes in a regular manner with increasing coal rank (Fig. 16). In the Northern Anthracite field the mean porosity is 1.7% (or negligible). Northwestward, it increases to 3.1% in the semianthracitic Bernice basin, 5.0% in the low volatile bituminous Barclay basin, and 6.0% in the medium volatile bituminous Blossburg basin, and 8% in the high-volatile bituminous field.

Pressure, temperature, and time all influence the evolution of porosity and bulk density, as do other variables, such as the chemistry of the formation fluids, the permeability of the sedimentary layers, and the composition, size, shape, and sorting of the original detrital grains. Diagenetic processes influencing porosity and bulk density include cementation, pressure solution, dissolution, replacement, recrystallization, and mechanical compaction. Based upon detailed analysis of thin sections, Paxton (1983) demonstrated that most of the reduction in porosity and concomitant increase in bulk density could be attributed to: 1) compression and lateral elongation of ductile grains, so as to fill adjacent pore spaces, and 2) a regional increase in the quantity and degree of sutured grain contacts. In comparing any given grain size between different basins, suturing increases from northwest to southeast, along with coal rank, giving way to pervasive stylolitization in the semianthracite and anthracite fields. Mechanical compaction can alone account for 80% to 100% of the observed porosity loss, depending on initial grain size and packing. Grain suturing and stylolitization, as well as local quartz and clay cementation can account for further reductions in these coarser and more porous sandstones.

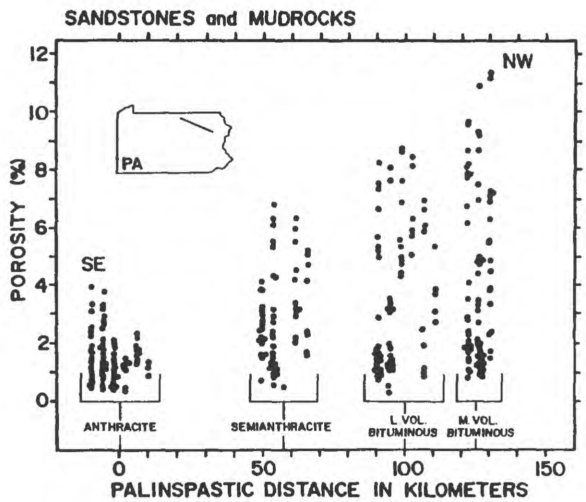


Figure 16. The range of porosities of sandstones in north-central Pennsylvania undergoes a continuous decrease from northwest to southeast along the section line shown in the key map. Low porosity sandstones are present in all basins, but the maximum porosity progressively decreases to the southeast (Paxton, 1983).

Features of the sutured grain contacts, stylolites, and grain compression indicate that compaction was directed perpendicular to bedding and occurred prior to the most intense Alleghanian tectonism. Pressure solution planes are always parallel or sub-parallel to bedding, irrespective of bedding orientation, suggesting that the stresses that produced them were vertical, due to the weight of the overlying strata. Consistent with this observation, optical reflectance fabrics in coals from the Western Middle Anthracite field also demonstrate that most coalification occurred prior to major Alleghanian folding (Levine and Davis, 1989 a & b; cf. section in this guidebook on reflectance anisotropy).

Compactional features in the sandstones suggest that burial depths were not uniform but increased gradually from west to east. Former burial depths in the study area were estimated by comparing the measured values of porosity and bulk density with porosity decline curves published in the geologic literature (Paxton, 1983). Based upon these comparisons, the low mudrock porosities suggest minimum burial depths of 3-5 km across the entire study area. Sandstone porosities are sufficiently large and variable for maximum depth estimates to be made. In conjunction with the mudrock bulk densities, they indicate burial depths of 3 to 6 km in the medium volatile bituminous Blossburg basin, 4 to 6 km in the low volatile bituminous Barclay basin, and 6 to 7 km in the semianthracitic Bernice basin. Burial depths of strata in the Northern Anthracite field may have been as great as 7 to 9 km.

These estimated depths are controversial, however; As noted by Daniels *et al.* (1990), development of compactional features such as sutured quartz grain contacts may have been aided in part by higher temperatures rather than by burial compaction alone. If so, then in the presence of elevated (overall) geothermal gradient the observed reductions in porosity may have occurred at shallower depths.

Possible Influence of Basin-wide Hydrologic Flow on Heat Transfer and Geothermal Gradient

(adapted from Daniels, 1992)

There are several problems with a deep burial mechanism for coalification in the Anthracite region including: the unusually large inferred thicknesses of both the total Paleozoic section (~20 km) and the Devonian/Carboniferous/Permian molasse sequence (~12 km), the extremely rapid burial rates required by estimates of the duration of coalification (< 15 m.y.), and the subsequent removal of the entire overburden. In consideration of these problems, Levine (1986) proposed that a significant component of the former overburden may have been emplaced tectonically via thrust sheets, thereby producing a geologically rapid burial of the coal-bearing rocks; but because thermal re-equilibration through heat conduction is a relatively slow process (Oxburgh and Turcotte, 1974), coalification and diagenesis should postdate deformation. However, vitrinite reflectance data (Levine and Davis, 1989b), quartz suturing (Paxton, 1983), secondary remanent magnetization (Miller and Kent, 1988), and mineralogical data (Daniels, 1992) all indicate that coalification and diagenesis in the Anthracite region occurred prior to and during foreland deformation, not after.

An alternative model to explain high temperatures in the region would be that of heat transfer by advective groundwater flow (Levine, 1986; Daniels *et al.*, 1990). The mineralogy of coal cleat in the Anthracite region suggests the occurrence of hydrothermal alteration durial coalification. Although there are no known large igneous intrusions that can account for hydrothermal alteration observed in coal joints, gravity-driven artesian migration of basinal fluids in the Appalachian foreland basin could have produced similar results. According to this model, orogenic uplift on the eastern flank of the Appalachian basin during the Alleghanian orogeny created a gravity-driven flow system that flushed hot basinal fluids out of the core of the Alleghanian orogen toward the west and northwest (Hearn *et al.*, 1987; Elliot and Aronson, 1987; Bethke and Marshak, 1990). Brine migrations can efficiently transport heat and thereby increase subsurface temperatures to values greater than would be expected from thermal conduction.

Figure 17 shows schematic cross-sections of the Appalachian hinterland and foreland basin during the early (Lackawanna) phase (Fig. 17a) and the later main phase of the Alleghanian orogeny (Fig. 17b). Computer simulations (Bethke, 1986) and present-day observations (Hitchon, 1984) suggest that meteoric recharge in topographically high hinterland regions creates high fluid head potentials which can drive hot basinal fluids out of the orogenic core of mountain belts. Fluids flushed out of deeper rocks close to the orogen carry heat and solutes toward the foreland along permeable zones. This mechanism could account for observed diagenesis and coalification in the Anthracite region. The large amount of conglomeratic strata below and interbedded with coal seams in eastern Pennsylvania is likely to have provided permeable conduits for basinal fluids.

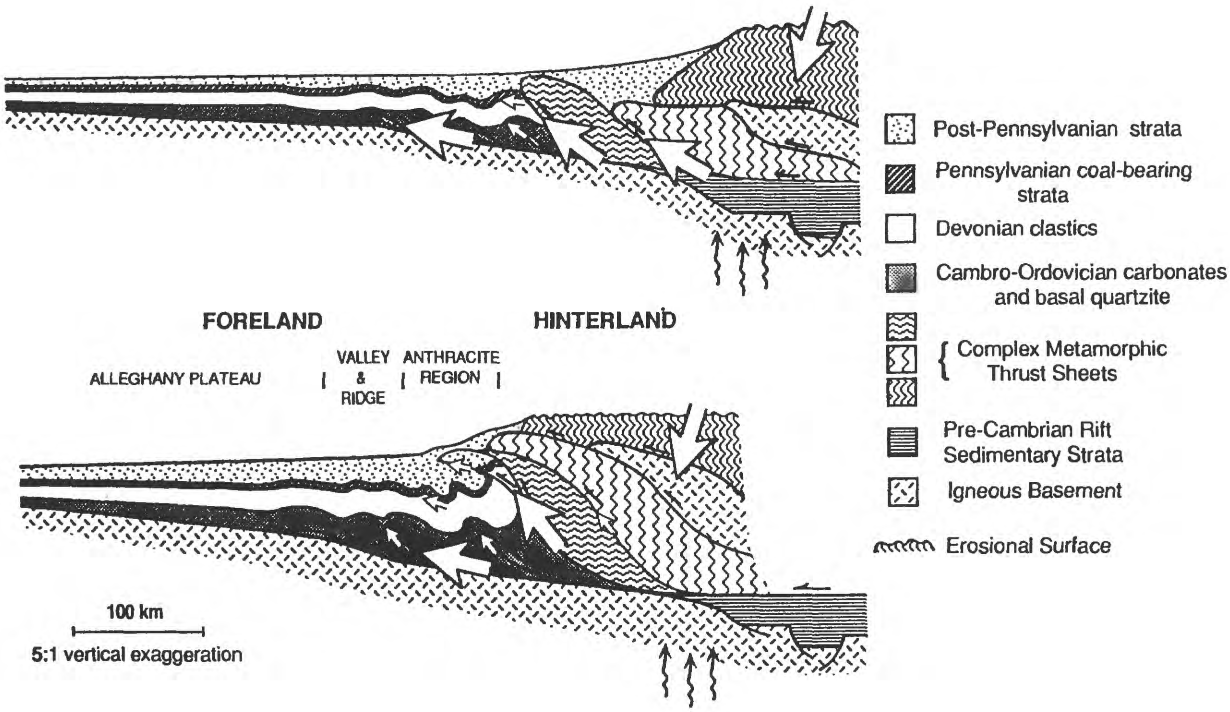


Figure 17. Schematic northwest-southeast cross-section of Appalachian foreland basin and hinterland during (a) an early phase of uplift and (b) main phase of Alleghanian orogeny. White arrows show hypothetical fluid migration paths along décollement zones and through permeable strata (from Daniels, 1992).

Influence of Hydrologic Heat Transfer on Geothermal Gradients.

Measurements of thermal gradients in modern hydrothermal fields show that basins with a significant amount of surfaceward advection have nonlinear geothermal gradients. Although temperatures at all depths are elevated by surfaceward advection, high geothermal gradients are created only near the surface, with normal or below-normal gradients observed at moderate and deep depths, respectively. A non-linear concave-upwards thermal gradient is compatible with advective heat transport by upwelling groundwater (Bredehoeft and Papadopulos, 1965; Domenico and Palciauskas, 1973).

A linear extrapolation, which assumes a constant thermal gradient throughout the entire sedimentary pile may significantly overestimate the actual burial depth. Moreover, if conduction were the only mechanism of heat transfer during coalification, geothermal gradients should be higher in the coal-bearing section than in the overlying rocks, due to the extremely low thermal conductivity of coal compared to clastic rocks. Thus, in areas such as the Anthracite region where erosion has removed substantial amounts of former overburden, conductive (linear) thermal gradients in the eroded overburden cannot be assumed from "normal" geothermal gradients in the remaining section and, therefore, former burial depths cannot necessarily be easily determined.

An additional benefit of the hydrologic heat transfer model is that it is consistent with the relative timing of coalification and deformation. Gravity-driven fluid migration could have begun after initial uplift of the hinterland, but prior to (and during) the latest phase of Alleghanian deformation in the foreland. Initial uplift of the hinterland, as evidenced by the first influx of coarse Pottsville conglomerates, may represent an early stage of Alleghanian orogenesis, whereas the final phase, which deformed the foreland, would have post-dated deposition of the Llewellyn Fm.

REFLECTANCE ANISOTROPY OF COALS FROM THE ANTHRACITE REGION

Jeffrey R. Levine

Background

Vitrinite reflectance is usually anisotropic when measured in polarized light--exhibiting directional maximum, minimum, and intermediate values that are interpreted to have developed in response to directed stresses ambient during coalification (Teichmüller and Teichmüller, 1966; de Vries *et al.*, 1968; Hower and Davis, 1981a; Levine and Davis, 1984, 1989a, 1989b). The three-dimensional patterns of anisotropic reflectance in coal can be represented by a form resembling an ellipsoid, referred to here as the Vitrinite Reflectance Indicating surface (or VRI; Fig. 18). The radius of the VRI in any given direction is proportional to the reflectance (Hevia and Virgos, 1977). Most naturally occurring VRIs reported in the literature fall into one of three geometries, namely: uniaxial negative, biaxial negative, and biaxial positive.

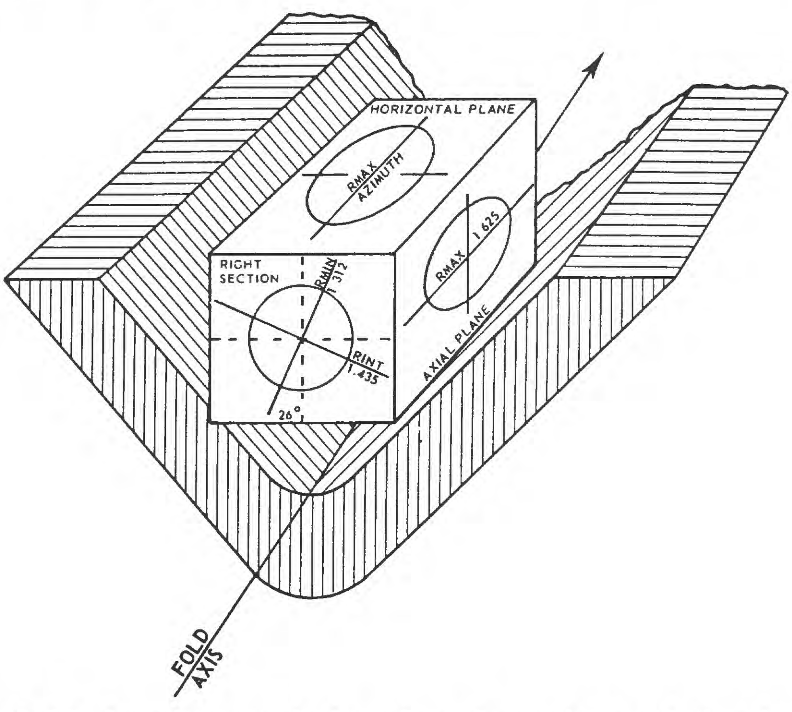


Figure 18. The three planes examined to estimate the magnitudes and orientations of the principal reflectance axes. The apparent maximum reflectance axis (R_{max}') in the Axial Plane section is used to estimate the true R_{max} axis. R_{max}' and R_{min}' in the Right Section correspond to R_{int} and R_{min}, respectively.

Past studies have shown that the shape and orientation of VRIs are indicative of the structural regime in which the coal was metamorphosed (Fig. 19). The simplest observed VRI geometry, and the model generally used in the past to describe vitrinite reflectance, is that of a uniaxial negative ellipsoid, or oblate spheroid. In this model there is a unique minimum principal axis of reflectance (R_{min}) perpendicular to a plane of maximum reflectance (R_{max}). In tectonically undeformed sedimentary basins, the R_{min} axes of uniaxial negative VRIs are aligned orthogonal to bedding, suggesting that this pattern is derived from vertical compression due to the weight of the overlying strata during sedimentary burial (Dahme and Mackowsky, 1951; Williams, 1953; Petrascheck, 1954; Krylova, 1971; Hower and Davis, 1981a). Theoretical, experimental, and empirical evidence support this interpretation (Levine and Davis, 1984).

In some instances, vitrinite exhibits a biaxial rather than a uniaxial reflectance pattern, wherein there are three principal reflectance axes, designated R_{max}, R_{int}, and R_{min}. In weakly biaxial coals, R_{int} is closer in magnitude to R_{max} than to R_{min} (biaxial negative) and reflectance in the R_{max}/R_{int} plane is only slightly anisotropic (Stone and Cook, 1979; Hower and Davis, 1981a). In biaxial positive VRIs, R_{int} is closer in magnitude to R_{min} than to R_{max} (Levine and Davis, 1984; Kilby, 1988). Also, in coals having biaxial reflectance patterns, the principal reflectance axes are typically reoriented with respect to bedding (Cook *et al.*, 1972; Hower and Davis, 1981b; Levine and Davis, 1984; present study). In all examples where biaxial reflectance patterns have been reported, the strata are strongly folded or faulted, suggesting

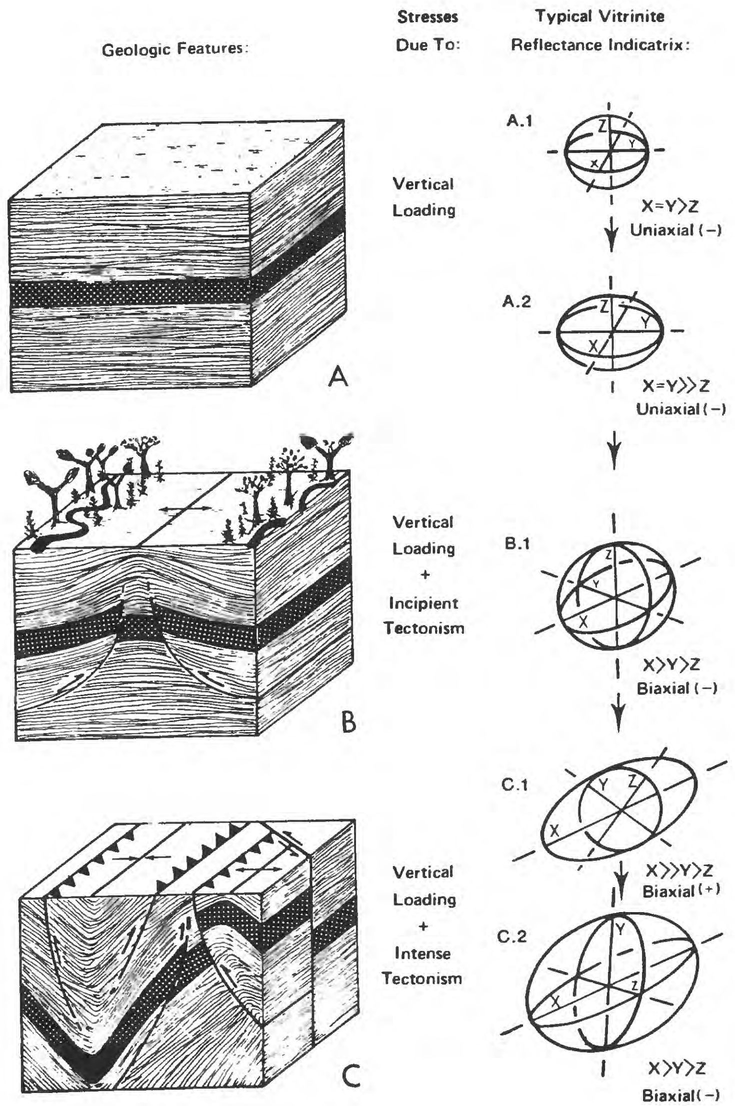


Figure 19. The geometric forms of vitrinite reflectance indictrices (VRIs) are characteristic of the rank attained and the tectonic setting in which they developed, assuming that coalification was at least partly syntectonic. This model, developed primarily on the basis of data presented herein, is consistent with other published studies and interpretations of vitrinite reflectance anisotropy (Dahme and Mackowsky, 1951; Williams, 1953; Petrascheck, 1954; Krylova, 1971; Stone and Cook, 1979; Hower and Davis, 1981). Uniaxial negative VRIs (A.1. & A.2.) are indicative of coalification in tectonically undeformed, subsiding basins (A). Biaxial negative VRIs with R_{min} axes near vertical (B.1.) are indicative of mild tectonic deformation (B). Biaxial positive VRIs (C.1.) indicate tectonic "constriction" and are found in strongly deformed terranes (C). Strong tectonic oppression may also produce biaxial negative VRIs (C.2.). Uniaxial positive VRIs are an unusual transitional form. X represents R_{max}, Y represents R_{int}, and Z represents R_{min}. X, Y, and Z increase in magnitude with increasing coal rank (cf. Fig. 21).

that the same geologic stresses responsible for the tectonic deformation also imparted the reflectance patterns to the coal.

Geologic evidence indicates that during coalification, minimum reflectance develops incrementally parallel to maximum compressive stress and maximum reflectance develops incrementally parallel to minimum compressive stress (Levine and Davis, 1984). Therefore, incremental changes in the principal reflectances may, in some circumstances, be indicative of stress directions during coalification. In a similar manner, the vitrinite reflectance indicatrix may be thought of as somewhat analogous to a finite strain ellipsoid in that it evolves (at least in part) in response to stresses ambient during coalification and may, in some cases, have a similar symmetry and orientation to that of finite strain markers. However, there are several significant limitations to this analogy.

Graphical Representation of Vitrinite Reflectance Anisotropy

Complete representation of the coal VRI requires depicting both its shape and spatial orientation. In the present study, orientation has been expressed by plotting the three principal reflectance axes as points on lower hemisphere, equal area stereo net projections. VRI shapes are depicted on "axial ratio diagrams" which show the ratio of R_{max}/R_{int} (a) as the ordinate and R_{int}/R_{min} (b) as the abscissa (Fig. 20). Because these ratios are never less than 1, the origin is plotted at a=1, b=1.

The utility of the axial ratio diagrams is apparent when considering the possible range of VRI shapes. For uniaxial negative VRIs R_{max} and R_{int} are of equal magnitude. Hence the R_{max}/R_{int} (a) ratio is 1 and these (pancake-shaped) VRIs plot along the b (horizontal) axis. At the opposite extreme are (cigar-shaped) uniaxial positive VRIs wherein the R_{int}/R_{min} ratio is equal to 1 and which plot along the a (vertical) axis. Intermediate shapes are plotted at intermediate positions on the diagram, with a line of slope=1 separating the biaxial positive field (wherein R_{int} is closer in magnitude to R_{min} than R_{max}) from the biaxial negative field (wherein R_{int} is closer in magnitude to R_{max} than to R_{min}).

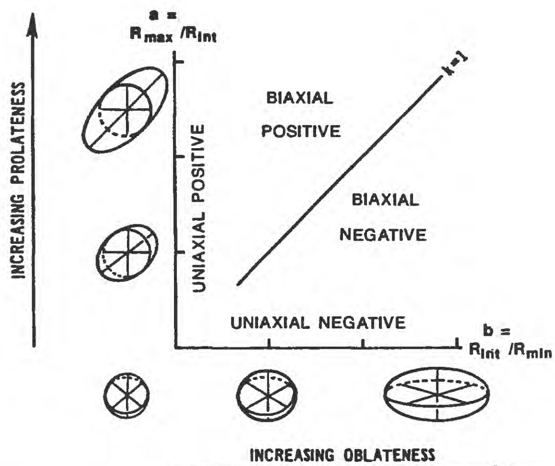


Figure 20. Axial ratio diagrams of vitrinite reflectance are used to depict the various possible shapes of the vitrinite reflectance indicating surface.

Results: Western Middle Anthracite field

On average the three principal reflectance axes of coal tend to increase with increasing rank (Fig. 21), but at different rates, depending on the tectonic setting in which they developed.

The shapes and orientations of 27 vitrinite reflectance indicatrices of coals from the Western Middle Anthracite field (WMF) clearly demonstrate the effects of coalification in a stress environment dominated by tectonic forces. Samples exhibit a full range of ellipsoidal shapes, from biaxial negative to biaxial positive (Fig. 22). However, few coals (only 7 of 27) plot within the biaxial positive field, indicating that it is only under unusual circumstances that these VRIs are transformed from their original biaxial negative geometry into a biaxial positive form. Dip direction of the enveloping bedding does not appear to have any systematic control on VRI shape or orientation; however, the coals may be grouped into two broad fields on the basis of rank. The lower rank samples, collected from the western end of the basin, are clustered relatively close to the origin, whereas the higher rank coals, collected from the eastern portion of the basin, form a diffuse group more removed from the origin.

