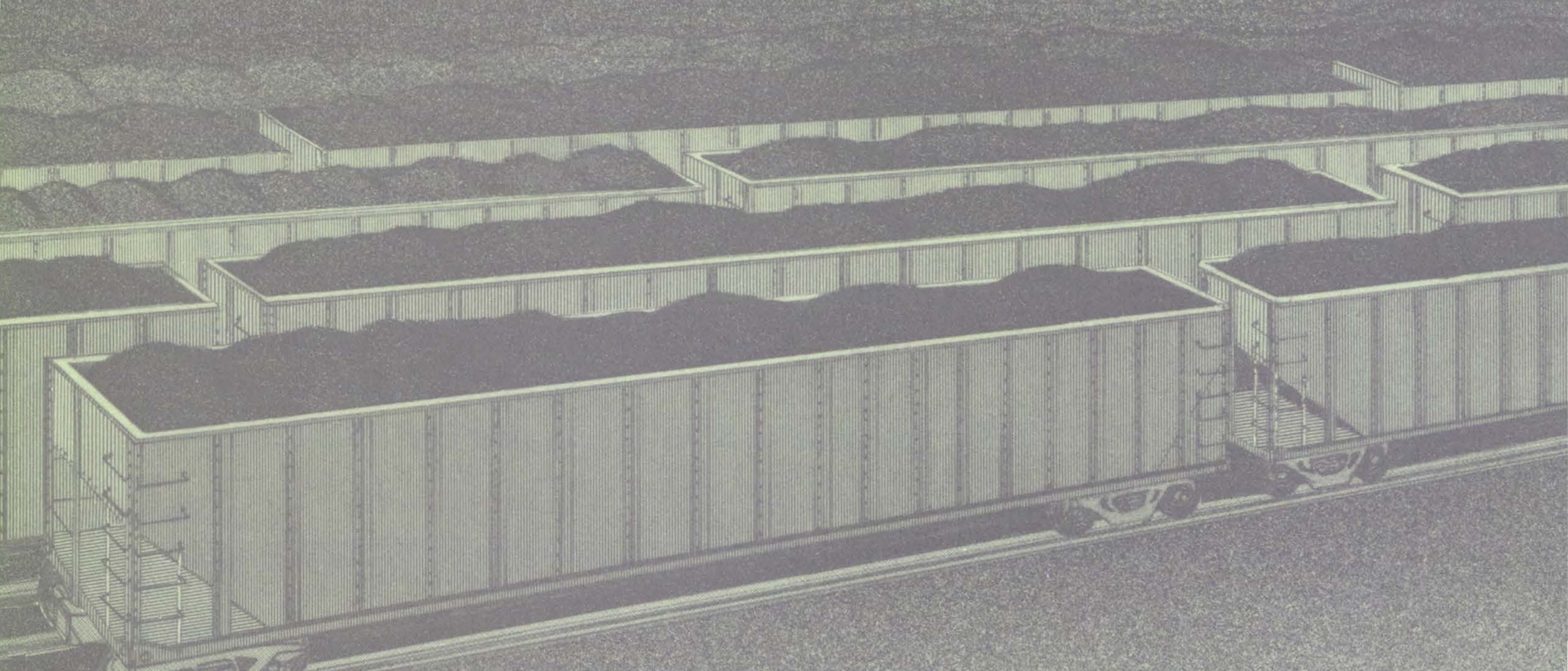
Report of Investigations No. 136

ESTIMATION OF COAL RESOURCES IN TEXAS GULF COAST, OHIO NORTHERN APPALACHIAN, AND WYOMING POWDER RIVER BASINS: A Comparison of Statistical Approaches

by
Susan J. Tewalt, Mary A. Bauer, David Mathew, M. P. Roberts, W. B. Ayers, Jr., J. W. Barnes, and W. R. Kaiser



BUREAU OF ECONOMIC GEOLOGY • W. L. FISHER, DIRECTOR
The University of Texas at Austin, Austin, Texas 78712
1983

TEXAS ENERGY AND NATURAL RESOURCES ADVISORY COUNCIL
for
ELECTRIC POWER RESEARCH INSTITUTE

ESTIMATION OF UNCERTAINTY IN COAL RESOURCES

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ABSTRACT

Official estimates of United States coal resources published during the past 15 years vary from less than 1.5 to 3.5 trillion metric tons (1.7 to 3.9 trillion short tons). These differences imply that a high degree of uncertainty exists in resource assessment. This report identifies sources of uncertainty in coal resource estimation.

Our report focuses on the comparison of variability in coal resource estimates in areas of different ancient depositional environments. The Texas Gulf Coast Basin was chosen for this study because it exhibits a full range of ancient depositional environments: (1) upper alluvial plain, (2) lower alluvial/upper delta plain, (3) delta plain, and (4) strandplain/lagoonal. Four lignite deposits, each representing one of these depositional environments, were evaluated.

Important sources of uncertainty in resource estimation include variability of seam thickness, areal distribution, and the number of seams. To test the degree of uncertainty caused by variations in seam thickness, the numbers of boreholes considered in each lignite deposit are reduced and resources calculated for each reduction in data. Various techniques of resource calculation (manual, computer, and geostatistical) are used to investigate the uncertainties associated with each method. Classical statistics is the method used to determine the number of boreholes required to obtain resource estimates of individual seams within a given confidence interval under specified conditions; geostatistical methods (variograms and kriging) are used to measure variability in resource estimates.

Classical statistical methods show that the minimum number of evenly distributed boreholes required to characterize resources of a lignite seam to within a precision of 20 percent is substantially less than might be expected intuitively and depends on the coefficient of variation of seam thickness. Geostatistical methods indicate that a substantial further reduction in the minimum number of boreholes is possible when a spatial dependency structure can be established by means of a variogram. Resource figures for seams calculated by manual, computer, and geostatistical methods at various levels of data density are well within those predicted by classical statistical theory. These studies demonstrate that the maximum seam thickness variation occurs at the margins of lignite seams and that variations in thickness of individual lignite seams are not a major source of uncertainty in resource estimation, given the level of data usually available. However, determination of the areal extent and seam boundaries of coal beds is a major source of uncertainty.

Data availability for regional-scale resource analysis nullifies seam-by-seam (deposit) methodologies. Our regional test area was the Wilcox Group outcrop in east-central Texas. Geostatistics did not yield a dependency structure for the entire area, therefore alternate methods were used: (1) equal weighting over the entire area; (2) equal weighting within grid cells; and (3) equal weighting within internally homogeneous blocks chosen using statistical or geologic parameters. Our methodology was successfully transferred to the Tongue River Member, Wyoming, and the Allegheny Formation, Ohio. Tonnages calculated for Wyoming and Ohio exceeded official estimates because we included deep-basin, thick continuous coals.

Depositional models were used to calculate resources for the entire Gulf Coast. Calculated resources indicate the magnitude of total resources, but do not quantitatively measure the associated uncertainty.

INTRODUCTION

The magnitude of coal resources in the United States is a disputed figure. The World Power Conference's 1968 survey (Fettweis, 1979) listed U.S. coal resources at 1.5 trillion metric tons (1.7 trillion short tons). McKelvey (1972) referred to resource estimates of 3.0 trillion metric tons (3.3 trillion short tons), whereas the U. S. Geological Survey (Averitt, 1974) considered coal resources of the United States to be 3.5 trillion metric tons (3.9 trillion short tons). These discrepancies imply that a high degree of uncertainty exists in resource assessment. The goal of this project is to identify sources of uncertainty in coal resource estimation. The research described in this report identified sources of this uncertainty based on the detailed analyses of four lignite deposits. This research is the initial part of a project in the Electric Power Research Institute's (EPRI) Supply Program to assess the costs and conditions affecting the future availability of coal in the United States.

Uncertainties are associated with almost every aspect of resource estimation. The first prerequisite for any resource estimation entails an awareness of the uncertainties involved and the possible implications of these uncertainties. For example:

- Is the sampling method suitable?
- Is the drilling depth sufficient?
- Are the density and pattern of drilling adequate?
- How reliable are outlines of coal versus no-coal areas?
- Are the geological characteristics (seam thickness and continuity) understood?
- How accurate is the final resource estimate?
- Is the resource estimate transferable to reserves and eventually to supply models?

Uncertainties can be categorized as geologic and nongeologic (institutional). Geologic uncertainties can be defined as those resulting from variation of the natural depositional system. For example, seam thickness and seam continuity are features controlled by specific geologic processes. Institutional uncertainties, on the other hand, comprise all those uncertainties associated with resource evaluations that are imposed on the data by economic, social, legal, or technical constraints. Institutional uncertainties are common to all resource estimations, irrespective of the geologic setting.

It is the contention of this study that geologic uncertainty is mainly a function of the depositional history of ancient coal environments. For example, alluvial plain coals are more variable in thickness and less laterally extensive than delta plain coals and are thus more difficult to characterize as to resources (that is, they require more data).

This study focuses on the comparison of variability in coal resource estimates in areas of different ancient depositional environments. This comparison is based on geological, chemical, and statistical analyses of the available lignite data in the Tertiary of the Texas Gulf Coast Basin. The Texas Gulf Coast Basin was chosen because it exhibits a full range of ancient lignite depositional environments: (1) upper alluvial plain, (2) lower alluvial/upper delta plain, (3) delta plain, and (4) strandplain/lagoonal. Four lignite deposits, each representing one of these depositional environments, were evaluated: (1) Wilcox Group of East Texas, (2) Wilcox Group of east-central Texas, (3) Jackson Group of East Texas, and (4) Jackson Group of South Texas. A detailed geologic evaluation is presented for each lignite deposit.

This report is a natural extension of past research on ancient depositional environments of Texas lignite conducted by the Bureau of Economic Geology. Through these efforts a regional depositional model for the lignite-bearing units has been developed (Kaiser and others, 1978; Kaiser and others, 1980). The more detailed analyses undertaken in this study have permitted testing and modification of the depositional models. What has emerged is a better understanding of three-dimensional depositional models, particularly the importance of thickness and continuity of individual lignite seams. A computer data storage and retrieval system was developed for rapid statistical analyses, mapping, and resource calculations. Statistics (classical and Matheronian geostatistics) were used to measure variability in resource estimates at the deposit level for individual lignite seams.

This report discusses data in terms of their contribution to the uncertainty in evaluating resources. A discussion of the regional geologic setting of the Texas Gulf Coast Basin precedes a detailed geological investigation of the four lignite deposits. Various methods of resource estimation and statistical and geostatistical analyses are undertaken to characterize variability in coal resource estimation.

DATA USED IN RESOURCE ESTIMATIONS AND THEIR UNCERTAINTIES

Since institutional uncertainties are common to all resource estimations irrespective of the geologic setting, it is important to identify the uncertainties associated with a variety of data types. In this study, different data types were utilized, including driller's logs, geophysical logs, mine maps and exposures, and coal analyses. Table 1 summarizes the institutional uncertainties arising from these various types of data.

Certain social, economic, and legal constraints limit the availability of data and are sources of institutional uncertainties in regional resource estimations. In some cases data are unavailable in a particular area because no exploration was initiated for possible economic reasons. Drilling is not undertaken for legal reasons on some Federal lands, such as national forests and military bases; state-owned lands, consisting of parks and recreation areas; or in residential areas, cemeteries, and so on. Frequently surface features preclude drilling; for example, potentially productive acreages of Texas are overlain by lakes and reservoirs.

Limited borehole information on lignite exists in the public sector, but proprietary data presented in public reports are usually protected by generalizations, particularly by schematic representations. Adequate industry data do exist, but are unavailable to the public for proprietary reasons. This unavailability can put serious constraints on public resource evaluation. The restricted nature of the data and the reluctance of industry to reveal these data cannot be overemphasized as a major impediment to data acquisition. Hence, proprietary data contribute enormously to uncertainties in public resource estimation.

In summary, institutional uncertainties are artifacts of a sampling program and are, therefore, unique to that program. Institutional uncertainties can be minimized to some extent by well-planned and carefully monitored sampling programs. Resource estimates in the public sector, as in this study, are based upon data that are not homogeneous. For example, in this report the sampling programs were carried out by different companies with different objectives and different equipment.

Table 1. Institutional uncertainties.

DATA TYPE	SOURCES OF UNCERTAINTY IN RESOURCE ESTIMATION
Driller's logs	Insufficient drilling depth
Wash boring descriptions	Mixing of rock cuttings resulting in inaccurate lithologies, thicknesses, and depths
Core descriptions	Poor core recovery, lack of expertise in lithologic descriptions
Geophysical logs	Malfunction of logging tools Logging speed Insufficient drilling depth Misinterpretation of log for lithologies and thicknesses Choice of log suites
Mine maps and rock exposures	Inaccuracies in thickness measurements
Coal quality analyses	Improper sampling and analyzing procedures Inaccurate specific gravity determinations* (reflected in tonnage conversion factor)

*Specific gravities for Texas Wilcox lignite range from 1.21 to 1.62. Conversion factors for these figures are 1,644 and 2,201 short tons/acre ft. For a 44,000-acre area with a seam thickness of 1 m (3 ft), a conversion factor of 1644 yields 197,280,000 short tons while a factor of 2201 yields 216,480,000 short tons.

GEOLOGIC INVESTIGATIONS

Geologic Setting

Texas lignite occurs in three Eocene (lower Tertiary) geologic units—the Wilcox Group, the Jackson Group, and the Yegua Formation (table 2). These units crop out as narrow belts that parallel the Gulf Coast in the inner Texas Coastal Plain. The Wilcox Group also crops out as a semicircular area around the Sabine Uplift of East Texas (fig. 1). The units extend deep into the subsurface, dipping 1 degree to 2 degrees gulfward until, for example, the Wilcox is 3,048 m (10,000 ft) or more below the surface at Houston. The Wilcox and Jackson Groups are the most important lignite-bearing geologic units; therefore, they are emphasized in this report. Only those geographic regions pertaining to the four lignite deposits are included in the discussion of geologic setting.

Table 2. Stratigraphic occurrence of Texas lignites.

<table>
<tr><td rowspan="2">OLIGOCENE</td><td colspan="2">North of
Colorado River</td><td>South of
Colorado River</td></tr>
<tr><td colspan="3">Catahoula Formation</td></tr>
<tr><td rowspan="4">EOCENE SERIES</td><td>Jackson Group</td><td>Whitsett Formation
Manning Formation[a]
Wellborn Formation
Caddell Formation</td><td>lower Jackson[a]</td></tr>
<tr><td>Claiborne Group</td><td>Yegua Formation[a]
Cook Mountain Formation
Stone City Formation
Sparta Formation
Weches Formation
Queen City Formation
Reklaw Formation
Carrizo Formation</td><td>upper Yegua[a]

Laredo Formation

El Pico Clay
Bigford Formation</td></tr>
<tr><td>Wilcox Group[a]</td><td>Calvert Bluff Formation[a]
Simsboro Formation
Hooper Formation or
undivided Wilcox[a]</td><td>lower Wilcox[a]</td></tr>
<tr><td></td><td colspan="2">Midway Group</td></tr>
</table>

[a]Principal lignite-bearing units.

Wilcox Group

The Wilcox Group between the Colorado and Trinity Rivers (fig. 1) ranges from 370 to 1,067 m (1,200 to 3,500 ft) thick and is bounded by the Midway Group below and Carrizo Sand above. It has been divided into three formations: Calvert Bluff, Simsboro, and Hooper. The Calvert Bluff, 152 to 610 m (500 to 2,000 ft) of sand and mud, is the major lignite-bearing unit; it conformably overlies the Simsboro Formation, which contains some lignite. The Simsboro is a massive sand, as thick as 244 m (800 ft) that conformably and unconformably overlies the Hooper, which consists of 122 to 305 m (400 to 1,000 ft) of mud, sand, and lignite.

