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ON THE COVER

Rioarribasaurus, formerly Coelophysis, a small bipedal dinosaur that probably roamed through Pennsylvania during the Late Triassic (see article on page 2). Photograph by Claire Messimer.

PENNSYLVANIA GEOLOGY

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Near-Surface Geology—Critical to Modern Land Management Decisions

In H. G. Wells' early twentieth century fantasy novel of a trip to the moon, the reaction of moon people to the fact that earth dwellers did not know very much about the interior of their own planet was astonishment. Unfortunately, if these imaginary moon dwellers were to make contact with earth today, nearly a century later, they would be similarly astonished. For the truth is that we have limited information about the details of the near-surface geology of our earth, our nation, and our state. Perhaps it is for this reason that the nationally respected U.S. Geological Survey (USGS) is now being challenged for its lack of focus on modern geologic and topographic information applicable to human needs. Current U.S. congressional initiatives recommend abolishing or significantly reducing the USGS, U.S. Bureau of Mines, and other federal agencies that provide earth-resource information. An article on these initiatives was published in the January 1995 issue of Geotimes, the journal of the American Geological Institute. A copy of this article may be obtained by calling or writing to me.

The Association of American State Geologists, representing the state geological surveys, noted recently that only about 25 percent of our nation's land surface has been geologically mapped at a detail sufficient to meet modern information needs. In Pennsylvania, bedrock reconnaissance geologic information is available for of all of the state, but the same is not true for the extensive surficial geological materials that in most areas cover the bedrock. Addressing the surficial as well as more detailed bedrock information gaps is now the primary objective of our Pennsylvania Survey.

The task of state and federal geological surveys is to map the earth's surface and to investigate and explain the interior of our planet. By focusing on information on near-surface geological materials and processes, difficult management decisions can be made that will allow use of the earth's surface, as well as its interior, in a manner that contributes to human well-being. In my opinion, removing a credible source of such information, whose value constantly increases as we develop and use more of the earth's surface, through abolishment of the federal geologic and topographic survey, would not be in the best interest of our nation.

Donald M. Hoskins
State Geologist
THE GRATERFORD DINOSAURS:
Tracking Triassic Travelers

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Paleontologists are often asked to identify a "dinosaur bone," "dinosaur egg," or "dinosaur track." More often than not, these turn out to be nothing more than a soup bone, concretion, or some nondescript sedimentary structure, much to the chagrin of the proud discoverer. On rare occasions, these finds are scientifically significant. Such is the case with the recent discovery of dinosaur footprints at the State Correctional Institution at Graterford, Pa.

DISCOVERY. Late in 1993, inmate Wayne Covington, an amateur archaeologist and paleontologist, accidentally discovered footprints in an outcrop of the Late Triassic Lockatong Formation, which was exposed in a ravine on prison property. Personnel at The State Museum of Pennsylvania were notified of the discovery, and together with a geologist from the Pennsylvania Geological Survey, they conducted a joint field trip to assess the site.

The Graterford site consists of several rock layers that crop out in two ravines. The surfaces of these rock layers occur within a 2-meter (7-ft) sequence and contain scattered fossil footprints of various sizes. These are trace fossils, or ichnites (from the Greek ichno, meaning trace or track). The footprints are oriented in various directions, and some trace the path of a single individual. A few of the footprints are superimposed on preserved mudcracks and ripple marks. The myriad of footprints, and the extent of the locality, make it the largest dinosaur trackway site ever discovered in Pennsylvania.

Two large trackway horizons were uncovered and removed for study and conservation. The largest measured over 6 m (20 ft) long and 3 m (10 ft) wide. Prior to removal, a grid system was outlined on the bedding surface using natural subparallel fractures as a guide. In order to preserve the integrity of the trackway, each grid unit was se-
quentially numbered so that the trackway could be easily reassembled back in the museum laboratory. The sections, measuring approximately 1 m (3 ft) square and 10 to 15 cm (4 to 6 in.) deep, were cut using a portable rock saw (Figure 1). Crowbars were then used to pry up and remove the trackway sections.

HISTORY. The occurrence of dinosaur footprints in eastern North America is not new or uncommon. The first historical account of fossil footprints is credited to a young boy named Pliny Moody, who discovered a series of footprints in 1802 while plowing a field in the Connecticut River valley (Hitchcock, 1858).

