STRUCTURAL CONTROLS ON ENVIRONMENTS OF DEPOSITION, COAL QUALITY, AND RESOURCES IN THE APPALACHIAN BASIN IN KENTUCKY

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Investigations involving isopach, isopleth, and structure mapping reveal a relationship between tectonic features and the occurrence and quality of coal in the Eastern Kentucky Coal Field.

The Eastern Kentucky Syncline was the dominant factor controlling development of the Fire Clay coal bed. Lobes of thick coal are oriented perpendicular to the axis of this syncline indicating a westward-flowing drainage pattern and westward progradatiom during peat deposition. Further controls exerted by this syncline are evident from lobes of coal higher in sulfur and ash along the syncline axis and from the 36 cm (14 inch) isopach which effectively separates the thicker and continuous coal from thin and discontinuous coal. The syncline axis appears to have been the boundary between marine and fresh-water conditions during peat deposition.

Other structural features such as the Irvine-Paint Creek Fault System and the Paint Creek Upift influenced peat deposition by controlling marine conditions, fresh-wafer drainage, and topography.

INTRODUCTION

The Appalachian Basin is one of the world's largest coal-producing regions. Nearly 450 million tons of coal were produced from the Appalachian Basin in 1982, with 115.4 million tons coming from the Eastern Kentucky Coal Field. The coals of this region are predominantly bituminous in rank, and although they vary considerably in quality, low-sulfur steam and coking coals characterize the major production. Recognizing the influence of tectonic structures on the quality and distribution of these coals is fundamental to an understanding of the geology. An interpretation of the effects of structural controls on environments of deposition, coal quality, and coal resources is important for a better understanding of these vital energy resources.

Models of the environments of deposition for peat accumulation have been widely discussed (COBB *et al.*, 1981; FERM & HORNE, 1979; HORNE & FERM, 1978). The origins of sulfur and ash in coals have also been thoroughly investigated by many workers (GLUSKOTER & SIMON, 1968; RAO & GLUSKOTER, 1973; WARD, 1977; GLUSKOTER & HOPKINS, 1970; MACKOWSKY, 1968; REIDENOUER *et al.*, 1979; WILLIAMS & KEITH, 1963; CURRENS, 1981). However, the importance of structural controls upon coal-forming environments. and subsequently upon the quality and distribution of coal resources, has been discussed only in general terms. The controls of tectonics on coal in the Appalachian region have been discussed by HORNE & FERM (1978) and HANEY *et al.* (1975). The purpose of this paper is to utilize data on sulfur and ash of a selected coal bed, together with detailed regional isopleth and isopach maps and mapped tectonic structures, to interpret the controls on sedimentation and coal quality exerted by tectonic structures.

REGIONAL GEOLOGY

The Appalachian Basin in eastern North America lies to the west of the folded and faulted Valley and Ridge Province and extends from Pennsylvania to Alabama (Fig. 1). The Appalachian Basin has a maximum length of about 1,690 km (1,050 miles) and width of 400 km (250 miles). The basin is divided into the northern, central, and southern regions. This paper focuses on the Eastern Kentucky Coal Field in the central region. The Eastern Kentucky Coal Field is contiguous with coal fields of West Virginia, Virginia, and Tennessee. and together they compose the central