Stratigraphically, lignite occurs as a persistent zone in the lower part of the Calvert Bluff Formation just above the Simsboro Formation and in the upper part of the Calvert Bluff. The Simsboro Formation thins, breaks up, and changes facies northward toward the Trinity River and is actually a facies equivalent of the Calvert Bluff Formation in Leon, Freestone, and Anderson Counties. Lignites equivalent to the Simsboro sands occur at this transition. Hooper lignites are most numerous and thickest in the upper part of the formation just below the Simsboro.

Northeast of the Trinity River and on the Sabine Uplift (fig. 1) the Wilcox Group is composed of 122 to 427 m (400 to 1,400 ft) of undivided sand, mud, and lignite. Lignite is found throughout the Wilcox Group, but is most common in its upper two-thirds.

Jackson Group

Between the Colorado and Angelina Rivers (fig. 1) the Jackson Group has been divided into four formations (Kaiser and others, 1978) and includes about 305 m (1,000 ft) of mud, sand, and lignite extending from the top of the Yegua Formation to a correlative point at or near the base of the Catahoula Formation updip and the Vicksburg Formation downdip. Lignite occurs at the outcrop in the Manning and upper part of the Wellborn Formations and in their subsurface equivalents.

South of the Atascosa River (fig. 1) the Jackson Group has been informally divided so that the lower Jackson typically includes about 61 to 213 m (200 to 700 ft) of mud, sand, and lignite between the Yegua Formation and the muddy middle part of the Jackson Group (Kaiser and others, 1980). Lignite previously assigned to the Jackson-Yegua (Kaiser, 1974) has been informally reassigned to the lower part of the Jackson, a genetic package of sediment including some strata previously placed in the underlying Yegua Formation. This package is easily recognized throughout South Texas.

Depositional Models

The concept of facies has been used ever since geologists, engineers, and miners recognized that features found in particular rock units were useful for correlating

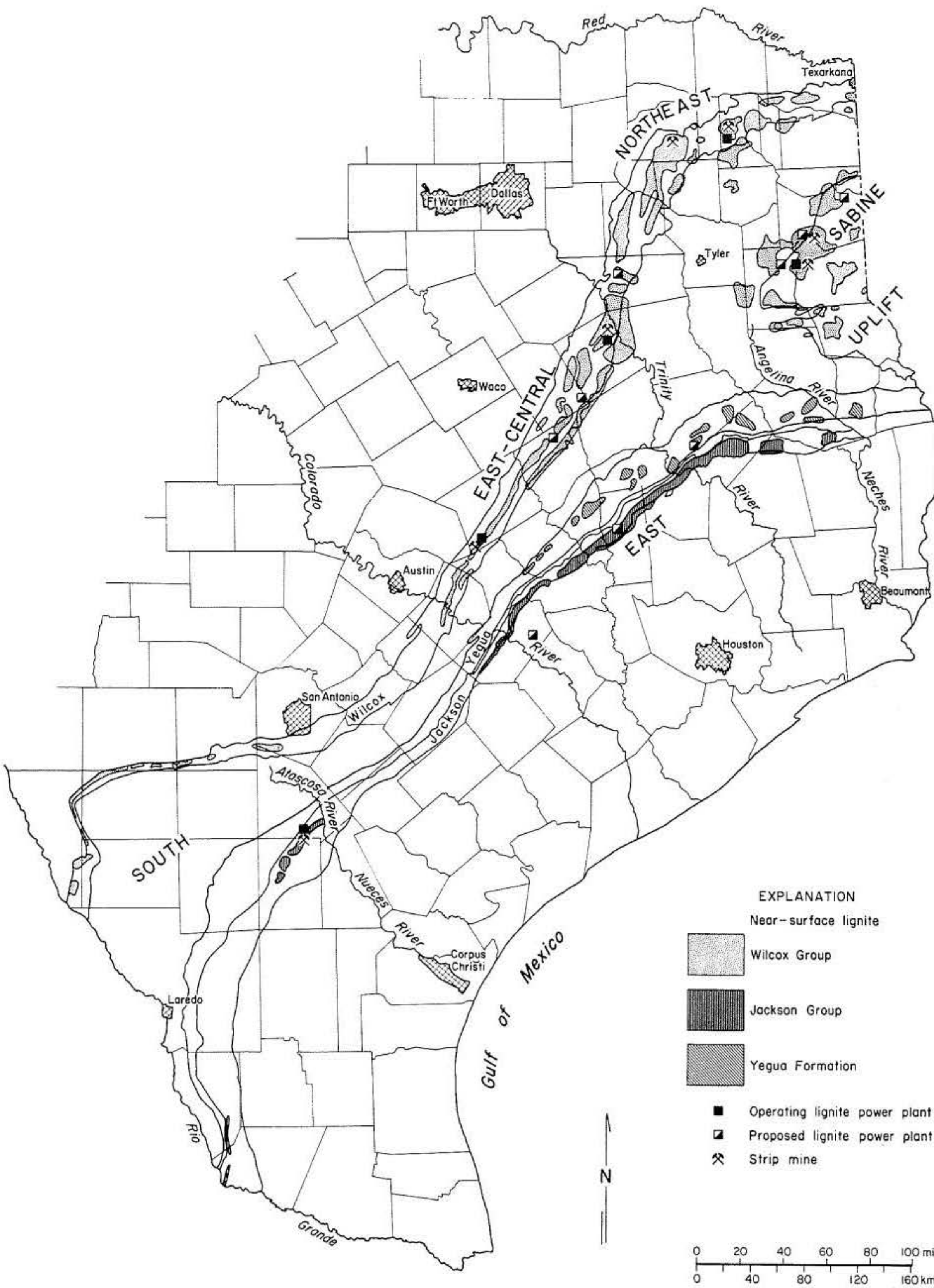


Figure 1. Distribution of near-surface lignite in Texas (Kaiser and others, 1980).

those units and for predicting the occurrence of coal, oil, or mineral ores (Reading, 1978). A modern depositional system is an assemblage of related facies, environments, and associated processes. An ancient depositional system is, therefore, a three-dimensional assemblage of sedimentary facies linked genetically by inferred sedimentary environments and depositional processes. This genetic linkage results from a holistic interpretation of the rocks that yields inferred environments and processes compatible with modern analogs.

A depositional model built upon the relationship between sand-body geometry and lignite occurrence has been developed for Texas lignite from regional lithofacies and lignite-occurrence maps constructed from approximately 4,000 oil and gas logs. The model is facies-dependent and permits resource estimation where data are meager. Specific aspects of the models are discussed below, using the Wilcox Group and the Jackson Group as examples.

Wilcox Group

The Calvert Bluff, Simsboro, and Hooper Formations of the Wilcox Group in east-central Texas contain sands that form complex channel networks displaying straight, dendritic, and bifurcating geometries characteristic of fluvial and deltaic depositional systems (fig. 2).

On modern deltas, channel-sand belts with straight or slightly dendritic geometries characterize the transition zone between the lower alluvial and upper delta plain (Smith, 1966). Such a transition zone is exposed at the Calvert Bluff outcrop and is present in the shallow subsurface where major sand bodies are composed of multistory and multilateral fine- to coarse-grained meanderbelt deposits as thick as 61 m (200 ft) (Kaiser, 1978). Underlying Simsboro sands occur in thick, multilateral channel-sand belts displaying straight or slightly dendritic geometries. McGowen and Garner (1970), in an outcrop study, interpreted sands in the Simsboro Formation as coarse-grained meanderbelt deposits. Laterally extensive sand belts of large net thickness in the subsurface of Milam and Burleson Counties and meandering sand belts of low net thickness in Anderson County indicate, in addition, the probable presence of braided-stream and fine-grained meanderbelt deposits. Sand-body geometries in the Hooper Formation are similar to those of the Calvert Bluff Formation. Areally, in the Wilcox of east-central Texas, lignite occurs in elongate concentrations roughly parallel to the paleoslope or perpendicular to the outcrop (fig. 3).

Sites of peat accumulation were hardwood swamps located in interchannel basins developed between the bounding alluvial ridges of the ancient river courses. Modern analogs of Calvert Bluff interchannel basins are the Des Allemands-Barataria and Atchafalaya Basins of the Mississippi delta system (Kaiser, 1978). Gulfward these basins diminish in size and increase in number as trunk streams bifurcate into distributary networks that enclose progressively smaller interdistributary basins. Peat is thickest and laterally most extensive at the junction of the alluvial and delta plains. Likewise in ancient strata the thickest and best quality coals are found at this juncture. A single, thick inland swamp peat may be time-correlative with several coastal marsh peats genetically related to thin, overlapped delta lobes (Frazier and others, 1978). Similarly, basinward in the Calvert Bluff the number of lignites increases and the median thickness decreases (Kaiser, 1978). Lignite equivalent to the Simsboro is found primarily in sand-deficient interchannel areas (Kaiser and others, 1980).

In East Texas the undivided Wilcox Group is composed of fluvial sands (fig. 4). Two prominent north-south-oriented channel sand belts, a western and an eastern belt, merge basinward and lose their separate identities in Anderson and Cherokee Counties. An excellent dendritic- or tributary-channel geometry characteristic of the upper alluvial plain occurs in the region. Lignite is most abundant in the sand-poor interchannel areas between the two major channel sand belts and the tributaries feeding these belts (fig. 5). As in the Calvert Bluff and Simsboro, peat accumulated in hardwood swamps established between bounding alluvial ridges.

Jackson Group

In the Jackson Group between the Colorado and Angelina Rivers (fig. 1), lithofacies mapping reveals a lobate sand-body geometry that becomes digitate downdip to the south and southwest. Within individual lobes a bifurcating or distributive geometry is either displayed or suggested (fig. 6); hence, an ancient delta system termed the "Fayette delta system" by Fisher and others (1970) is clearly indicated. Fluvially dominated delta lobes were supplied sediment by a fluvial system preserved in the Whitsett Formation, which marks the culmination of the Jackson progradational or regressive cycle. Lignite occurrences are lobate in plan view and mirror the sand percent map; in fact, lignite and relatively high sand percentages overlap almost exactly (figs. 6 and 7). Palynology (Elsik, 1978) and digitate and bifurcating sand-body geometries suggest that marshes on the lower delta plain were sites of organic accumulation (Kaiser and others, 1978). Thicker, laterally extensive lignites are postulated to be ancient blanket peats that accumulated on foundering delta lobes and spanned a variety of inactive environments ranging from distributary-channel to lake and bay fills.

South of the Atascosa River (fig. 1) linear, strike-oriented sand bodies characterize the lower part of the Jackson and are interpreted to represent strandplain/barrier-bar sands (Fisher and others, 1970; Kaiser and

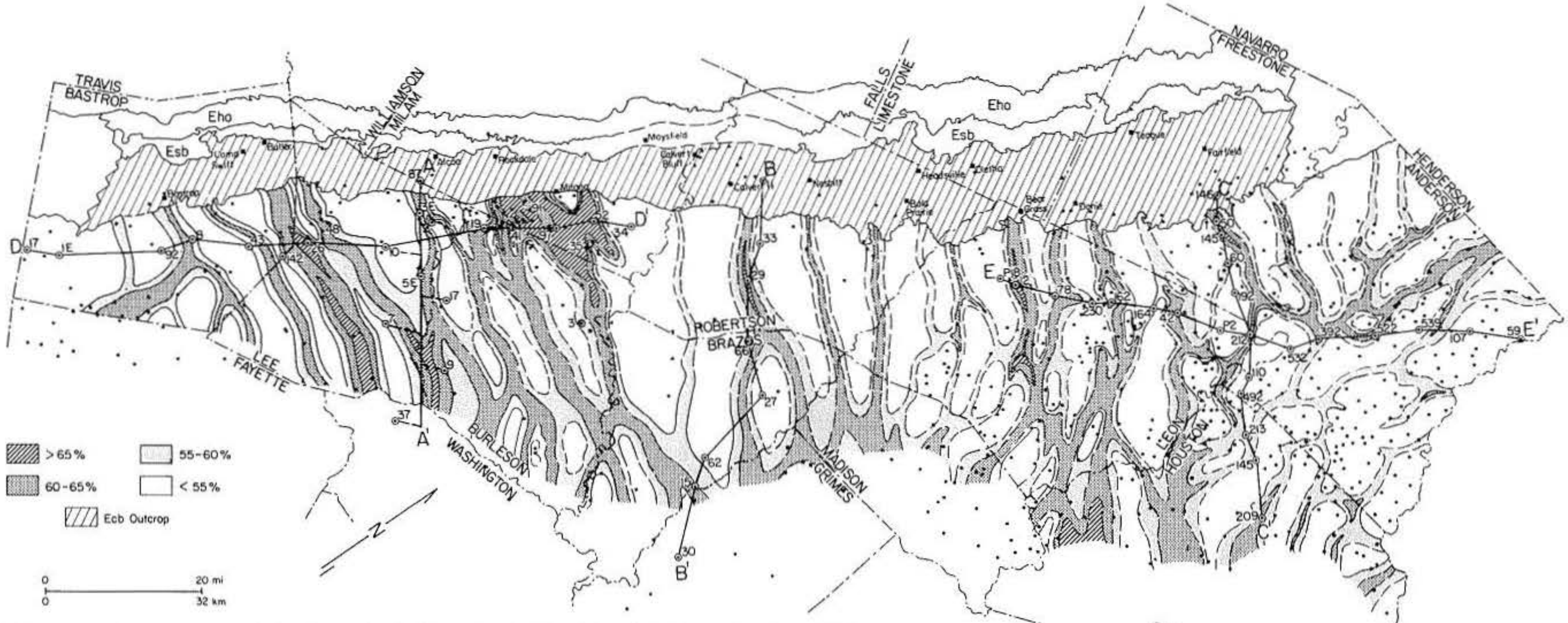


Figure 2. Sand-percent map of the Calvert Bluff Formation (Wilcox Group) (Kaiser and others, 1978).

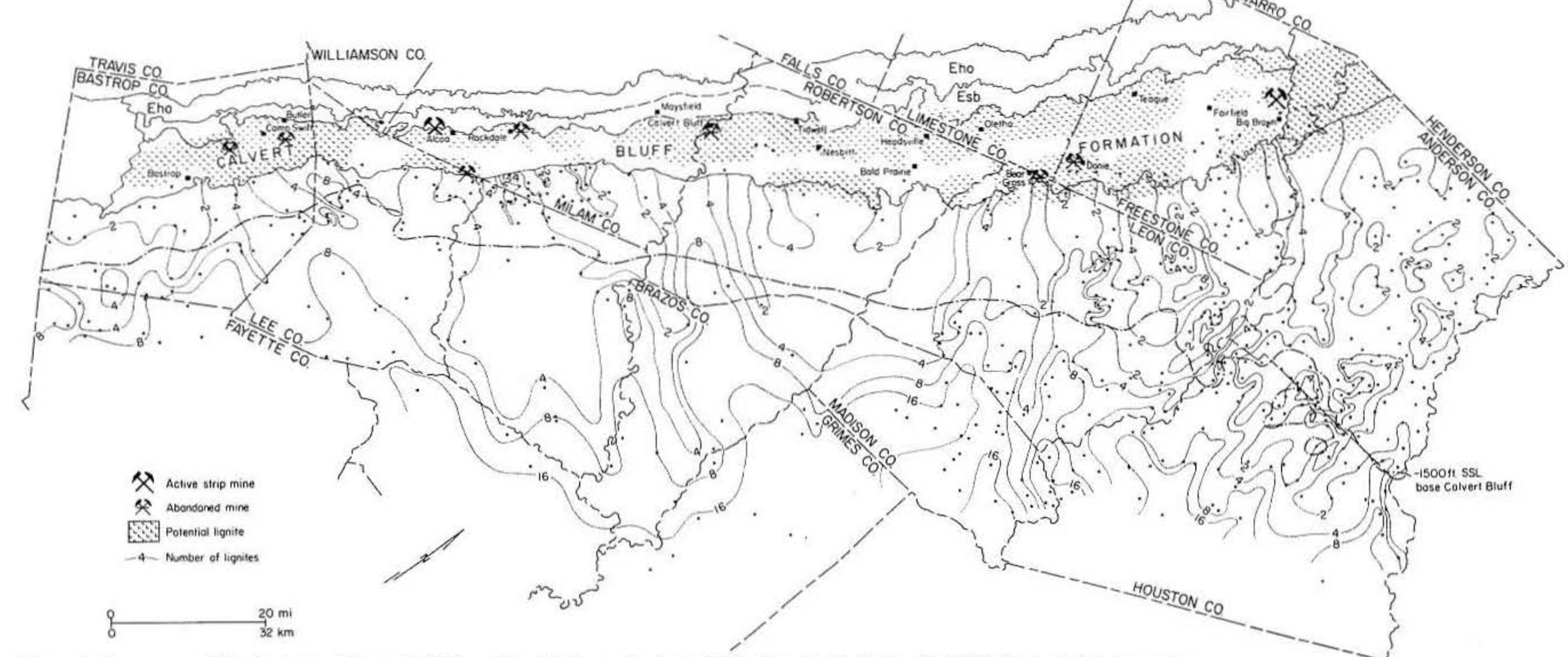


Figure 3. Occurrence of lignite in the Calvert Bluff Formation (Kaiser and others, 1978). Deep-basin lignite, identified from electric logs using operational definition, shown by isopleths (number of lignite seams).