When the young Moody stumbled upon these tridactyl (three-toed) tracks, dinosaurs were completely unknown to humans. In fact, the first fossilized dinosaur remains (isolated teeth) were not discovered and described until 1822, by Gideon Mantell, and the comparative anatomist Sir Richard Owen did not coin the term “Dinosauria” (which means “terrible lizard”) until 1841. The distinctive three-toed tracks, although much larger, were similar in shape to those made by modern-day birds.

Figure 1. Using a cut-off saw, sections of the trackway were cut along a marked grid and were removed and taken to the museum to be studied.
Hence, they were considered by the common folk of the time to have been made by giant “poultry” or “Noah’s Raven” (Hitchcock, 1858).

During the early and middle 1800’s, thousands of Connecticut Valley footprints were discovered and became the subject of intense study by Rev. Edward Hitchcock, who published comprehensive accounts of these fossil tracks (Hitchcock, 1836, 1858, 1865). By the middle of the nineteenth century, over 21,000 footprints had been collected from various Connecticut Valley sites and were deposited in the Appleton Cabinet (now the Pratt Museum) of Amherst College in Amherst, Mass. (Hitchcock, 1865).

Hitchcock recognized that the footprints came from strata equivalent to the Liassic (Late Triassic) and Jurassic rocks of Europe and that these units occurred discontinuously in Massachusetts, Connecticut, New Jersey, Pennsylvania, Virginia, and North Carolina (Hitchcock, 1858). Hitchcock died not knowing that many of the footmarks he studied were made by prehistoric reptiles known today as dinosaurs.

For over a century, three-toed footprints were considered to have been made by dinosaurs that walked exclusively on their hind legs (obligatory bipedal dinosaurs). It was assumed that these dinosaurs walked solely on their hind legs because no manus prints (those made by the forelimbs) had been described in association with pes prints (those made by the hind limbs). Recently, Olsen and Baird (1986) reexamined a number of footprints from the Passaic and Lockatong Formations of the Jurassic-Triassic Newark Supergroup basins of New Jersey and Pennsylvania. They noted tridactyl manus impressions associated with some of the footprints and concluded that these tracks were made by a facultative quadrupedal dinosaur (one that occasionally got down on all fours), rather than a bipedal dinosaur. These prints, which were previously named Gigandipus? (Anchisauripus) milfordensis (Bock, 1952), were reclassified and put into a new ichnogenus, Atreipus, and were considered to have been made by an ornithischian (“bird-hipped”) dinosaur rather than a saurischian (“lizard-hipped”) dinosaur (Olsen and Baird, 1986).

The morphology of the manus prints associated with some of the Atreipus pes prints seems to exclude Atreipus from the dinosaur order Saurischia, because these manus prints are characterized (in part) by having well-developed tridactyl impressions of digits II, III, and IV rather than digits I, II, and III (see the sidebar at the top of the next page on “Fingers and Toes,” and Figure 2) as would be expected with
FINGERS AND TOES. Paleontologists and biologists have devised a convenient way of referring to the fingers of the forelimb and the toes of the hind limb. Fingers and toes are called digits, and each digit is composed of bones referred to as phalanges (singular, phalanx). The proximal phalanx (the one closest to the body of the animal) articulates with a metacarpal (if in the forelimb) or metatarsal (if in the hind limb). The number of phalanges of each digit varies by digit and by species of animal (Figure 2). Digits are assigned Roman numerals. In the forelimb, digit I is the pollex (thumb); in the hind limb, digit I is the hallux (large toe in humans). The next digit (next to the thumb or large toe) is II, and so on.

Paleontologists have ascertained that the phalangeal formula for primitive reptiles is 2.3.4.5.3 (Romer, 1956). That is, there are 2 phalanges in the pollex, 3 phalanges in the next digit, and so on. In saurischian dinosaurs, digit II is the longest; in theropod dinosaurs, digit I of the forelimb is either absent or reduced, digit IV of the forelimb is reduced or absent, forelimb digit III has reduced (short) first and second phalanges, and digit IV of the hind limb is reduced. The ornithischian dinosaurs are in part characterized by a reduced digit V composed solely of a small metatarsal (no phalanx) (Benton, 1990).