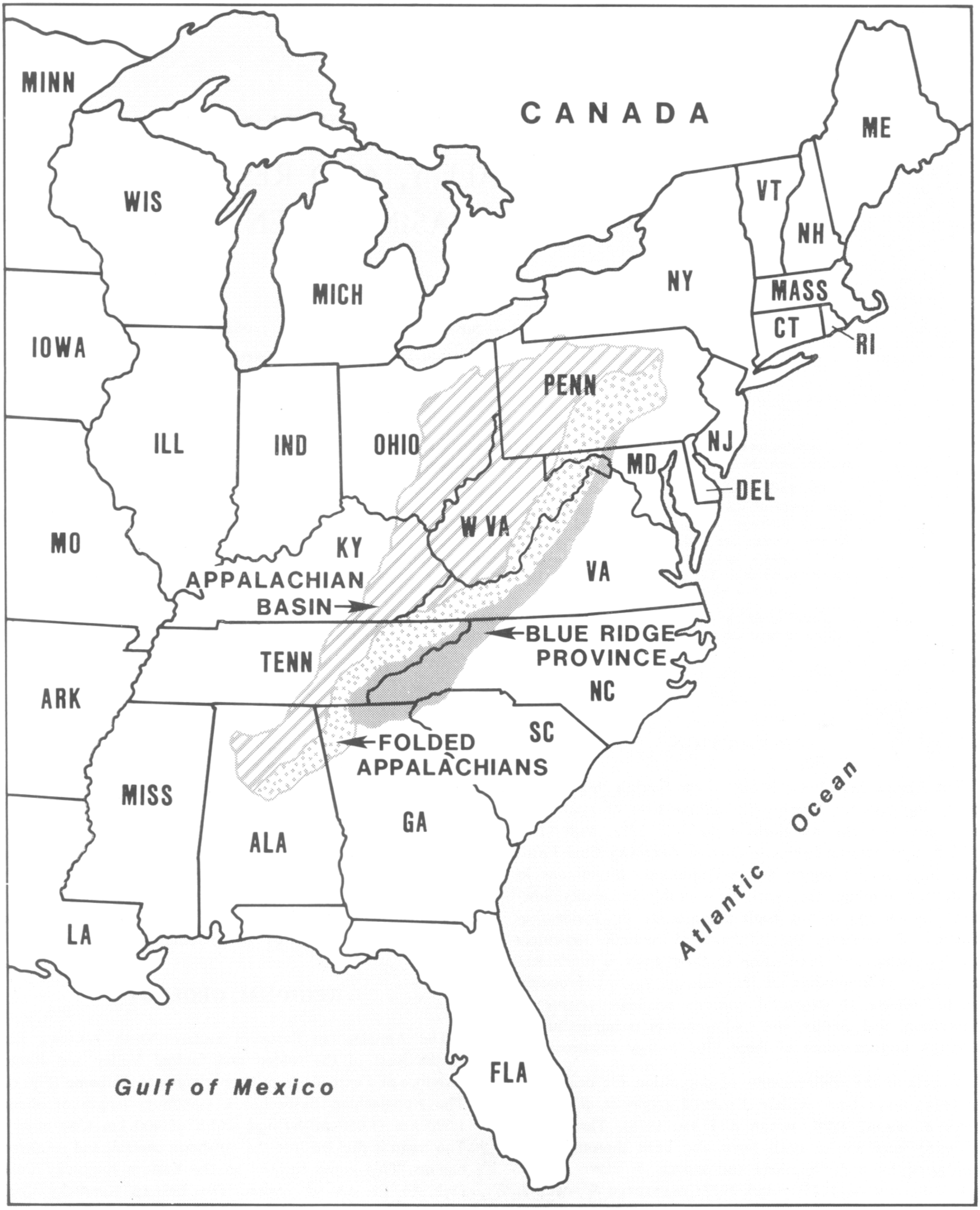

Figure 1. Location of the Appalachian Basin in North America.

region of the Appalachian Basin. Upper Carboniferous (Pennsylvanian) strata are the youngest rocks in the central region and are also the principal coal-bearing units. Therefore, many coal beds occur at or near the surface over much of the central region.

The Carboniferous strata in the central region are generally characterized as composed of marine limestones and shales in the lower part (Mississippian) separated in places by an unconformity from the progradational, clastic-dominated, deltaic deposits of the upper part (Pennsylvanian) (ETTENSOHN & CHESNUT, 1983). This Carboniferous sequence attains a maximum thickness of about 2,100 m (7,000 feet), and the coal-bearing Pennsylvanian sequence alone attains a maximum thickness of 1,400 m (4,600 feet).

Throughout the central region. the lower contact of Carboniferous strata with the subjacent Devonian rocks appears to be conformable; however, the nature of the Mississippian-Pennsylvanian boundary is the subjet of debate. Though in the past, the boundary has been considered to be an erosional unconformity (CAMPBELL, 1898; RICE *et al.*, 1979), CHESNUT (1982) and ETTENSOHN & CHESNUT (1983) state that an erosional unconformity is present throughout Kentucky but that a conformable contact exists in small areas of Virginia and West Virginia. RICE *et al.* (1979) stated that Mississippian deposition was continuous from Late Mississippian to Early Pennsylvanian time in southeastern Kentucky. HANEY *et al.* (1975) and HANEY (1979) considered the nature of the contact to be structurally controlled, stating that deposition in most places was continuous from Late Mississippian to Early Pennsylvanian time but that the boundary is unconformable in the vicinity of structural highs; progressively away from structural highs there is evidence of continuous transition from marine to nonmarine rocks across the boundary. In Alabama, the stratigraphic succession includes components of an upward transition from shallow marine to deltaic and coastal clastic sediments; thus the Mississippian-Pennsylvanian contact can be regarded as part of a depositional continuum rather than as part of a regional unconformity (THOMAS, 1979). The boundary in northwestern Pennsylvania is well defined where it is disconformable; however, elsewhere it is difficult to define, indicating a transitional-conformable sequence except where influenced by uplift which caused erosion (EDMUNDS *et al.,* 1979).

MAJOR STRUCTURAL FEATURES

The major structural features of the Eastern Kentucky Coal Field are the Allegheny Synclinorium, the Irvine-Paint Creek Fault System, the Paintsville-Warfield Anticline, the Eastern Kentucky Syncline, and the Pine Mountain Thrust Fault (Fig. 2).

'The Allegheny Synclinorium is a large basin extending from Kentucky to Pennsylvania. It contains the youngest Pennsylvanian-age coals in the central region of the Appalachian Basin.

The Irvine-Paint Creek Fault System is an east-west trending zone of folds and faults which includes the Paintsville-Warfield Anticline, the Walbridge Fault, Johnson Creek Fault, Paint Creek Uplift, and others. The faults are normal and are generally downthrown to the south. This system can be traced across the Eastern Kentucky Coal Field. Distinct differences in Pennsylvanian deposits in the vicinity of this fault system were noted by WANLESS (1939). Pennsylvanian-age rocks are generally thicker south of this fault system.

The Eastern Kentucky Syncline was first described by MCFARLAN (1943). It is a broad synclinal feature trending southwest to northeast in the southern part of the area and more nearly east-west in the northern part. This syncline dies out to the south but is divided into eastern and western basins. The western basin is interrupted by the Rockcastle Uplift on the west. The eastern basin contains the most significant coal resources.