Figure 4. Sand-percent map of the undivided Wilcox Group (Kaiser and others, 1978).

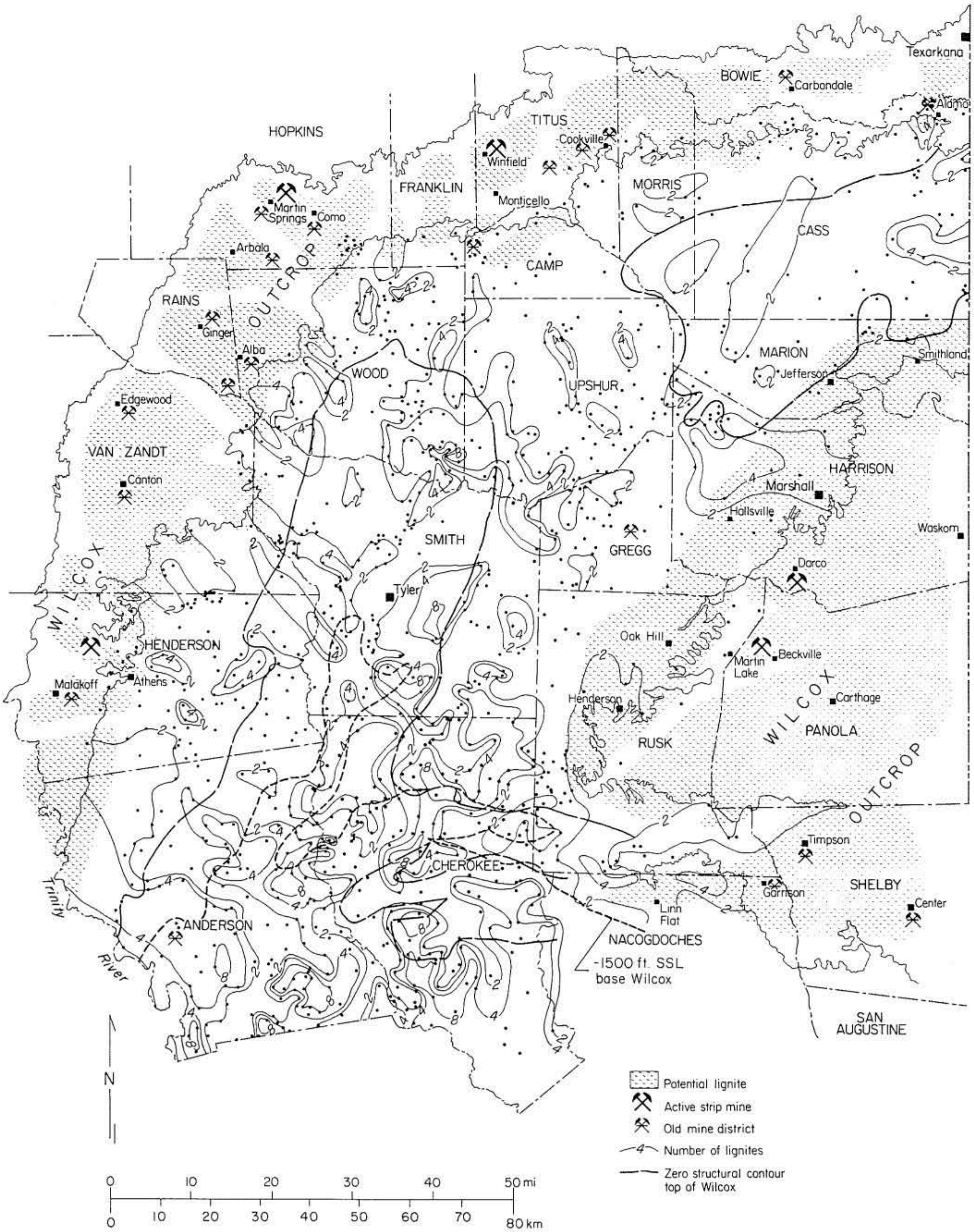


Figure 5. Occurrence of lignite in the undivided Wilcox Group (Kaiser and others, 1978).

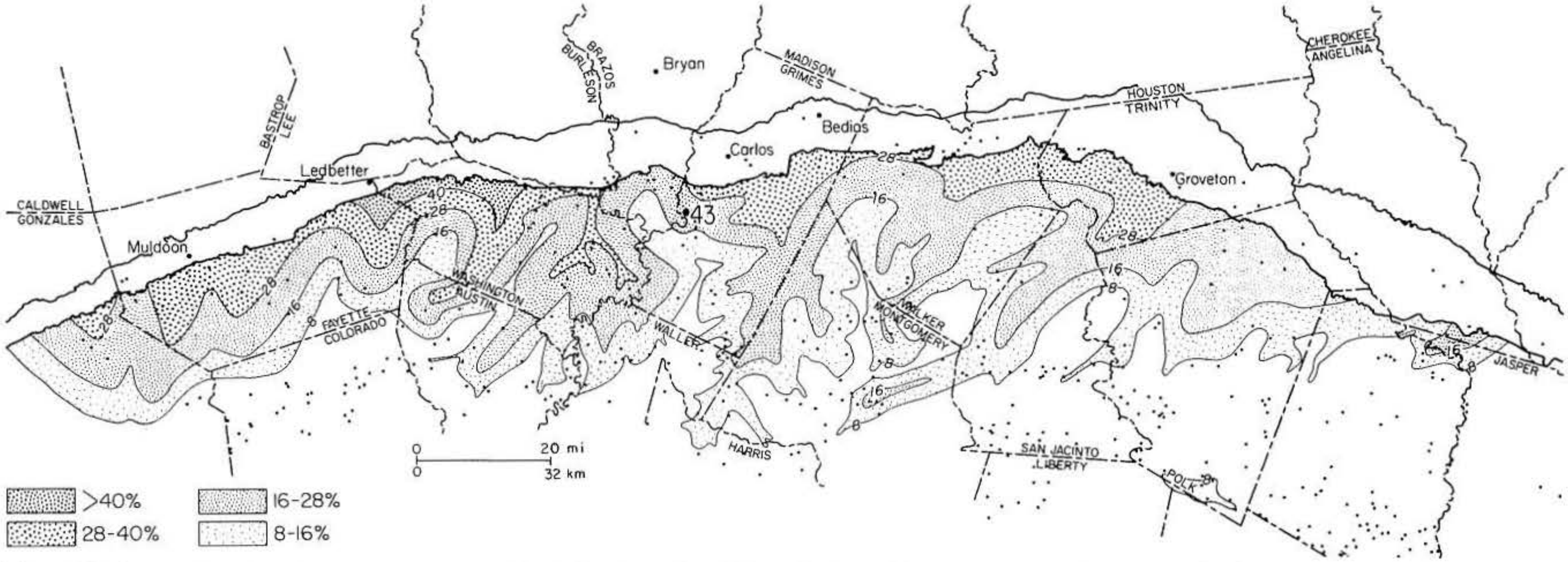


Figure 6. Sand-percent map of the Jackson Group, exclusive of the Whitsett Formation (Kaiser and others, 1978), between the Colorado and Angelina Rivers.

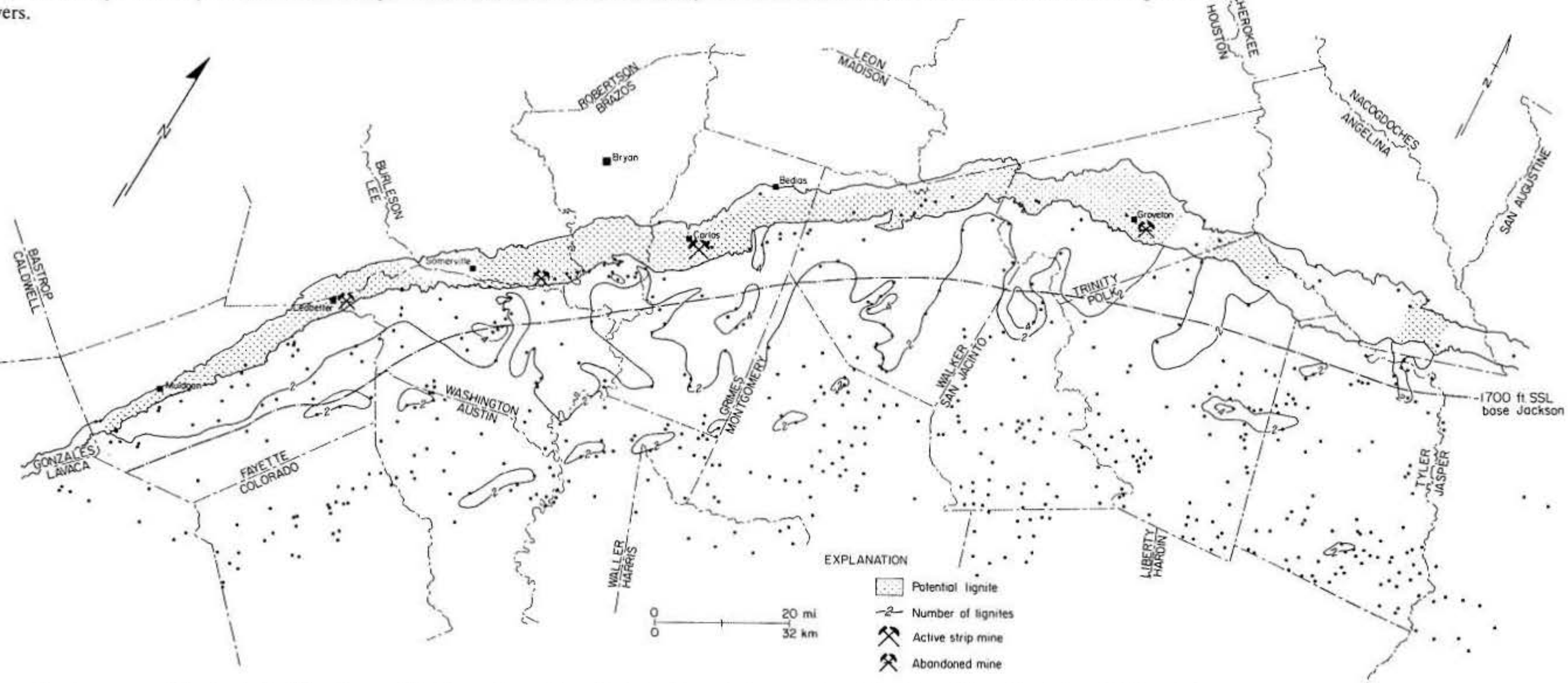


Figure 7. Occurrence of lignite in the Manning and Wellborn Formations (Jackson Group), between the Colorado and Angelina Rivers (Kaiser and others, 1978).

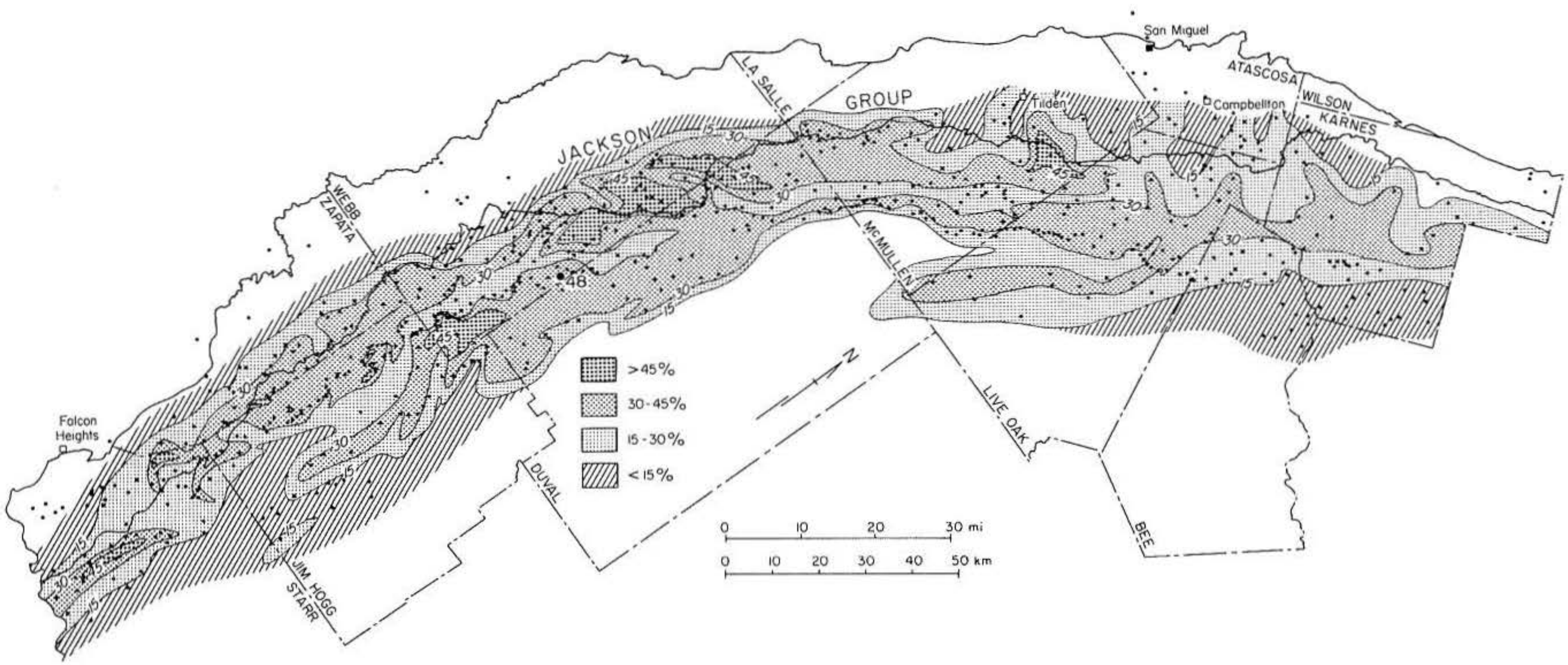


Figure 8. Sand-percent map of the lower Jackson Group, south of the Atascosa River (Kaiser and others, 1980).