Figure 2. Manus (forelimb) and pes (hind limb) of the crocodile Crocodylus (A and B) and the theropod dinosaur Allosaurus (Antrodemus) (C and D) showing digits and phalangeal formulas (colored phalanges). (After A. S. Romer, Osteology of the Reptiles, University of Chicago Press. © 1956 by the University of Chicago. All rights reserved. Published 1956. Second impression 1968. Printed in the United States of America.)

theropod (advanced saurischian) dinosaurs (Olsen and Baird, 1986). However, there are other tridactyl pes prints that occur alone. Were these tracks made by a two-legged or a four-legged beast?
Surprisingly, the evidence is inconclusive for two reasons. First, the taxonomy of tridactyl footprints is confusing because a plethora of names has been given to the various similar prints. Second, the relationships of footprints to each other, and to the animals that made them, is far from certain.

Four ichnospecies of *Atreipus* are recognized in eastern North America (Olsen and Baird, 1986) and are similar to those named *Grallator* and *Anchisauripus*, which have been considered to be members of different ichnofamilies! *Grallator*-like footprints, and those currently called *Grallator* (*Grallator*) and *Grallator* (*Anchisauripus*), are still considered to have been made by Late Triassic obligatory bipeds like the well-known saurischian dinosaur *Rioarribasaurus* (=*Coelophysis*) (Lockley, 1991). Twelve ichnogenera have been recognized in the sedimentary rocks of the Newark basin, seven of which have been reported as occurring in the Lockatong Formation (Silvestri and Szajna, 1993).

**THE GRATERFORD TRACKWAYS.** At the Graterford site, three, or possibly four, distinct footprints have been uncovered, three of which can be attributed to dinosaurs. The smallest prints, which are nondinosaurian, measure no more than 2 cm (0.8 in.) in length. They are pentadactyl (five-fingered) in form and pertain to "lizard-like" footprints called *Gwyneddichnium* or *Rhynchosauroides* (not figured). The largest of the dinosaur pes prints, some of which are associated with tridactyl manus impressions, are considered *Atreipus milfordensis* and measure 15 cm (6 in.) in length (Figure 3). A few of these large prints are not associated with manus impressions and may belong to another ichnogenus called *Grallator* (*Anchisauripus*). Owing to variations in preservation, these prints may have, in

![Figure 3. A pes print of the ichnotaxon *Atreipus milfordensis* from the Graterford site.]
Figure 4. A pes print of the ichnotaxon Coelosaurichnus sp. from the Graterford site. Its occurrence in the Lockatong Formation extends the biostratigraphic range of the footprint earlier in time.

fact, been made by dinosaurs within the same taxon.

Of particular significance is the occurrence of the tridactyl dinosaur footprint referable to Coelosaurichnus. These pes prints measure 9 to 9.5 cm (3.5 to 3.7 in.) in length and have an elongated middle toe (digit III) with a digit divarication (angle formed between two digits) of 28 degrees (Figure 4). If our identification of these prints is correct, this is the first occurrence of this ichnotaxon in the Lockatong Formation and is the oldest known occurrence of this footprint in the Newark Supergroup, based on data provided by Silvestri and Szajna (1993).

TRAVELING THE TRIASSIC TURNPIKE. What dinosaurs made these tridactyl footprints? We know that three-toed dinosaurs roamed between what is now the United States, Great Britain, and South Africa before the supercontinent of Pangaea began to break up some 220 million years ago. The skeletal remains of two relatively small and very closely related ceratosaur dinosaurs have been found on the continents of North America, Europe, and Africa. The saurischian dinosaur Rioarribasaurus is known from Late Triassic sediments of the southwestern United States. Syntarsus has been discovered in Late Triassic rocks of England and Rhodesia (Zimbabwe). It is also known from the Early Jurassic Kayenta Formation of Arizona and now appears to be present in the Late Triassic Rock Point Formation (Chinle Group) of New Mexico (Sullivan, in preparation). These dinosaurs
are believed to be responsible for some of these tracks (see cover photograph).

The interchange of vertebrate life between these distant places was certainly not an uncommon event. During the Late Triassic, Pennsylvania, the southwestern United States, and Europe were all situated near the equator (Figure 5). As in the present, southern Africa was then geographically distant, yet land connected these vastly separated regions, allowing for faunal dispersal. Perhaps these dinosaurs wandered along the equatorial corridor, leaving their footprints in Pennsylvania. They continued to do so until the vast rift that ultimately became the Atlantic Ocean prevented their wanderings.