The Pine Mountain Fault is a thrust fault about 193 km (125 miles) long with several miles of horizontal displacement along two nearly vertical strike-slip faults bounding the thrust sheet at both ends (MCFARLAN, 1943). The position of rocks along the Pine Mountain Fault before thrusting took place is shown by a dashed line on Figure 2.

The Pine Mountain Fault and Allegheny Synclinorium probably only affected sedimentation during Alleghenian time (Late Pennsylvanian), but the other structural features discussed could have affected sedimentation during all or part of the Pennsylvanian Period.

These folds and faults are related to orogeny and are therefore tectonic in origin (WHEELER, 1978; RAST, 1983). These tectonic movements are probably the result of a collision between the North American and African continents (RAST, 1983; BAMBACH *et al.*, 1980). It has been surmised that the Avalonian (Acadian) continental fragment may have intervened between the colliding plates and created a highland source area for Upper Carboniferous sediments deposited in the central region of the Appalachian Basin. The Upper Carboniferous coal beds, therefore, would have resulted from the temporary isostacy achieved by contemporaneous interactions of structural movements, progradation, and peat accumulation, and subsequent preservation by deep burial due to subsidence of the Appalachian Basin.

GENERAL COAL GEOLOGY

The coal-bearing Middle Pennsylvanian rocks of the central region of the Appalachian Basin consist of numerous fining-upward, fluvial, point-bar-type deposits alternating irregularly with coarsening-upward, marine, bay-fill-type deposits. Figure 3 shows the generalized geologic column for the Pennsylvanian rocks of eastern Kentucky. The Fire Clay coal bed was selected in this study to characterize the impacts of tectonic structures on coal development. The Middle Pennsylvanian coals were formed in a variety of

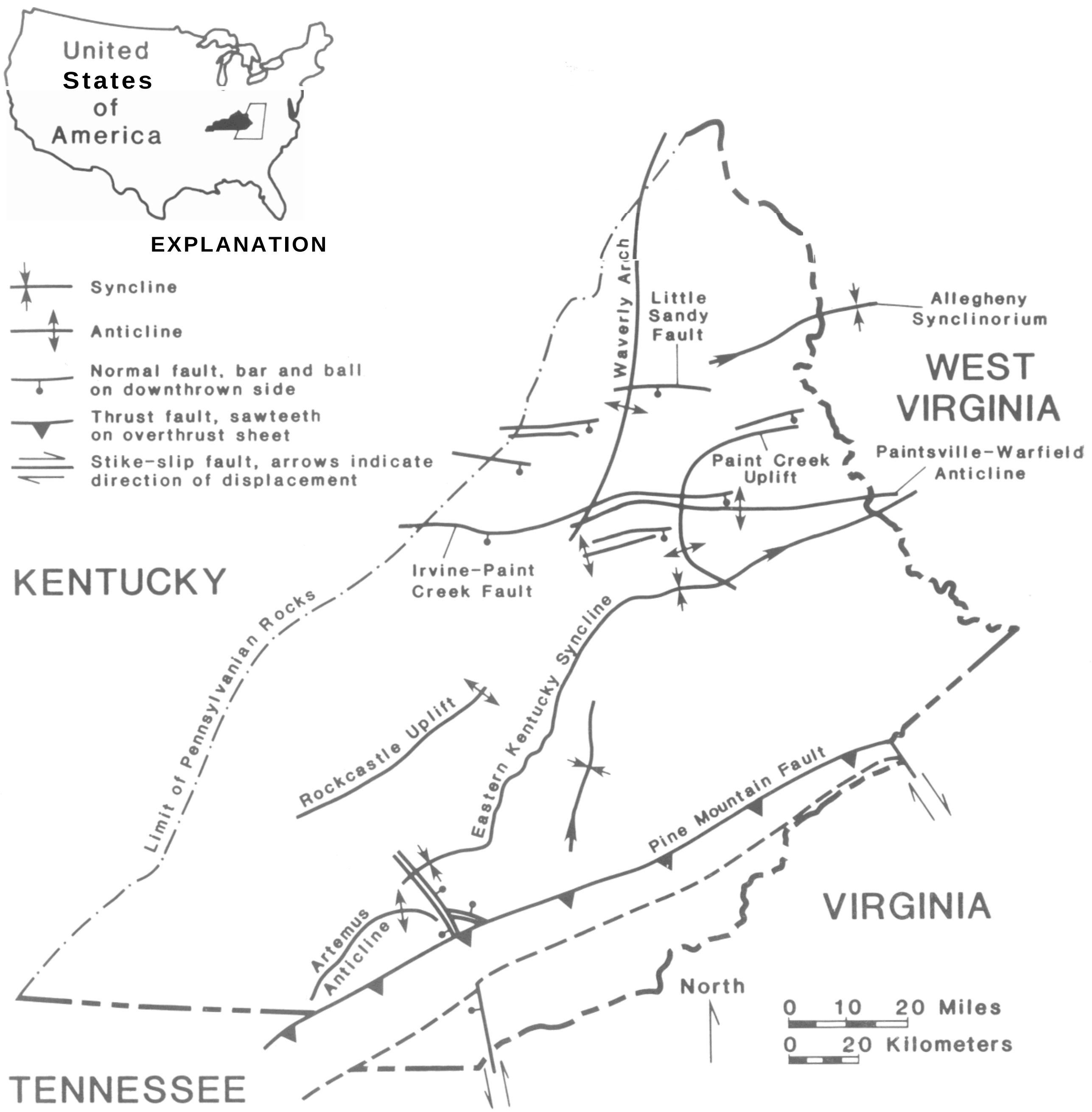

Figure 2. Tectonic structures in the Eastern Kentucky Coal Field, with palinspastic reconstruction of the Pine Mountain Overthrust Fault.