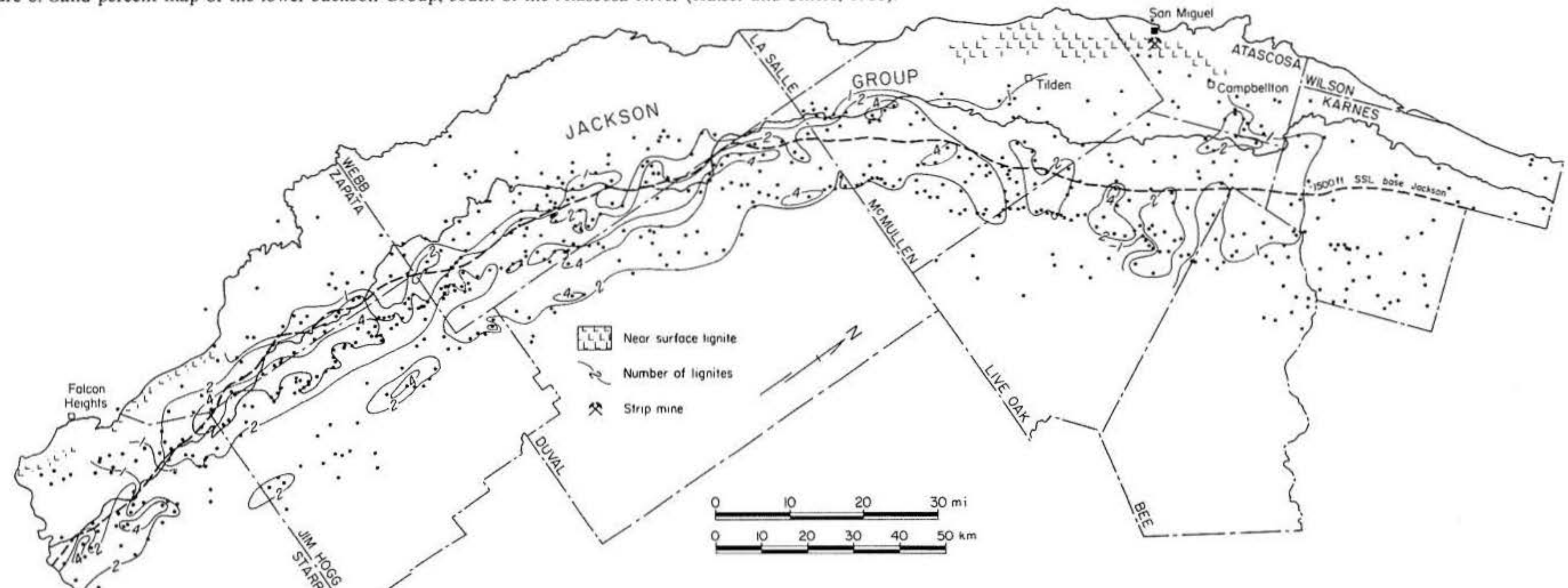


Figure 9. Occurrence of lignite in the lower Jackson Group, south of the Atascosa River (Kaiser and others, 1980).

others, 1978). They form a well-defined, north-northeast-trending belt of mud-bounded sand 32 to 40 km (20 to 25 mi) wide fed partly by small dip-oriented channel sands (fig. 8). The latter may represent the preserved remnants of small deltas that prograded across the ancient lagoon with seaward barrier islands, just as the contemporary Colorado and Brazos Rivers have done. Lignite occurrences are elongate and coincide with maximum sand development. From south to north they extend continuously through three counties until broken into discrete, irregular occurrences to the north in Live Oak County (fig. 9). Gaps between occurrences are believed to have been caused by syndepositional and/or postdepositional fluvial-deltaic or tidal channel deposition and erosion. Lignite tops strandplain/barrier-bar beach sequences. Holocene analogs of Jackson linear, regressive shorelines and associated environments occur on the Nayarit coast of western Mexico where marsh peats are accumulating in a strandplain/lagoonal system (Curray and others, 1969). Progradational upward-coarsening strandplain/barrier-bar sediments are closely analogous to sequences recognized in the lower Jackson strata.

TECHNICAL APPROACH TO EVALUATION OF LIGNITE DEPOSITS

Introduction

To quantify the contribution of geologic, as opposed to institutional, uncertainties to resource evaluation, a thorough understanding is needed of the factors controlling thickness and areal distribution of coal. In Texas a clear relationship exists between lignite seam geometry and the depositional environment in which the lignite formed. Regional depositional models, developed from the analysis of entire stratigraphic intervals (for example, the Calvert Bluff Formation of the Wilcox Group), indicate a qualitative relationship between sand-body geometry and lignite occurrence (Kaiser and others, 1978). However, the models give no information about seam thickness variations or areal distribution of individual seams.

Four densely drilled lignite deposits were chosen, one from each of the four depositional environments previously discussed. For each deposit, the areal distribution of the major and minor seams, interpretation of the depositional setting, and the factors controlling seam geometry and thickness were evaluated. Geologic interpretations of the spatial distribution of lignite seams and host sediments are presented in stratigraphic cross sections and lithofacies maps. Accuracy in the correlation of lignite seams depends upon the lateral spacing between boreholes, the amount of stratigraphic interval penetrated, and the lateral variability of the lignite seam and surrounding sediments. The lateral variation of lithologies between boreholes is illustrated in the lithofacies map. Lithofacies maps were constructed by selecting certain stratigraphic intervals that could be defined from laterally continuous beds, such as a coal or an interval between coals. This enabled documentation of the depositional environment before, during, and after coal formation. Types of lithofacies maps constructed include sand-percent maps, log pattern maps, and isopach maps. The geologic setting and types of available data precluded the use of the same suite of maps in all four deposits.

A combination of coal quality parameters (such as ash content, Btu, sulfur) was used to improve seam correlation and to aid our understanding of depositional settings. Due to the proprietary nature of coal analyses, a limited amount of this data was available for this study. Where the amount of data was sufficient, lignite quality was related to seam geometry through comparison of isoline maps of ash and Btu with seam isopach maps.

Depositional Setting—Alluvial Plain

Introduction

The Wilcox alluvial plain deposit comprises approximately 18,212 hectares (45,000 acres) and has been drilled on 335-m (1,100-ft) centers (fig. 10). Commercial lignites occur in this deposit in a 40- to 18-m (130- to 60-ft) stratigraphic interval consisting of sands, muds, and silts. Even though the interval coarsens upward into massive sands, the overall character is cyclic, and most of the major lignites occur in the finer grained part associated with small, upward-coarsening sequences.

The deposit has three thick lignite seams that vary between 0.91 and 2.7 m (3 and 9 ft) in thickness; more than 50 percent of all seams are less than 0.6 m (2 ft) thick (fig. 11). The seams described in this deposit have been numbered from top to bottom: seam no. 3, seam no. 4, and seam no. 6.

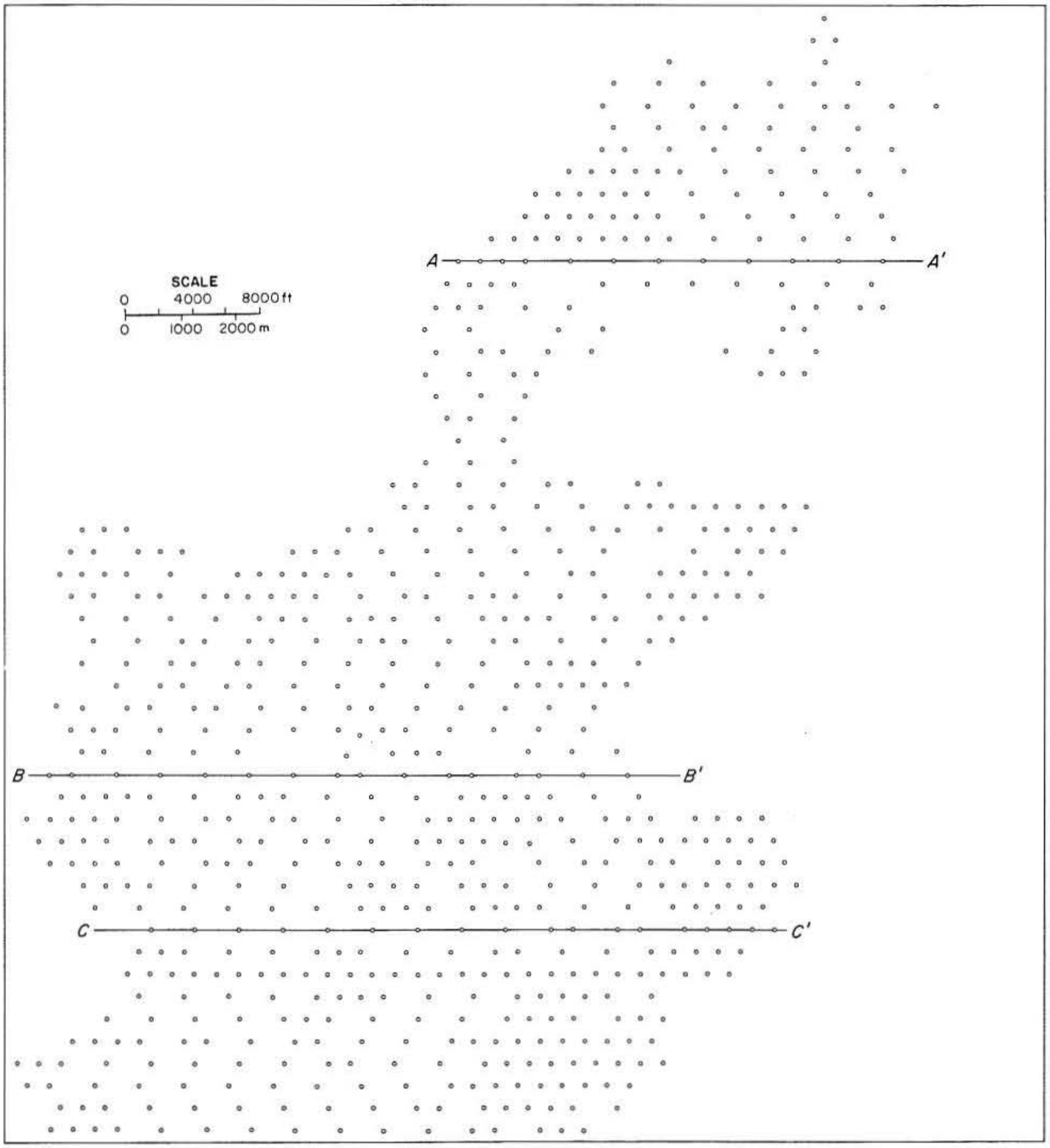


Figure 10. Locations of cross sections A-A', B-B', and C-C; and spatial arrangement of boreholes, alluvial plain deposit, Wilcox Group of East Texas.

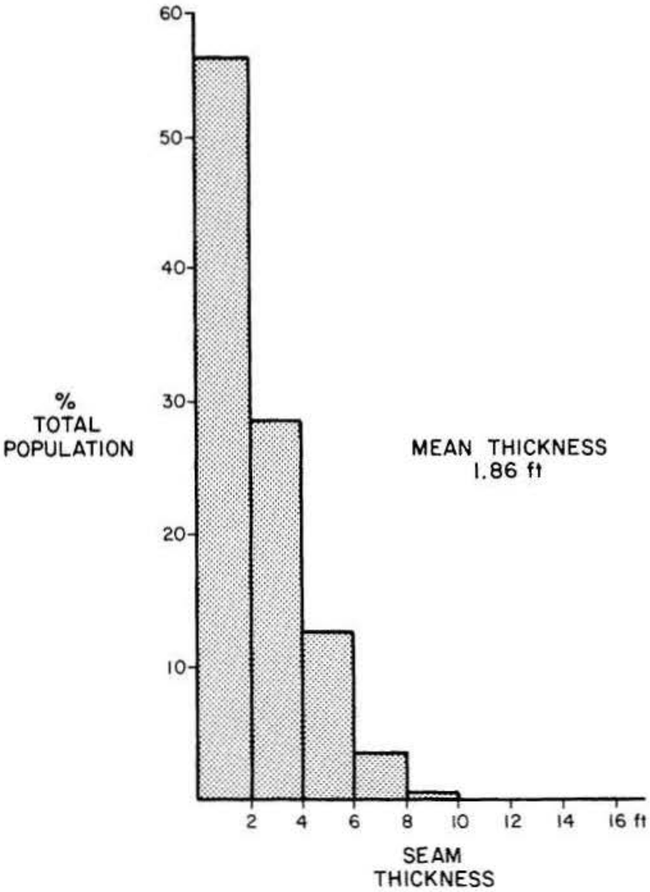


Figure 11. Histogram of seam thickness vs. percentage of total seam population, alluvial plain deposit, Wilcox Group of East Texas, showing an exponential-type distribution.