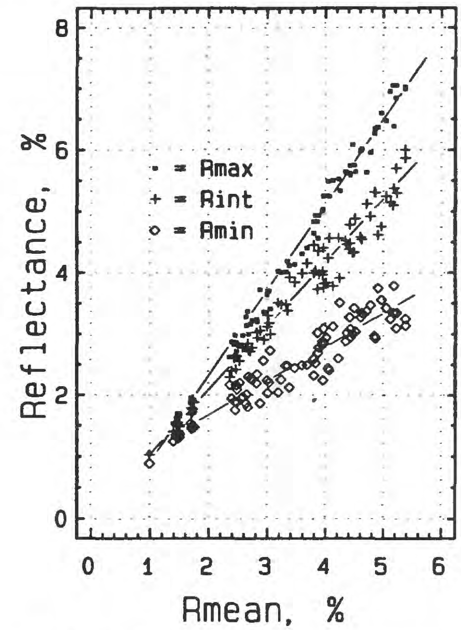


Figure 21. Principal reflectances versus rank for samples from the study area.

R_{max} axes are more-or-less aligned with the regional trend of fold axes in the Western Middle Anthracite field (Fig. 23b). In their present-day orientation (Fig. 23c), R_{min} axes of the Western Middle field coals are scattered fairly evenly about a great circle distribution, the pole to which plunges 8^o at azimuth 082. Poles to bedding of the coal-bearing strata are also scattered about a great circle distribution (Fig. 23 a), the pole to which is essentially identical (8^o at azimuth 081) to the one defined by the R_{min} axes. The close coincidence of these two poles indicates that the R_{min} axes were reoriented by Alleghanian folding and faulting.

When the R_{min} axes are rotated with bedding such that bedding is returned to its original flat-lying orientation (i.e. the bedding pole is rotated along a great circle to vertical), the R_{min} axes converge into a loose grouping centered about a pole which plunges steeply to the north (Fig. 23d). Whereas the R_{min} axes remain somewhat scattered about a great circle distribution (which is vertical in this case, rather than inclined), most of the rotated R_{min} axes (20 of 26) lie within 30^o of the bedding pole.

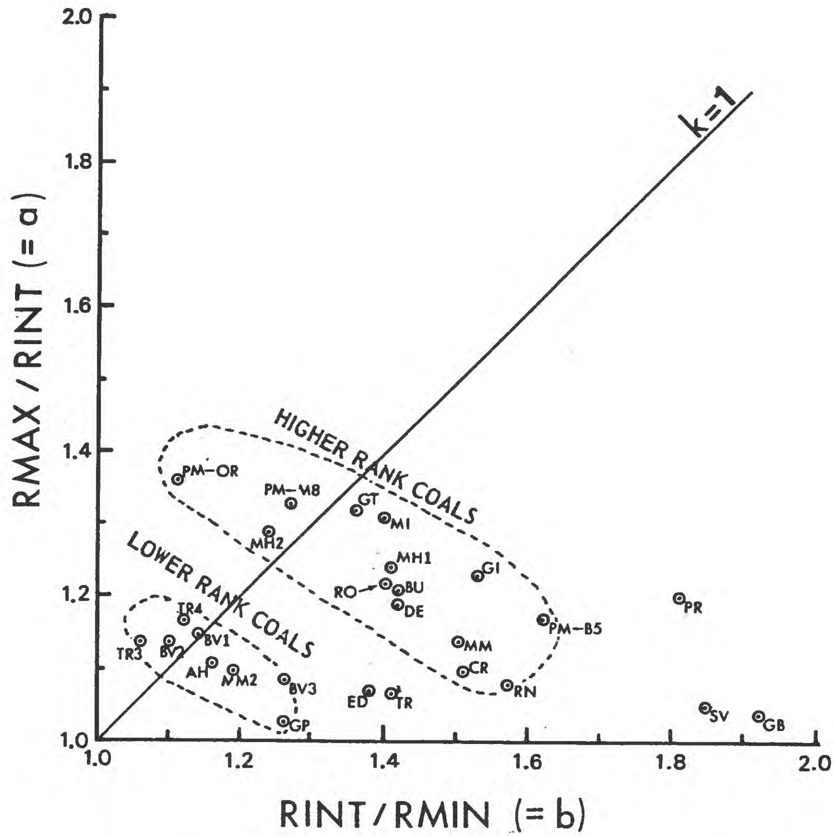


Figure 22. Axial ratio diagram of coals from the Western Middle field.

The "fold test" of Graham (1949) was employed to measure the statistical significance of the increased convergence of the unfolded R_{min} axes. The Fisher "k" statistic for R_{min}, which measures dispersal on the surface of a sphere, is 8.95 when bedding is rotated to horizontal and 2.27 when the strata are in their present, folded configuration. The ratio of k statistics (k_2/k_1 = 3.94) easily passes the fold test at the 99% confidence level (k_2/k_1 must be greater than 2.15), which strongly indicates that the R_{min} orientations were imparted to the coal largely prior to, and were subsequently scattered by, Alleghanian folding. However, the lack of precise convergence of the R_{min} axes also suggests that some reorientation of the optical fabric may have occurred during or after the Alleghanian tectonism as well.

Previously published analyses of vitrinite optical anisotropy in the Broad Top coal field in south central Pennsylvania (Fig. 1) demonstrated that coalification there occurred *subsequent* to folding, as indicated by the R_{min} axes maintaining an identical orientation on opposite-dipping limbs of a fold (Levine and Davis, 1984). Thus, relative to the Western Middle field, the Broad Top coals were either influenced by an early stage of Alleghanian folding or a late stage of Alleghanian or post-Alleghanian heating.

An additional clue regarding the relative timing of coalification versus Alleghanian tectonism is provided by reflectance anisotropy of sporinite macerals (Levine and Davis, 1989b). In some anthracite samples, sporinite can be readily distinguished from its vitrinite matrix by its having a distinct optical fabric. The maximum and minimum reflectances of the sporinite grains are not coincident with those of the vitrinite; hence, they appear alternately darker or lighter in color as the stage is rotated in polarized light. In all cases where this has been observed in the Western Middle field, the maximum reflectance axis of the sporinite is oriented parallel with bedding laminae. This suggests that a "burial" reflectance fabric was imparted to the sporinite during a discrete coalification interval while the beds were still flat lying, and that this fabric managed to survive subsequent stages of coalification and tectonic deformation during which the vitrinite fabric was reoriented. We speculate that the observed sporinite reflectance fabrics were imparted during the coalification interval encompassing the 1st and 2nd "coalification jumps" (Stach *et al.*, 1975), when the sporinite undergoes a rapid change in chemical and physical composition and (normally) becomes visually indistinguishable from vitrinite. At normal coalification gradients, this change occurs at a depth range of about 2 to 4 km (Tissot and Welte, 1978), suggesting that *at least* this much overburden was deposited on top of the extant coal-bearing section prior to the onset of Alleghanian tectonism.

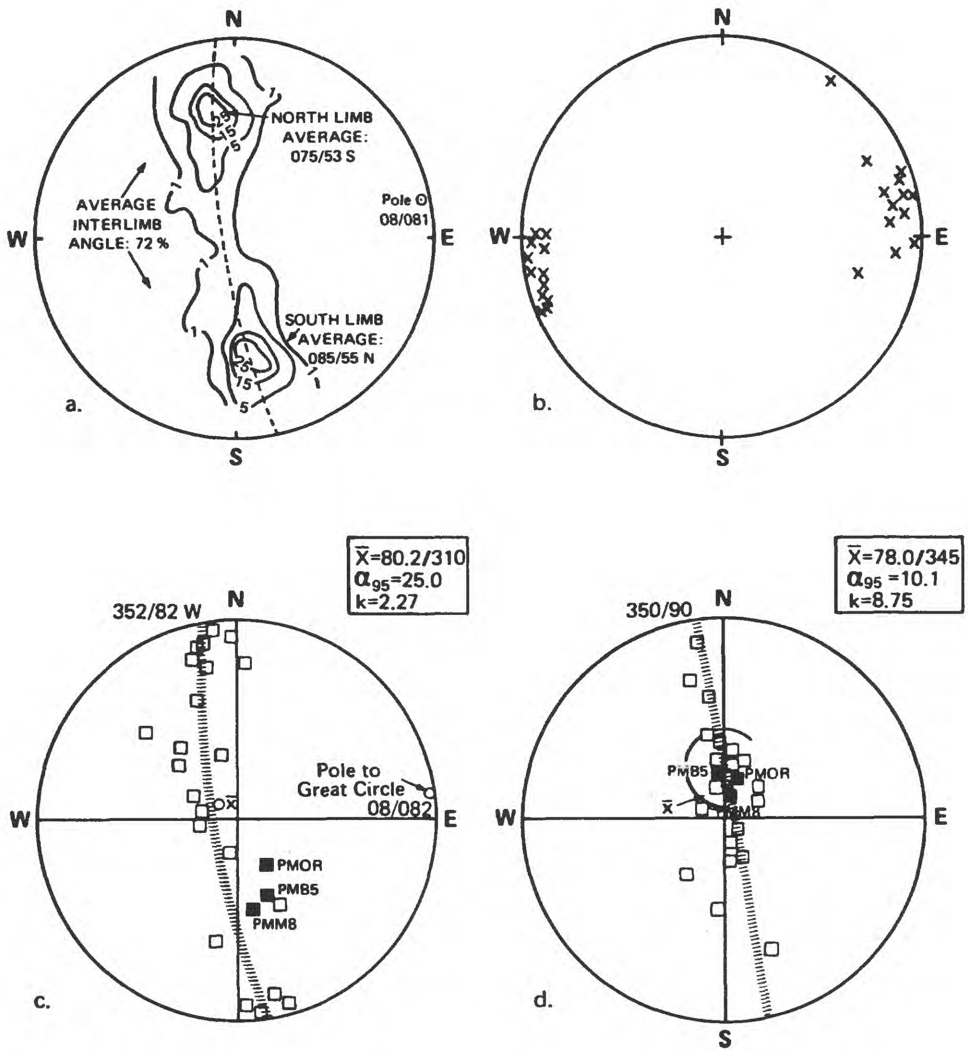


Figure 23. Stereo net diagrams of reflectance axes and structural features from the Western Middle anthracite field: a.) The mean fold axis orientation in the western end of the Western Middle field is the pole to the great circle of 170 bedding poles (08/081) (data from Arndt *et al.*, 1963 and Arndt *et al.*, 1973). The spatial distribution of bedding poles indicates the tight, chevron-style fold geometry. Contour values indicate the density of bedding poles determined on a Kalsbeek counting net. b.) R_{max} orientations exhibit a range of azimuths from approximately 070 to 090, generally parallel to the regional fold axis orientations. c.) R_{min} axes, plotted as open squares. Solid squares indicate the three oriented samples from the Pioneer Tunnel (Stop #2) from the Orchard (#12) bed (PMOR), Mammoth lower split (#8) bed (PMM8), and Buck Mt. (#5) bed (PMB5). The hatchured line represents the best-fit plane through these points, the pole to which plunges gently to the east precisely parallel to the regional trend of the fold axes. d.) R_{min} axes, rotated such that bedding is horizontal. The clustering of points after bedding is returned to horizontal (indicated by the small circle) proves statistically that the R_{min} orientations were imparted to the coal mainly prior to folding. The steep, cratonward average plunge of the unfolded R_{min} axes may be related to the stress field within the foreland basin deformational prism. The reason for the divergence of some coals from the main cluster is unknown, but probably represents local variability in the stress/strain history. Even aberrant points, however, lie along the same great circle distribution (hatchured line).

PALEOBOTANY

Christopher Wnuk

Paleobotany in North America began in the Anthracite fields. It was here that Lesquereux began his comprehensive compilation of the Carboniferous floras of the coal measures in the eastern United States. This work began when Lesquereux joined the First Geological Survey of Pennsylvania in 1851 and published a report on the coal floras in 1858 contained in H.D. Rogers volume *Geology of Pennsylvania.* Lesquereux's work for the Second Geological Survey of Pennsylvania was published in the three volume *Reports of Progress P between 1879 and 1884.* In these volumes, Lesquereux described several hundred new plant species, published the first biostratigraphic range charts of the U.S. coal measure floras, and attempted a biostratigraphic correlation among all of the coal basins in the eastern U.S.

Lesquereux was followed by David White who in 1900 published a comprehensive biostratigraphy of the Pottsville Formation based on the study of Pottsville sediments in the Southern Anthracite field. This study was prompted by the need to correlate among the isolated occurrences of mineable Pottsville coals (the Lykens coals) scattered throughout the Anthracite fields, and the need to correlate among so called Pottsville sediments throughout the Appalachian basin.

The German paleobotanist Bode visited the Anthracite fields during the 1950's and in 1958 published a report correlating the North American Carboniferous floras to those of the European continent (Bode, 1958).

These studies were the primary biostratigraphic reports that were used in correlating the coal deposits in the Carboniferous of the U.S. until 1964 when Read and Mamay published USGS Professional Paper 454-K, *Upper Paleozoic Floral Zones and Floral Provinces of the United States.* This floral zonation of the Carboniferous relied on floral data collected throughout the U.S., but was still heavily dependent on data from the Anthracite fields.

The biostratigraphic primacy of the Anthracite fields was only recently supplanted when Gillespie and Pfefferkorn published a biostratigraphy in 1979 based on the Pennsylvanian System stratotype located in West Virginia. The Anthracite region is one of three places that were thought to have a continuous Mississippian through Pennsylvanian section, and, consequently, was strongly considered as a likely location for the Pennsylvanian System stratotype. West Virginia was finally chosen because it was believed to contain the most complete Mississippian through Pennsylvanian boundary. Subsequent studies Gillespie and Englund (in press) suggest that there may in fact be an unconformity at the Mississippian/Pennsylvanian boundary in the Anthracite fields, though this issue has not yet been resolved.

Paleozoic floras from the Late Devonian up to and possibly including the earliest Permian can be found within the Anthracite basin (Read, 1955; Read and Mamay, 1964; Wood et al., 1969a; and Eggleston *et al.* 1988). Lesquereux (1880) listed 253 taxa in the coal flora of the Anthracite region. In the coal rich parts of the section plant remains are easily recovered in the carbonaceous shales and siltstones, particularly the "roof" shales that overlie the coal beds. With persistence, floral collections can also be recovered from shale and siltstone beds that are not associated with the coal beds. Sandstones and conglomerates frequently contain flood rafted accumulations of large fossil tree trunks, usually lycopods. These trunks may be several meters in length but are poorly preserved due to mechanical abrasion and the coarseness of the sediment. These accumulations typically occur concentrated with lag deposits in channels. Plant fossils are preserved in a variety of depositional environments including lacustrine, channel, floodplain, and oxbow settings.

The floras in roof shales and log jams are typically transported assemblages that are no longer compositionally representative of the original plant communities from which they were derived. Rather they are preferentially sorted accumulations of elements from one or more plant communities. Moreover the plants are typically dissociated into their component plant parts, i.e. leaves, branches, trunks, fructifications, etc., so that it is nearly impossible to reconstruct the original plant even if all of the component parts are present. Transported assemblages are important for biostratigraphy and certain taxonomic studies, but are poorly suited for paleoecological and paleoclimatological studies because they do not represent natural ecological associations.

Of much greater interest to ecological and climatological studies are *in situ* floras - floras that were preserved where they grew. These have been traditionally regarded as very rare occurrences, and in the past, only floras preserved in growth position were regarded as being *in situ.* However, recent studies in the Anthracite fields (Wnuk, 1985, 1986, 1989a; Wnuk and Pfefferkorn, 1984, 1987) have shown that there exists a large population of *in situ* floras distinctly different from those that are found in growth position. These are prostrate floras occurring in extremely carbonaceous shales that overlie underclays and are often, but not always transitional to coal beds. These floras typically consist of large trunks that may exceed 20 m in length, preserved on a surface which also contains the upright root bases of the stems. These floras may also contain smaller stems and axes, and very rarely, leaves and fructifications. These underclay floras are considered representative of the composition of the Pennsylvanian forests that occupied the site at a given moment of time.

Preliminary investigations in the Anthracite fields indicate that such underclay floras are widespread throughout the section, especially in the Middle Pennsylvanian part. There have been few assessments of coal beds outside of the Anthracite fields. Such floras appear to be less common in the Appalachian region, but preliminary surveys suggest that these underclay floras are ubiquitous under certain depositional conditions. The parameters controlling the distribution of these underclay floras have not yet been established.

The studies by Wnuk (1985, 1989) and Wnuk and Pfefferkorn (1984, 1987) indicate that careful analysis of the underclay floras can yield valuable information about paleobiology, paleoecology, and especially local and regional paleoclimatology that cannot be derived by other means. Because of the unique structural characteristics of the Anthracite fields and the abundance of abandoned strip mines, the *in situ* floras can be studied easily on the steeply inclined bedding plane surfaces that remain after the coal has been removed. The Anthracite fields provide an unequaled opportunity to study such floras in the United States and possibly are unique in the world. During this field trip you will visit one of the *in situ* accumulations (Bear Valley) that has been studied extensively. Details of the information that can be derived from such occurrences are discussed in Stop #1 of this guidebook.

ECONOMIC GEOLOGY

Jane Eggleston

Mining Methods

Surface Mining

Two methods of surface mining have gained widespread acceptance for winning anthracite coal in northeastern Pennsylvania. The long pit mining method is a continuous operation that advances along the outcrop of a moderately to steeply dipping coal bed, or more than one bed if closely associated. Block pit mining concentrates on one particular block of coal and overburden and is usually applied in areas where geologic conditions are favorable, such as on crests of anticlines, in troughs of synclines, and along gently dipping beds. Average production of both is about 10 tons/man-day (8-hour shift).

Both long pit and block pit mining methods, in which the equipment operates from outside this pit, are effective to depths of 45-60 m (150 to 200 ft). Beyond this depth, the open-pit mine concept must be applied. Roads must be built within the pit to allow haulage both in and out. Drilling and excavation equipment actually operate on terraces within the pit. Shovels and end-loaders move and load the coal and dozers are primarily employed in overburden excavation. Mining is done in a semi-terraced fashion. By utilizing this open-pit method, a few anthracite mines are currently working to depths of 120-180 m (400 to 600 ft). The open pit concept has received a great deal of interest for anthracite recovery in recent years because it provides a means of recovering the thinner, less easily mined beds and the pillars left behind after deep mining, as well as deeper virgin-coal reserves.

Culm Bank Recovery

The recovery of anthracite from culm banks, silt banks, and refuse piles is a very straightforward process. The loose material requires no drilling or blasting, and may be loaded directly into haul trucks using either small power shovels, small draglines, or front-end loaders. Depending on its physical character, anthracite content, and utilization intent, the material may be processed on-site, processed through a preparation plant, or delivered directly to the point of utilization. Production from culm bank recovery operations, on the average, exceeds 40 tons per man-day (8-hour shift).

Underground Mining

Underground mining of anthracite, which once was the principal method of anthracite production in this region has declined in recent years. It now constitutes only about 17 percent of the total yearly production. This decline is directly related to the high labor intensity and the associated low levels of productivity (averaging 4 tons/man-day (8-hours)) great depths now involved in reaching virgin coal, and the enormous quantities of water that must be pumped to keep the mines dry.

Breast and pillar mining is the major method used, and entry to the mine may be accomplished by drift, tunnel ("adit"), slope, shaft, or a combination of these. In breast and pillar mining, two horizontal headings are driven along the strike of the coal bed from the entry (Fig. 24). The lower and larger of the two openings, the gangway, is used for haulage and intake ventilation. The second, upper heading, known as the monkey, is driven to provide a path for return air, and an access point for breast development. Connecting passages - chutes and manways - are driven upward from the gangway to the monkey heading as the latter is advanced. Since coal beds in breast and pillar mines are steeply dipping, the roof rock of the gangway is coal, which, at many places, is difficult to support.

Breasts are driven updip from the monkey through the coal bed to ultimate heights of 60-90 m (200 to 300 ft). They are generally 6-9 m (20 to 30 ft) wide (along strike) and are connected to adjacent breasts by headings spaced approximately 15 m (50 ft) apart. Coal is drilled and blasted, and falls through the breast and along a chute onto a mine-car in the gangway. Extraction percentages for breast and pillar mining have exceeded 80 percent under good roof conditions. Breast development normally requires a two-man crew, which is capable of advancing upward at a rate of 2 m (6 ft per 8-hour shift. The rate of advance is low because all equipment, supplies, and timbers (for roof support) must be manually carried or hoisted upward as much as 90 m (300 ft) to the working face.

Production

Production in the Pennsylvania Anthracite region reached a peak of 99.6 million tons in 1917, then steadily declined to a low of 2.9 million tons in 1983. In 1991, total production was about 3.2 million short tons. (Fig. 25) Nearly 53 percent was from open-pit surface mines, 12 percent was from deep mines, and 35 percent from reprocessing of old cleaning plant refuse. Beginning in 1988, cleaning plant refuse was burned directly in new, fluidized bed electric plants, increasing the demand for this material.

Coal Resources

Principal Coal Beds

Principal coal beds and their relative stratigraphic position within the three fields are shown in Figure 3. Many of the upper beds shown on these stratigraphic sections occur only locally and thus only have local economic importance. About 90 percent of the coal mined in these fields has come from beds in the lower part of the stratigraphic section, including the: Lykens Valley (lowest), Buck Mountain, Seven-Foot, Skidmore, Mammoth, Holmes, Primose, and Orchard coal beds. Of these principal coal beds, the Mammoth (Nos. 8-9) is the most extensively mined, having contributed more than 30 percent of the total anthracite production. The Buck Mountain (No. 5) ranks second, having contributed about 25 percent of total production.

Resources

The latest resource study, funded by the U.S. Bureau of Mines (Resource Technologies Corporation, 1984) used the most recent published geologic maps and available mine maps to evaluate resources and to estimate reserves for three mining methods: shallow surface mining (strip mining), deep surface mining (open pit mining), and underground mining. Results indicate that, as of January, 1981, a total of 19,582 million short tons of anthracite remained in the four major fields (Table 2). About 1,505 million short tons is currently recoverable, of which 1,150 million short tons are recoverable by conventional "strip mining" and underground mining and 355 million short tons are recoverable by "open pit" mining. Recoverable coal is defined as coal lying above mine-water pool level, under undeveloped land surface areas, and minable where current technology is used. Open-pit mining reserves are further defined as less than 1,000 feet deep, and were estinmated only for the Western Middle and Southern fields, where sufficient contiguous unmined reserves are known to make open-pit mining economically viable.

In addition to the in-ground resources, 620 million cubic yards of coal refuse and silt (silt-sized coal and rock), which are scattered throughout the four fields, are estimated to contain approximately 84 million short tons of anthracite. This material remains from past mining and processing, and is believed to contain an average of 409 percent coal whereas other refuse from mechanical cleaning contains about 10-15 percent.

Chemical and Physical Properties of Pennsylvania Anthracite

The high percentage of fixed carbon (92-98 percent, moisture and ash free basis) inherent in anthracite coal makes it higher rank than bituminous coal. On an "as received" basis, carbon measures about 74-82 percent, and is lowest in the Southern field and the western part of the Western Middle field.

BTU value is about 14,430-15,450 (moisture and ash free), and "as received" it averages 13,000-14,000. It is higher in general toward the west, as is the volatile matter. (In bituminous coal, higher BTU's occur in lower volatile coals.) Volatile matter generally measures 2-8 percent (moisture and ash free), which makes it a low-volatility coal. Moisture is also low, at 0.5-14.6 percent, and usually is lowest toward the west.

Sulfur is moderately low, ranging between 0.3 and 1.2 percent (as received). It increases toward the west. Washability tests show that in most cases the anthracite coals will qualify as compliance coal (1.2 lbs. $SO_2/10^6$ BTU).

Hydrogen ranges from 2.5 to 3.1 percent (as received), and tends to increase toward the west, as does nitrogen (0.7-0.9 percent, as received). Oxygen decreases toward the west, however, with a range from 3-7 percent.

Trace element analyses of 2 anthracite samples (Daniels, 1992) indicate that the coal matrix contains significant amounts of Ti, V, Zr, and Cu. In addition, in an analysis of 24 anthracite samples, Daniels determined that "the C, H, and N composition of organic matter varies systematically with coal rank. As maximum vitrinite reflectance increases, the amount of organic C in the coal increases, whereas organic H, N, H/C, and N/C values in coal decrease."