fluvial and deltaic-type environments in a prograding system whose source was generally to the east. The coal-forming environments have been broadly characterized as upper and lower delta plain (FERM *et al.*, 1979). In this paper coal-forming environments such as salt marsh, poorly-drained swamp, and well-drained swamp (ROBERTS *et al.*, 1981) are used to explain differences in coal quality and thickness.

STRUCTURAL CONTROLS ON COAL THICKNESS

The Fire Clay coal (also named the Hazard No. 4 coal) of the Eastern Kentucky Coal Field is one of the most extensive coal beds in the central region of the Appalachian Basin. Field identification, correlation, and coal-bed mapping are aided by the occurrence of distinctive flint clay

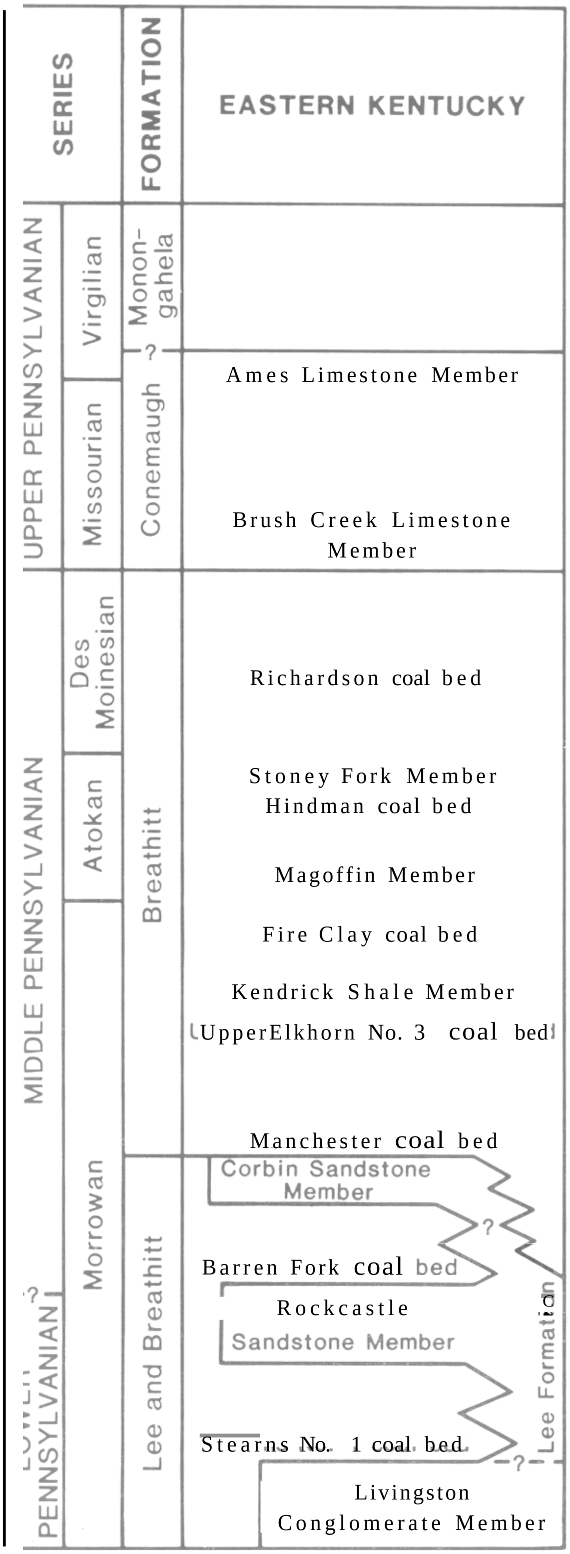

Figure 3. Generalized stratigraphic column for the Eastern Kentucky Coal Field.

parting of volcanic origin (CHESNUT, 1983) in the coal bed. An isopach map based on 3,500 thickness measurements (Fig. 4) shows the regional distribution of this coal bed in the Eastern Kentucky Coal Field. Comparison of the geometry of Fire Clay coal isopachs with mapped structural features reveals close relationships between tectonic structures and the distribution of this coal bed.

The thickest and most continuous occurrence of Fire Clay coal is east of the axis of the Eastern Kentucky Syncline (Fig. 4). The irregular isopach of 36 cm (14 inches) coal, an arbitrary boundary between thin, discontinuous coal and thicker, continuous coal, generally coincides with the axis of the Eastern Kentucky Syncline. The thickest coal in this area, however, occurs in elongated lobes that trend east-west, perpendicular to the syncline axis, and protrude in places across the axis of the syncline. The larger protrusions extend from a minor syncline just east of the major Eastern Kentucky Syncline. The Eastern Kentucky Syncline, especially the eastern flank, was therefore a major structural factor in the formation of the coal bed.