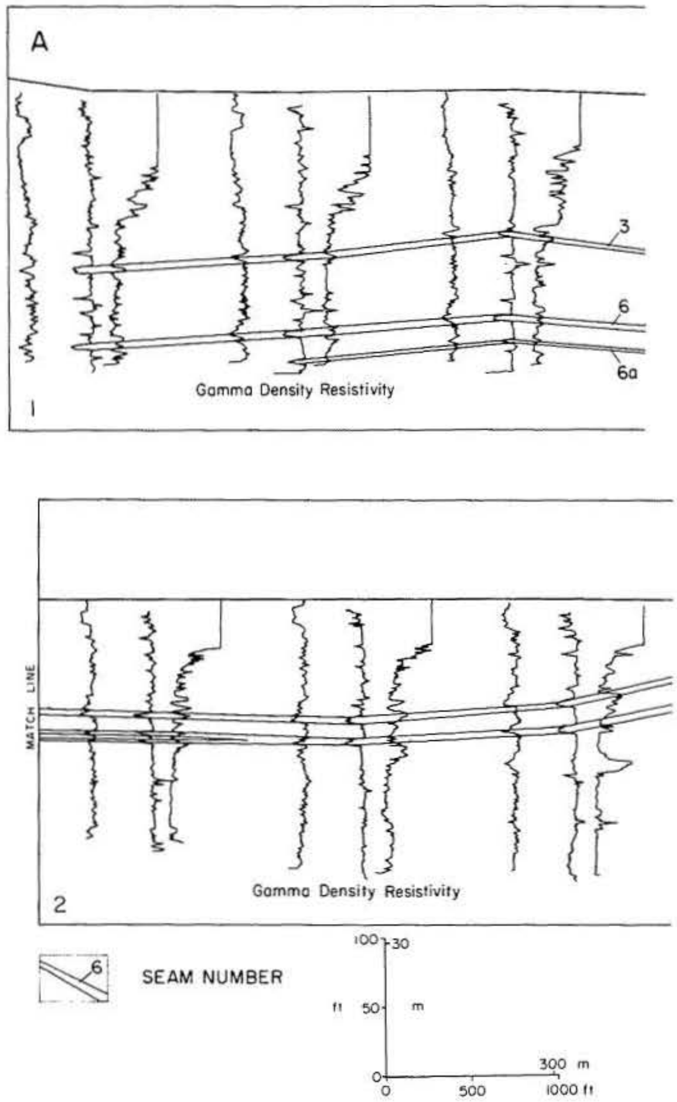


Figure 12. Dip-oriented cross section A-A′, alluvial plain deposit,

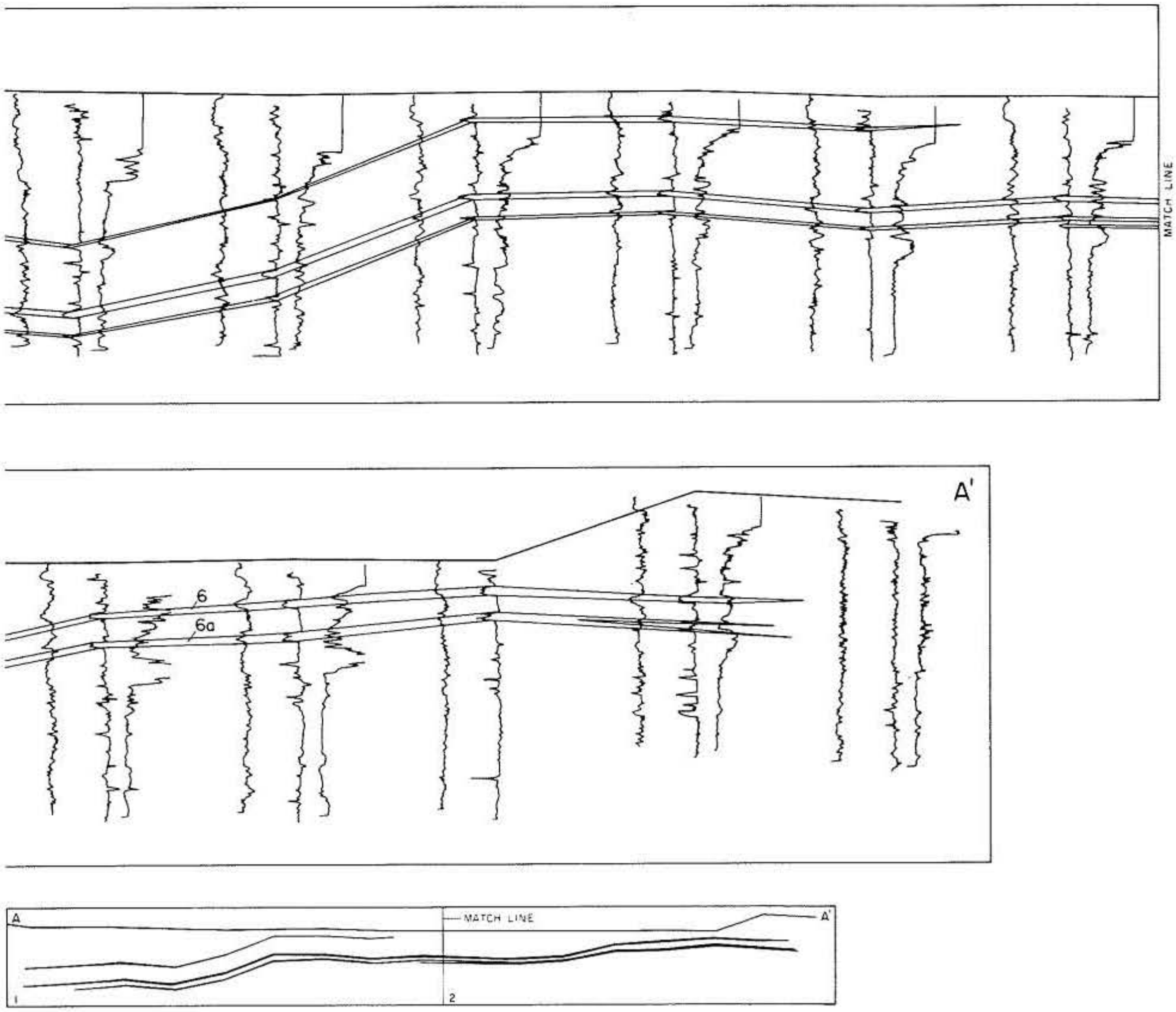
Geologic Evaluation

There are few partings within the major seams of the deposit and they are limited in areal extent. However, splitting of single lignite seams into separate seams is common and occurs abruptly in this deposit, especially in the case of seam no. 3 on cross sections A-A′, B-B′, and C-C′ (figs. 12, 13, and 14; see fig. 10 for locations). Seam discontinuities occur on all three cross sections but are best exemplified by the major discontinuity of seam no. 6 in the center of cross section B-B′ (fig. 13), where on the right-hand side, the seam splits as it passes into the barren area, making correlation with the seams on the left-hand side very questionable.

Minor faults of approximately 15 m (50 ft) over horizontal distances of less than 305 m (1,000 ft) are common (fig. 14). These displacements caused correlation problems in certain areas of the deposit.

Depositional setting of host sediments.—The sedimentary interval containing the lignites of this deposit is discussed from bottom to top as part of a geologic evaluation investigating and interpreting the depositional processes responsible for seam geometry. Four types of log patterns occur in the interval 15 m (50 ft) below seam no. 6 (fig. 15). Each pattern represents a distinct depositional facies. Patterns 1a and 1b are interpreted as massive fluvial sand. Pattern 2 is interpreted as upward-coarsening sequences from clay to silt to very fine grained sand, either lake fill or crevasse splay in origin. The low-density spikes are lignite. Pattern 3 represents upward-coarsening sequences from clay to silt, which probably formed as an infilling of an interchannel swamp or lake by small crevasse splays. Pattern 4 indicates mud with occasional thin beds of carbonate (calcite or siderite) or carbonate-cemented muds deposited in a lake environment.

Pattern distribution in the succession below seam no. 6 indicates a depositional setting characterized by a meandering channel system approximately 914 m



Wilcox Group of East Texas.

(3,000 ft) wide. The channel system flowed from north to south (fig. 15) and contained peripheral lakes and peat swamps. The upward-coarsening crevasse splay and lake-fill deposits form the platform upon which seam no. 6 is deposited.

The sediments between seams no. 6 and 3 consist predominantly of fine-grained silts, muds, and lignites and occasional thin sand units. Three distinct log patterns occur in this interval and are similar to patterns 1, 3, and 4 recorded for the succession below seam no. 6. The distribution of these patterns (fig. 16) indicates a major sand channel depositional complex approximately 2.4 km (1.5 mi) wide, trending northwest to southeast across the area, which either eroded the lignite or was contemporaneous with the lignite-forming swamps. The areas bordering the channel complex show a succession of peat swamp and lake environments (patterns 2 and 3, fig. 16). The cyclic repetition of upward-coarsening sequences suggests periods of swamp drowning and redevelopment, possibly due to overbank flooding and crevassing. Pattern 3 (fig. 16) appears as large, linear, channel-like features greater than 4.8 km (3 mi) long and approximately 914 m (3,000 ft) wide. These features represent abandoned mud-filled channels.

The interval above seam no. 3 is dominated by channel-fill sand. Partings of splay origin within seam no. 3 are possibly precursor events to the destruction of the no. 3 swamp and the entire lignite-bearing zone in this part of the succession. Peat accumulation in the no. 3 swamp ended through gradual subsidence and drowning,

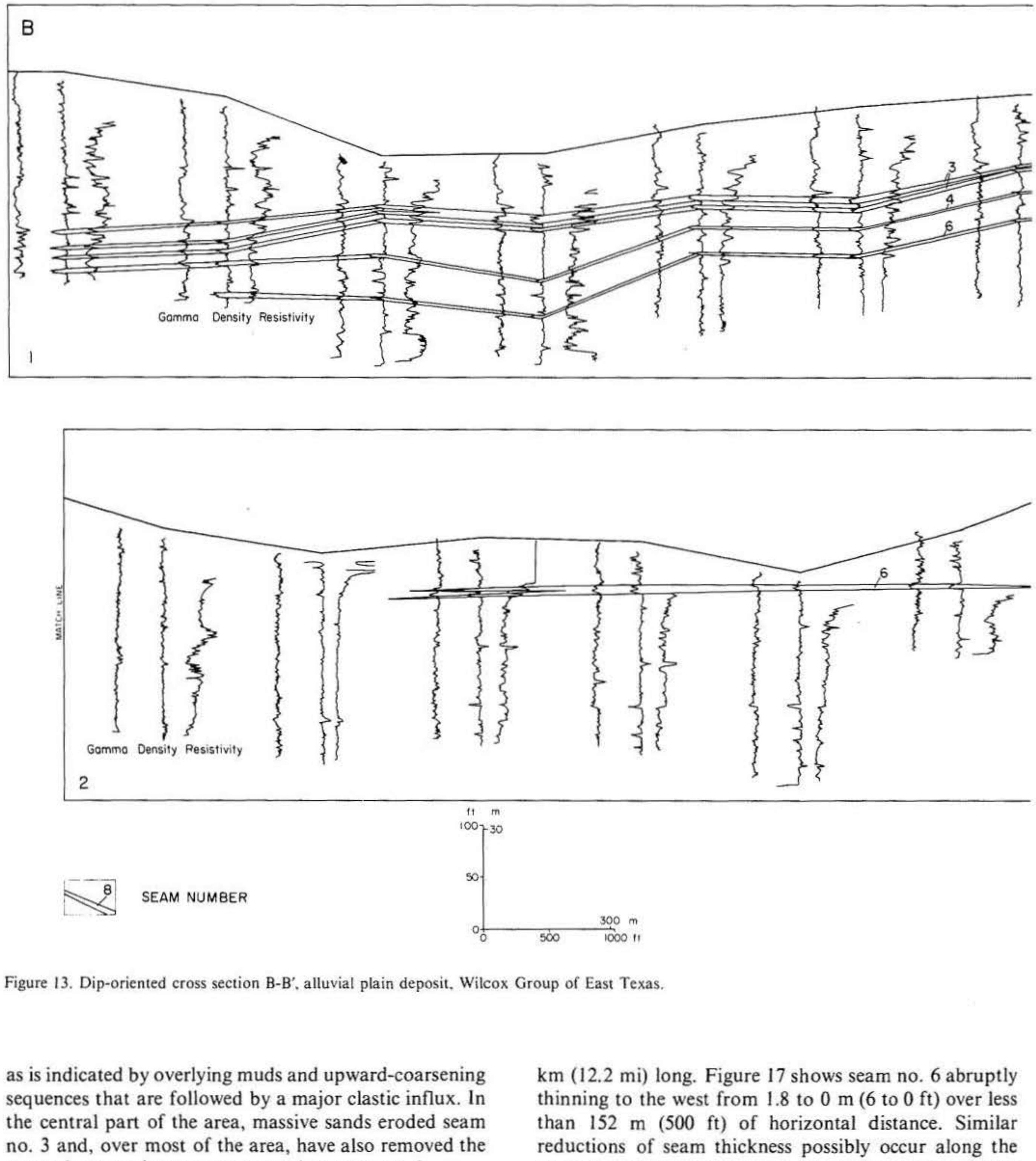


Figure 13. Dip-oriented cross section B-B', alluvial plain deposit, Wilcox Group of East Texas.

as is indicated by overlying muds and upward-coarsening sequences that are followed by a major clastic influx. In the central part of the area, massive sands eroded seam no. 3 and, over most of the area, have also removed the upward-coarsening sequence capping seam no. 3.

Depositional setting of lignite seams.—The relationship between the areal distribution of the lignite seams and the depositional environments depicted in the lithofacies maps is presented for seams no. 6, 4, and 3. The areal distribution and thickness of seam no. 6 (fig. 17) ranges from 0 to 2.9 m (0 to 9.6 ft) in a narrow belt approximately 7.2 km (4.5 mi) wide and greater than 19.6 km (12.2 mi) long. Figure 17 shows seam no. 6 abruptly thinning to the west from 1.8 to 0 m (6 to 0 ft) over less than 152 m (500 ft) of horizontal distance. Similar reductions of seam thickness possibly occur along the eastern margin of this trend. However, because of the data distribution, only two small sections of this boundary are recorded. Cross sections A-A', B-B', and C-C' (figs. 12, 13, and 14) document the nature of the boundary between the lignite and barren areas by the interfingering relationships between seam no. 6 and the muds and silts of the barren areas. This suggests that the peat-forming environments of seam no. 6 were bounded

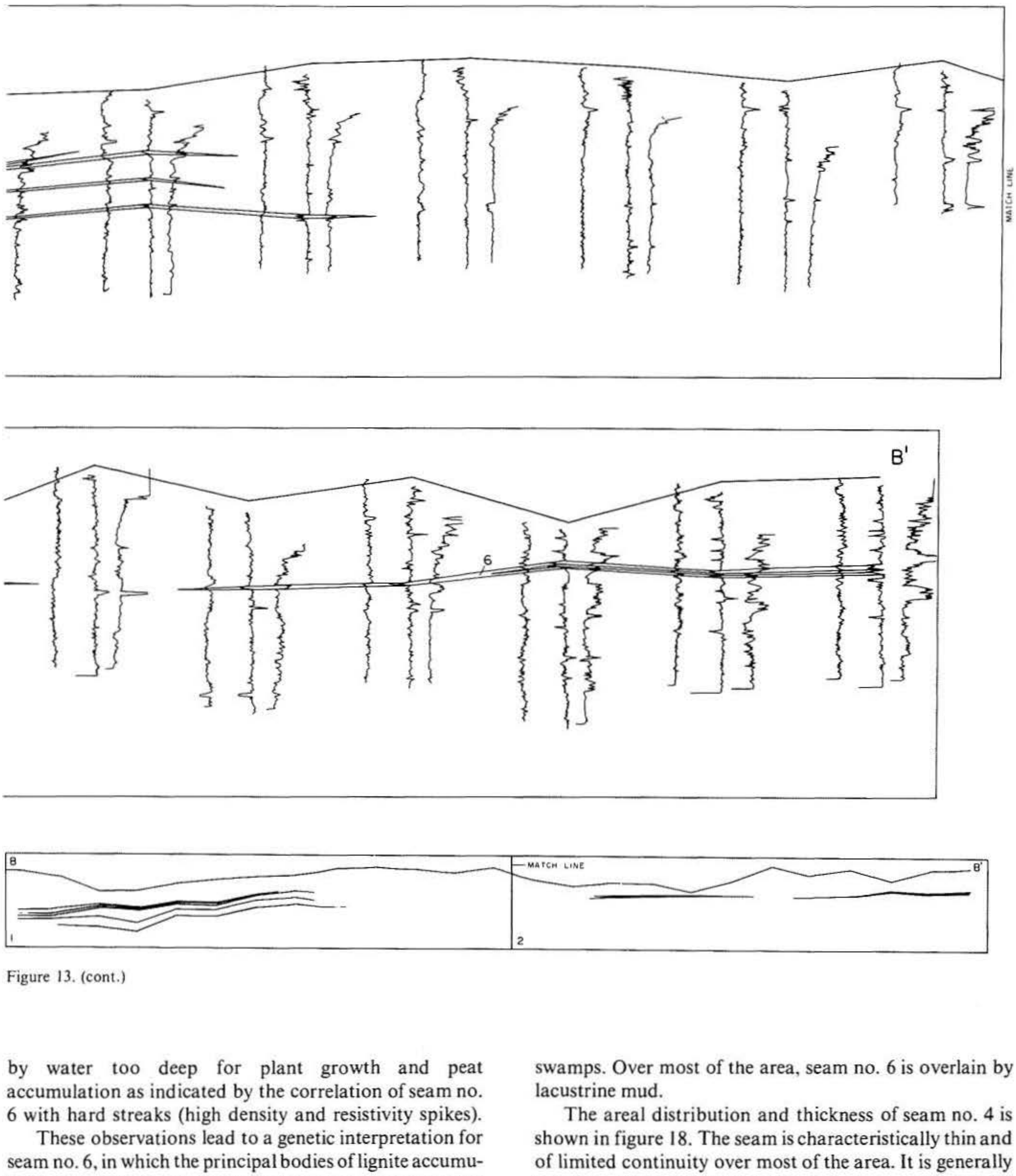


Figure 13. (cont.)

by water too deep for plant growth and peat accumulation as indicated by the correlation of seam no. 6 with hard streaks (high density and resistivity spikes).

These observations lead to a genetic interpretation for seam no. 6, in which the principal bodies of lignite accumulated as islands of peat surrounded by watery areas (lakes or abandoned channels). A close correlation exists between the channel system below seam no. 6 (fig. 15) and the left margin of the belt of thick lignite. These peat islands compacted to a greater degree than the surrounding sediments and thus were finally encroached by the watery areas. In certain parts of the deposit, crevasse splays inundated the peat swamps. Over most of the area, seam no. 6 is overlain by lacustrine mud.