The Hardgrove grindability index is low, indicating that anthracite coal is resistant to grinding, ranging from 32 to 69.8; it is generally higher toward the west and highest in the eastern portion of the Southern field. True specific gravity decreases toward the west, and ranges from 1.5 to 1.75 for rice size samples. Anthracite's ash softening temperature, which indicates the behavior of the ash during combustion, is near the high limit for coal, averaging 2900°F. However, in the Southern field the ash softening temperature is lower, in the medium fusibility range between 2200°F and 2600°F.

Most of the mined anthracite is cleaned and sized through a coal preparation plant. These plants in the Anthracite region may utilize any of five types of equipment: heavy media separators, hydrotaters, mechanical classifiers, cyclone classifiers, or cone cleaners. Of these, heavy media separation is the most commonly used technique for cleaning anthracite coal. The technique chosen for cleaning anthracite depends upon coal properties such as coal size, percent reject, and washability characteristics.

The Future of Pennsylvania Anthracite

Anthracite production has declined to only about 3 percent of what it was in 1917. Reasons for the decline include availability of cheaper and cleaner fuels, strikes and consequent unreliability of anthracite supply, inconvenience in handling anthracite and ash in home heating, labor intensive mining methods, difficulty in mechanization of mines because of such geologic conditions as hard rock and contorted steeply dipping, highly faulted coal beds, depletion of the more easily accessible coal beds, and costly legal responsibilities to rectify such problems as mine water, subsidence, mine fires, burning culm piles, and the so-called "lunar" landscapes (highwalls, gaping pits, and massive spoil piles) left by mining. Because the combustive nature of anthracite differs from that of bituminous coal, industrial plants must design their facilities to the particular characteristics of anthracite such as high ignition and burning temperatures and grinding difficulty. Many companies are reluctant to build a plant specifically for anthracite-burning when the source of anthracite is so limited and befraught with extraction problems. Even with anthracite's excellent quality (low sulfur, high Btu and fixed carbon, low volatility) and proximity to northeastern U.S. markets and East coast port facilities, there are many obstacles which the mining industry must overcome.

Field	Total Remaining Resources	Tonnage Above 1000 Feet (Demonstrated Reserve Base)	Recoverable Tonnage By: Conventional Strip Mining, Underground Mining, Open Pit Mining (Reserves)
Northern	2,762,383,000	2,306,957,000	253,000,000
Western Middle	3,352,009,000	1,820,096,000	440,000,000
Southern	13,294,649,000	2,966,149,000	716,000,000
Eastern Middle	172,811,000	167,052,000	96,000,000
TOTALS	19,581,852,000	7,260,254,000	1,505,000,000

(from Resource Technologies Corporation. 1984)

Table 2. Remaining Pennsylvania anthracite reserves (short tons).

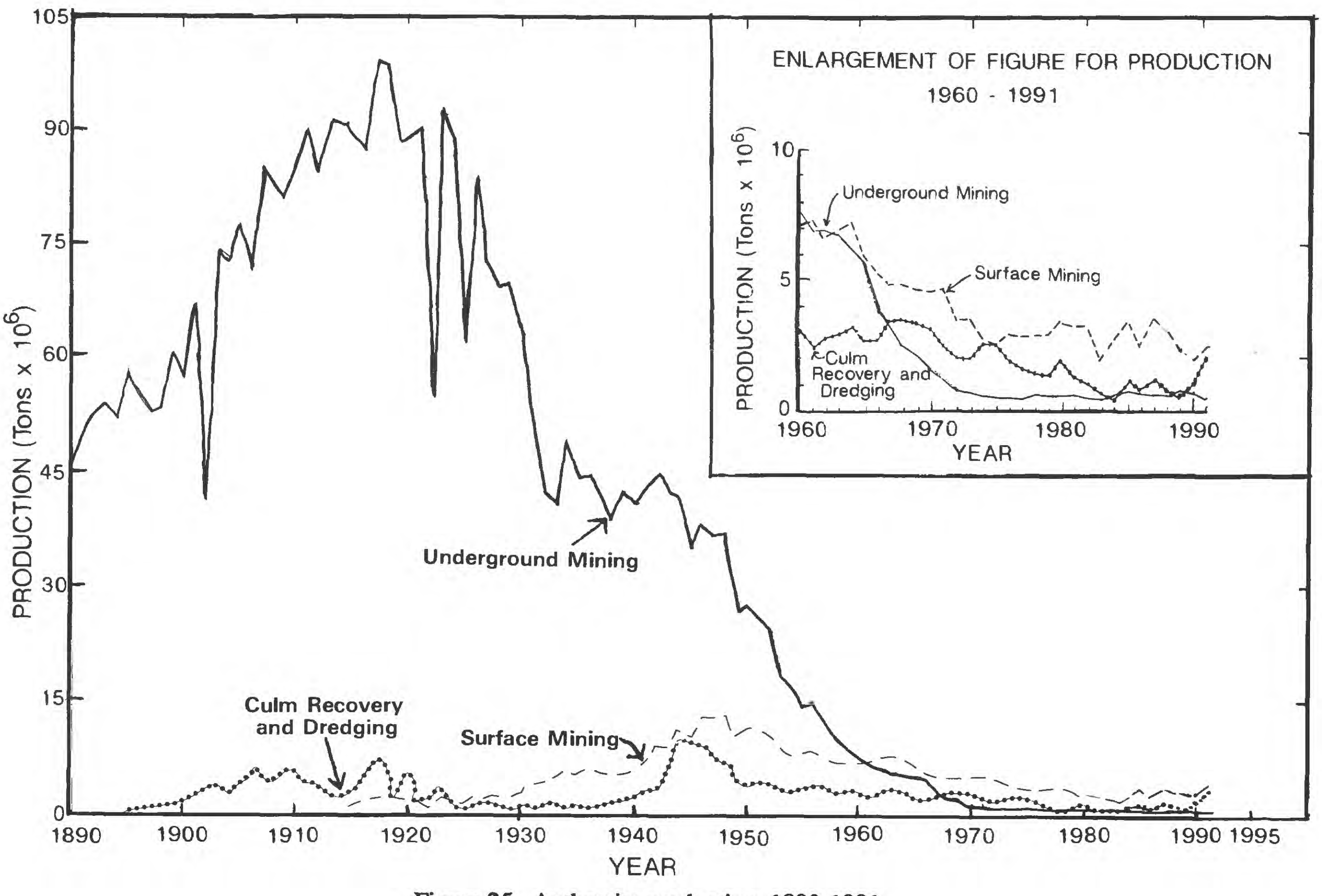


Figure 25. Anthracite production, 1890-1991.

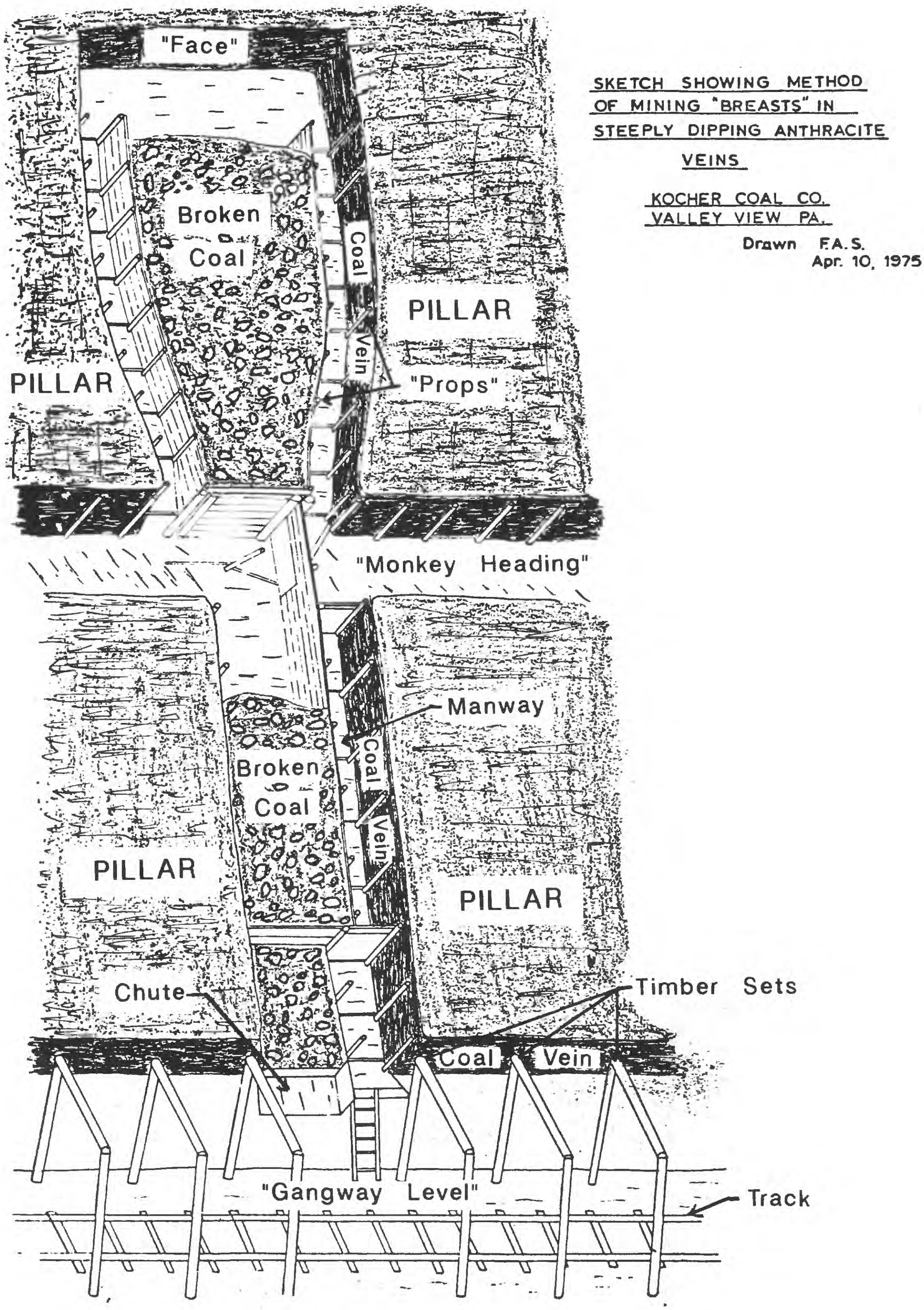


Figure 24. Schematic cross-sectional view of breast-and-pillar underground mining method used in the Pennsylvania Anthracite fields (drawing courtesy of Kocher Coal Co., Valley View, PA).

MINING AND LABOR HISTORY

David C. Glick

The earliest documented use of anthracite was in 1769, when the Gore brothers, blacksmiths, used "hard coal" under forced draft in their forge near Wilkes-Barre, Pennsylvania. However, records indicate that anthracite was known in Pennsylvania as early as 1698 and that Indians traded it to a blacksmith in Nazereth, Pennsylvania, between 1750 and 1755. Anthracite was used somewhat in the Revolutionary War effort, but because of competition with more familiar and easily ignited wood and bituminous coal, demand grew only slowly. The open fireplaces in use at the time did not allow for easy ignition and many people refused to believe the "stone coal" would burn properly at all. Another problem was transportation of the coal from the mining region to the population centers of Philadelphia and Baltimore. Roads were inadequate and anthracite, like other bulk materials, was transported primarily by river. The rivers leading from the Anthracite region were shallow and rocky; they were navigated principally at high water in spring, a dangerous practice. This kept supply low and erratic.

All of these factors generally improved through the years. Scattered use of anthracite demonstrated its utility; and its advantages of long burning time and low smoke production were also noticed. It was used most widely in blacksmith's forges. Fireplace and grate design were improved to allow more efficient burning of anthracite. River transportation was improved by dredging and canals were built. The War of 1812 also had a positive effect, by creating demand for forging coal and by cutting off the supply of bituminous coal imported from Britain.

In 1815, at the iron furnace of White and Hazard outside Philadelphia, the method of burning anthracite in a conventional iron furnace was accidentally discovered: the furnace door was intended to remain open for other fuels, but closing it forced the draft through the bed of fuel as required for anthracite. Through entrepreneurial efforts including leasing an operating mine, finding investors, manipulating the state legislature, purchasing timber lands for materials, surveying and building dams and locks on the Lehigh River and building the arks to transport the coal, White and Hazard formed the Lehigh Coal and Navigation Company which played a major role in the increasing use of anthracite in the cities. The Lehigh and other canals were then constructed and by 1840 the company was shipping 280,000 tons of coal along the various canal routes. They also built railroads to move the coal from mines to water routes; these ranged from the original gravity driven wagons running on wooden rails to stationary steam engine power, until the steam locomotive was introduced. Their competitors on the Schuylkill and Delaware rivers had similar histories; together they created the nation's largest canal network in the 1830's and proved the importance of transportation to the development of the anthracite industry. Later the railroads, including the Reading Railroad overpowered the canals. The railroads and the anthracite industry grew synergistically, with anthracite-fired hot blast furnaces producing iron for rails and rolling stock and also providing for abundant cargo of coal and iron. This led to other heavy industries in the Anthracite region and surrounding areas, such as the Bethlehem Steel Company in Bethlehem to the south of the anthracite fields.

Industrialists such as Asa Packer and Charles Brodhead accumulated staggering wealth and power through their control of the economy of the region. Under their dominance, the entire industry was vertically integrated, with all facets of production falling under the ownership of one organization, including mining of anthracite, limestone, and iron ore, railroads for transportation, and furnaces for iron and steel production.

As the anthracite mining industry developed from small open pits on hillsides to extensive underground workings with associated above-ground cleaning and shipping facilities, immigrants came to the area in search of jobs. The folded and often steeply dipping anthracite seams require the use of techniques specific to these conditions, and required extensive handwork even after the more flat-lying bituminous coal mines had moved to heavy machinery. A miner and his assistant advanced each face, drilling and blasting, removing the coal and loading it into a rail car. Mules then hauled the cars to the mine exit. Other jobs underground involved ventilation, transportation, supervision and safety. Surface jobs centered around the "breaker" building where the coal was picked free of rock as it moved down chutes under gravity feed. Many of these less skilled jobs were performed by boys 8 or 9 years of age or even younger. Most boys started in the breaker. Others called "nippers" were attendants at the wooden doors controlling ventilation in the mine--a job characterized by endless lonely hours in the dark and cold. In 1885 a law set the minimum working age at 12; in 1903 it was raised to 14, but the laws were seldom enforced. The mining companies received a lot of work for the low wages they paid the boys, and families need the income; no one was anxious to change the system. In the early days a breaker boy worked 10 hours a day, 6 days a week for 45 cents a day.

Mining was dangerous work with roof falls, heavy coal cars, methane explosions, blasting accidents and heavy equipment on the surface. It was a rare family which had not lost a member or friend to a mine accident. Miners became resigned to this, and it is said this has deeply influenced society in the region.

In addition to the threat of mine injury, economic difficulties plagued the mining community. The local coal company often controlled the provision of housing, food, supplies and medical care, making miners and their families completely dependent. Rent for company houses and goods from company stores were subtracted from the paycheck, leaving little actual pay. Taking home one-quarter of one's supposed pay was common and, in some cases, after all deductions were made, the miner owed money to the company. Wives and children were forced to work to try to make ends meet -- wives and daughters often in the many silk and other fabric mills in the region, and sons in the mine operations.

People willing to endure these working conditions for the prevailing wage came from a number of different immigrant nationalities. Following the 1845 potato famine and a continuing pattern of eviction by land owners, over 1 million Irish emigrated to America. The large proportion of these found work in the mines and related industries in the Anthracite region. They did not escape religious and ethnic discrimination but they did have the advantage of being the first large immigrant population. Later immigrants came people from Eastern Europe, their many ethnic and national origins being undifferentiated by the Americans, who simply called them "Slavs". The Slavic population in the region grew from 2% in 1880 to over 40% in 1900; the percentage of Slavic mine employees grew from 5% to 50% in the same period. These immigrants were discriminated against by the earlier immigrants, who had now become established.

Inequities of wages, working conditions, and living conditions provided the impetus for the organization of labor unions in the region, leading ultimately, in the words of Clarence Darrow, to "the greatest conflict between capital and labor which the world has ever seen". The organizers' task was made difficult, however, by the remoteness of the region, differing mining practices between Anthracite fields, mistrust between ethnic groups, and opposition by mining companies. Labor organizations started locally, but in 1868 a larger union, the Workingman's Benevolent Association, brought local groups together and eventually included 80% of anthracite workers. Although the union won wage concessions from small companies, it was unsuccessful against the large companies, which by then were mostly tied to the railroads. Organized labor threatened the security of these companies, and F.B. Gowen, President of the Philadelphia and Reading Company, set out to crush the WBA. A long strike in 1875 was characterized by violence on both side. The strike eventually failed and miners returned to work with wage cuts rather than increases. It was during this period that one of the most discussed sequences of events of the region's history began. Gowen claimed that the violence on the part of the unions was traceable to a secret organization called the Molly Maguires. The "Mollies," Gowen claimed, retaliated against the anti-union coal and railroad companies and the companies' regional Coal and Iron Police with threats, arson and murder. Gowen hired the Pinkerton detective agency which selected a new agent, James McParlan, to infiltrate the Molly Maguires in 1873. McParlan was apparently very successful, rising quickly to a position of responsibility in the Shenandoah branch of the Mollies. McParlan provided information on members and their activities to Pinkerton, and high-placed Mollies began to be arrested and brought to trial. McParlan continued undercover a little too long, and narrowly escaped execution when it became obvious that he was an informant. In a major trial in 1876, McParlan testified for the prosecution for four days, reporting that Mollies from different towns would arrange to perform each other's crimes to hide the motive and provide alibis for the obvious suspects. The trials have been characterized as sensational, staged, and lacking in proper procedure. Over a dozen Mollies were hanged and many others were imprisoned; few high-ranking Mollies escaped. Because of the secret nature of the organization and the failure of due process at the trials, the Mollies' organization, motives, actions and even their existence is still open to debate. The trials of 1876 brought an end to the Mollies, but not to union organization and violence between miners and operators. These events form the background for Sir Arthur Conan Doyle's Sherlock Homes novel, *The Valley of Fear*, and were the basis of a Hollywood feature film, The Molly Maguires, starring Sean Connery. The mining community of Eckley in the Eastern Middle field was "restored" by Paramount Pictures for the filming, by removing paint from all the buildings, tearing up paved streets, and burying all electrical and telephone lines. The site has now been converted to a state Historical Park.

1877 saw the beginning of a series of strikes of anthracite and railroad workers. Strikers would march from town to town shutting down mines and breakers, risking attack by company police. Companies planned to continue operations with the hope that strikes would not cross ethnic and Anthracite field boundaries, but miners realized their weakness in this stand and increasingly bound together. The Knights of Labor and the Miners' and Laborers' Amalgamated Association saw some success for a time, then faded. But in 1890 the United Mine Workers Union was formed by the merger of other groups. Its membership grew rapidly, especially in the Schuylkill (Western Middle and Southern) field. During an 1897 strike, an organized march of UMW widely supported members ended in shots by a posse and the deaths of at least 19 strikers. This resulted in much more extensive strikes. Although the miners soon returned to work, they felt an increasing need to organize and the UMW grew rapidly under organizer John Fahy. In 1900, under the new UMW president John Mitchell, who was personally organizing the anthracite region, a strike was called. The union was unsure of its prospects for success, with only a small percentage of miners as members, but far more than just the UMW members joined the strike. With the additional political pressure of the U.S. presidential election, coal operators made some concessions and work resumed on October 29, which became known and celebrated as "Mitchell Day".

Another strike in 1902, involving 140,000 workers, became the nationally important "Great Strike". President Theodore Roosevelt intervened, helping force the creation of an arbitration commission. Testimony before the commission helped establish the plight of the miners and brought increasing national sympathy to miners and the labor movement. However, further strikes and manipulations by industry weakened the UMW. The 1925-26 strike lasted five months and reduced supplies of anthracite when the nation was turning to other fuels; markets vanished and production declined further. Continued depression in the 1930s and more strikes formed a cycle which brought extremely hard times to the region. The industry's decline has continued, with unemployment high and many of the residents leaving to find work elsewhere.

Recommended reading:

Portions of the preceding account of the history of the Anthracite region, and the following section on Cultural History, were drawn from the following sources:

Cornell, W.A., and Altland, M., 1957, Pennsylvania Milestones: Penns Valley Publishers, State College. 368 p.

Cuff, D.J., W.J. Young, E.K. Muller, W. Zelinsky, and R.F. Abler, eds, The Atlas of Pennsylvania: Temple University Press, Philadelphia. 288 p.

Goodcharles, F.A., 1944, Chronicles of central Pennsylvania: Lewis Historical Publishing Co., New York, 4 Volumes.

Miller, D.L., and Sharpless, R.E., 1985, The kingdom of coal - work, enterprise, and ethnic communities in the mine fields: University of Pennsylvania Press, Philadelphia, 360 p.

Mobil Oil Corp., 1991, Mobil Travel Guide: Middle Atlantic States: Prentice-Hall, New York

Stingelin, R.W, 1965, Late-glacial and Post-glacial vegetational history in the north central Appalachian region [Ph.D. thesis]: University Park, PA, Pennsylvania State University, 191 p.

Work Projects Administration, 1940, Pennsylvania - a guide to the keystone state: Oxford University Press, New York, 660 p.

Fourty years I worked with a pick and a drill
Down in the mines against my will,
The Coal King's slave, but now it's passed;
Thanks be to God I'm free at last.

--from the tombstone of an anthracite miner

CULTURAL AND PHYSICAL GEOGRAPHY OF THE FIELD TRIP ROUTE

David C. Glick and
Jeffrey R. Levine

We begin our field trip in the Nittany Valley, situated in the Valley and Ridge province of central Pennsylvania. Settlers first approached this region from the southeast, moving up the Susquehanna and Juniata Rivers and into the valleys to establish farms. Iron refining, using local ore and charcoal from trees on the forested mountains, brought more settlers. Through the latter part of the 19th century, small iron furnaces were common in central Pennsylvania, but as the trees and the ore ran out, production was consolidated in the larger industrial centers..

Following the Merrill Land Grant College Act of 1862, Pennsylvania chose the Farmers' High School, founded in 1855, to become the land-grant supported Pennsylvania State College. At that time the area was sparsely settled and relatively remote; the first few classes numbered under 100. The school grew, becoming The Pennsylvania State University in 1953, and now has a total enrollment over 67,000 at 23 campuses across Pennsylvania.

The population of State College and enrollment at the University have followed a parallel course. Each now number over 30,000. The total population of the "metropolitan area" extending about 20 miles from State College through Bellefonte is over 100,000.

To the right, as the field trip route turns from Rt. 322 onto Rt. 45, lies the town of Boalsburg nestled at the foot of Tussey Mountain. This is the home of the Boal Mansion and Columbus Chapel and the Pennsylvania Military Museum. Boalsburg claims to be the site of the first observance of Memorial Day (now a Federal holiday) when casualties of the Civil War were honored in 1864. In the mountainous area to the south of Boalsburg, typical logging and iron furnace operations took place during the 19th century. Five miles into the mountains lies Bear Meadows, a typical northern upland peat bog. Although south of the glaciated region, the bottom of the 12-foot peat deposit reflects the climate during the last glaciation and post-glacial stages beginning over 10,000 years ago. Palynological samples are conifer-rich in the lowest peat and show a transition to various deciduous flora nearer the surface.

As we pass by the southern end of Mt. Nittany near Boalsburg, we leave Nittany Valley and enter Penn's Valley, an elongate anticlinal valley floored by lower Paleozoic carbonates. Tussey Mountain on the right (southeast) and Nittany Mountain on the left (northwest) are both upheld by the erosionally resistant sandstones of the Ordovician Bald Eagle Formation and the basal Silurian Tuscarora Formation. The Tuscarora is a thick, highly quartz-rich sand which has been quarried as a glass sand in some localities. The picturesque round barn on the left is often used in illustrations of the area.