Conversely, the Fire Clay coal is thin or absent on the western side of the Eastern Kentucky Synclinc except for the lobes of thicker coal which protrude across the axis from the eastern flank The existence of the Rockcastle Uplift (Fig. 4) may have contributed to the lack of substantial Fire Clay coal dcvelapment on the western flank of the syncline.

North of the Eastern Kentucky Syncline, thicker coal exists in a large lobe centered over the Paintsville-Warfield Anticline (Fig. 4). The thickest coal in this area is restricted to isolated patches along the downthrown side of the Irvine-Paint Creek Fault. However, the central part of this area, at the intersection of two structural highs, the Paint Creek Uplift and the Paintsville-Warfield Anticline (Fig. 4), contains only thin coal. In this area, faulting appears to have been the major factor related to thick coal development. Moderately thick coal deposits developed along the Paintsville-Warfield Anticline, but the combined effects of intersecting structural highs inhibited Fire Clay coal development in some areas.

The Fire Clay coal is thin to absent in the vicinity of the Irvine-Paint Creek Fault System especially on the upthrown side of faults. The faults of this system have normal displacement and are generally downthrown to the south. Several isolated patches of thicker coal occur north of the Little Sandy Fault.

STRUCTURAL CONTROLS ON COAL QUALITY

The ash and sulfur content of a coal determine to a very large extent the market value of the coal as a fuel. Both of these coal-quality parameters relate directly to the environment in which the peat accumulated prior to burial and coalification.

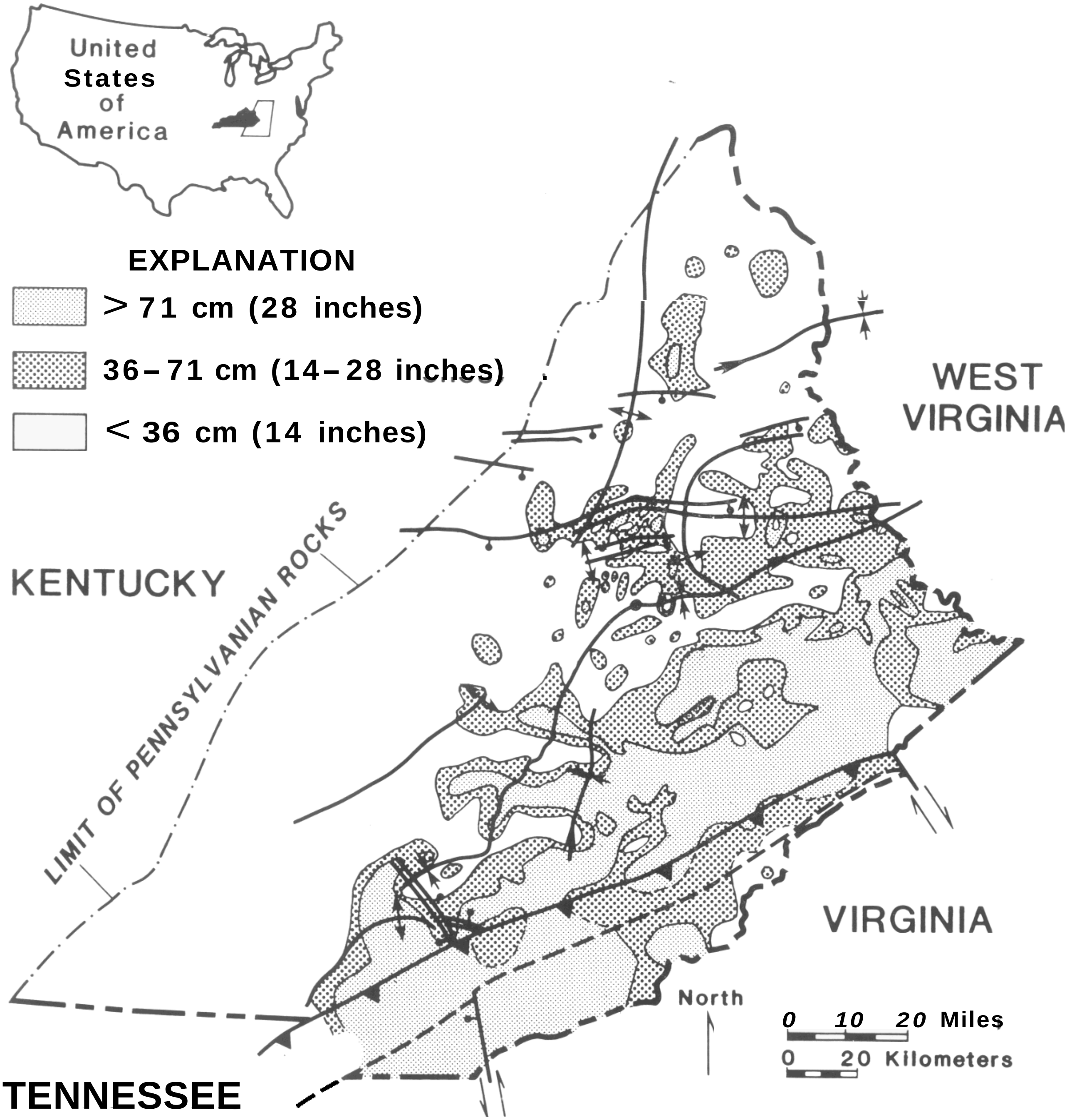

Figure 4. lsopach map of the Fire Clay coal bed in the Eastern Kentucky Coal Field