The areal distribution and thickness of seam no. 4 is shown in figure 18. The seam is characteristically thin and of limited continuity over most of the area. It is generally less than 0.6 m (2 ft) thick but can be up to 1.8 m (6 ft) thick. The seam is limited by a large northwest-southeast-trending sand channel complex in the center of the area. Unlike seam no. 6, seam no. 4 has no distinct thickness trend. There is, however, a slight tendency for the thicker lignites to occur between and along the margins of the abandoned mud-fill channels. Similar occurrences have

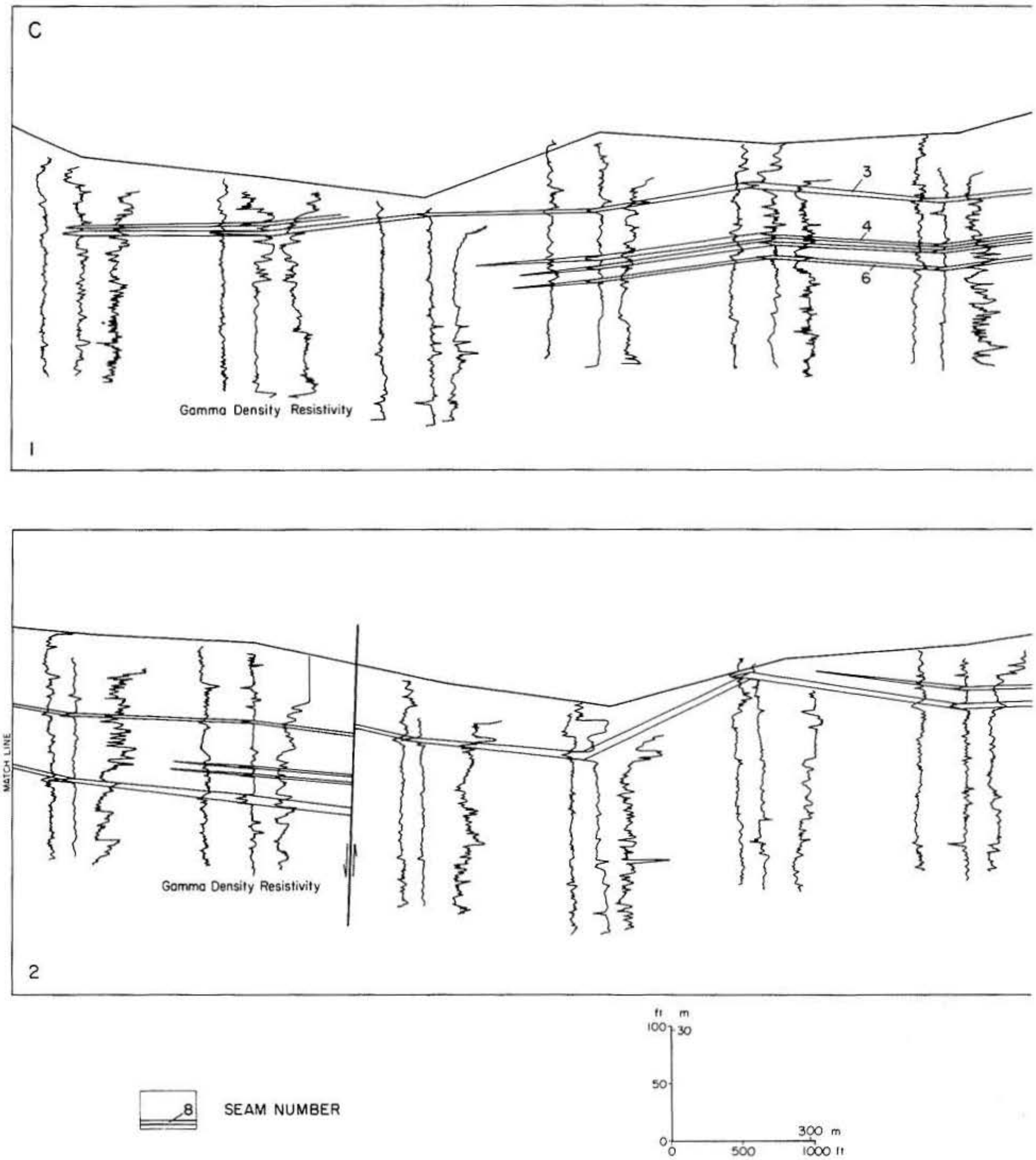


Figure 14. Dip-oriented cross section C-C', alluvial plain deposit, Wilcox Group of East Texas.

been documented in modern peat swamps (Frazier and Osanik, 1961). The depositional setting of seam no. 4 is less stable than that documented for seam no. 6. This instability is indicated by the seam's many discontinuities, which possibly resulted from clastic influx from the numerous channels draining the area (fig. 18).

Figure 19 shows the areal distribution and thickness of seam no. 3. The main body of thick lignite occurs in a linear belt approximately 5.3 km (3 mi) wide. Seam no. 3 is limited in the center of the area by the same sand channel complex that affected seam no. 4. Indications of a second sand channel complex occur in the extreme southwest corner of the area. The belt of thick seam no. 3 occurs between these two channel complexes and trends parallel to the main channel.

The center of figure 19 shows that part of seam no. 3 has been removed by channel scour. Seam no. 3 thins as it approaches the sand channel complexes. In certain

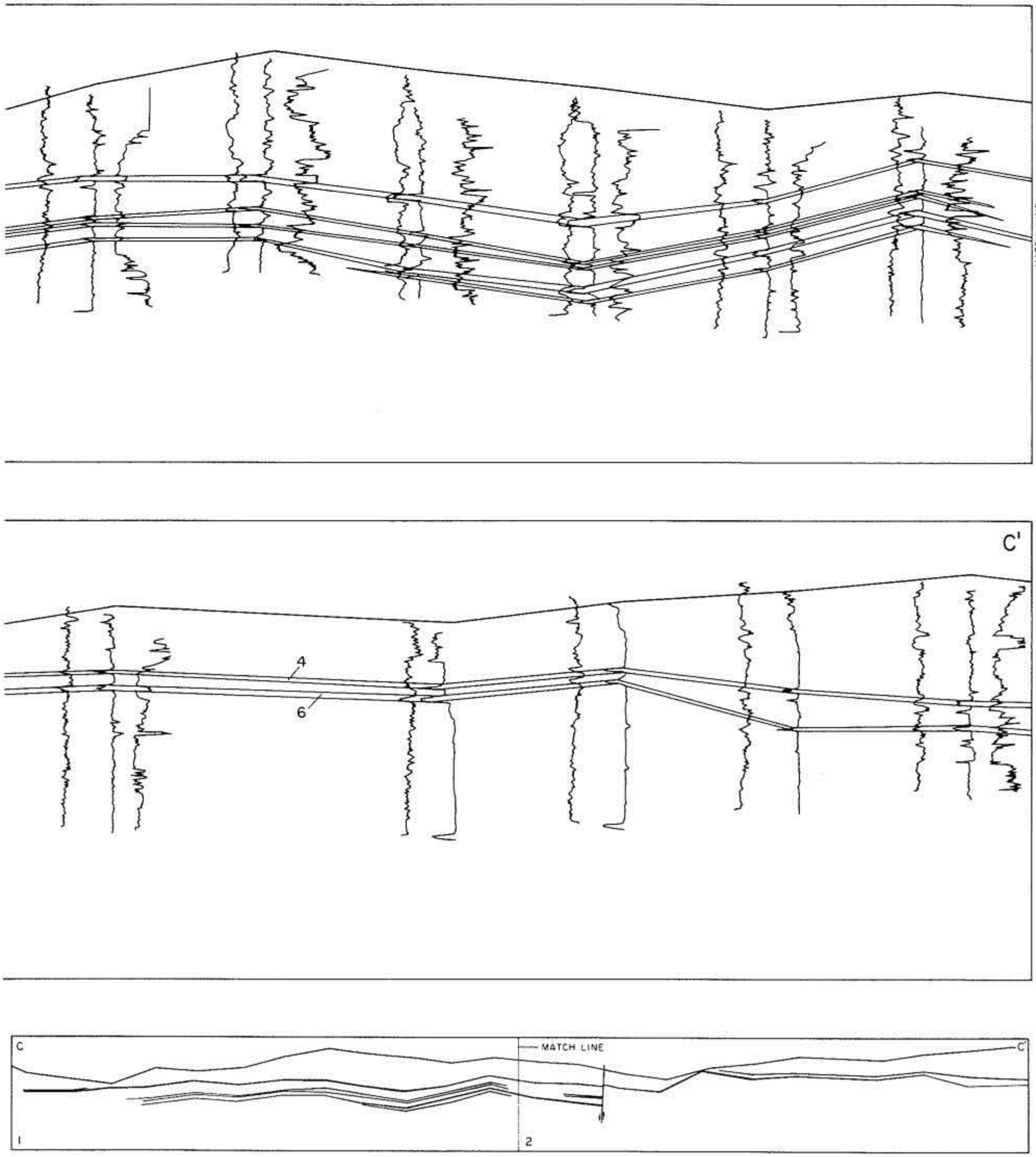


Figure 14. (cont.)

locations seam thinning is very rapid, from 1.8 to 0.6 m (6 to 2 ft) in less than 61 m (200 ft) of horizontal distance. The thinning is the result of the seam splitting into separate benches (fig. 20). Splits are attributed to overbank flooding and crevassing.

Lignite Quality Evaluation

The Btu/lb and percent-ash contour maps of seam no. 6 (figs. 21 and 22) appear very similar because a lignite's calorific value is inversely related to the amount of ash present. A visual correlation was found between poor-quality (low-Btu, high-ash) lignite and thinner areas near the geologic boundaries of seam no. 6 (fig. 17). However, there appeared to be no comparable overall correlation between lignite quality contours and isopach contours. In fact, in some areas of the percent-ash and Btu maps, the contour trends were opposite to those of lignite isopach contours. We are uncertain whether this was due to

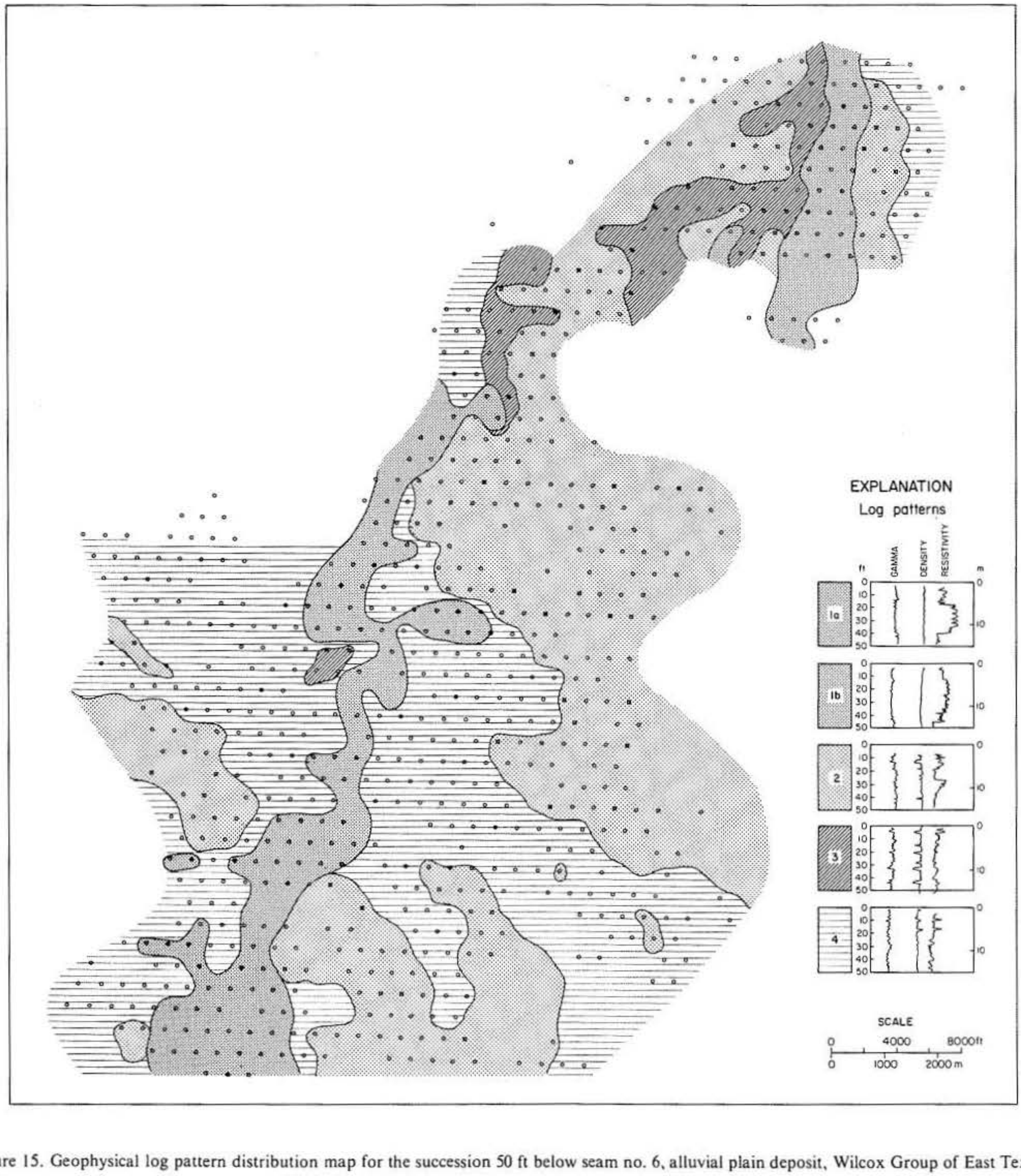


Figure 15. Geophysical log pattern distribution map for the succession 50 ft below seam no. 6, alluvial plain deposit, Wilcox Group of East Texas.

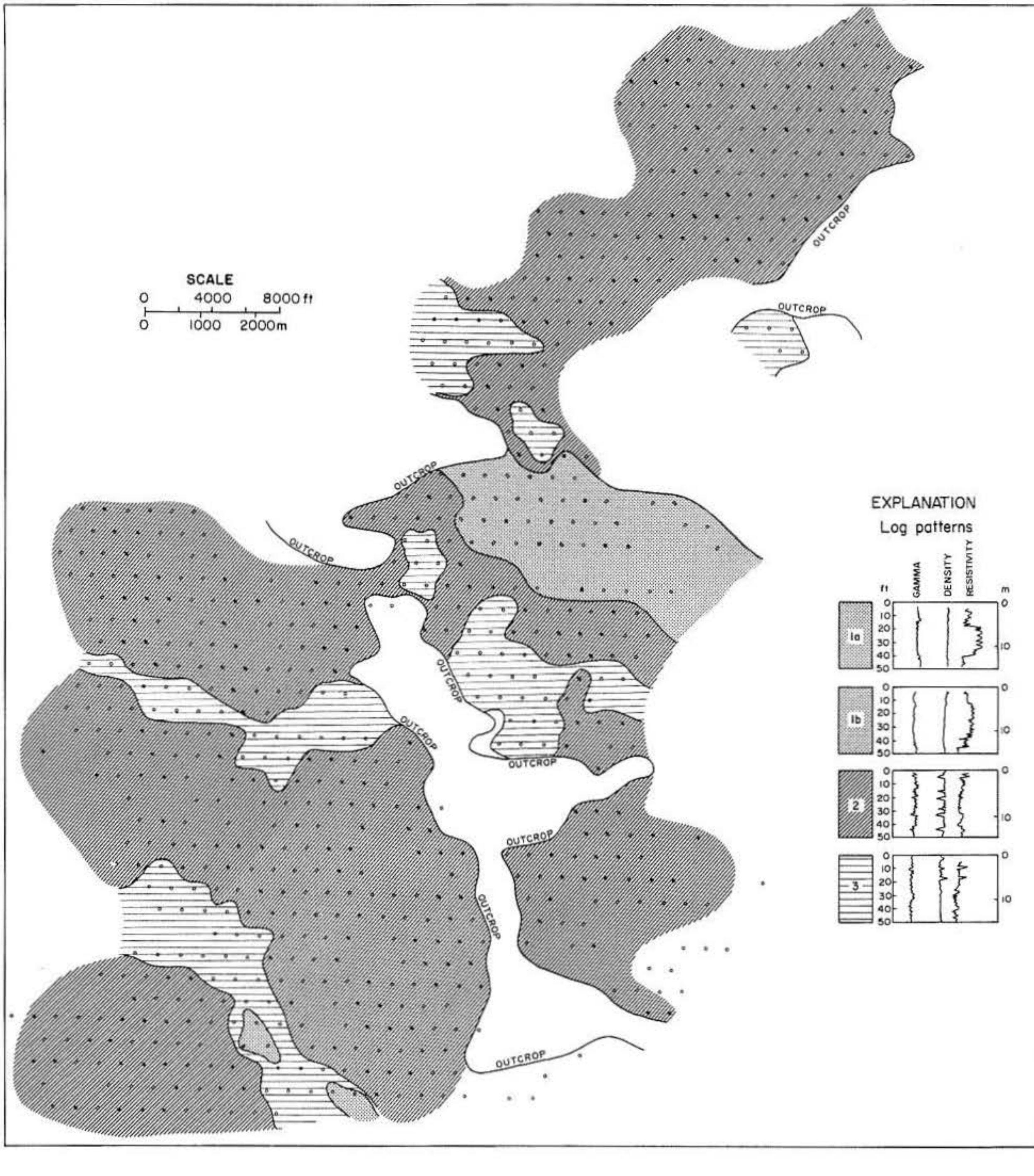


Figure 16. Geophysical log pattern distribution map for the succession between seams no. 6 and 3, alluvial plain deposit, Wilcox Group of East Texas.