At Old Fort, south of Centre Hall we pass the site of the Centre County Grange Fair, an annual late summer event focusing on agriculture in the region. The Grange Fair features an encampment of over 900 green canvas tents, plus over 1100 more recreational vehicles and trailers, arranged row upon row, covering many acres. Families from small towns throughout the region live in these tents for a week during Grange Fair, providing a welcome opportunity to relax and socialize with family and friends. This unique tradition has continued at this site for 118 years.

Also at Centre Hall we enter an area of farmland settled by the Amish and other Pennsylvania German (Pennsylvania "Dutch") religious sects. The stricter of these groups still prohibit the use of all modern inventions including self-propelled vehicles, electricity, telephones, indoor plumbing, and even buttons. Other groups are not as strict but still avoid excessive ornamentation in an effort to remain "plain" folk. Horse-drawn buggies are a common site on the roads in this area.

The limestone and dolomite underlying Penn's Valley has led to the formation of many caves. To the north of the road beyond Centre Hall is one of the more unusual, Penn's Cave, which is flooded by water throughout the year and may be toured only by boat. A few miles further and to the south is Woodward Cave, one of the largest dry caverns in Pennsylvania, with an auditorium chamber that is occasionally used for choral concerts because of its acoustics.

Millheim is a typical small central Pennsylvania mill town, centered around a now defunct fabric mill. The millrace which diverted the stream to supply power is still visible.

The town of Aaronsburg was laid out with wide streets by Aaron Levy in 1786 with the hope that the state capital would be moved there from Philadelphia. In 1812, it was moved to Harrisburg instead, and Aaronsburg has remained just a quiet little country town with very wide streets. A stone house on the north side of the road, just east of the center of town, was built in 1789 and is believed to be the oldest remaining residence in the Centre County. Penn Staters may recognize it as the home of Dr. & Mrs. William Spackman.

Bald Eagle State Forest, which occupies some of the land northeast of Aaronsburg, provides a view of the indigenous hardwood forest covering much of central and northern Pennsylvania. This forest supports a diverse population of wildlife including black bear and abundant white tailed deer. Mifflinburg, a picturesque small town, was named for Thomas Mifflin, first governor of the Commonwealth of Pennsylvania under the 1790 constitution.

Lewisburg, one of the larger towns of the region, is the home of Bucknell University, which appears on the left-hand side of the field trip route.

Northumberland, lying at the confluence of the East and West Branches of the Susquehanna, was the home of Joseph Priestley, British Unitarian theologian and scientist, after fleeing from England in 1794 until his death in 1804. Priestley is well known both for his liberal religious views and for his scientific contributions, including the discovery of oxygen. Penn State University maintains a collection of Priestley's writings. In the region of Northumberland, streams draining the Western Middle anthracite field of the Anthracite region meet the Susquehanna River. Coal washed down the streams has been commercially recovered by dredging the Susquehanna here and further downstream.

At Sunbury, the field trip route crosses the Susquehanna River, which drains 46% of Pennsylvania and portions of southern New York. In June of 1972, a devastating flood, associated with the remnants of hurricane Agnes, innundated the entire Susquehanna Valley, causing widespread destruction and loss of life. Previous rains had reduced the soil's absorptive capacity when most of the area received at least 25 cm of additional rainfall (up to a peak of 45 cm at Shamokin). Unusually heavy runoff began immediately. Up and down the river, from Scranton/Wilkes-Barre (in the Northern Anthracite field) to Harrisburg the river rose as much as 5 meters above flood stage.

Sunbury is built on the site of the old Indian capital of central Pennsylvania. Local names commemorate Shikellemy, the Indian emissary, who greeted the first white visitors in 1742. Fort Augusta was built nearby in 1755 and served for years as an important jumping-off point for pioneers. In 1883 Thomas Edison built one of his early electric plants for lighting the city of Sunbury.

Progressing east from Sunbury, we enter the Western Middle field of the Anthracite region. The rugged, mountainous Anthracite region was settled later than the farm lands in the surrounding areas. The first town on the field trip route in the Anthracite region is Shamokin, once dominated by the Shamokin Coal and Iron Co., organized in 1836. Textile mills are also found here, as in most towns in the region. St. Edward's Church in Shamokin is said to have been the first church in the world lighted by electricity.

Mt. Carmel is one of the oldest towns along our route, settled prior to the Revolutionary War. It is said that almost every race and nation on earth is represented here, evidence of the succession of immigrant groups who came here to earn their living in the coal mines. Mt. Carmel was among the busier towns during anthracite's heyday, when it was home to the two largest coal breakers in the world. Mt. Carmel residents retain a strong sense of community and ethnic pride characteristic of much of the Anthracite region. In recent years local workers acquired buses to transport them to Harrisburg for work when local jobs became scarce, rather than move away from their town.

Ashland was the site of many mines and factories, and is now the home of an Anthracite Museum and the Pioneer Mine Tunnel (Stop #1 on our trip). South and east of Ashland, we follow the highway through Frackville and St. Clair to the end of our tour at Pottsville. Pottsville's economy supported the mining industry through manufacture of mining equipment and was also a rail center for shipping coal. Notable for Molly Maguire activity and the seat of Schuylkill County, Pottsville was thinly disguised as "Gibbsville" in a number of novels and stories by John O'Hara including *Appointment in Samarra* (1934) and *10 North Frederick* (1955).

The Centralia Mine Fire

Centralia was already notorious for mine subsidence problems even before abandoned underground mine workings caught fire in 1962. The origin of the fire is still shrouded in controversy. The weight of evidence suggests that the fire began on a spring day in May 1962 in an old mining pit on the southeast side of town, just below Odd Fellows Cemetery. For several years the pit had been used as an illegal trash dump and was considered a public nuissance. Suddenly, very conveniently, on May 27, the heap of trash was aflame. According to evidence gathered by journalist David DeKok (1986), the fire was set deliberately in an effort to clean up the dump site prior to a Memorial Day celebration in the town. Volunteer firefighters and borough workers responded and eventually brought the flames under control. The men turned and headed back to town. What no one knew at that time, however, was that the fire still burned. It had simply dropped out of sight. The fire spread to the remnants of the coal seam that lay below the open pit and, eventually, into the honeycomb of tunnels from an abandoned underground mine that criss-crossed at shallow depth beneath the streets of Centralia (description adapted from Jacobs, 1986).

Flames and escape of hot vapors provided evidence that the fire was continuing to burn, and the summer of 1962 saw several futile attempts to contol it. Over the course of the next 20 years, numerous efforts and millions of dollars were expended in a fruitless struggle to contain the fire. In the meantime, local residents were occasionally overcome by the fumes, and gas monitors were installed in most homes. On one occasion a young boy disappeared into a smoking fissure that opened up beneath his feet. Miraculously, he was rescued.

In the early 1980s dwellings began to be razed and the citizens relocated, and finally, in December, 1983, President Ronald Reagan signed a bill approving a mass relocation of the community's remaining residents. However, some residents have refused to leave their homes.

Today, 30 years after it started, the Centralia mine fire continues to burn, as evidenced by the smoke which may still be seen rising from vents pipes and fissures in and around the town. Although mine fires like this one are burning in other parts of the Anthracite region as well, Centralia has been of national interest because of the disruption of, and threat to, so many lives.

For additional information about the Centralia mine fire, see the following references:

DeKok, D., 1986, Unseen danger. A tragedy of people, government, and the Centralia mine fire: Philadelphia, PA, University of Pennsylvania Press, 299 p.

Jacobs, R., 1986, Slow burn. A photodocument of Centralia, Pennsylvania: Philadelphia, PA, University of Pennsylvania Press, 152 p.

Overview of a typical coal-mining community in the Pennsylvania Anthracite region in the late 19th century. Company-owned homes were situated a short walk from the mines. Forests were extensively logged for construction and mining materials. (Courtesy of the George Bretz Collection, Albin O. Kuhn Library, University of Maryland, Baltimore County)

Shenandoah City Colliery, photographed with available light near the mine portal. (Courtesy of the George Bretz Collection, Albin O. Kuhn Library, University of Maryland, Baltimore County)

Breaker boys at their work in the Eagle Hill Colliery. Children were commonly employed in the coal breakers to hand pick the "slate" from the coal. Working conditions were miserable, the hours long, and the work tedious. (Courtesy of the George Bretz Collection, Albin O. Kuhn Library, University of Maryland, Baltimore County)

A breaker operation, 1800s. Older, disabled miners could find work alongside young boys in the coal breakers. (Courtesy of the George Bretz Collection, Albin O. Kuhn Library, University of Maryland, Baltimore County)

Much of the early mining work was done by hand. Here a miner drills a shot hole into the face of a breast, using a Patent Drill or coal auger (Courtesy of the George Bretz Collection, Albin O. Kuhn Library, University of Maryland, Baltimore County)

Funeral for a victim of a mine accident. The open casket indicates that the victim's body was not recovered. (Courtesy of the George Bretz Collection, Albin O. Kuhn Library, University of Maryland, Baltimore County)

FIELD TRIP ROUTE AND STOP DESCRIPTIONS

Itinerary

This trip will be conducted on Saturday, July 25, 1992, departing from the campus of Penn State University, State College, Pennsylvania at 7:00 AM. We will travel eastward into the Pennsylvania anthracite mining area, and make Stop #1, at Reading Anthracite Company's abandoned Bear Valley (surface) Mine in mid-morning. Stop #2 will include a guided tour of the reopened Pioneer Tunnel underground mine, a picnic lunch, and time for visiting the nearby Anthracite Museum. After lunch, we will make Stop #3 at Reading Anthracite Company's Wadesville (open-pit) mine, and then Stop #4 at the Pottsville type section roadcut. Time permitting, we will make Stop #5, at the world famous Saint Clair plant fossil locality, where those who wish can collect fossils. If time does not permit this stop, a collection of fossils (collected earlier by field trip leaders and assistants) will be available for participants to take. We plan to return to State College by 7:00 PM. Figure 26 is the map of the field trip route.

Summary of Field Trip Route

The field exursion will proceed along the following route:

- depart campus of The Pennsylvania State University and proceed east on U.S. Route 322
- at Boalsburg, turn north on PA Route 45 passing through Centre Hall, Millheim, and Mifflinburg
- at Lewisburg, turn south on U.S. Route 15
- at Sunbury, turn east on PA Rt. 61 to Shamokin
- in Shamokin, turn south on PA Rt. 125, 2.6 miles to dirt road; 0.05 mi-turn left; 0.05 mi-turn right; 0.3 mi-Bear Valley mine (Stop #1)
- return to PA Rt. 61 in Shamokin; continue south; pass through Kulpmont; pass through Centralia, site of 30-year-old mine fire; pass through Mt. Carmel; enter Ashland to Pioneer Tunnel and Anthracite Mining Museum (Stop #2; lunch)
- continue south on PA Rt. 61 through Frackville to St. Clair; turn west on Hancock St.; turn right at Reading Anthracite Company's Wadesville mine (Stop #3)
- continue south on PA Rt. 61 to Pottsville; Stop #4 is a long road-cut on the east side of Rt. 61, on the south end of town
- from the center of town in St. Clair, proceed east on East Hancock St. toward Mahanoy City; 2.7 miles to gravel road on south--entrance to Reading Anthracite abandoned surface mining operation (pyrophyllite plant fossil locality; Stop #5)

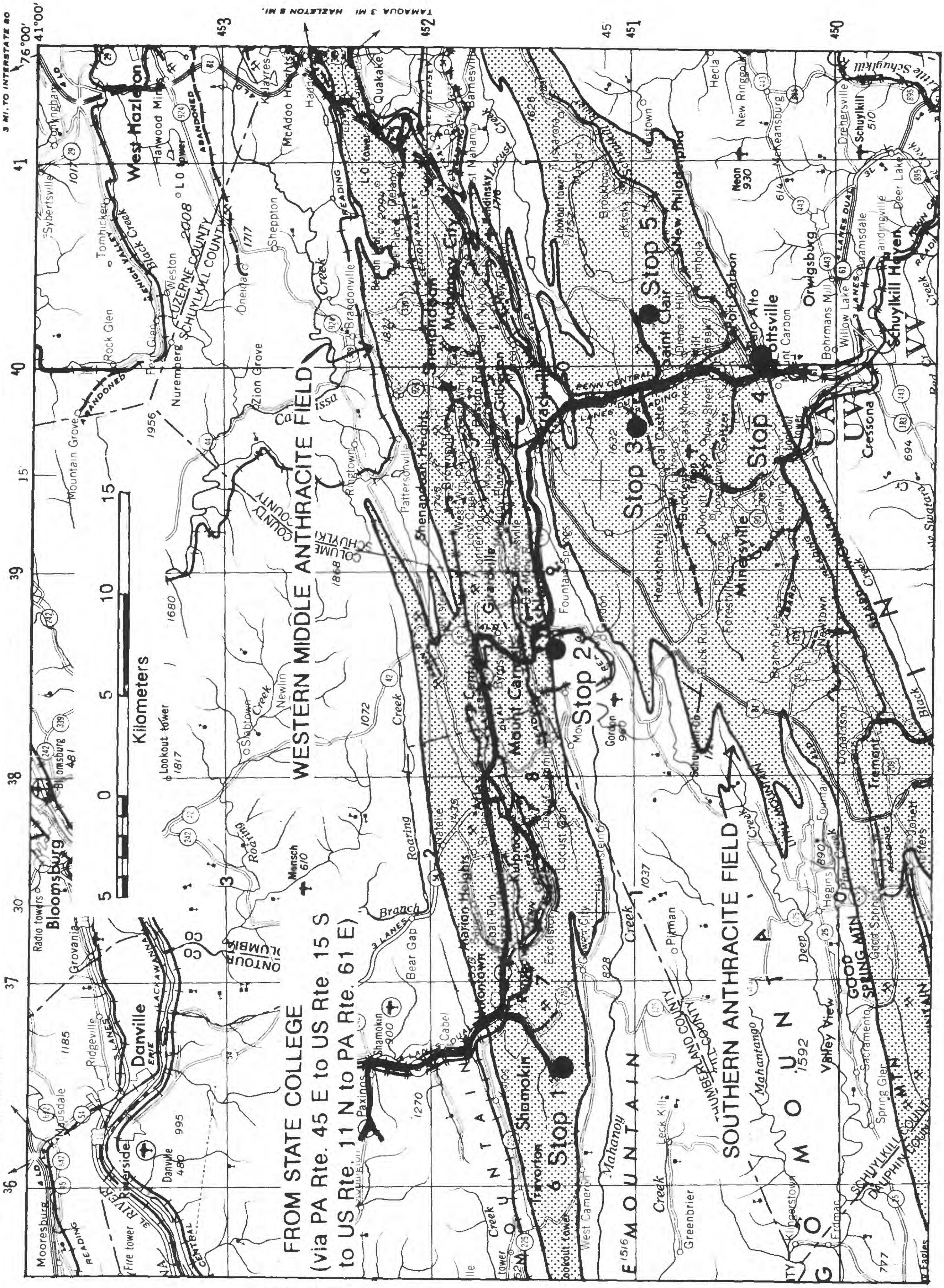


Figure 26. Route map of Pennsylvania Anthracite basins field trip.

Stop Descriptions

STOP #1. Bear Valley Mine

Jeffrey Levine and
Christopher Wnuk

Structural Geology. Stop #1, at the abandoned Bear Valley strip mine, is one of the classic geological field localities in the world. In addition to providing a remarkable three-dimensional view of the complex structural styles of the region, a detailed analysis of the structural features, conducted over the course of many years by Prof. R. P. Nickelsen of Bucknell Univerisity has provided a remarkably lucid picture of how the tectonic deformation evolved through time.

The Bear Valley mine exposes a series of complex 3rd-order anticlines and synclines involving strata in and around the Mammoth (8, 8-1/2, & 9) coal zone. The dip slope forming the far (southern) face of the mine and the "whaleback" anticline are comprised of the sandstone unit underlying the Mammoth Bottom Split (#8). Most of these bedding surfaces show ironstone concretions. Most of the #8 coal was removed during mining, but a small remnant block remains in the far southeastern corner.

The mine is situated on the southern limb of the (1st-order) Western Middle field synclinorium. The general dip of the strata on this limb (neglecting local perturbations such as at the Bear Valley mine), is approximately 45-60^{o} to the north. Stratigraphically younger coals are exposed toward the axis of the synclinorium to the north of the mine.

Two aspects of the large-scale structures at the mine are particularly striking: 1) the apparent disharmony between the folds underlying the #8 bed (including the "whaleback") and the folds in the overlying strata and 2) the vertical, isoclinal attitude of the two opposite limbs of the "whaleback" anticline. Clearly the thick, mechanically incompetant coal beds in this stratigraphic interval have allowed a high degree of deformation to occur in the surrounding clastic units.

Careful analysis of deformation mechanisms at this locality (Nickelsen, 1979) has permitted interpretation of a sequence of structural stages, numbered I through VII (Figs. 29 & 30), which have influenced these rocks. The effects of each progressive stage was superimposed on the stage(s) that preceded it. Stage I (cleating in coal) began when the beds were still essentially flat-lying, whereas Stage VII occurred after the beds had been rotated to their present attitude.

Nicklesen (1981) has interpreted the origin of the folding at this locality to be due to "buckling", but an alternative interpretation (Levine, 1983, 1991) is that the folds formed under conditions of bedding-parallel shear strain along the fold limbs of the Western Middle field synclinorium (Figs. 31 & 32). The Bear Valley fault, a high angle reverse fault having an antithetic sense of motion, can be traced into the Mine from the west, but disappears within the mine pit area. The folding can be interpreted as indicating the same sense of shearing as the fault, as depicted in Figure 31. Other similar structures have been observed elsewhere in the Western Middle Anthracite field (Levine, 1983).

Things To Do to Observe Structural Features at Stop #1:
(adapted from Nickelsen, 1981)

1) At location #1, (Fig. 27), observe disharmonies of 3rd-order folds. Look across to south wall of mine to observe Stage IV wrench fault system and stage IV thrust fault.

2) At location #2, look toward the south at the north limb of the Whaleback Anticline, showing Stage IV thrusts and conjugate wrench faults, Stage V folding, and Stage VI extension joints and faults.

3) At location #3, look up close at Stage IV wrench fault and thrust faults. Observe ironstone concretions, which show only Stage II joints and slickensided surfaces. Observe "offset" of Stage II joints by Stage III pressure solution cleavage planes which, in turn, are "dragged" against Stage IV fault planes.

4) At location #4, walk down into south syncline to observe Stage IV wrench faults, cleavage-bedding intersections, thrust faults, and Stage VI extensional grabens.

5) Walk out onto the Whaleback Anticline, observe features exposed on wall to the south. Pause briefly to reflect upon the wonders of nature, then quickly return to the bus.

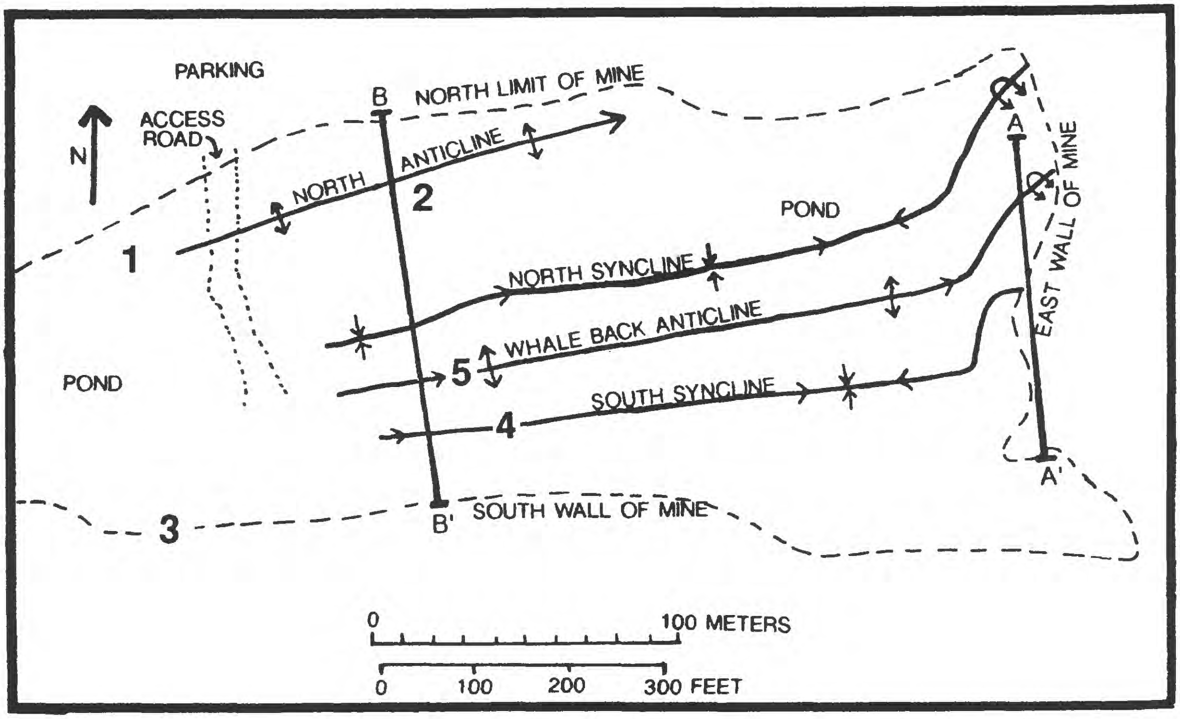


Figure 27. Plan view of Bear Valley strip mine, showing major structural features and localities of particular interest (adapted from Nickelsen, 1979).

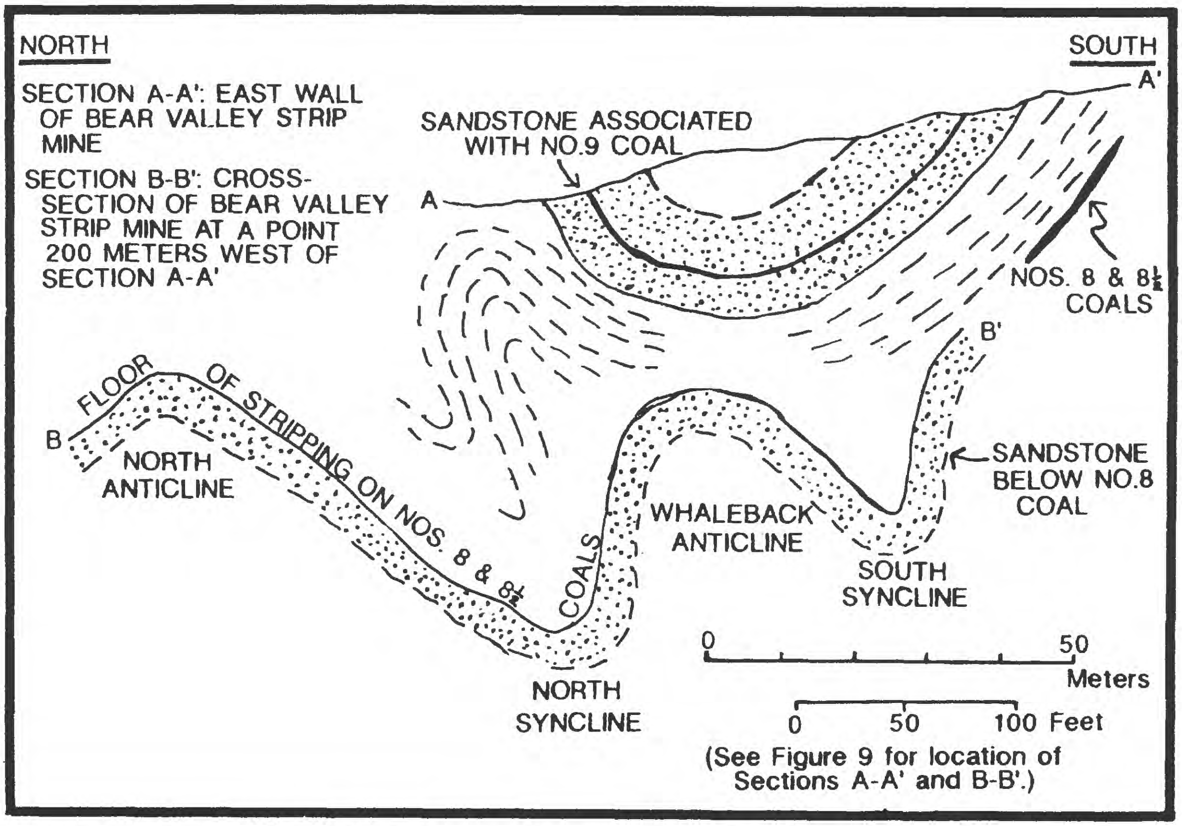


Figure 28. Composite cross section across Bear Valley strip mine, superimposing on a single section line cross section A-A' (east end of mine) and section B-B' (central part of mine)(adapted from Nickelsen, 1979).