The discovery at Graterford provides new information concerning vertebrate life during the Late Triassic of Pennsylvania. Except for the discovery of a couple of ornithischian dinosaur teeth a hundred years ago (Hunt and Lucas, 1994), and isolated footprints occasionally observed in our state, direct evidence of dinosaur life has been conspicuously absent. The search continues for skeletal remains of the elusive Pennsylvania dinosaur.

We thank Wayne "Fang" Covington and Ahmed Sabur for preparing the trackway site and for their enthusiastic support and help in
this project. Thanks are extended to Robert Larkin, who brought the
discovery to our attention; Superintendent Donald Vaughn, Deputy
Superintendent Thomas Stachelek, and their staff at the State Cor­
rectional Institution, for allowing us to collect the Graterford footprints;
and Dr. Hartmut Haubold (GeiseltalMuseum, Halle, Germany) for his
discussions and insight on ichnite identifications.

NOTE: The Graterford locality continues to be an active research
field site. Because of our ongoing research, and the fact that it is lo­
cated on state prison property, only personnel authorized by the State
Correctional Institution at Graterford are permitted on the grounds.

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COAL UNDER THE MICROSCOPE: Interpreting the Cause of Coal-Rank Change in Pennsylvania

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INTRODUCTION. A previous article by Davis (1992) dealt with aspects of coal character that were imposed at the time that plant-derived peat was laid down in swamps. The present article is concerned with the subsequent history of those bodies of peat while they were buried and subjected to the metamorphic influences of elevated temperatures and pressures over an extended period of time.

Pennsylvania is one of the world's most unique field areas in which to study the transformation undergone by coal as a result of its burial and heating within the earth's crust. Eastward across most of the state's 300-mile width, coals vary in rank from high-volatile bituminous, through medium- and low-volatile bituminous, to semianthracite and anthracite (see back cover). Geologists have studied these coals and their associated rocks in efforts to determine what geological factor or factors would have brought about such very distinct changes. This article contains a review of the substantial evolution of ideas concerning the cause of these changes in rank. Some emphasis will be placed on studies conducted at The Pennsylvania State University concerning the optical properties of coal measured under the microscope.

COAL AS A TEMPERATURE/STRESS INDICATOR. The concept of metamorphic rocks is well known. Subjected to high temperatures and pressures, limestone becomes marble, and shale becomes slate or schist. Organic matter from plants is more sensitive to temperature than most of the minerals that compose these inorganic rocks. It tends to undergo chemical transformations at lower temperatures; consequently, the sedimentary rock sequences that make up coal-bearing measures can contain a wide range of coal ranks depending on the temperatures that have been experienced. These ranks range from
lignite to anthracite. Some rare lignite occurs in Pennsylvania, but economic deposits of coal are limited to the range from bituminous to anthracite.

Any characteristic of coals that varies systematically through the rank range can be used as an index of rank. Thus, the percentage yield of volatiles when a coal is heated under prescribed conditions is an index of rank, as is the carbon content and the calorific value. Volatile matter (on a dry, ash-free basis) decreases eastward from about 43 percent at the Ohio border to about 2.5 percent in the anthracite fields.

Another index of rank is the property known as reflectance. Anthracite is much brighter in appearance than bituminous coal; this feature can be quantified very precisely using a microscope equipped with a photomultiplier to measure the amount of light reflected off the surface of the brightest bands contained in the coal. These bands, typically a few millimeters thick, are composed of a material called vitrinite, a component derived mainly from the wood and bark of plants. The reflectance of vitrinites increases progressively through the rank range of coals (Figure 1) because their molecular structures become increasingly enriched in aromatic carbon structures. An advantage of reflectance as an indicator of rank compared to chemical indices, such as the amount of volatile matter or the amount of carbon, is that the latter are substantially influenced by the kinds and proportions of plant-derived materials present in a coal, and these can vary widely. Reflectance is measured only on vitrinite and so is less dependent on that kind of variability.