The total sulfur content of the Fire Clay coal ranges from 0.7 to 3.2 percent and has a mean value of 1.1. percent (dry, ash free). The organic sulfur of this coal ranges from 0.6 to 1.4 percent and has a mean of 0.7 percent (dry, ash free). The pyritic sulfur content ranges from 0.2 to 2.1 percent and has a mean of 0.3 percent (dry, ash free). The variation in sulfur content in the Fire Clay coal is principally due to the pyritic sulfur which resulted from sulfate available from marine or brackish water during peat deposition. Therefore, elevated total sulfur in the Fire Clay coal is an indication of marine incursions into the environment of peat deposition,

The ash content of the Fire Clay coal ranges from 2.5 percent to nearly 30 percent with a mean value of

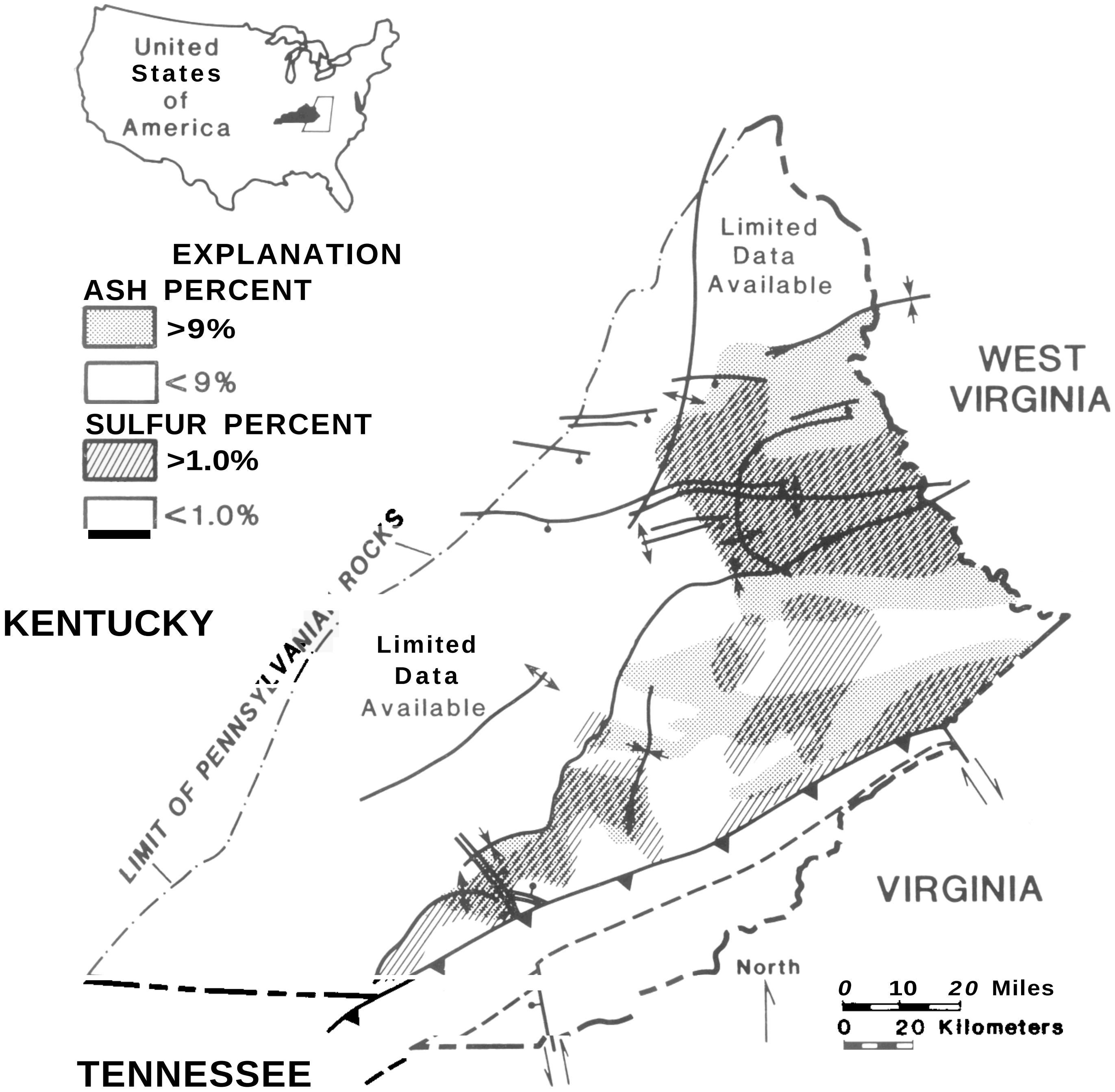

Figure 5. Isopleth map showing percentages of ash and sulfur in the Fire Clay coal bed in the Eastern Kentucky Coal Field.

percent (dry basis). The ash content of the Fire Clay is chiefly attributed to an influx of detritus into the peat. The ash content shown in Figure 5 is based upon ASTM channel samples (ASTM, 1981) where all impurities 9.5 mm (3/8 inch) or larger are removed during sampling in order to better characterize the coal itself and to avoid overly influencing the results by sampling mineral partings and larger concretions. The results for ash content reported here reflect the envionment of peat accumulation and the effect of sedimentary processes on that environment.