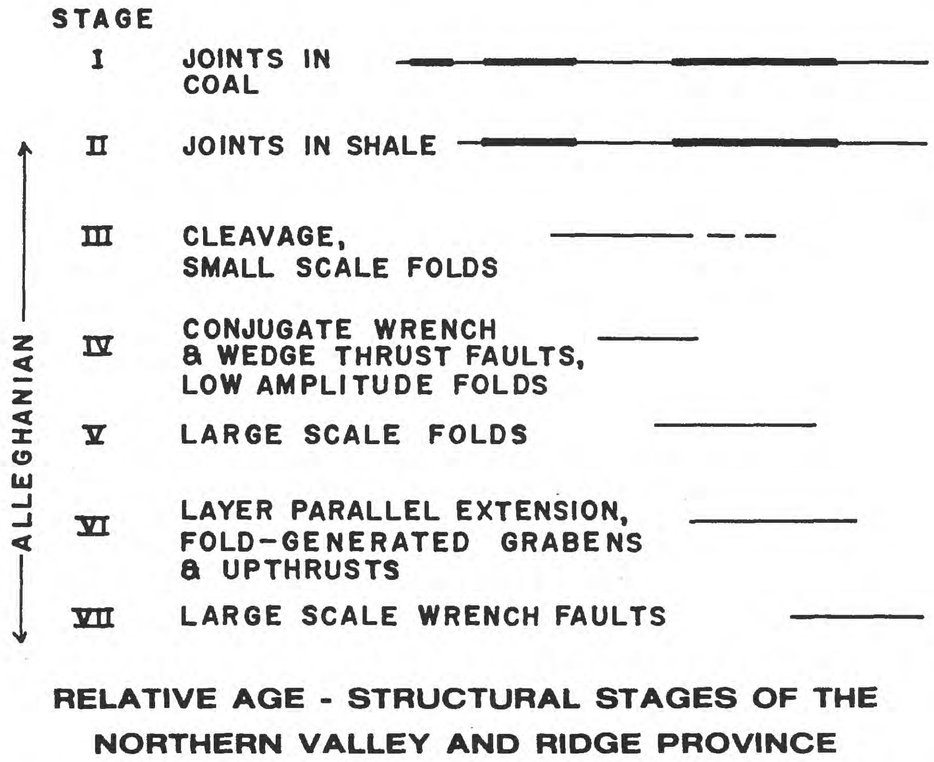


Figure 29. Summary diagram depicting the relative ages of structural stages influencings strata at Bear Valley mine (from Nickelsen, 1979, 1981)

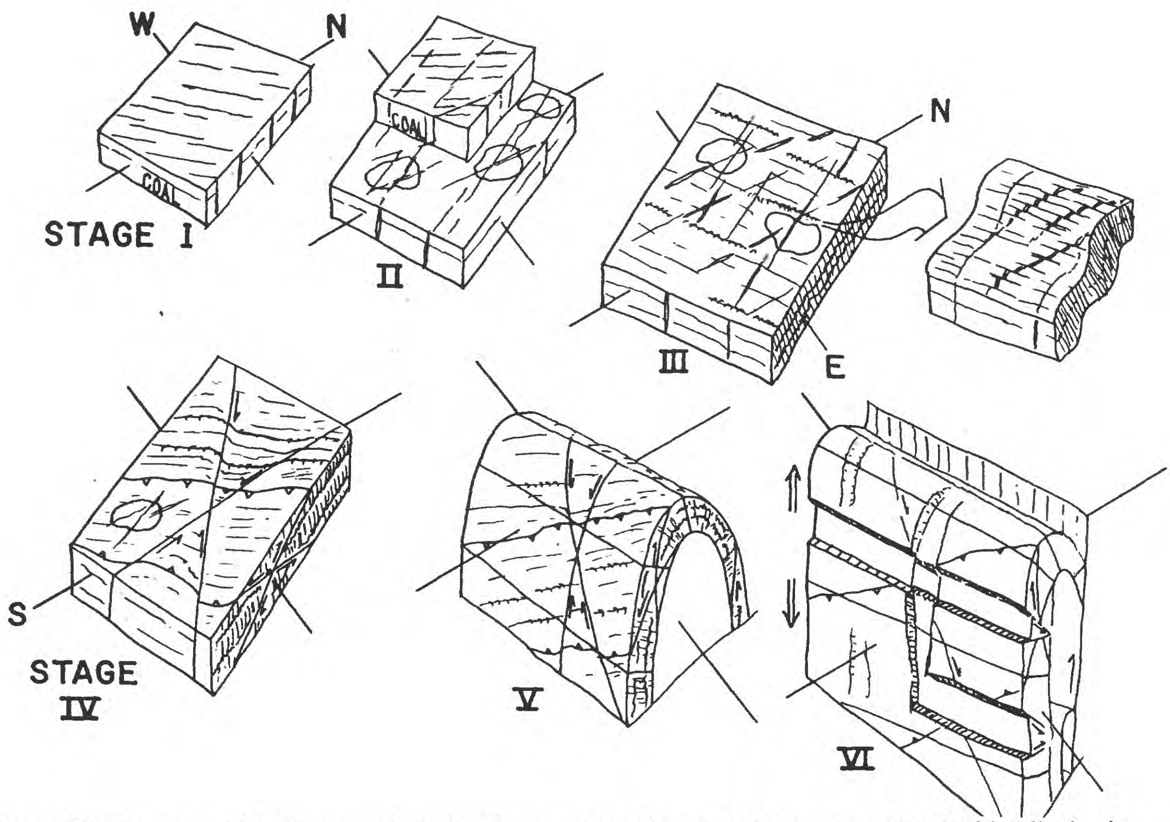


Figure 30. Representative diagrams depicting the sequence of structural stages associated with Alleghanian orogenic activity, as expressed at Bear Valley mine (from Nickelsen, 1979).

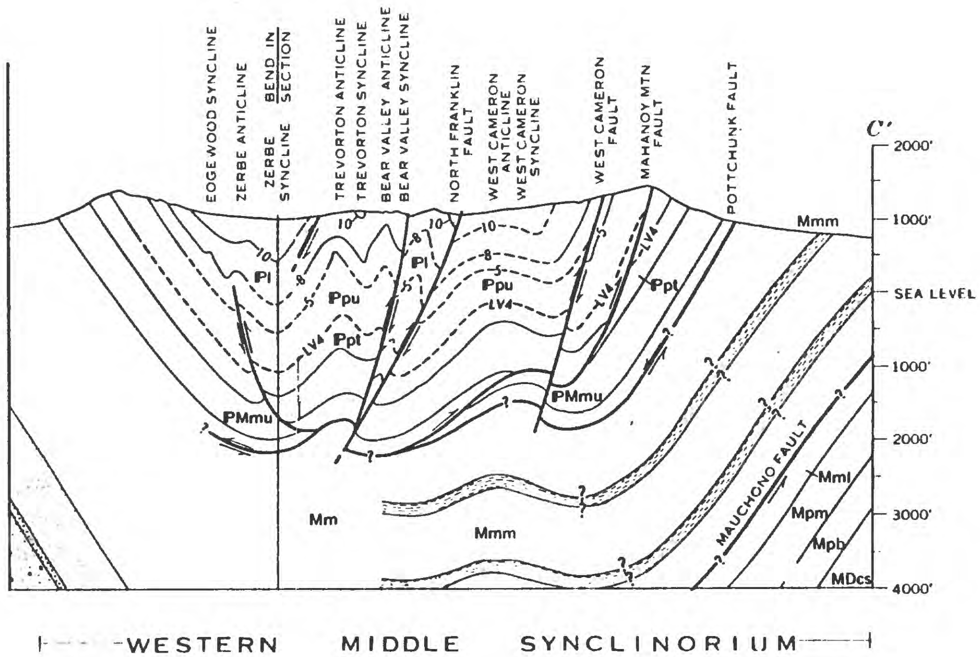


Figure 31. High angle reverse faults in the western end of the Western Middle Anthracite field generally show their upthrown side toward the center of the basin. Fault planes generally dip toward the centers of the basin (from Arndt et al., 1973).

PROGRESSIVE DEVELOPMENT OF AN INTRAFOLIAL SHEATH FOLD

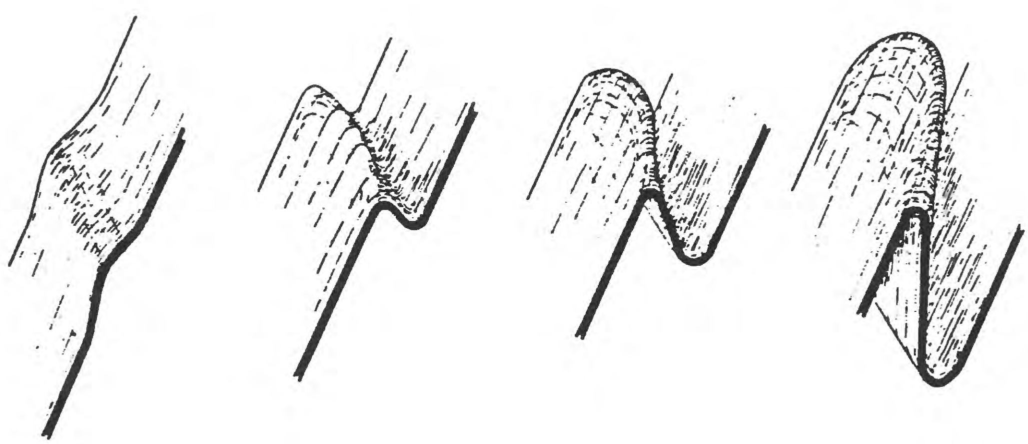


Figure 32. Progressive development of intrafolial sheath fold (Minnigh, 1980) produces a fold geometry similar to that observed in Bear Valley mine and other localities in the Western Middle Anthracite field.

Paleobotany. An excellent example of an *in situ* underclay flora is preserved in the Bear Valley strip mine. This kind of preservation however, is not unique to this site. Approximately 18 km of underclay bedding plane surfaces have been studied at 84 localities in the Western Middle Anthracite field, mostly from the Mammoth coal zone (Nos. 8, 8.5, and 9). The majority of these localities were in the Shamokin and Treverton 7.5 minute quadrangles. Spot checks were made in the Mt. Carmel, Ashland, Shenandoah, and Delano quadrangles, but these remain relatively unexplored as are the majority of the quadrangles in the Northern, Southern, and Eastern Middle Anthracite fields.

The studies of the floral composition of the Mammoth underclays indicate that the plant communities which colonized the clastic substrates below the coal were locally heterogeneous. The floras at these sites can be grouped into 4 broadly defined community types: (1) lycopod dominated associations, (2) pteridosperm dominated associations, (3) associations containing mixtures of pteridosperms and lycopods, and (4) associations containing tree-ferns. These community types can be further subdivided into 23 compositional variants that are defined by the presence and abundance of particular taxa. Line transect studies indicate that species composition can vary from one community type or sub-type to another along a single outcrop. Stratigraphic changes in community composition occur within beds as well. The environmental and edaphic factors controlling this observed community heterogeneity have not yet been determined. For additional information see Wnuk (1989b).

As you stand on the north flank of the Bear Valley mine on the main haul road passing the mine, the distinctive lineations of the large *Sigillaria* and *Lepidodendron* trunks that are preserved here can be seen in the extreme southeastern corner of the mine. Westward along the southern flank of the mine you will note that there is a slight color change from black shales, to medium gray shales and siltstones. These lighter colored sediments do not contain trunks, but do exhibit distinct curving lineations belonging to *Stigmaria*, which are lycopod roots.

Trunk remains are mostly confined to the southeastern corner of the mine where more than 100 stems are preserved. *Sigillaria* stems occasionally occur in other parts of this mine, but these are isolated individuals that tend to be poorly preserved. Except for apparent variations in organic content of the underclay shales (as indicated by the minor color differences across the outcrop), the lithologic characteristics of the underclay are approximately uniform across the outcrop. Variation in preservation potential of the various parts of the outcrop are hypothesized to be controlled by minor differences in the watertable that affected the oxidation rate of the accumulating organic debris.

The detailed stratigraphy of the underclay in the southeastern corner of the mine is shown in Figure 33. This figure also shows the species and plant part (i.e. leaves, trunks, seeds, etc.) distribution of the plant remains in the upper top meter of the underclay. Two techniques were used to determine the distribution of the plant remains at this site. All of the large trunk remains were counted across the whole outcrop. The frequency distribution of the smaller remains was determined by making 47 meter square quadrant counts in the fossiliferous area. In all cases, the stratigraphic position of the surface was noted.

Two fossiliferous carbonaceous shales occur in the underclay. The lower carbonaceous shale averages 5 cm in thickness and is dominated by pteridosperm stems and petioles. The lycopods *Sigillaria*, *Lepidodendron aculeatum*, and *Knorria* (probably of *L.aculeatum*) are subordinate in abundance, and *Calamites* stems are rare. The middle shale unit is light gray and is intensely rooted but otherwise unfossiliferous. The upper carbonaceous shale is dominated by lycopods. *Bothrodendron punctatum* is the most abundant lycopod in this unit. *Lepidodendron aculeatum* and *Sigillaria* are much less common. Pteridosperm remains are subordinate, and *Calamites* is absent. Successional trends are also seen the upper shale. *Bothrodendron* is most abundant in the lower part of the shale and *Lepidodendron* and *Sigillaria* are absolutely confined to the lowest part of the upper carbonaceous shale. Pteridosperms in contrast increase in abundance upward within the unit.

The lower carbonaceous shale is deposited on top of a rooted, rippled sandstone that is poorly exposed, but is interpreted to be either a channel or lake margin deposit. The flora in the carbonaceous shale is interpreted as the remains of a marginal vegetation that colonized the surface of the sandstone as relative water levels fell. The composition of this flora is consistent with the composition of the floras that dominated subaerial terrestrial environments during the Pennsylvanian (Gastaldo, 1982). The specific scenario that led to the development of the middle underclay shale and the upper carbonaceous shale unit are highly speculative. I would postulate that small changes in water table and sediment accumulation rates influenced both the ability of organic material to be preserved in the sediment and the floral composition. The rooted underclay was probably a more oxidizing environment and organics were decomposed before they could be preserved in the accumulating sediment. Lycopods are generally more tolerant of elevated watertables and their dominance of the upper carbonaceous shale suggests an increased water table which would also account for the preservation of the plant fossils. The decline in the abundance of the various lycopod species upward within the upper carbonaceous shale probably reflects a gradient of water saturation tolerance among the individual lycopod species. The apparent increase in abundance of the pteridosperms upward within the upper carbonaceous shale is anomalous, since the pteridosperms are expected to decline as water tables rise. However, this may be due to a preservational bias. The upper carbonaceous shale becomes more organic upward as it grades into coal. As less clastic material is available to the system, plant remains become more difficult to recognize, because all of the organic material becomes compressed into coal. The identified pteridosperm remains tend to be small petiole fragments.

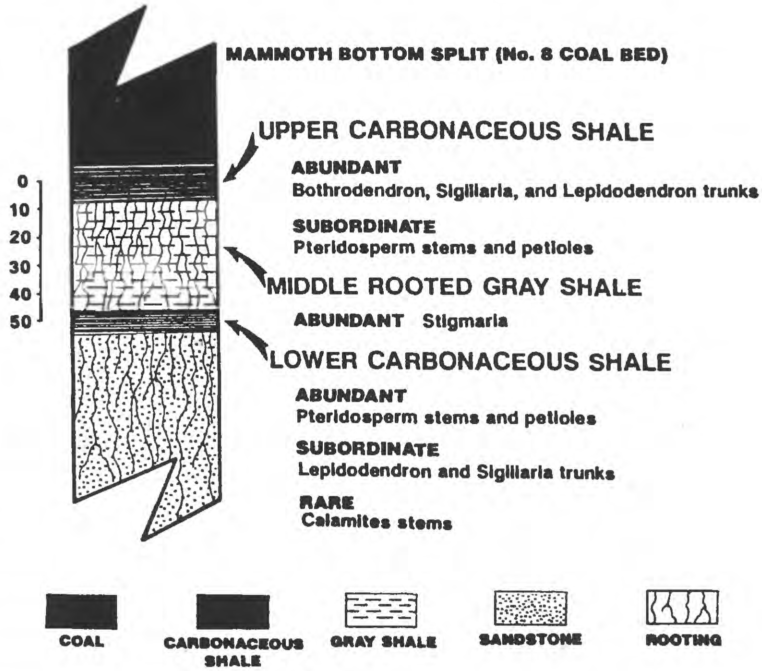


Figure 33. Detailed stratigraphy of underclay in the southeastern corner of the Bear Valley mine.

Plants are known to be sensitive environmental indicators. As we learn more about factors which affect plant communities, we will be better able to understand the environmental significance of community associations and the successional changes which affect them. The floras at Bear Valley show pronounced evidence that climatic and edaphic factors had a significant, recognizable effect on the growth and development of the plants.

The characteristics of the surficial ornamentation of Lycopod trunks can provide a key to the growth and developmental history of the lycopods *Lepidodendron rimosum* and *L. bretonense* (Wnuk, 1985). The parameters outlined by Wnuk (1985) are believed to apply to the *Bothrodendron* stems also. *Bothrodendron* is reconstructed to be a determinate plant with lateral side branches that were gradually shed as the plant grew (Wnuk, 1989a). Generally the size of the branches became smaller as the plant grew taller, and the branches became closer together. Deviations from these known developmental pathways have been correlated to variations in environmental and edaphic conditions. On the longer *Bothrodendron* stems, for instance, there are intervals on the stem where the branch scars are closer together and sometimes smaller than expected based on the general growth curves. These areas of growth retardation have been interpreted as evidence that the plant was stressed, and therefore stunted during its growth. Similar growth responses have been documented in other lycopod species (Wnuk, 1985). In all of the cases of growth retardation the lycopod stems are closely associated with fusain in the same bedding surface. In Bear Valley, the occurrence of scattered fusain-like pebbles in the carbonaceous shale suggests associated forest fires, and therefore, that the anomalous growth may have been due to drought conditions. There is a second kind of anomaly exhibited by *Bothrodendron* stems. These stems have the smallest branch scars of any stems in the population but unexpectedly the interbranch separations are the largest within the population. These stems also have small diameters and all of the anomalous stems are concentrated in a small area of the outcrop. This spatial segregation suggests that the growth conditions were locally unfavorable for these plants, consequently the six anomalous individuals were stunted. The nature of these unfavorable conditions are unknown. They may include unfavorable watertables, insect or fungal damage, sunlight regime, or some other factor.

The flora of the upper carbonaceous shale is a Type 3 association; it is a mixture of pteridosperms and lycopods. The fossil remains indicate that *Bothrodendron* grew to a height of 25 m and dominated the upper canopy. The forest also contained taller emergent trees of *Lepidodendron aculeatum* and *Sigillaria* sp. The *Bothrodendron* forest contained an understory composed of pteridosperms and rare calamites. There is no evidence of a herbaceous layer.

STOP #2. Pioneer Tunnel, Ashland, PA

Jane Eggleston
(adapted in part from Wood *et al.*, 1963)

Pioneer Tunnel is an authentic mining operation that was abandoned 58 years ago and was reopened as a tourist attraction by Ashland Community Enterprises - a non-profit community development organization. It is located at the south-western edge of Ashland, well down the north slope of Ashland (Mahanoy) Mountain. Participants of this field trip will be taken on a conducted tour of the mine by the miners who have restored the Pioneer Tunnel.

Pioneer Tunnel is in the east-central part of the Western Middle field about 22 km (14 mi) from the eastern end. Ashland (Mahanoy) Mountain to the south of STOP #2 delineates the southern margin of the field, which is about 6 km (4 mi) wide at this point. The Western Middle field is composed of fairly symmetrical, large amplitude folds. Pioneer Tunnel was driven down-section through strata forming the south limb of the Mahanoy syncline, one of the larger and more persistent subsidiary folds in the Western Middle synclinorium (Fig. 34). Locust Mountain anticline, which is the most prominent anticline in the coalfield, lies north of Mahanoy syncline. The south limb of the anticline is broken by the Locust Gap and other associated thrust faults. The Locust Gap fault is a low-angle thrust; it is one of the earliest faults and is intimately folded with the strata that it cuts in the Mahanoy syncline. Strata in the overlying plate of the fault have been moved as much as 2,000 ft north of correlative strata in the underlying plate.

About 490 m (1,600 ft) of the Llewellyn Formation occurs in the Mahanoy syncline north of STOP 2. The Buck Mountain (No. 5), Mammoth Bottom Split (No. 8), Mammoth Top Split (No. 9), Forty-Foot (No. 9-1/2), Holmes (no. 10), Primrose (No. 11), Orchard (No. 12), Little Orchard (No. 13), and Diamond (No. 14) coal beds have been mined in large-scale underground operations in the Mahanoy syncline, north and south of Ashland. The entrance to the Pioneer Tunnel is 1 m stratigraphically below the No. 13 coal bed, which locally dips south in a minor syncline on the south limb of Mahanoy syncline. The tunnel crosses the axis of the minor syncline a few feet in from the entrance, and, from that point south about 240 m (800 ft) of north-dipping older rocks are encountered in the tunnel heading which terminates in the Buck Mountain (No. 5) coal at the base of the Llewellyn Formation.

Pioneer Tunnel is named from the Pioneer Colliery, which operated in Mahanoy Mountain at Ashland in the late 19th century. The original mine opening was from the eastern end of the mountain where the Buck Mountain (No. 5) coal seam was mined. Then, in 1918, the Pioneer Tunnel was begun by driving northward from the Buck Mountain bed until the surface (current Tunnel entrance) was reached in 1927. The Tunnel was used for a haulage way until 1931 when, for economic reasons, mining ceased and the Tunnel entrance was collapsed by blasting.

The Pioneer Tunnel is an example of "adit" mining, with a horizontal tunnel driven through the rock at right angles to the strike of the coal beds (cf. Fig. 24). The "adit," or tunnel, measures 385 m (1,250 ft) from the entrance to the Buck Mountain (No. 5) bed. We will travel the full distance into the mine on rebuilt mine cars. Once inside, a guide who is experienced in underground mining of anthracite will describe the mining technique and the geologic characteristics of the mine.

Local mining historians estimate that about 500,000 tons of coal were mined from workings tributary to the Pioneer Tunnel. All underground transportation was powered by mule teams and surface transportation by steam locomotives similar to the present "lokie" pulling the tourist train.

Typical coal analyses from this part of the Western Middle Anthracite field are those of the Mammoth Bottom Split (No. 8) coal bed from the Bast Mine, about 3 km northeast of STOP #2 (Table 3).

Things To Do at Stop #2:

1) Underground mine tour

2) Visit the Pennsylvania Anthracite Mining Museum (but don't dally!)

3) Eat lunch

4) Socialize and enjoy the company of organic petrologists from around the world.

Dry Basis		Stove	Pea	Rice
Screen (Round Mesh Screen)		- 2 7/16 + 1 5/8	- 13/16 + 9/16	- 5/16 + 3/16
Moisture (As Received)		3.0 %	4.0 %	7.0 %
Volatile Matter	-- From	4.50%	4.50%	4.50%
	-- To	5.25%	5.25%	5.25%
Fixed Carbon	-- From	85.12%	85.87%	84.87%
	-- To	86.12%	86.12%	85.87%
Ash	-- From	9.0 %	9.25%	9.25%
	-- To	10.0 %	10.00%	10.25%
Sulfur		0.60%	0.60%	0.60%
BTUs per Pound		13,400	13,300	13,250
Ash Fusion Temperature (Softening Point)		+2850°F	+2850°F	+2850°F

Table 3. Coal analyses from Mammoth Bottom Split (No. 8) coal bed, Bast mine (from Eggleston and Edmunds, 1989).