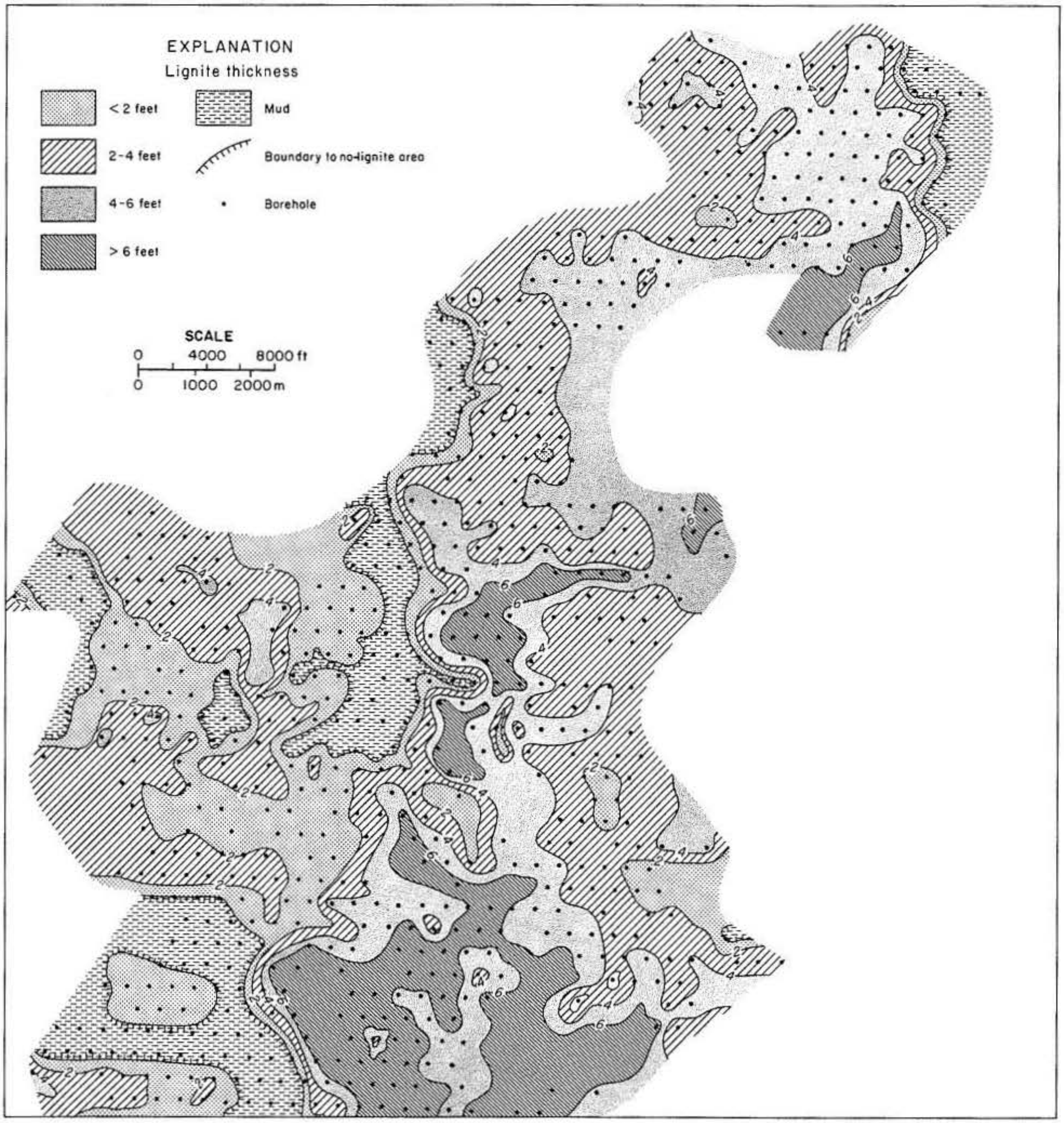


Figure 17. Isopach map of seam no. 6, alluvial plain deposit, Wilcox Group of East Texas.

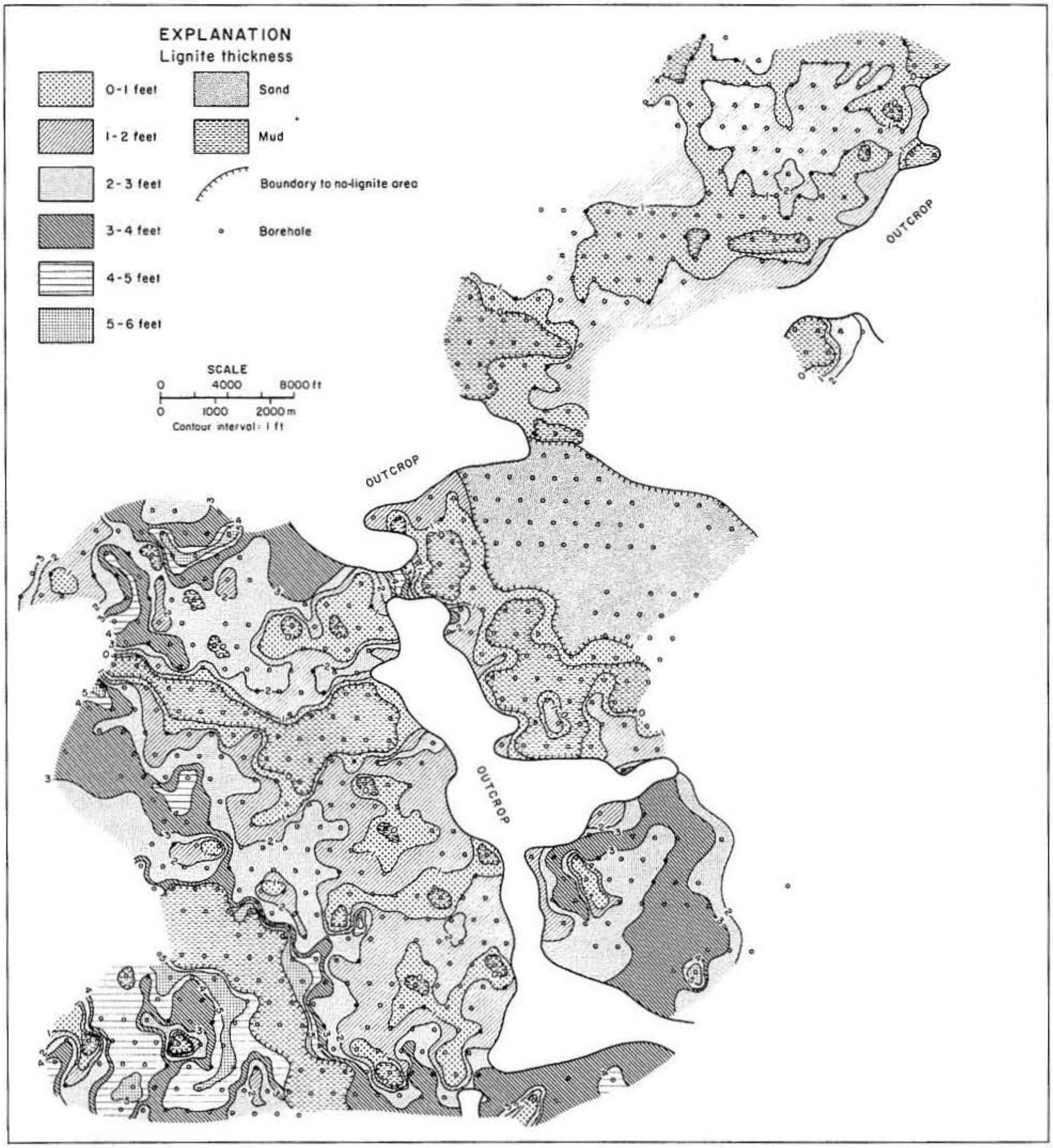


Figure 18. Isopach map of seam no. 4, alluvial plain deposit, Wilcox Group of East Texas.

Table 3. Comparison between individual seam quality and regional lignite quality.

Analysis (%) DCB		Detailed Deposit		Regional Lignite Quality	Analysis (%) DCB		Detailed Deposit		Regional Lignite Quality
		Wilcox Seam No. 3	Wilcox Seam No. 6				Wilcox Seam No. 3	Wilcox Seam No. 6	
Ash	X	25.06	24.56	21.87	Carbon	X	54.16	54.74	58.96
	S	7.91	8.85	13.29		S	6.06	6.70	5.73
	S^2	62.54	78.34	176.66		S^2	36.76	44.94	32.79
Volatile Matter	X	39.87	40.27	40.72	Hydrogen	X	4.11	4.12	4.59
	S	4.01	4.34	6.35		S	0.47	0.51	0.39
	S^2	16.12	18.80	40.27		S^2	0.22	0.26	0.15
Fixed C	X	35.07	35.17	37.40	Nitrogen	X	0.94	0.97	1.00
	S	4.94	5.71	7.72		S	0.14	0.17	0.17
	S^2	24.43	32.64	59.63		S^2	0.02	0.03	0.03
Btu	X	9,423	9,462	9,763	Chlorine	X	0.03	0.03	0.07
	S	1,115	1,153	1,801		S	0.02	0.02	0.06
	S^2	1,244,017	1,330,169	3,242,574		S^2	0.00	0.00	0.00
Total S	X	2.30	1.28	1.42	Oxygen	X	13.41	14.06	17.39
	S	1.01	0.78	0.79		S	2.15	2.83	3.99
	S^2	1.03	0.61	0.62		S^2	4.62	8.04	15.92
No. of analyses		79	98	110	No. of analyses		78	98	45

X = Mean; S = Standard Deviation; S^2 = Variance

insufficient data or if there was no direct, easily discernible correlation between quality and seam thickness. The top left corner of the Btu and ash-percent contour maps indicates an extremely high-ash, low-Btu sample. It is unlikely that the analytical values for this point are valid; the results probably indicate some problem in the sample collection process.

The variability of lignite quality is shown in table 3, which compares two seams of this deposit with the mean values of lignite quality for seams in the Wilcox Group of East Texas. Part of this variability in quality can be attributed to the precision (repeatability and reproducibility) of the methods used to analyze coal.

Summary of Geologic Features

The alluvial plain setting of East Texas is characterized by high sand-percent channel belts and low sand-percent interchannel areas. The major lignite deposits of this region occur in the interchannel areas. The deposit evaluated in this report shows most of the characteristics of the alluvial plain setting.

The individual seams are lenticular, the thickest lignite occurring in the center of these bodies and thinning abruptly along the margins. Adjacent to the individual lignite bodies are barren areas that are characteristically channel-like and filled with either mud or sand. Channels are normally parallel to the individual lignite bodies. Large irregular and circular mud-filled areas (ancient lakes) completely surrounding some of the lignite bodies are common.

Depositional Setting—Alluvial/Delta Plain Transition

Introduction

The alluvial/delta plain transition deposit lies in the outcrop of the Calvert Bluff Formation. The deposit comprises approximately 5,666 hectares (14,000 acres) and has been drilled on 152-m (500-ft) centers. Figure 23 shows the distribution of data utilized in this evaluation.

Geologic Evaluation

Field observations determined that the thickest seam of the deposit is overlain by an upward-coarsening, fine-grained, thinly laminated sequence consisting of silts and muds. Sandy channel sequences scoured out the laminated sediments and lignite seams in certain locations. These sand channel complexes consist of a mud-clast conglomerate at their bases fining upward into large, trough-crossbedded, medium-grained sands and finer grained overbank material. The thickest seam in this deposit is continuous, although it contains many partings that thin and thicken rapidly. The rider seams are discontinuous in outcrop.

Cross sections.—Two strike sections, A-A′ and B-B′ (figs. 24 and 25; see fig. 23 for locations), constructed across the deposit using geophysical logs and driller's logs, indicate the presence of seams above and below the main lignite

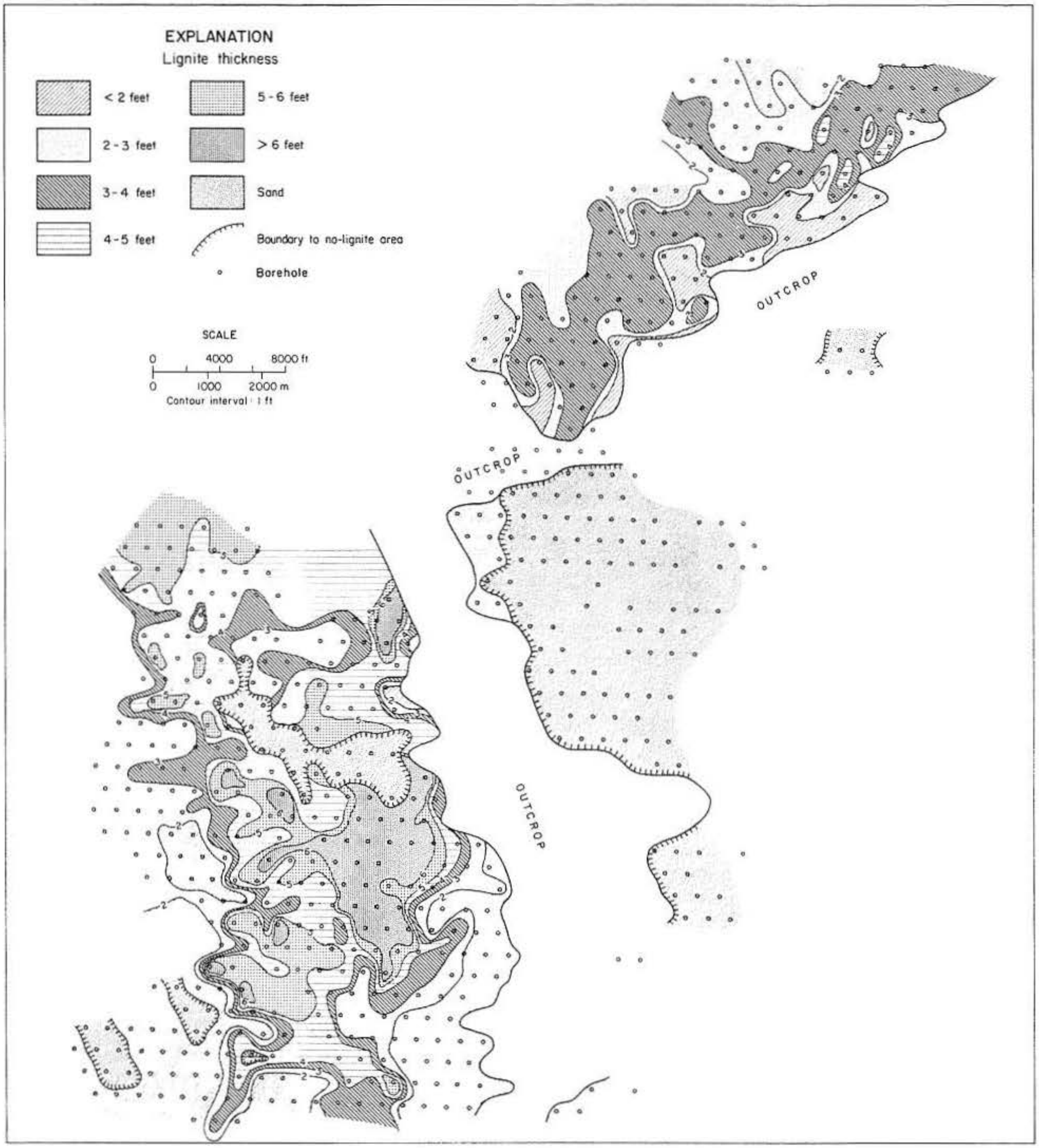


Figure 19. Isopach map of seam no. 3, alluvial plain deposit, Wilcox Group of East Texas.