Figure 5 shows the distribution of sulfur and ash in the Fire Clay coal. The areas of highest ash and sulfur coincide very well and occur in lobes with undulate margins along the axis of the Eastern Kentucky Syncline and in a large

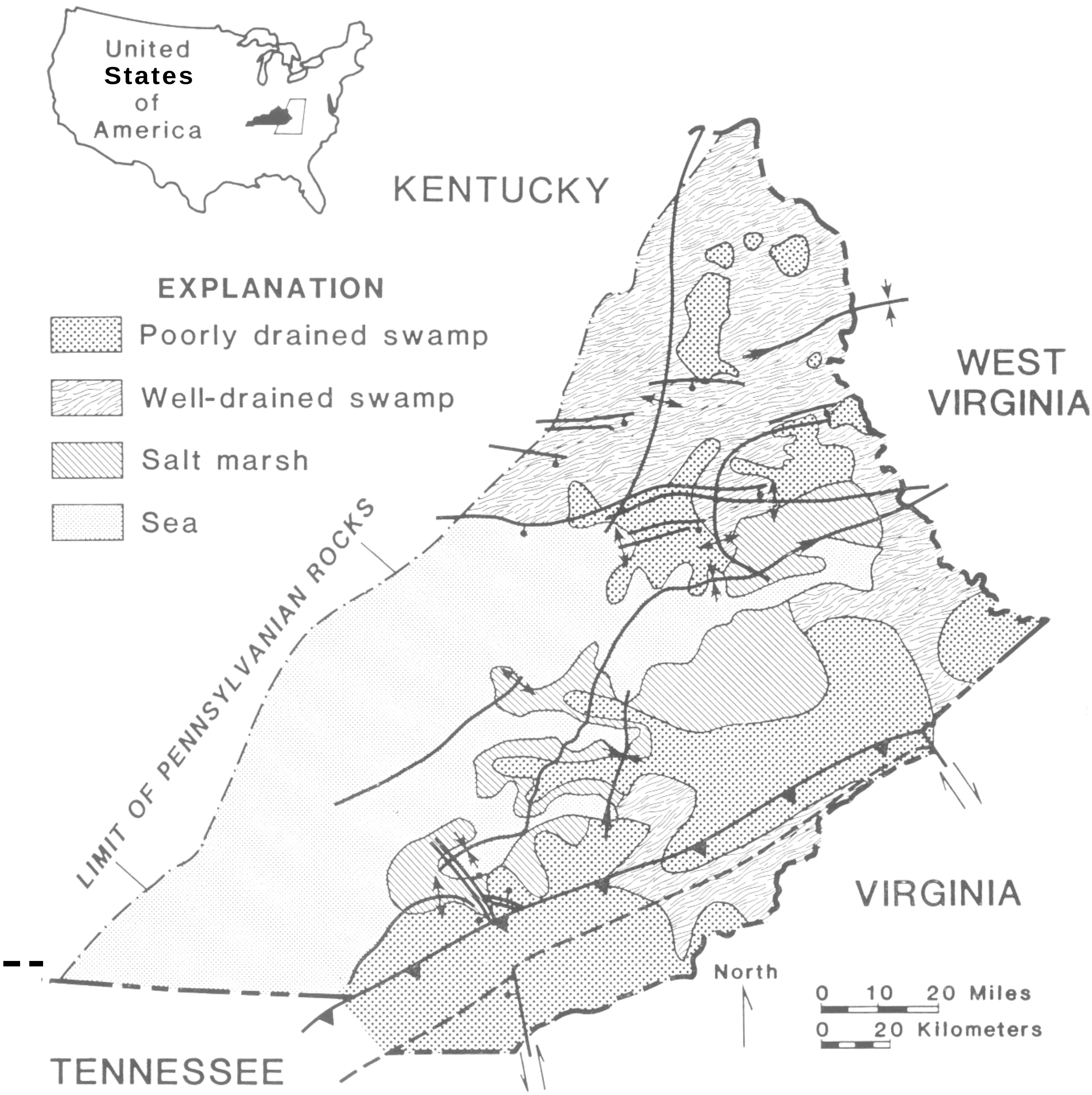

Figure 6. Inferred environments of peat deposition for the Fire Clay coal bed in the Eastern Kentucky Coal Field

lobe centered around the Paintsville-Warfield Anticline. The areas of highest ash and sulfur overlap very little with areas of thickest and most continuous coal. Rather these high-sulfur/high-ash areas extend along the axis of the Eastern Kentucky Syncline where the coal thins, occur along the Paintsville-Warfield Anticline, and are present in an area of particularly high ash which occupies most of the Irvine-Paint Creek faulted area (Fig. 5). Conversely, the areas of low ash and sulfur coincide very well with areas of thickest coal. Therefore, the distribution of sulfur and ash relates closely to the same tectonic features that controlled coal thickness.