Proximate Analysis	Coal (As received)	Coal (Moisture free)	Coal (Moisture and ash free)
Moisture (percent)	2.4		
Volatile matter (percent)	3.9	4.0	4.5
Fixed carbon (percent)	83.9	86.0	95.5
Ash percent	9.8	10.0	
	100.0	100.0	100.0
Sulfur (percent)	0.8	0.8	0.9
BTU/lb.	13,040	13,360	14,850
Kcal/kg	7,244	7,422	8,250
Specific Gravity	1,681		

Table 4. Representative chemical analysis of anthracite at the St. Nicholas breaker (from Eggleston and Edmunds, 1989).

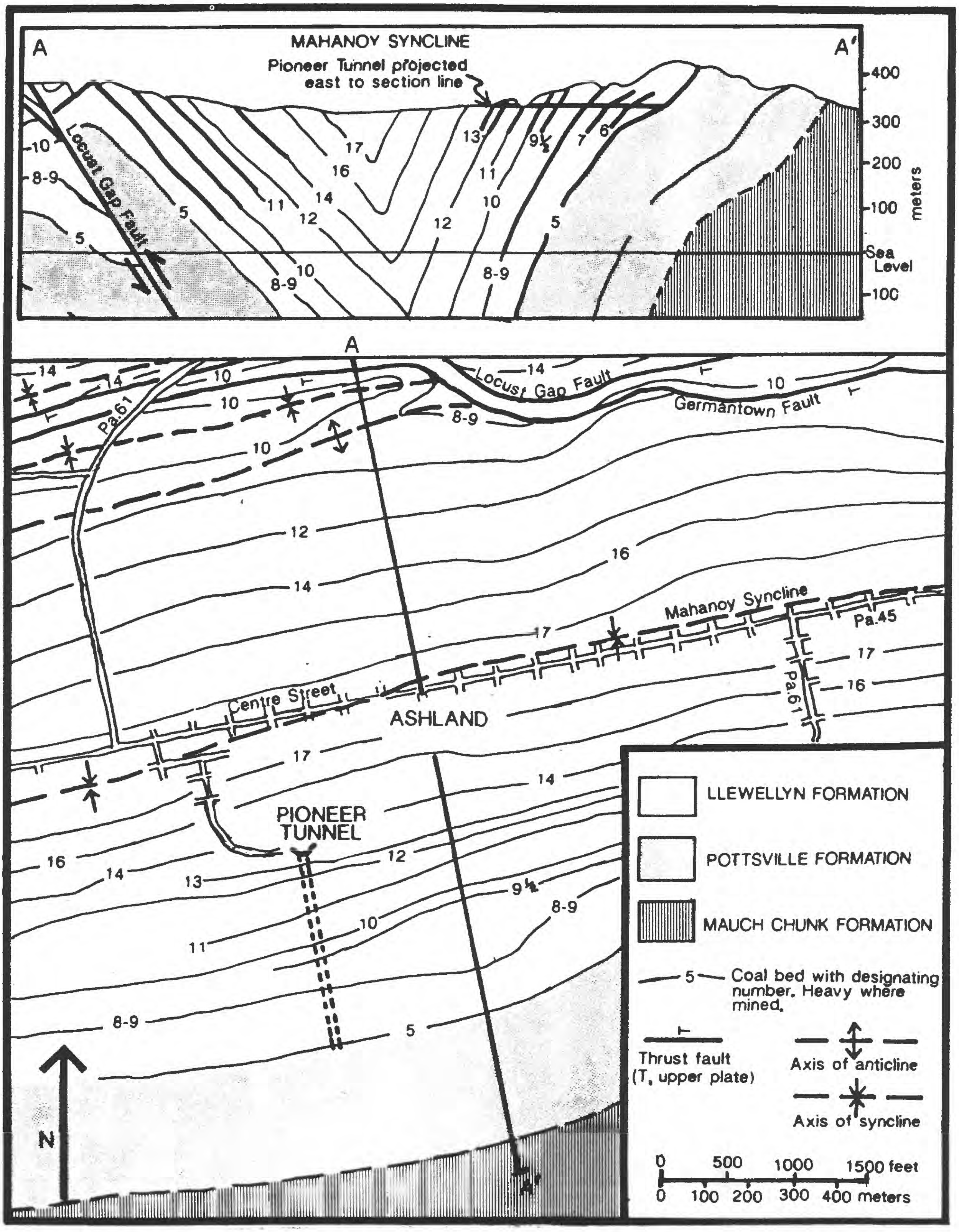


Figure 34. Geologic sketch map and cross-section across Mahanoy Syncline (modified from Wood *et al.*, 1963)

STOP #3. Wadesville Surface Mine, Reading Anthracite Coal Company

Jane Eggleston

Reading Anthracite Coal Company is one of the oldest and largest mining companies in the Pennsylvania Anthracite region. The company was founded in 1871 as The Philadelphia and Reading Coal and Iron Company by its parent company, The Philadelphia and Reading Railroad, in order to purchase coal lands in the Southern and Western Middle Anthracite fields and therefore insure revenue to the railroad. Although the company was originally formed to lease coal lands, as operators on these lands fell on hard times and were forced into bankruptcy, the company took over these operations and became a mining company. Whereas in the early days most of the mining was done by the underground breast-and-pillar mining method, surface mining eventually dominated, and today all of Reading's operations are surface mines. Mined coal is trucked to the Company's St. Nicholas Breaker, a heavy-media preparation plant, for processing. Table 4 presents chemical analyses, on a dry basis, for various size fractions of anthracite.

The Wadesville operation is Reading's largest, producing about 700,000 tons of coal per year. A 7400 Marion 14 cu yd dragline removes the coal and a 191M Marion 12 cu.yd shovel moves the overburden. A 651 Huff 12 cu yd front end loader loads the coal into 85 ton Euclid trucks for transport to the preparation plant. Pumps operate full-time at a nearby abandoned mine shaft and in the pit to prevent flooding by underground mine-pool water.

Figure 35 depicts a cross-section extending from south to north across the west end of the pit. The excavation is more than 150 m (500 ft) deep in places, and lies within a shallow syncline. Mining is concentrated on splits of the Mammoth coal bed (Nos. 8 and 9), which together total about 12 m (40 ft) of coal. The Bottom Split is 6 m (20 ft) thick. Its underlying shale ("bottomrock") forms the impressive face on the north side of the pit. The Top Split of the Mammoth bed is 6-7 m (19-22 ft) thick and is separated from the lower split by .6-1.2 m (2-4 ft) of shale. Three other coal beds are also mined here. The Four Foot (No. 9.5) lies about 37 m (120 ft) above the Mammoth and is only about 1.2 m (4 ft) thick. The Holmes (No. 10) coal bed is about 23 m (75 ft) above the Four Foot is and ranges in thickness from 2.7-4 m (9-13 ft); however, only about 1.8-2.4 m (6-8 ft) is coal and the remainder is bone and shale. The Primrose (No. 11) coal bed lies about 26 m (85 ft) above the Holmes, and is 4.6-6 m (15-20 ft) thick. The Orchard (No. 12) and Little Orchard (No. 13) coal beds, lying 33.5 m (110 ft) above the Primrose, are exposed only in the very top of the pit and for the most part have already been mined.

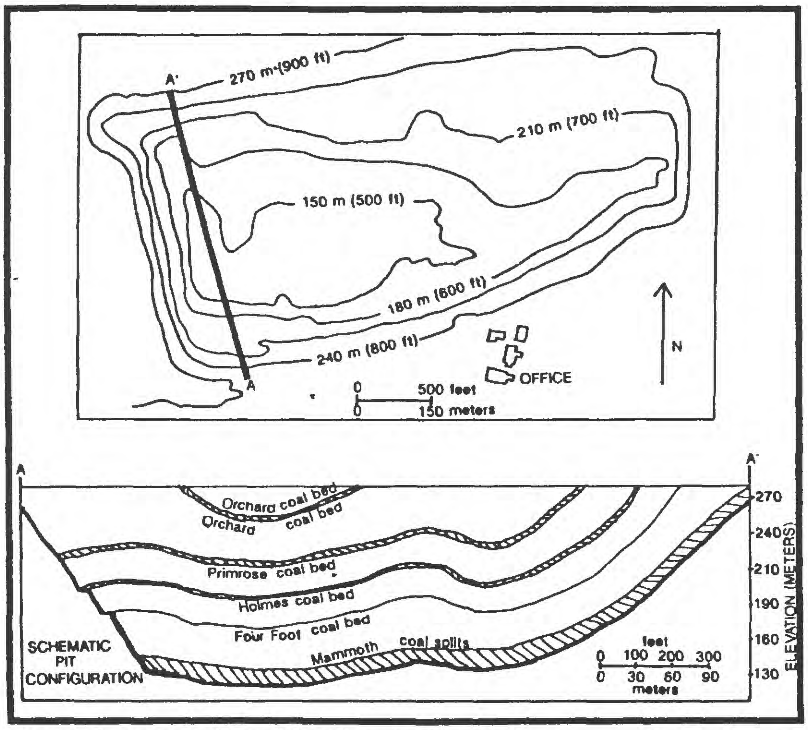


Figure 35. Contour map and cross-section of Reading Anthracite Company surface mine at Wadesville, PA (from Eggleston and Edmunds, 1989)

STOP #4: Pottsville Formation Type Section

adapted from Levine and Slingerland, 1987

Significance of Site. The rocks at this site are exposed along a road cut on the eastern side of Pennsylvania Route 61, 0.4 to 0.8 km (0.3 to 0.5 mi) south of Pottsville, Pennsylvania, on the southern margin of the Southern Anthracite field where the Schuylkill River has cut a deep gap in Sharp Mountain. The outcrop exposes a 600+ meter-thick section of Upper Carboniferous molasse, representing the northwestward influx of clastic detritus into the Appalachian foreland basin from an orogenic source terrane formerly situated along the present Atlantic Coastal Plain. The alternation of facies (Fig. 36) reflects the gradual but progressive evolution of depositional environments from a semi-arid alluvial plain (Mauch Chunk Fm.) to a semi-humid alluvial plain (Pottsville Fm.) to a humid alluvial plain dominated by peat swamps (Llewellyn Fm.). This transition, documented by dramatic changes in sedimentary facies, facies sequences, and maximum clast sizes, clearly reflects regional (perhaps even world-wide) climatic changes occurring near the end of the Mississippian; however, incipient Alleghanian tectonism and the evolution of many new plant groups occurring at this time may have played an influential role as well.

Subsequent to their deposition, the Carboniferous sediments were deeply buried, metamorphosed, tectonically deformed in the Alleghanian Orogeny, uplifted, and largely eroded. The Southern Anthracite field now preserves the thickest, coarsest-grained, most proximal to the source, and most stratigraphically continuous occurrence of Upper Carboniferous molasse in the central Appalachians.

Stratigraphic and Geomorphic Overview. Molasse sediments of the Anthracite region are stratigraphically subdivided on the basis of grain size and predominant coloration (Wood et al., 1969a). The fine-grained, red Mauch Chunk Fm. (Middle to Upper Mississippian) intertongues with and is replaced by the coarse-grained, grey Pottsville Fm. (Lower to Middle Pennsylvanian), which in turn gives way to the finer-grained, grey to black, coal-rich Llewellyn Fm. (Middle Pennsylvanian), representing the youngest extant molasse in the region. The former presence of many kilometers of overlying rocks is implied by the high coal rank and compaction of the Llewellyn sediments (Paxton, 1983; Levine, 1986).

The Mauch Chunk Fm. is informally subdivided into three members (Wood et al., 1969a). The middle member represents the 'type' Mauch Chunk red bed lithofacies. The lower and upper members represent respectively the zones of intertonguing with the underlying Pocono Fm. and the overlying Pottsville Fm. The upper contact of the Mauch Chunk is defined as the top of the uppermost Mauch Chunk-type red bed (Fig. 36).

The Pottsville Fm. is formally subdivided into three members (Wood *et al.*, 1956), each representing a crudely fining-upward megacycle. Of the three, the Tumbling Run and the Sharp Mountain Members are the coarser-grained, while the intervening Schuylkill Member is finer-grained and contains a greater proportion of coal. The lower contacts of the Schuylkill and Sharp Mountain Members are defined at the base of major conglomeratic units. The base of the Schuylkill Member is by no means obvious at the outcrop, but the "Great White Egg" quartz pebble conglomerate at the base of the Sharp Mountain Member is very distinctive. The contact between the Pottsville and Llewellyn Fms. is placed at the base of the lowermost thick, stratigraphically persistent coal horizon, the Buck Mountain (#5), which has been correlated over large areas of the Anthracite fields (Wood *et al.*, 1963).

Chronostratigraphic age designations in the Anthracite region, based upon the 13 Upper Paleozoic floral zones defined by Read and Mamay (1964; also see Edmunds *et al.*, 1979), indicate the Pottsville section is conformable, extending from Zone 3 in the upper Mauch Chunk Fm. (Chesterian Series) to Zone 10 in the Lower Llewellyn Fm. (Des Moinesian/Missourian Series); however, Zones 7 and 8 have not been explicitly recognized at this site. The Mauch Chunk/Pottsville contact, occurring between Zones 3 and 4, corresponds roughly to the Mississippian/ Pennsylvanian systemic boundary. In areas of the central Appalachians other than the Southern and Middle Anthracite fields, Zones 4, 5, and 6 are absent, suggesting the presence of a significant disconformity between the youngest Mississippian and oldest Pennsylvanian strata (see discussion in Edmunds *et al.*, 1979).

The strata exposed at the site are slightly overturned and comprise part of the southern limb of the Minersville Synclinorium, forming the southern margin of the Southern Anthracite field. They attained their present attitude during the late Paleozoic Alleghanian Orogeny when northwest-directed tectonic forces produced a progression of deformational phases that migrated northwestward across the foreland basin. At the Pottsville site all structural phases are superposed (Wood and Bergin, 1970; Nickelsen, 1979).

The structure and stratigraphy of the Upper Paleozoic molasse sequence are revealed geomorphically by the relative resistance to erosion of the near-vertical component units. The Pocono sandstone, subjacent to the Mauch Chunk Fm., upholds Second Mountain, the major ridge visible to the south of the Pottsville section. The Mauch Chunk Fm. underlies the valley between Second and Sharp Mountains. The distinctive double ridge of Sharp Mountain is formed by the Tumbling Run and Sharp Mountain Members of the Pottsville Fm. The Schuylkill River, which excavated the gap in Sharp Mountain, flows southeasterly across the Valley and Ridge Province on its course to the Chesapeake Bay, opposite to the streams that originally deposited the Pottsville sediments.

Sedimentology of the Pottsville Section - Facies States and Composition. Sedimentary bed forms, sediment composition, facies sequences, and paleobotany reveal a significant alteration in paleoclimatic conditions across the Pottsville section, ranging from generally semi-arid, poorly vegetated conditions at the base to perenially humid, lush conditions at the top. Ten general facies have been defined at this site and are described in Table 5. Transition matrix analysis reveals two repeating motifs, one characteristic of the Mauch Chunk and one of the Pottsville. When compared to facies sequences from modern environments of deposition, the Mauch Chunk sequence is similar to that of Bijou Creek, Colorado, a sandy, braided, ephemeral stream subject to catastrophic floods (Miall, 1977). Facies S_3 and S_4 probably comprised sand flats or shallow channel deposits; S_{5i} and S_{2t} comprised waning flow deposits or overbank deposits more removed from the active channel. M_1 represents intra-channel, slack water deposits and M_2 represents overbank soils.

The Pottsville sequence is similar to that produced by the Donjek River, Yukon Territory, a gravel-sand mixed bedload, perennial braided stream (Miall, 1977). Facies G_2, S_1, and S_3 formed in the lower parts of the active channels by longitudinal braid bar migration. Facies S_{2t} and S_{5t} formed in the upper parts of active channels or minor channels and on the tops of braid bars. Facies S_{5i} and M_1 formed on bar tops, abandoned channels, and overbank areas, and facies C was deposited in inter-channel swamps. The channels forming the Pottsville Fm. were deeper with greater cross-sectional areas, and lower width/depth ratios than those forming the Mauch Chunk Fm. In consequence, maximum clast size is greater as is the thickness of cross-bed sets.

Sandstone petrology, organic matter content, clay mineralogy, and features of the paleosols (Table 5) all show a progressive trend to more highly leaching, less oxidizing (i.e. more humid) conditions higher in the section. Sandstones are compositionally mature throughout the section but become even more mature up section. The Tumbling Run Member of the Pottsville Fm. contains the highest variety and proportion of non-quartzose fragments while the Sharp Mountain Member contains the highest proportion of vein quartz (Meckel, 1967). Preservation of organic matter in the upper part of the section implies conditions of low Eh, maintained by continuous saturation by stagnant or slowly moving water. Clay minerals are enriched in alumina and depleted in iron higher in the section indicating a greater degree of chemical and biological leaching.

Paleosols occurring throughout the section are particularly useful in revealing paleo-environmental conditions. Most paleosols of the Pottsville and Llewellyn Fms. formed as underclays beneath peat swamps and, therefore, must have been water-saturated during most of their development. In contrast, paleosols of the Mauch Chunk Fm., classified as vertisols by Holbrook (1970), exhibit a variety of features indicating episodic wetting/drying cycles (Table 5).

Caliche, occurring as thin bed-parallel laminae or in nodular layers less than 1 m in thickness is common in the middle member of the Mauch Chunk (Fig. 36) and occurs occasionally in the upper member. Caliche forms in seasonally arid conditions when surface evaporation produces supersaturation of dissolved salts, especially calcium carbonate and silica. The laminar caliche is interpreted to have formed at the sediment surface in shallow ponds during evaporative cycles (Holbrook, 1970). A surface or near-surface origin is indicated for the nodular caliche as well (*ibid.*) based on: 1) sedimentary laminations that pass from the surrounding sediment into the concretions, 2) nodules occurring as intraformational clasts in conglomerates, 3) the presence of carbonate as nodules in the shales but not as cement in the adjacent sandstones and 4) ball and pillow structures occurring between the nodules and the underlying (but not the overlying) sediments.

The composition of the organic matter and clay minerals has been strongly influenced by diagenetic conditions during burial. The coal has been elevated to anthracite rank. Expandable layer clays are not present and illite is of the highly ordered 2-M form, representing "anchizone" alteration. Pyrophyllite is an anchizone alteration product of kaolinite that forms only in Fe-depleted rocks. (cf. Hosterman *et al.*, 1970). Ammonium illite is thought to form at high coal rank in organic matter-rich sediments by nitrogen released

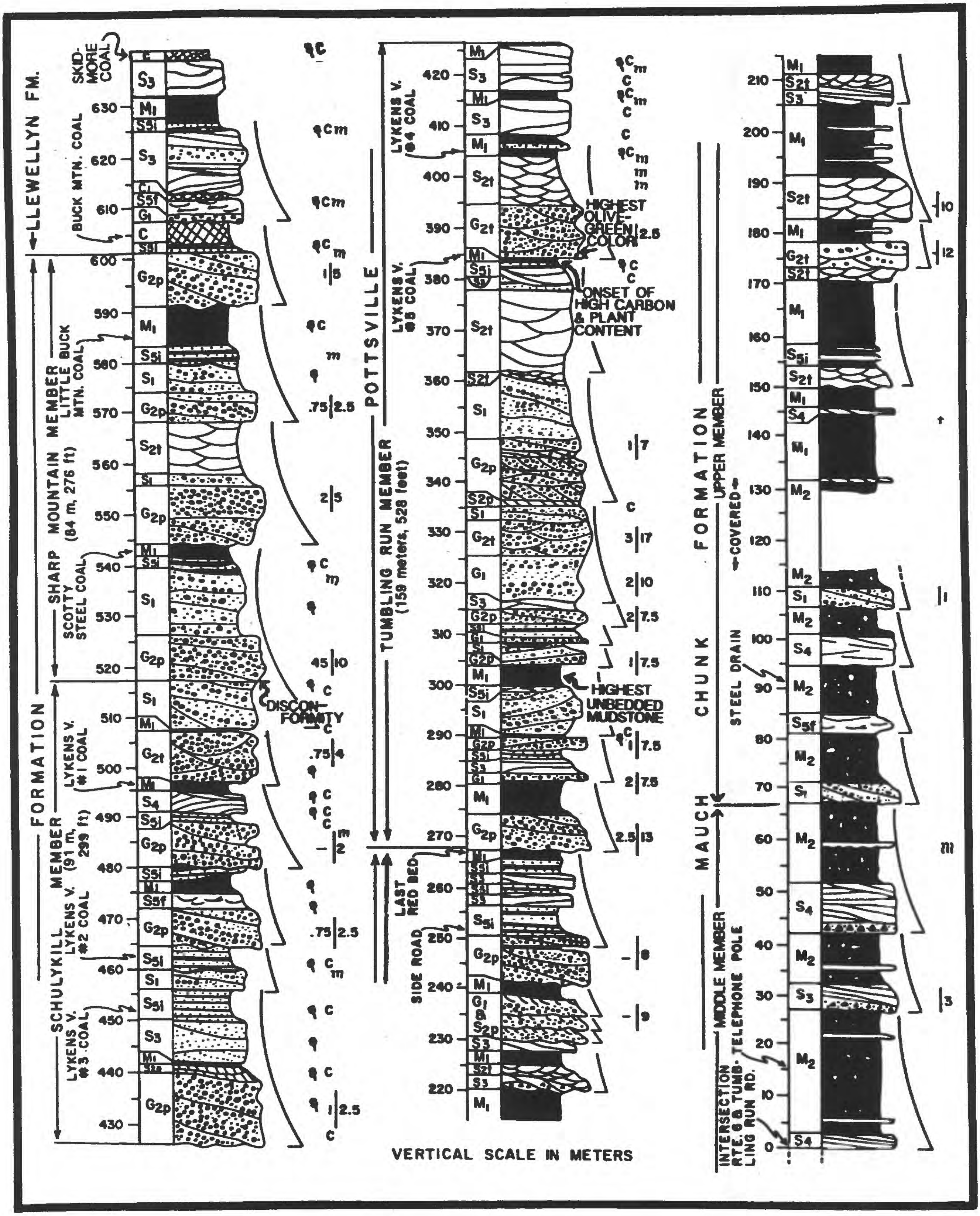


Figure 36. Stratigraphic column of Pottsville section.