Several relationships have been developed between vitrinite reflectance and the temperature and time of coalification. Such relationships serve as models, which permit the calculation of temperatures in sedimentary basins over geologic time using measured reflectances and estimates of the duration of coalification.

Reflectance measurements usually vary somewhat depending upon the orientation of the specimen on which the determination is made. This is because the molecules of vitrinite, during their growth in response to the elevated temperatures experienced during burial, tend to develop a preferred orientation in response to the directed pressures to which they are subjected. Consequently, such measurements can be used to evaluate the extent of stresses imprinted upon the coal; these include stresses arising from burial and those imposed by tectonic forces.
EARLY STUDIES. David White, a geologist with the U.S. Geological Survey (USGS), made an extensive study of coalification in fields across the United States (White and Thiessen, 1913; White, 1925). In the Appalachian fields in particular, he found conspicuous evidence of an increase in rank eastward, in the direction of greatest horizontal compression as revealed by the intensity of folding and faulting. He concluded that this supported the thrust-pressure theory of coalification, although he recognized that time was also a factor, and conceded that temperatures could also have been involved. He noted that in Pennsylvania, as in other fields, metamorphism could be greater in districts where there had been no buckling or overthrusting to diminish the intensity of the stresses.

Like White, Taisia Stadnichenko (1934) recognized that variations in climate and vegetation, and the activities of biological agents, could not have been responsible for the significant variation in coal rank.
found in Pennsylvania. She also discounted the possible role of heat because of the apparent absence of igneous batholiths, and of depth of burial because of the lack of evidence for major eastward thickening of rocks younger than the Pennsylvanian coal measures. The field evidence, she concluded, supported White's championship of the thrust-pressure theory. The highest rank coals along the Allegheny Front occur in the Windber district; Stadnichenko noted that this region is flanked to the east by an apron or buttress of older competent rocks. This buttress would have transmitted most of the full force of the compressive thrusting westward into the coal-bearing strata. To the north and south of this district, the coal measures lie opposite areas of greater folding and thrusting, the supposed effect of which was to partially neutralize the metamorphic influence of the horizontal stresses.

J. Roberts (1924) developed a theory of anthracitization based upon his studies of coals in South Wales, including laboratory experimentation. From this, he drew an analogy with the Pennsylvania field on the basis of White's descriptions and concluded that temperature was the essential metamorphic agent. He was of the opinion that the intense folding of the rocks would have contributed to the relatively high temperatures required (in the region of 550°C, or 1022°F, according to his experiments).

The refuting of the thrust-pressure theory can be attributed substantially to the work of M. and R. Teichmüller in Europe (1966). Coal rank in the European Ruhr basin is least at its southern margin, which is where folding of the beds has been most intense. Moreover, lines of equal volatile matter, which originally would have been parallel to the earth's surface, are now parallel to the folded coal seams there. Together, these observations indicate that the present pattern of rank distribution in this basin could not have been the result of the folding pressure. As for the hypothesis that shear stress or frictional heat associated with the major thrusts in tectonically active areas could have contributed to the regional pattern of coal rank, the Teichmüllers demonstrated that these factors were influential only in the immediate vicinity of the thrust planes. Frictional heat, they pointed out, is dissipated rapidly.

As a result of broad field studies, G. H. Wood and coworkers at the USGS concluded in 1969 that the general eastward attainment of anthracitic rank in the state was due to increased burial. They recognized also that the lines of coalification were parallel to the larger and even some of the smaller structural features; they considered that this
observation, and the fact that rank increased into the cores of synclines, validated White's conclusion that rank increases toward areas of greater deformation. H. Damberger (1974) of the Illinois Geological Survey, however, reached a different conclusion, noting that some of the data of Wood and his coworkers suggested that the rank trends and the coalbeds were discordant, with the younger seams in the axes of synclines having higher ranks than those on the flanks. He explained this by postulating that anthracitization had been accomplished by magmatic heating associated with the emplacement of a deep-seated intrusion during the late Paleozoic to early Mesozoic. In 1982, J. R. Levine and A. Davis offered yet another explanation for the high ranks found in the cores of synclines. They attributed the phenomenon to a purely structural cause, citing evidence for significant uplift of the coal-bearing rocks by high-angle reverse faulting in the centers of the basins.