STRUCTURAL CONTROLS ON ENVIRONMENTS OF PEAT DEPOSITION

Figure 6 is a reconstruction of the generalized environments of deposition for the Fire Clay peat This truction is inferred from the ash, sulfur, and thickness characteristics of the Fire Clay coal. The environments of peat deposition recognized in this reconstruction are (1) poorly drained swamp, (2) well-drained swamp, (3) salt marsh, and (4) marine. Their inferred characteristics are as follows.

Poorly Drained Swamp.-This environment is characterized by very high peat accumulation and preservation, very low detrital influx, and very limited or no marine influence.

Well-Drained Swamp.-This environment is characterized by moderate peat accumulation and preservation, moderate detrital influx, and very limited marine influence.

Salt Marsh.-This environment is characterized by moderate to low peat accumulation, moderate to high detrital influx, and moderate to high marine influence.

Marine.-This environment is dominated by marine conditions and has very little peat accumulation.

These depositional environments for Fire Clay peat deposition correspond closely to the major structural features (Fig. 6). A coal bed as extensive as the Fire Clay developed in a variety of contiguous environments. The relationships between paleogeography and the major structural features show the influences exerted by the different structural features upon river drainage, position of the most favorable swamp environments, and position of the marine-influenced environments.

DISCUSSION AND CONCLUSIONS

From an economic standpoint the Fire Clay (Hazard No. 4) coal bed is one of the most important in the Eastern Kentucky Coal Field. Nearly 15 million tons of this coal are mined annually, and remaining resources are over 8 billion tons. The Fire Clay coal is an extremely valuable resource not only because of its large remaining resources but also because of its high quality. The average heating value of the Fire Clay is 14,850 Btu per pound (dry, ash free). It has a mean total sulfur content of 1.1 percent (dry, ash free) and a mean ash content of 8.6 percent (dry basis).

Significant variations in quality and thickness do occur in the Fire Clay coal, and relationships between recently completed coal isopach and quality maps and mapped structural features can be used to explain these variations. These variations are attributed to the influences exerted by tectonic structures on the environments of peat deposition of the Fire Clay coal. Recognizing the structural controls on quality and quantity of Fire Clay resources results in a predictive tool for exploration of reserves and a methodology to be applied to other coals. As coals of increasingly higher quality are sought to meet new stricter government regulations on coal usage, then approaches similar to this one will help in identifying resources that comply with these standards.

The Eastern Kentucky Syncline was the dominant control for favorable Fire Clay coal development. A broad coastal area containing extensive swamps and river systems developed on the eastern flank of the Eastern Kentucky Syncline. The thickest coal, in lobes greater than 108 cm (32 inches) in this area, is low in sulfur and ash, suggesting poorly drained swamps isolated from both clastic sedimentation and marine influences. These lobes are oriented perpendicular to the axis of the syncline indicating the existence of a paleoslope parallel to the dip of the syncline and, therefore, tectonically controlled.

The axis of the Eastern Kentucky Syncline divides the area of thin or absent coal from the thickest coal occurrences. Also the highest sulfur and ash occur in the thinner coal along this axis, demonstrating increased sedimentation and marine influences. This relationship suggests a tectonic control for the position of the margin of the marine environment during peat accumulation.

The intersection of the Paintsville-Warfield Anticline and the Paint Creek uplift may have been an area too high topographically in relation to adjacent land to allow peat accumulation and preservation.

The Irvine-Paint Creek Fault System controlled Fire Clay peat deposition because thicker patches of coal in this area are restricted to the downthrown side of faults. Where thin coal exists along this fault system, the coal is low in sulfur and high in ash, indicating peat accumulation in well-drained swamps with active fluvial processes. This fault system is the northernmost boundary of the highest quality Fire Clay coal.

The quality and thickness of the Fire Clay coal were controlled by tectonic features which existed at the time of peat deposition. The Fire Clay coal bed developed in a paleogeographic setting composed of contemporaneous environments such as marine, salt marsh, poorly drained swamp, and well-drained swamp. The relationship of these environments was determined by tectonic movements on gentle synclines, anticlines, and faults, progradation from east to west, and drainage consistent with progradation.

Specific findings about the development of the Fire Clay coal are summarized below.

1. The same tectonic features controlled both coal thickness and coal quality.
2. A paleoslope perpendicular to the axis of the Eastern Kentucky Syncline is inferred from coal-isopach geometry and indicates topographic control by the syncline.
3. The orientation of lobes of thick coal is consistent with progradation across the Eastern Kentucky Syncline from east to west.
4. The axis of the Eastern Kentucky Syncline is the approximate boundary between marine and nonmarine environments.
5. The intersection of structural highs inhibited the development of coal.

6. Normal faulting along the Irvine-Paint Creek Fault System resulted in isolated patches of coal restricted to the downthrown sides of faults.

ACKNOWLEDGMENTS

The authors wish to thank RUSSELL A. BRANT, Principal Investigator for the Eastern Kentucky Coal Resources Project. The authors are grateful to the U. S. Geological Survey for providing the sulfur and ash data and support for the coal-quality mapping under U. S. Department of the Interior Grant 14-08-0001-A-0077, Mr. FRED SIMON Project Liaison Officer. The authors are indebted to ROGER POTTS and RICHARD SMATH for preparation of illustrations, to DONALD HUTCHESON for editing the manuscript, and to NORMA REYNOLDS for typing the manuscript.

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