CODE:	G_1	$G_{2T\&P}$	S_1	$S_{2T\&P}$	S_3	S_4	$S_{5F\&I}$	M_1	M_2	C
SYMBOL:		t p		t p			f i			
NAME:	Crudely bedded sandy conglom.	Cross bedded sandy conglom.	Plane bedded pebbly sandst.	Cross bedded pebbly sandst.	Coarse, plane bedded sandst.	Fine, plane bedded sandst.	Flaser or interbedded sandst. & mudst.	Noncalcareous mudst.	Calcareous mudst.	Coal
COLOR:	Pale gray ss. with variegated conglom.	Dusky yellow conglom. with gray sandst.	Light olive gray	Grayish orange to pink	Pale red (Mauch Ch.) Pale olive (Pottsv.)	Grayish to pink	Gray red (Mauch Ch.) or dark gray (Pv.)	Ruddy (MC) to light brown to black (Pv.)	Ruddy to brown	Black as coal
GRAIN SIZE:	Coarse sand to pebble conglom.	Pebble conglom. to very coarse sand	Coarse to granule with pebbly stringers	Coarse to granule	Coarse to very coarse	Very fine to fine sand	Fine sand with interbed. mud	Fine clay to silt	Fine clay & silt with carbonate concretions	Finely macerated plant fragments
INTERNAL BED FORMS:	Subhoriz. interstat. coarse sand & pebble conglom. Lenticular medium thick beds	Medium to very thick lenticular beds. Matrix supported conglom. (Note 1)	Low angle laterally contin. wedge sets. Medium to thick, concave upward	Cross bedding Lg. scale trough (S_{2t}) or Sm. scale planar (S_{2p})	Decimeter thick tabular or wedge sets. Lateral cont. to 10s of m. Mass. or par. laminated	Tab. or wedge shape beds. Laterally extensive thin to thick parallel laminae	Small scale cross-strata with mud flasers (S_5f) or laminated w/ mud layers (S_5i) (Note 2)	Finely laminated or rooted see Note 3	Stratified or paleosol features (see Note 3.) M. C. only	Finely stratified but sheared during tectonic deform.
COMPOSITION MAUCH CHUNK TYPE:	(No specific data)		Maturity: mature	Monoxl quartz: 50%	Feldspar: <1%	Rock fragments plus mica. Avg. 15% Generally sedimentary or low-grade metamorphic origin; primarily zircon & tourmaline.		90% of M. C. Shales are red beds (org.-void) Relatively Fe-rich. Clays: 80% illite; 20% chlorite. $CaCO_3$ & SiO_2 concretions in M_1.		None
PV.—LLEWELL.—TYPE:	Vein qtz > sandstone, chert, conglom., silt, and shale > low to med grade metamorph. incl. phyllite, slate and schist		more mature	60%	<1%	(3-38%) Med. to high-grade metamorphic minerals first appear in upper Mauch Chunk indicating unroofing of these rocks in source terrane		All are gray to black org.-bearing Fe-poor, Al-rich. Primarily ill. & chlor. with →40% kaol. & pyrophyllite. No caliche.		- 92% fixed carbon, dry mineral matter free.
TYPICAL BASE:	Undulatory, sharp	Undulatory, sharp, erosive	Undulatory, sharp, erosive	Gradational from S_1 or erosive from M_1	Gradational or sharp	Sharp, planar dips to 15°	Gradational from S_1 or S_3	Gradational from S_2 or S_1	Gradational	Gradational from M_1
TOP:	Gradational	Grades to S_{2t}	Sharp, undulatory, fine gr.	Grad. to S_3 or M_1	Grad. to S_{2t} or S_{5i}	Grad. to M_1	Grad. to S_1 or M_1	Sharp or erosive	Sharp or erosive	Ero. to G_1, Grad. to M.
NOTES:	1. G_2 bed continuity ranges from 3m to across outcrop. Lenses subparallel to 2nd-order truncation surfaces; either laterally extensive tangential low angle (<15°) planar cross-strata (G_{2p}) or large-scale (2-4 m) cut-and-fill troughs (G_{2t}). 2. S_5 unit contains abundant dark brown calcareous root traces, desiccation cracks, and raindrop impressions in Mauch Chunk or plant fragments in Pottsville. 3. Paleosol features of M_1 & M_2 - In Mauch Chunk, paleosols are "vertisols" with wetting/drying features, including wedge-shaped peds, blocky joints, mud cracks, raindrop impressions, pretectonic slickensides, & caliche. Paleosols in Pottsville Fm. are "underclays" with abundant root impressions, leached clay minerals, & no bedding.									
OTHER SYMBOLS:	Intraformational conglomerate; Calcareous concretions; Root traces; Plant fragments; Carbonaceous; Erosional contact; 3|10 average (3) and maximum (10) clast size in centimeters; Fining and thinning upward cycle; Disconformity									
TRANSITION MATRIX SUMMARY SEQUENCES:	Mauch Chunk No. 1 $S_4 \rightarrow M_2$; Mauch Chunk No. 2 S_3, S_{2t}, S_{5i}, M_1; Pottsville $G_{2p} \rightarrow S_1 \rightarrow S_{2t} \rightarrow M_1$, $S_3 \rightarrow S_{5i}$, S_{5f}									

(Compositional information from Meckel, 1967; Wood et al., 1969; Holbrook, 1970; Hosterman et al., 1970)

Table 5. Facies states, sequences, composition, and features of the Pottsville section.

Things to Do at Pottsville Section (Stop #4)

1) Stay away from the highway.

2) Walk up section, observing changes in the composition, grain size, and sedimentary bed-forms of the strata. Look for cycles.

3) Look for paleosols and caliche horizons, raindrop impressions, mud cracks, and other evidence of seasonally dry climates during Mauch Chunk deposition. Compare characteristics of the caliches with "underclays" in the coal-bearing section.

4) Look for the first appearance up-section of organic matter-rich sediments and coal

5) Find someone to argue with about the paleoclimatic significance of red beds; or what sort of climatic conditions are required for peat accumulation; or which was the more important in causing the influx of the Pottsville conglomerates--climatic changes or tectonics.

during late stages of coalification (Paxton, 1983). These transformations imply temperatures of ca. 225-275 C and 6-9 km of burial.

Tectonic Significance of the Pottsville Section. During deposition of the Pottsville section the depositional margin of the basin lay in the vicinity of Philadelphia as indicated by paleocurrent directions and regional trends in maximum grain size (Pelletier, 1958; Meckel, 1967; and Wood et al., 1969a). Northeast-flowing streams carried sediments toward the basin axis which trended northeast-southwest across western Pennsylvania. Time equivalent Upper Carboniferous rocks are alluvial in eastern Pennsylvania and deltaic and shallow marine to the west (Edmunds *et al.*, 1979). The Mauch Chunk Fm. documents a relatively quiescent interval represented variously by fine-grained sedimentation and soil development in the east, an erosional disconformity toward the west, and shallow marine carbonate sedimentation along the basin axis. The influx of coarse clastics in the Pottsville interval has traditionally been ascribed to tectonic uplift in the source (e.g. Meckel, 1967), but while this might be partly true, it is neither a necessary nor sufficient explanation. The simplest explanation is that the change to more humid climatic conditions in the Pennsylvanian produced larger sediment yields and stream discharges. The continued influx of clastic sediments would represent isostatic unloading of the Acadian source terrane.

An additional factor influencing the stratigraphic succession may have been the diversification and proliferation of terrestrial plants during the middle Carboniferous. Plant evolution could have helped to stablize stream banks, allowed peat accumulation rates to equal or exceed basin subsidence, and influenced climatic patterns.

The intertonguing of Mauch Chunk and Pottsville facies in the upper member of the Mauch Chunk clearly indicates an alternation of depositional environments, but it is problematical whether this represents the lateral migration of two co-existing sub-environments in the sense of Walther's Law, or the sedimentological adjustment of an entire depositional system to cyclic climatic changes. In the former case, the Pottsville Fm. would represent a higher elevation, proximal, more humid facies and the Mauch Chunk a more distal, flood basin facies, subject to wetting more by flooding than by rainfall.

The interpreted tectonic and paleoenvironmental setting during Mauch Chunk deposition would have resembled in many respects the current alluvial plain extending from the Zagros Mountains to the Persian Gulf where arid conditions produce little clastic influx from the tectonically active mountain belt. The adjacent foreland basin axis--lying parallel to the mountain belt--receives primarily carbonate sedimentation. Were a future global climatic change to transform the Middle East into a humid region, the margins of the Persian Gulf could perhaps evolve into a broad peat-forming environment such as existed in the Appalachian basin during Pottsville and Llewellyn times.

Paleobotany at the Pottsville type section

Christopher Wnuk

The road cut along Route 61 south of Pottsville exposes the top of the Mauch Chunk Formation, the Pottsville Formation type section, and the basal part of the Llewellyn Formation. Although this exposure cannot be regarded as a spectacular collecting locality, it is paleobotanically significant because of the biostratigraphic range exposed here. The exposed section spans the range from Read and Mamay's Floral Zone 3 through Floral Zone 10.

Collections of fragmentary *Adiantites* from Floral Zone 3 can be made in some of the olive colored reduced shales of the Mauch Chunk Formation on the south flank of Sharp Mountain along the road to Silver Creek Reservoir. White (1900) indicates that fossil floras can also be recovered from the redbeds of the Mauch Chunk, but good collections from these units will require a considerable effort.

Plant collections can be made in some of the dark carbonaceous shales of the Pottsville Formation. White (1900) found 12 collecting localities in the old type section along the Pennsylvania Railroad cut that lies directly below the Route 61 section. The best prospects for collecting plants at this locality are in the shale float derived from the highest Pottsville coals. The floras tend to be fairly low in diversity, and are dominated by lycopod and pteridosperm remains. Large coalified lycopod trunks are common in the conglomerate and sandstone beds, especially in the Sharp Mountain Member. Floral Zones 3 through 9 are included in the interval between the highest red bed at the base of the section and the Buck Mountain (No. 5) at the top, though floras representative of all of these zones have not been recovered at the type area.

The basal part of the Llewellyn Formation is exposed along the road to Palo Alto on the north flank of Sharp Mountain. Several thick coal beds are exposed here, and their roof shales tend to have abundant and diverse floras. Again, the best collecting is in the float that accumulates at the base of the coal bed. Floras characteristic of Floral Zone 9 and 10 can be collected from this part of the section.

STOP #5: Saint Clair Fossil Plant Locality

Christopher Wnuk

The St. Clair locality is world famous for its plant fossils. Most of the white on black plant fossil specimens that are commonly found for sale in rock and mineral shops are derived from this locality. The unique coloration of these fossils has been investigated by Myer *et al.* (1977). They indicate that these remains are not compressions but are preserved in three dimensions. The remains consist of graphite and pyrophyllite. They suggest that the original plant tissues were first replaced by another mineral phase, possibly pyrite, which was then replaced by the pyrophyllite at the higher metamorphic grades represented by anthracitization process. Woody structures which were not initially replaced with pyrite were converted to graphite during the metamorphism. Myer *et al.* indicate that nucleation and growth of the pyrophyllite were controlled by the leaf structure.

Floral investigations by Scheihing and Pfefferkorn (1980) indicate that, on the average, lycopsids constitute 5 percent of the flora, sphenopsids 5 percent, ferns 12 percent, and pteridosperms 78 percent. Among the pteridosperms, *Alethopteris serli* is the dominant species accounting in some collections for up to 78 percent of the material. *Alethopteris pennsylvanica, Neuropteris scheuchzeri, N. ovata*, and rare ferns can also be found. All told, more than 80 plant species have been reported from this locality (see Sevon *et al.*, 1982). Persistent collectors may be rewarded with the discovery of some insect remains among the plant material. The remains of cockroaches, ancestral crickets, and ancestral dragonflies are also sometimes encountered in these sediments (Sevon *et al.*, 1982).

The St. Clair collecting locality is in a gently inclined contour strip mine that removed down to the Buck Mountain (No. 5) coal of the Llewellyn Formation (Sevon *et al.*, 1982). The rarity of ferns in this horizon indicates that it is of early Westphalian D age (H.W. Pfefferkorn, personal communication) and belongs within Floral Zone 9 (though historically the biostratigraphic assignment has been confused as the discussion in Sevon *et al.* (1982) would indicate).

This exposure is another example of an underclay flora, but its characteristics are distinctly different from the flora preserved in the Bear Valley mine. The most striking difference between the two localities is the abundance of foliage in the St. Clair mine and the rarity of large trunk remains. St. Clair appears to be less organic than Bear Valley; the exposed shales are medium to dark gray at St. Clair as compared to black in Bear Valley. *Stigmaria*, indicating rooting by lycopods is also much less common at St. Clair compared to Bear Valley.

Underclay floras dominated by foliage remains indicate a different genetic history from the more typical floras dominated by trunks and smaller axes. The St. Clair assemblage probably accumulated in a flood plain lake. Foliage from a pteridosperm dominated marginal vegetation preferentially entered and was preserved in the lake sediments. Since this was a low energy system as indicated by the fine grained nature of the underclay sediments, large trunks were unlikely to enter the depositional system. A very similar situation has been documented in the Bernice basin in Sullivan County by Wnuk and Pfefferkorn (1987). There the flora consists of a mixture of large trunks and abundant foliage. That site also is interpreted to be a shallow flood plain lake that was gradually filled with organic debris and subsequently colonized by the lycopods that formed the overlying coal. The lycopods rooted in the organic debris thereby protecting the fossiliferous mineral substrate from root bioturbation and concomitant destruction of the fossil remains. Since lycopods are very shallowly rooted, the average lycopod rarely roots deeper than 128 cm (Wnuk and Maberry, 1990), a shallow organic cover would protect the mineral substrate from root disturbance. A similar depositional history is suggested for the St. Clair assemblage.

COMPREHENSIVE BIBLIOGRAPHY

Arndt, H.H., unpublished, Coal rank map of the Western Middle anthracite field, Pennsylvania, based on volatile matter content (dry, ash-free).

Arndt, H.H. and Wood, G.H., Jr., 1960, Late Paleozoic orogeny in eastern Pennsylvania consists of five progressive stages: U.S. Geological Survey Prof. Paper No. 400-B, p. B182-184.

Arndt, H.H., Wood, G.H., Jr., and Schryver, R.F., 1973, Geologic map of the south half of the Shamokin quadrangle, Northumberland and Columbia Counties, Pennsylvania: U.S. Geological Survey Miscellaneous Investigations Map I-734.

Arndt, H.H., Danilchik, W., and Wood, G.H., Jr., 1963a, Geology of anthracite in the western part of the Shamokin quadrangle, Pennsylvania: U.S. Geological Survey Coal Investigations Map C-47.

Arndt, H.H., Wood, G.H., Jr., and Danilchik, W., 1963b, Geology of anthracite in the southern part of the Trevorton quadrangle, Northumberland County, Pennsylvania: U.S. Geological Survey Coal Investigations Map C-48.

Ashburner, C.A., 1886, Report on the Wyoming Valley Carboniferous limestone beds: Harrisburg, PA, Pennsylvania Geological Survey, 2nd, 1885 Annual Report, p. 437-450.

Beaumont, C., Quinlan, G., and Hamilton, J., 1988, The Alleghanian Orogeny and its relationship to the evolution of the eastern interior, North America, in Beaumont, C. and Tankard, A.J., eds., Sedimentary basins and basin-forming mechanisms, Canadian Society of Petroleum Geologists Memoir 12, p. 425-445.

Beaumont, C., Quinlan, G., and Hamilton, J., 1988, Orogeny and stratigraphy: Numerical models of the Paleozoic in the eastern interior of North America: Tectonics, v. 7, p. 389-416.

Beck, T., 1977, George M. Bretz photographer in the mines: Baltimore, MD, University of Maryland Baltimore County Library, 73 p.

Bergin, M.J., 1976, Bedrock geologic map of the anthracite-bearing rocks in the Wilkes-Barre West Quadrangle, Luzerne County, Pennsylvania: U.S. Geological Survey Miscellaneous Investigations Map I-838.

Bethke, C.M., 1986, Hydrologic constrants on the genesis of the Upper Mississippi Valley mineral district form Illinois basin brines: Economic Geology, v. 81, p. 233-249.

Bethke, C.M. and Marshak, S., 1990, Brine migrations across North America--The plate tectonics of groundwater: Ann. Rev. Earth and Planet. Sci., v. 18, p. 287-315.

Bode, H., 1958, Die floristische Gliederung des Oberkarbons der vereinigten Staaten von Nordamerika: Deutsche Geol. Gesell. Zeitschr. Jahrg., v. 10, pt. 2, p. 217-259.

Bonijoly, M., Oberlin, M., and Oberlin, A., 1982, A possible mechanism for natural graphite formation: International Journal of Coal Geology, v. 1, p. 283-313.

Bredehoeft, J.D. and Papadopulos, I.S., 1965, Rates of vertical groundwater movement estimated from the Earth's thermal profile: Water Resources Research, v. 1, p. 325-328.

Cook, A.C., Murchison, D.G., and Scott, E., 1972. Optically biaxial anthracitic vitrinites. Fuel, 51: 180-184

Cook, F.A. and Oliver, J.E., 1981, The late Precambrian-early Paleozoic continental edge in the Appalachian Orogen: American Journal of Science, v. 381, p. 993-1008.

Cook, F.A., Brown, L.D., Kaufman, S. and Oliver, J.E., 1983, The COCORP seismic reflection traverse across the Southern Appalachians: American Association of Petroleum Geologists Studies in Geology, v. 14, 61 p.

Cornell, W.A. and Altland, M., 1957, Pennsylvania Milestones: State College, PA, Penns Valley Publishers, 368 p.

Cuff, D.J., W.J. Young, E.K. Muller, W. Zelinsky, and R.F. Abler, eds, The Atlas of Pennsylvania: Philadelphia,PA, Temple University Press, 288 p.

Dahlstrom, C.D.A., 1970, Structural geology in the eastern margin of the Canadian Rocky Mountains: Bulletin of Canadian Petroleum Geology, v. 18, p. 332-406.

Dahme, A., and Mackowsky, M.-Th., 1951. Chemish-physikalische and petrographische Untersuchen an Kohlen, Koksen, and Graphiten; V. Mikroskopische, chemische, und röentgerographische Untersuchen an Anthrazitens. Brennstoff-Chemie, 32: 175-186.

Damberger, H.H., 1974, Coalification patterns of Pennsylvanian coal basins of the eastern United States: Geological Society of America Special Publication 153, p. 53-74

Daniels, E.J., 1989, Origin and distribution of minerals in shale and coal from the Anthracite region, eastern Pennsylvania [M.S. Thesis], Urbana, Illinois, University of Illinois, 97 p.

Daniels, E.J., 1992, Nature and origin of minerals in anthracite from eastern Pennsylvania [Ph.D. Thesis]: Urbana, Illinois, University of Illinois, 129 p.

Daniels, E.J. and Altaner, S.P., 1990, Clay mineral authigenesis in coal and shale from the Anthracite region, Pennsylvania: American Mineralogist, v. 75, p. 825-839.

Daniels, E.J., Altaner, S.P., Marshak, S., and Eggleston, J.R., 1990, Hydrothermal alteration in anthracite from eastern Pennsylvania: implications for mechanisms of anthracite formation: Geology, v. 18, p. 247-250.

Danilchik, W., Arndt, H.H., and Wood, G.H., Jr., 1962, Geology of anthracite in the eastern part of the Shamokin quadrangle, Northumberland County, Pennsylvania: U.S. Geological Survey Coal Investigations Map C-46.

Darrah, W.C., 1969, A critical review of the upper Pennsylvanian floras of eastern United States with notes on the Mazon Creek flora of Illinois: Privately published, Gettysburg, PA, 200 p., 80 pls.

Deurbergue, A., Oberlin, A., Oh, J.H., and Rouzaud, J.N., 1987, Graphitization of Korean anthracites as studied by Transmission Electron Microscopy and X-ray diffraction: International Journal of Coal Geology, v. i, p. 375-393.

Domenico, P.A. and Palciauskas, V.V., 1973, Theoretical analysis of forced convective heat transfer in regional ground-water flow: Geological Society of America Bulletin, v. 84, p. 3803-3814.

Donaldson, A.C. and Shumaker, R.C., 1981, Late Paleozoic molasse of Central Appalachians, in Miall, A.D., ed., Sedimentation and tectonics in alluvial basins: Geological Association of Canada Special Paper 23, p. 99-124.

Edmunds, W.E., Berg, T.M., Sevon, W.D., Piotrowski, R.C., Heyman, L., and Rickard, L.V., 1979, The Mississippian and Pennsylvanian (Carboniferous) systems in the United States - Pennsylvania and New York: United States Geological Survey Professional Paper 1110-B, 33 p.

Eggleston, J.R. and Edmunds, W.E., 1981, Field guide to the Anthracite coal basins of eastern Pennsylvania: Atlantic Margin Energy Symposium, Am. Assoc. Petroleum Geologists, 90 p.

Eggleston, J.R. and Edmunds, W.E., 1989, Anthracite Basins of Eastern Pennsylvania: International Geological Congress Field Trip Guidebook T242, Washington, D.C., American Geophysical Union, 29 p.

Eggleston, J.R., Wnuk, C., and Edmunds, W.E., 1988, The age of the upper part of the Llewellyn Formation in the Pennsylvania Anthracite region: Journal of the Pennsylvania Academy of Sciences, v. 62, p. 45.

Elliot, W.C. and Aronson, J.L., 1987, Alleghanian episode of K-bentonite illitization in the southern Appalachian basin: Geology, v. 15, p. 735-739.

Engelder, T., 1979, Mechanisms for strain within the Upper Devonian clastic sequence of the Appalachian Plateau, western New York: American Journal of Science, v. 279, p. 527-542.

Engelder, T. and Engelder, R., 1977, Fossil distortion and decollement tectonics on the Appalachian Plateau: Geology, v. 5, p. 457-460.

Ergun, S., 1968, X-ray studies of coals and carbonaceous materials: U.S. Bureau of Mines Bulletin 648, 35p.

Eugster, H.P. and Munoz, J., 1966, Ammonium micas: possible sources of atmospheric nitrogen: Science, v. 151, p. 683-686.

Faill, R.T., 1973, Kink band folding, Valley and Ridge province, Pennsylvania: Geological Society of America Bulletin, v. 84, p. 1289-1314.

Faill, R.T., 1977, Fossil distortion, Valley and Ridge province, Pennsylvania: Geological Society of America Abstracts with Programs, v. 9, p. 262-263.

Finkelman, R.B., Yeakel, J., and Harrison, W.J., 1987, Sodium in Upper Cretaceous coal beds of the Wasatch Plateau, Utah: Mode of occurrence, geologic controls, possible source and effects on utilization: Geological Society of America, abstracts with programs, v. 19, p. 663.

Fransolet, A.-M. and Bourguignon, P., 1978, Di/trioctahedral chlorite in quartz veins from the Ardennes, Belgium: Canadian Mineralogist, v. 16, p. 365-373.

Fransolet, A.-M. and Schreyer, W., 1984, Sudoite, di/trioctahedral chlorite: a stable low-temperature phase in the system MgO-Al_2O-SiO_2-H_2O: Contributions to Mineralogy and Petrology, v. 86, p. 409-417.

Gastaldo, R.A., 1982, A preliminary assessment of Early Pennsylvanian megafloral paleoecology in northeastern Alabama, in B. Mamet and M.J. Copeland, eds., Third North American Paleontological Convention, Proceedings, v. 1, p. 187-192.

Gastaldo, R.A., 1986, Implications on the paleoecology of autochthonous lycopods in clastic sedimentary environments of the Early Pennsylvanian of Alabama: Palaeogeog. Palaeoclim. Palaeoecol., v. 53, p. 191-212.

Geiser, P. and Engelder, T., 1983, The distribution of layer parallel shortening fabrics in the Appalachian foreland of New York and Pennsylvania: Evidence for two non-coaxial phases of the Alleghany Orogeny: Geological Society of America Memoir 158, p. 161-175.

Gillespie, W.H. and Pfefferkorn, H.W., 1979, Distribution of commonly occurring plant megafossils in the proposed Pennsylvanian System stratotype. in: Englund, K.J., Arndt, H.H., Henry, T.W. and the U.S. Geological Survey, eds., Proposed Pennsylvanian System stratotype: Virginia and West Virginia. Ninth International Congress of Carboniferous Stratigraphy and Geology, Field Trip No. 1.

Geiser, P. and Engelder, T., 1983, The distribution of layer parallel shortening fabrics in the Appalachian foreland of New York and Pennsylvania - Evidence for two non-coaxial phases of the Alleghanian orogeny: in Hatcher, R.D., Jr., Williams, H., and Zeitz, I., eds., Contributions to the tectonics and geophysics of mountain chains: Geological Society of America Memoir 158, p. 161-175.

Goodcharles, F.A., 1944, Chronicles of central Pennsylvania: New York, Lewis Historical Publishing Co., 4 Volumes.

Gradusov, B.P., 1971, Dioctahedral chlorites: Lithology and Mineral Resources, v. 6, p. 471-478.

Graham, J.W., 1949. The stability and significance of magnetism in sedimentary rocks. J. Geophys. Res., 54: 131-167.

Gwinn, V.E., 1964, Thin-skinned tectonics in the Plateau and northwestern Valley and Ridge provinces of the Central Appalachians: Geological Society of America Bulletin, v. 75, p. 863-900.