**RECENT STUDIES EMPLOYING OPTICAL PROPERTIES.** With burial and tectonic pressures out of consideration as causes of coalification, the emphasis in Pennsylvania has shifted to clarification of whether the lateral variations in temperature necessary to create the observed distribution of rank were achieved through differential burial or heat flow.

In 1981, J. C. Hower and A. Davis employed the change in coal rank with depth in one of the coalification models referred to above. In this way, they were able to estimate the differences in coalification temperature across the stratigraphic intervals represented by vertically separated coal horizons. They calculated that the paleogeothermal gradient in Westmoreland County, close to the Ohio border, was about 33°C/km (96°F/mi), whereas that in Somerset County, close to the Allegheny Front (see back cover), had been about 40°C/km (116°F/mi). Their estimate of depth of burial across the area was about 3.5 to 4 km (2.2 to 2.5 mi). Their evidence suggested that the depth of burial was more or less uniform across the area.

In 1986, J. R. Levine argued the case for normal paleogeothermal gradients across the state and for depths of burial as much as 6 to 9 km (3.7 to 5.6 mi) in the Anthracite region. He estimated geothermal gradients in two Southern Anthracite field boreholes in a manner similar to that used by Hower and Davis; the values he determined (about 33°C/km, or 96°F/mi) are similar to those reported above for the Allegheny Plateau. In support of his conclusion, Levine cited a
study of the trend of sandstone porosities across the North-Central and Northern Anthracite coalfields by S. T. Paxton (1983); the results of this study suggested that overburden thickness could have been as much as 9 km (5.6 mi) in the Anthracite region and 3 to 6 km (1.9 to 3.7 mi) in the medium-volatile-bituminous Blossburg basin. Levine proposed that the abnormally high overburden thicknesses were due to an unusual amount of crustal downwarp; some of the overburden could have been emplaced tectonically in the form of overthrust sheets.

Recently, E. Zhang and A. Davis (1993) applied a coalification model to reflectance data measured for eight boreholes drilled by the Pennsylvania Geological Survey through the coal measures in western Pennsylvania. Their approach required reconstructing the burial and uplift histories of the coal-bearing rocks across the area to the west of the Allegheny Front. They concluded that maximum burial depth had increased from 3 to 5 km (1.9 to 3.1 mi) and that the geothermal gradient had increased from 26 to more than 33°C/km (75 to more than 96°F/mi) eastward across the study area. Already the basis of Paxton's conclusion of a massive eastward increase in burial had been called into question; the loss of sandstone porosity that he observed could have been brought about by mineralogical change in addition to physical compaction.

In explaining the increasing geothermal gradient across western Pennsylvania, Hower and Davis (1981) had suggested that heat flow did not vary progressively across the area but that there were structurally defined heat-flow provinces; within provinces, heat flow would have been more or less uniform, but the major changes in coal rank coincide with zones overlapping the province boundaries. One of the coalification regimes delineated by Zhang and Davis (1993) is centered around northern Somerset County and has an unusual concentric pattern of coalification (Figure 1). These authors postulated that the high heat flow and paleogeothermal gradients suggested by the model for this regime could have been derived in part from hot fluids originating from an eastern source and channeled upward along fractures and faults concentrated in the area. Based upon mineralogical evidence, E. J. Daniels and coworkers (1990) had already concluded that the rate of anthracitization in eastern Pennsylvania could have been accelerated by heat from upwelling fluids. The driving force for these hydrothermal fluids was Alleghanian uplift on the eastern flank of the basin.
If Zhang and Davis are correct, both depth of burial and increasing paleogeothermal gradient were responsible for the eastward increase in rank in the western part of the state. However, a conclusive explanation for the coal-rank pattern and the origin of the anthracites in Pennsylvania remains elusive.

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IN COOPERATION WITH THE U.S. GEOLOGICAL SURVEY
TOPOGRAPHIC MAPPING
GROUNDWATER-RESOURCE MAPPING
COAL DISTRIBUTION AND RANKS IN PENNSYLVANIA

(See article on page 10)

EXPLANATION

BITUMINOUS FIELDS
- High-volatile bituminous coal
- Medium-volatile bituminous coal
- Low-volatile bituminous coal

ANTHRACITE FIELDS
- Anthracite
- Semi-anthracite

Bureau of Topographic and Geologic Survey
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Address Corrections Requested