Hatch, J.R., Gluskoter, H.J., and Lindahl, P.C., 1976, Sphalerite in coals from the Illinois Basin: Economic Geology, v. 72, p. 613-624.

Hearn, P.P., Jr., Sutter, J.F. and Belkin, H.E., 1987, Evidence for Late-Paleozoic brine migration in Cambrian carbonate rocks of the central and southern Appalachians: Implications for Mississippi Valley-type mineralization: Geochimica et Cosmochimica Acta, v. 51, p. 1323-1334.

Hemley, J.J., Montoya, J.W., Marinenko, J.W., and Luce, R.W., 1980, Equilibria in the system Al_2O_3-SiO_2-H_2O and some general implications for alteration/mineralization processes: Economic Geology, v. 75, p. 210-228.

Hevia, V. and Virgos, J .M., 1977. The rank and anisotropy of anthracites. The indicating surface of reflectivity in uniaxial and biaxial substances. J. Microscopy, 109, Pt. 1: 23-28.

Hitchon, B., 1984, Geothermal gradients, hydrodynamics, and hydrocarbon occurrences, Alberta, Canada: American Association of Petroleum Geologists Bulletin, v. 68, p. 713-743.

Holbrook, P.W., 1970, The sedimentology and pedology of the Mauch Chunk Formation at Pottsville, Pennsylvania and their climatic implications [Master's thesis]: Lancaster, Pennsylvania, Franklin and Marshall College, 111 p.

Hosterman, J.W., Wood, G.H., Jr., and Bergin, M.J., 1970, Mineralogy of underclays in the Pennsylvania Anthracite region: U.S. Geological Survey Professional Paper 700-C, p. C89-C97.

Hower, J.C, 1978, Anisotropy of vitrinite reflectance in relation to coal metamorphism for selected United States coals [PhD Thesis]: University Park, PA, The Pennsyvania State University, 339 p.

Hower, J.C. and Davis, A., 1981a, Application of vitrinite reflectance anisotropy in the evaluation of coal metamorphism: Geological Society of America Bulletin, Pt. 1, v. 92, p. 350-366.

Hower, J.C. and Davis, A., 1981b, Vitrinite reflectance anisotropy as a tectonic fabric element: Geology, v. 9, p. 165-168.

Juster, T.C., Brown, P.E., and Bailey, S.W., 1987, NH_4 bearing illite in very low-grade metamorphic rocks associated with coal, northeastern Pennsylvania: American Mineralogist, v. 72, p. 555-565.

Johnson, A.M., 1981, On the forms of folds in the central Appalachians: Geological Society of America Abstracts with Programs, v. 13, no. 7, p. 480-481.

Kilby, W.E., 1988. Recognition of vitrinite with non-uniaxial negative reflectance characteristics. Int. J. Coal Geol., 9: 267-285.

Kisch, H.J. and van den Kerkhof, A.M., 1991, CH_4-rich inclusions from quartz veins in the Valley-and-Ridge province and the anthracite fields of the Pennsylvania Appalachians: American Mineralogist, v. 76, p. 230-240.

Krylova, N.M., 1971. Optical properties of coal as indicators of tectonic stress, In Sediment Accumulation in the Genesis of the Carboniferous of the USSR (in Russian, Translation by Th. Kulakowski). Nauka Press, Moscow, pp. 239-249.

Lesquereux, L., 1858, General remarks on the distribution of the coal plants in Pennsylvania, and on the formation of the coal, in H.D. Rogers, Geology of Pennsylvania, v. II, Part 2: Philadelphia, J.B. Lippincott and Co., p. 837-884.

Lesquereux, L., 1879, Atlas to the coal flora of Pennsylvania and of the Carboniferous Formation throughout the United States: Second Geological Survey of Pennsylvania: Report of Progress P, 87 plates.

Lesquereux, L., 1880, Description of the coal flora of the Carboniferous Formation in Pennsylvania and throughout the United States: Second Geological Survey of Pennsylvania: Report of Progress P, v. I-II, 694p.

Lesquereux, L., 1884, Description of the coal flora of the Carboniferous Formation in Pennsylvania and throughout the United States: Second Geological Survey of Pennsylvania: Report of Progress P, V. III, 694-997p.

Levine, J.R., 1983, Tectonic history of coal-bearing sediments in eastern Pennsylvania using coal reflectance anisotropy (PhD Dissertation): University Park, PA, The Pennsylvania State University, 314 p.

Levine, J.R., 1986, Deep burial of coal-bearing strata, Anthracite region, Pennsylvania: sedimentation or tectonics?: Geology, v. 14, p. 577-580.

Levine, J.R. and Davis, A., 1984. Optical anisotropy of coals as an indicator of tectonic deformation, Broad Top Coal Field, Pennsylvania. Geol. Soc. Am. Bull., 95: 100-108.

Levine, J.R. and Davis, A., 1989a, The relationship of coal optical fabrics to Alleghanian tectonic deformation in the central Appalachian fold-and-thrust belt, Pennsylvania: Geological Society of America Bulletin, v. 101, p. 1333-1347.

Levine, J.R. and Davis, A., 1989b, Reflectance anisotropy of Upper Carboniferous coals in the Appalachian foreland basin, Pennsylvania, U.S.A., in Lyons, P.C. and Alpern, B., eds, Coal: Classification, coalification, mineralogy, trace element chemistry, and oil and gas potential: International Journal of Coal Geology, v. 13, p. 341-373.

Levine, J.R. and Slingerland, Rudy, 1987, Upper Mississippian to Middle Pennsylvanian stratigraphic section, Pottsville, Pennsylvania: Geol. Soc. America, Centennial Field Guide, Northeast Section, p. 59-63.

Mackowsky, M.-Th., 1975, Minerals and trace elements occurring in coal. In Stach, E., Taylor, G. H., Mackowsky, M.-Th., Chandra, D., Teichmüller, M., and Teichmüller, R., eds., Stach's textbook of Coal Petrology (second edition): Berlin, Gebrüder Borntraeger, p. 121-131.

McTavish, R.A., 1978, Pressure retardation of vitrinite diagenesis, offshore, north-west Europe: Nature, London, v. 271, p. 648-650.

Meckel, L.D., 1967, Origin of Pottsville conglomerates (Pennsylvanian) in the central Appalachians: Geological Society of America Bulletin, v. 78, p. 223-258.

Miall, A.D., 1977, A review of the braided river depositional environment: Earth Science Review, v. 13, p. 1-62.

Miller, J.D. and Kent, D.V., 1988, Regional trends in the timing of Alleghanian remagnetization in the Appalachians: Geology, v. 16, p. 588-591.

Miller, D.L. and Sharpless, R.E., 1985, The kingdom of coal - work, enterprise, and ethnic communities in the mine fields: Philadelphia, University of Pennsylvania Press, 360 p.

Minnigh, L.D., 1979, Structural analysis of sheath-folds in a meta-chert from the western Italian Alps: Journal of Structural Geology, v. 1, p. 275-282.

Miser, H.D. and Milton, C., 1964, Quartz, rectorite and cookeite from the Jeffrey quarry near North Little Rock, Pulaski County, Arkansas: Arkansas Geological Commision, Bulletin 21, 29 p.

Mobil Oil Corp., 1991, Mobil Travel Guide: Middle Atlantic States: New York, Prentice-Hall

Myer, G.H., De Santis, J., Grandstaff, B.E., and Grandstaff, D.E., 1977, A multistage model of preservation in some fossil plants: Geological Society of America, Abstracts with Programs, v. 9, p. 304.

Nickelsen, R.P., 1963, Fold patterns and continuous deformation mechanisms of the central Pennsylvanian folded Appalachians, in Guidebook to Tectonics and Cambro-Ordovician Stratigraphy, Central Appalachians of Pennsylvania: Pittsburgh Geological Society, p. 13-29.

Nickelsen, R.P., 1966, Fossil distortion and penetrative rock deformation in the Appalachian Plateau, Pennsylvania: Journal of Geology, v. 74, p. 924-931.

Nickelsen, R.P., 1979, Sequence of structural stages of the Alleghany Orogeny at the Bear Valley strip mine, Shamokin, Pennsylvania: American Journal of Science, v. 279, p. 225-271.

Nickelsen, R.P., 1981, Bear Valley strip mine in Eggleston, J.R. and Edmunds, W.E., Field guide to the anthracite coal basins of eastern Pennsylvania, Atlantic Margin Energy Symposium, Am. Assoc. Petroleum Geologists.

Nickelsen, R.P. and Hough, V.N.D., 1967, Jointing in the Appalachian Plateau of Pennsylvania: Geological Society of America Bulletin, v. 78, p. 609-630.

Orkan, N.I., 1986, Regional joint evolution and paleothermometry-barometry from fluid inclusions in the Valley and Ridge province of Pennsylvania in relation to the Alleghany orogeny [M.S. Thesis] University Park, PA, The Pennslvania State University, 194 p.

Orkan, N.I. and B. Voight, 1983, Fracture geometry and vein mineral paleothermometry-barometry from fluid inclusions, Valley and Ridge Province, Pennsylvania: Geological Society of America Abstracts with Programs, v. 15, p. 656.

Oxburgh, E.R. and Turcotte, D.L., 1974, Thermal gradients and regional metamorphism in overthrust terrains with special reference to the Eastern Alps: Schweizerische Mineralogische und Petrologische Mitteil, v. 54, p. 641-662.

Paxton, S.T., 1983, Relationships between Pennsylvanian-age lithic sandstone and mudrock diagenesis and coal rank in the central Appalachians [PhD thesis]: University Park, The Pennsylvania State University, 503 p.

Pelletier, B.R., 1958, Pocono paleocurrents in Pennsylvania and Maryland: Geological Society of America Bulletin, v. 69, p. 1033-1064.

Pennsylvania Bureau of Topographic and Geologic Survey, 1980, Geologic map of Pennsylvania (T.M. Berg, Chief Compiler), 3 sheets.

Percival, J.B. and Kodama, H., 1989, Sudoite from Cigar Lake, Saskatchewan: Canadian Mineralogist, v. 27, p. 633-641.

Petrascheck, W.E., 1954. Zur optischen Regelung tectonisch beanspruchter Kohlen. Tschermaks Mineralogische und Petrographische Mitteilungen, 4: 232-239.

Quinlan, G.M. and Beaumont, C., 1984, Appalachian thrusting, lithospheric flexure, and the Paleozoic stratigraphy of the Eastern Interior of North America: Canadian Journal of Earth Science, v. 21, p. 973-996.

Ramsay, J.G., 1974, Development of chevron folds: Geological Society of America Bulletin, v. 85, p. 1741-1754

Read, C.B., 1955, Floras of the Pocono Formation and the Price Sandstone in parts of Pennsylvania, Maryland, West Virginia, and Virginia: U.S. Geological Survey Professional Paper 263, 32p.

Read, C.B. and Mamay, S.H., 1960, Upper Paleozoic floral zones of the United States: U.S. Geological Survey Prof. Paper 400-B, p. B381-B383.

Read, C.B. and Mamay S.H., 1964, Upper Paleozoic floral zones and floral provinces of the United States: U.S. Geological Survey Professional Paper 454-K, 35 p.

Resource Technologies Corporation, 1984, Defining the anthracite resources of northeastern Pennsylvania: U.S. Bureau of Mines Contract No. J0333932, 228 p.

Rogers, J., 1970, The tectonics of the Appalachians: New York, John Wiley and Sons, 271 p.

Root, S.I., 1973, Structure, basin development, and tectogenesis in the Pennsylvania portion of the folded Appalachans, in DeJong, K.A. and Scholten, R., eds., Gravity and Tectonics: New York, John Wiley and Sons, p. 343-360.

Ross, J.V., Bustin, R.M., and Rouzaud, J.N., 1991, Graphitization of high rank coals--the role of shear strain: experimental consideration: Organic Geochemistry, v. 17, p. 585-596.

Scheihing, M.H. and Pfefferkorn, H.W., 1980, Morphologic variation in *Alethopteris* (pteridosperms, Carboniferous) from St. Clair, Pennsylvania, U.S.A.: Palaeontographica, v. 172B, p. 1-9.

Sevon, W.D., Berg, T.M., Inners, J.D., and Smith, R.C., 1982, Geology of the southern part of the anthracite coal fields of Pennsylvania: Field Guidebook, 74th Annual Meeting of the American Association of State Geologists, June 10, 1982, 38p.

Shirozu, H., 1978, Wall rock alteration of Kuroku deposits, in Sudo, T. and Shimoda, S., eds., Clays and Clay Minerals of Japan: Developments in Sedimentology, v. 26, p. 127-145: Elsevier, Tokyo.

Slingerland, R. and Beaumont, C., 1989, Tectonics and sedimentation of the Upper Paleozoic foreland basin in the Central Appalachians, in Slingerland, R. and Furlong, K., Sedimentology and thermal-mechanical history of basins in the Central Appalachian Orogen: Washington, D.C., American Geophysical Union, Field Trip Guidebook T152, 28th International Geological Congress, p. 4-24.

Spackman, W. and Moses, R.G., 1961, The nature and occurrence of ash forming minerals in anthracite, in Proceedings of the anthracite conference, Nov. 15-16, 1960: Pennsylvania State University Mineral Industries Experiment Station Bulletin 75, p. 1-15.

Spears, D.A. and Caswell, S.A., 1986, Mineral matter in coals: cleat minerals and their origin in some coals from the English Midlands: International Journal of Coal Geology, v. 6, p. 107-125.

Stach, E., Mackowsky, M.-Th., Teichmüller, M., Taylor, G.H., Chandra, D., and Teichmüller, R., 1975. Coal Petrology. Berlin, Gebrüder Borntraeger, 428 pp.

Stingelin, R.W, 1965, Late-glacial and Post-glacial vegetational history in the north central Appalachian region [Ph.D. thesis]: University Park, PA, The Pennsylvania State University, 191 p.

Stone, I.J., and Cook, A.C., 1979. The influence of some tectonic structures upon vitrinite reflectances. J. Geol., 87: 497-508.

Teichmüller, M., 1982, Application of coal petrological methods in geology, including oil and gas exploration, in Stach, E., Mackowsky, M-Th., Teichmüller, M., Taylor, G.H., Chandra, D., and Teichmüller, R., eds., Coal Petrology, 3rd edition: Gebrüder Borntraeger, Berlin-Stuttgart, p. 381-413.

Teichmüller, M. and Teichmüller, R., 1966, Geological causes of coalification, in Gould, R.F., ed., Coal Science: American Chemical Society, Advances in Chemistry Series, 55, p 133-155.

Teichmüller, M. and Teichmüller, R., 1979, Diagenesis of coal (Coalification), in Larson, G. and Chilangar, G.V. (Eds.), Diageneis in sediments and sedimentary rocks: Developments in sedimentology, v. 25A: Amsterdam, Elsevier, p. 207-246.

Tissot, B.P., and Welte, D.H., 1978. Petroleum Formation and Occurrence. Springer-Verlag, Berlin, 538 pp.

Turner, H.G., 1934, Anthracites and semi-anthracites of Pennsylvania: American Institute of Mining and Metallurgical Engineers Transactions, v. 108, p. 330-343.

Van der Flier-Keller, E. and Fyfe, W.S., 1988) Mineralogy of Lower Cretaceous coals from the Moose River Basin, Ontario, and Monkman, British Columbia: Canadian Mineralogist, v. 26, p. 343-353.

de Vries, H.A.W., de, Habets, P.J., and Bokhoven, C., 1968. Das Reflexionsvermögen van Steinkohle. Brennstoff-Chemie, 49: 11-21, 47-52, 106-110 (British Coal Utilization Research Association Translation No. 307).

Waples, D., 1980, Time and temperature in petroleum formation - application of Lopatin's method to petroleum exploration: AAPG Bull., v. 64, p. 916-926.

White, C.D., 1900, The stratigraphic succession of fossil floras of the Pottsville Formation in the Southern Anthracite field, Pennsylvania: U.S. Geol. Survey Ann. Rept. 20, pt. 2 (1898-99), p. 749-930.

White, C.D., 1913, Physiographic conditions attending the formation of coal in White, C.D. and Thiessen, R., The origin of coal: U.S. Bu. Mines Bull. 38, p. 52-84.

White, C.D., 1915, Some relations in origin betwen coal and petroleum: Journal of the Washington Academy of Sciences, v. 5, p. 189-212.

White, C.D., 1925, Progressive regional carbonization of coals: Transactions of the American Institute of Mining and Metallurgical Engineers, v. 71, p. 253-281.

Williams, E., 1953. Anisotropy of the vitrain of South Wales coals. Fuel, 32: 89-99.

Wnuk, C., 1985, The ontogeny and paleoecology of *Lepidodendron rimosum* and *Lepidodendron bretonense* trees from the Middle Pennsylvanian of the Bernice basin (Sullivan County, Pennsylvania): Palaeontographica 195B: 153-181.

Wnuk, C., 1986, Preliminary observations on the paleoecological significance and taphonomic history of underclay floras, in W.E. Cox and W.F. Snyder, eds., Proceedings, New River Symposium, Wytheville, Virginia, Oak Hill, Eastern National Park and Monument Association, p. 89-98.

Wnuk, C., 1989a, Ontogeny and Paleoecology of the Middle Pennsylvanian arborescent lycopod *Bothrodendron punctatum*, Bothrodendraceae (Western Middle Anthracite field, Shamokin Quadrangle, Pennsylvania): American Journal of Botany, v. 76, p. 966-980.

Wnuk, C., 1989b, Diversity of Middle Pennsylvanian clastic swamp communities: 28th International Geological Congress, Abstracts, v. 3, p. 373.

Wnuk, C. and Maberry, J.O., 1990, Enigmatic eight-meter trace fossils in the Lower Pennsylvanian Lee Sandstone, Central Appalachian Basin, Tennessee, U.S.A.: Journal of Paleontology, v. 64, p. 440-450.

Wnuk, C. and Pfefferkorn, H.W. 1984, The life habits and paleoecology of Middle Pennsylvanian medullosan pteridosperms based on an *in situ* assemblage from the Bernice basin (Sullivan County, Pennsylvania, U.S.A.): Review of Paleobotany and Palynology, v. 41, p. 329-351.

Wnuk, C. and Pfefferkorn, H.W., 1987, A Pennsylvanian age terrestrial storm deposit: Using plant fossils to characterize the history and process of sediment accumulation: Jour. Sed. Pet., v. 57, p. 212-221.

Wood, G.H., Jr., Arndt, H.H., and Carter, M.D., 1969b, Systematic jointing in the western part of the Anthracite region of eastern Pennsylvania: U.S. Geological Survey Bulletin 1271-D, p. 1-17.

Wood, G.H, Jr., Arndt, H.H., and Hoskins, D.M., 1963, Geology of the southern part of the Pennsylvania anthracite region: Annual Meeting of the Geological Society of America, Field Trip Guide Book 4, U.S. and Pennsylvania Geologic Surveys, 84 p.

Wood, G.H., Jr., Arndt, H.H., Yelonsky, A., and Soren, J., 1956, Subdivision of the Pottsville Formation in Southern Anthracite field, Pennsylvania: American Association of Petroleum Geologists Bulletin, v. 40, p. 2669-2688.

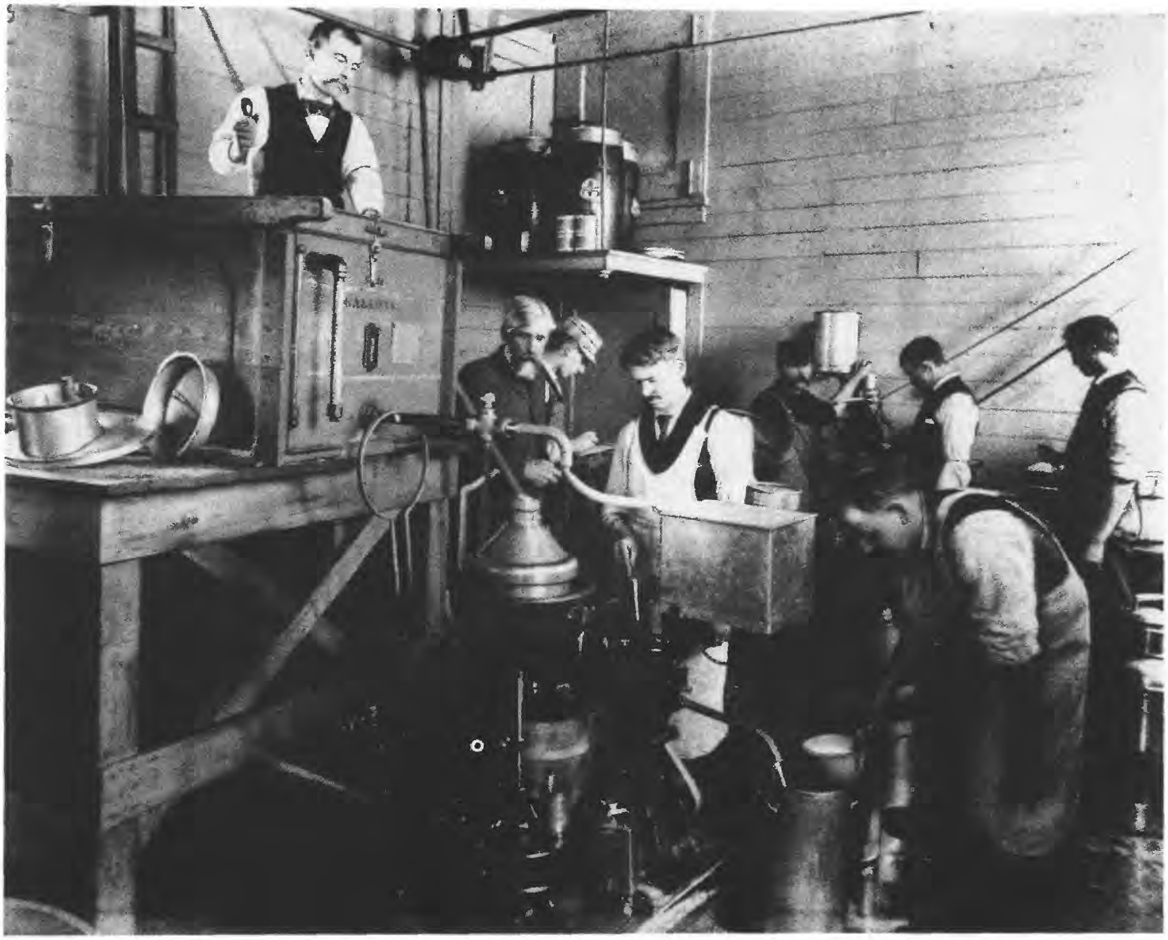
Wood, G.H., Jr. and Bergin, M.J., 1970, Structural controls of the Anthracite region, Pennsylvania, in Fisher, G.W., Pettijohn, F.J., Reed, J.C., Jr., and Weaver, K.N., eds., Studies of Appalachian tectonics - Central and Southern: New York, John Wiley Interscience, p. 161-173.

Wood, Gordon H., Jr., Trexler, J. Peter, and Arndt, Harold H., 1962, Pennsylvanian rocks of the southern part of the Anthracite region of eastern Pennsylvania: U.S. Geol Survey Prof. Paper 450-C, p. C41-C42.

Wood, Gordon H., Jr., Trexler, J. Peter, Arndt, Harold H. Yelenosky, Andy, and Soren, Julian, 1956, Subdivision of the Pottsville Formation in the Southern Anthracite field, Pennsylvania: Am. Assoc. Petroleum Geologists Bull., v. 40, No. 11, p. 2669-2688.

Wood, G.H., Jr., Trexler, J.P., and Kehn, T.M., 1969a, Geology of the west-central part of the Southern Anthracite field and adjoining areas, Pennsylvania: U.S. Geological Survey Professional Paper 602, 150 p.

Work Projects Administration, 1940, Pennsylvania - a guide to the keystone state: New York, Oxford University Press, 660 p.



The Creamery, Pennsylvania State College, photographed in 1894 (Courtesy of the George Bretz Collection, Albin O. Kuhn Library, University of Maryland, Baltimore County)

☆U.S. Government Printing Office : 1992 - 312-292/62221