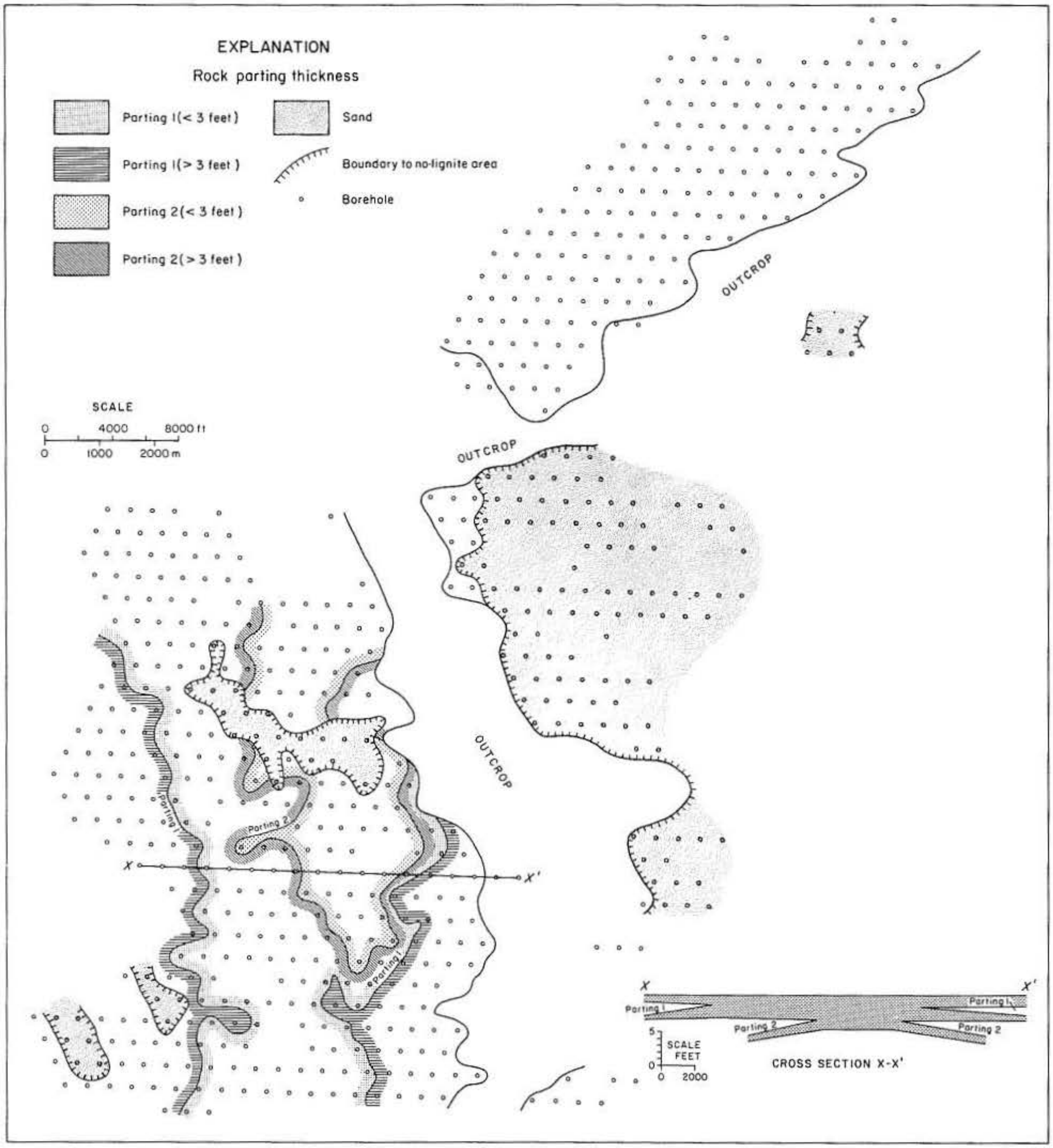


Figure 20. Areal distribution and thickness of the clastic partings within seam no. 3, alluvial plain deposit, Wilcox Group of East Texas.

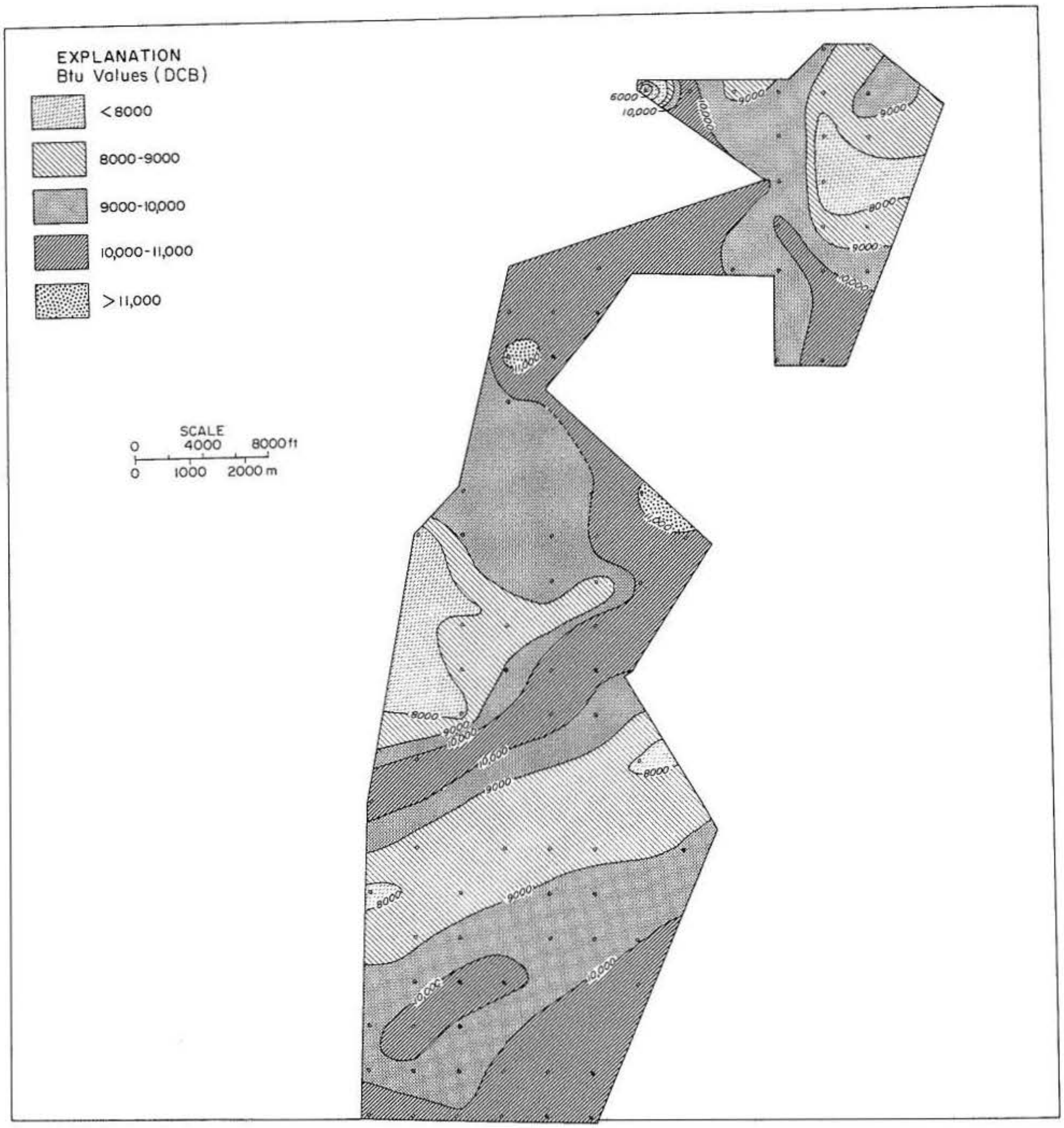


Figure 21. Isoline map of Btu values on a dry coal basis for seam no. 6, alluvial plain deposit, Wilcox Group of East Texas.

Figure 22. Isoline map of ash percent on a dry coal basis for seam no. 6, alluvial plain deposit, Wilcox Group of East Texas.

Figure 23. Locations of cross sections A-A' and B-B' and spatial arrangement of boreholes, Wilcox Group of east-central Texas.

interval. Four seams were identified and correlated over the deposit. From top to bottom these seams are numbered 89 and 90, with a rider (90a) and hanger (90b). Uncertainties in seam correlation arose from the scouring effect of channel sands, undulations in seam relief, and the limited drilling depth coupled with a regional dip of 1.7 degrees. The cross sections show that seams no. 90 and 90b are continuous over the deposit and that the main lignite interval is 37 to 18 m (120 to 60 ft) thick.

Three basic geophysical log patterns as seen on the cross sections characterize the sediments of the main lignite interval and represent the different facies of the lower alluvial/upper delta plain environment. The blocky and upward-fining sawtooth pattern commonly occurring above seam no. 89 and occasionally directly above seam no. 90 is interpreted as being sand with intervening silt and clay layers. This facies probably accumulated in fluvial channels of the lower alluvial/upper delta plain transition. Similar facies, with scoured bases and fine-grained tops, have been described from meandering river systems of modern rivers and deltas (Bernard and others, 1970).

The inverted "Christmas tree" log patterns are interpreted as upward-coarsening sequences from laminated clay to silt to fine-grained sand. Two different kinds of sequences occur. The more common type has stacked inverted "Christmas trees" that are often capped by hard streaks (calcite and siderite). The less common type is a single, thick, upward-coarsening sequence that is often capped by lignite. These laminated sediments are deposits of interchannel lakes, floodplains, or interdistributary bays. Sand is attributed to overbank flooding.

Depositional setting of host sediments.—Maps of interburden thickness were constructed by the computer for the interval between seams no. 90b and 90 (fig. 26); the interval between seams no. 90 and 90a (fig. 27); and the interval between seams no. 90 or 90a and 89 (fig. 28). Thickness distributions of the interburden reflected on these maps display lobate to channel-like patterns oriented in both strike and dip directions. Strike-oriented lobate patterns reflect the distal and proximal margins of crevasse splays, which range in width from 3,658 m (12,000 ft) to 274 m (900 ft). Dip-oriented patterns probably represent once active channels.

Depositional setting of lignite seams.—Computer-generated isopach maps for two lignite seams were prepared. Because of the thin laterally discontinuous interval between seam no. 90 and its rider seam no. 90a (fig. 29), the two seams were mapped together. Dip-oriented lobate features present in the seam map correspond to lobate features in the underlying parting map (fig. 26), thinner lignite corresponding to areas of thicker partings. Upon gradual redevelopment of a pre-splay swamp, the thickest

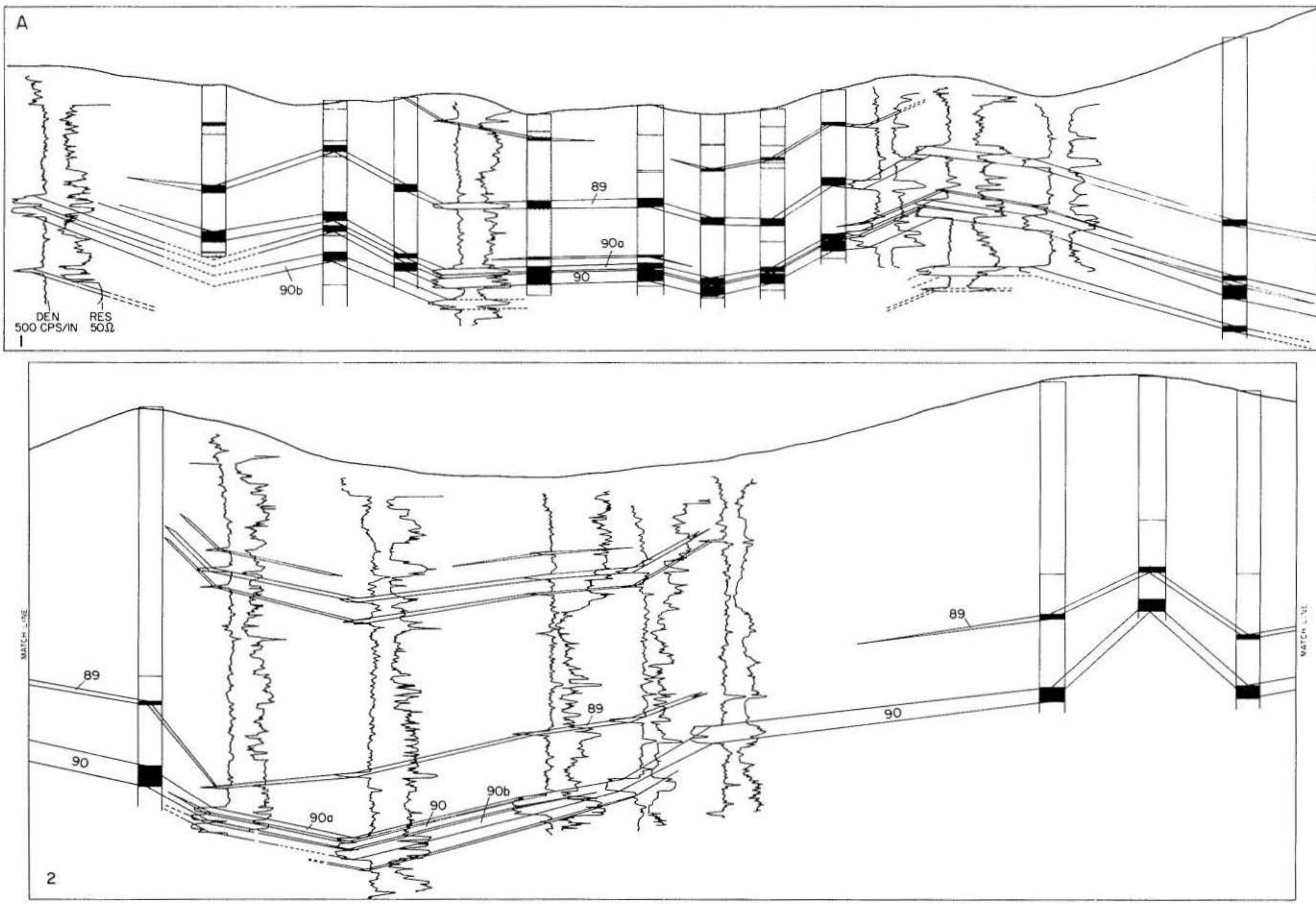
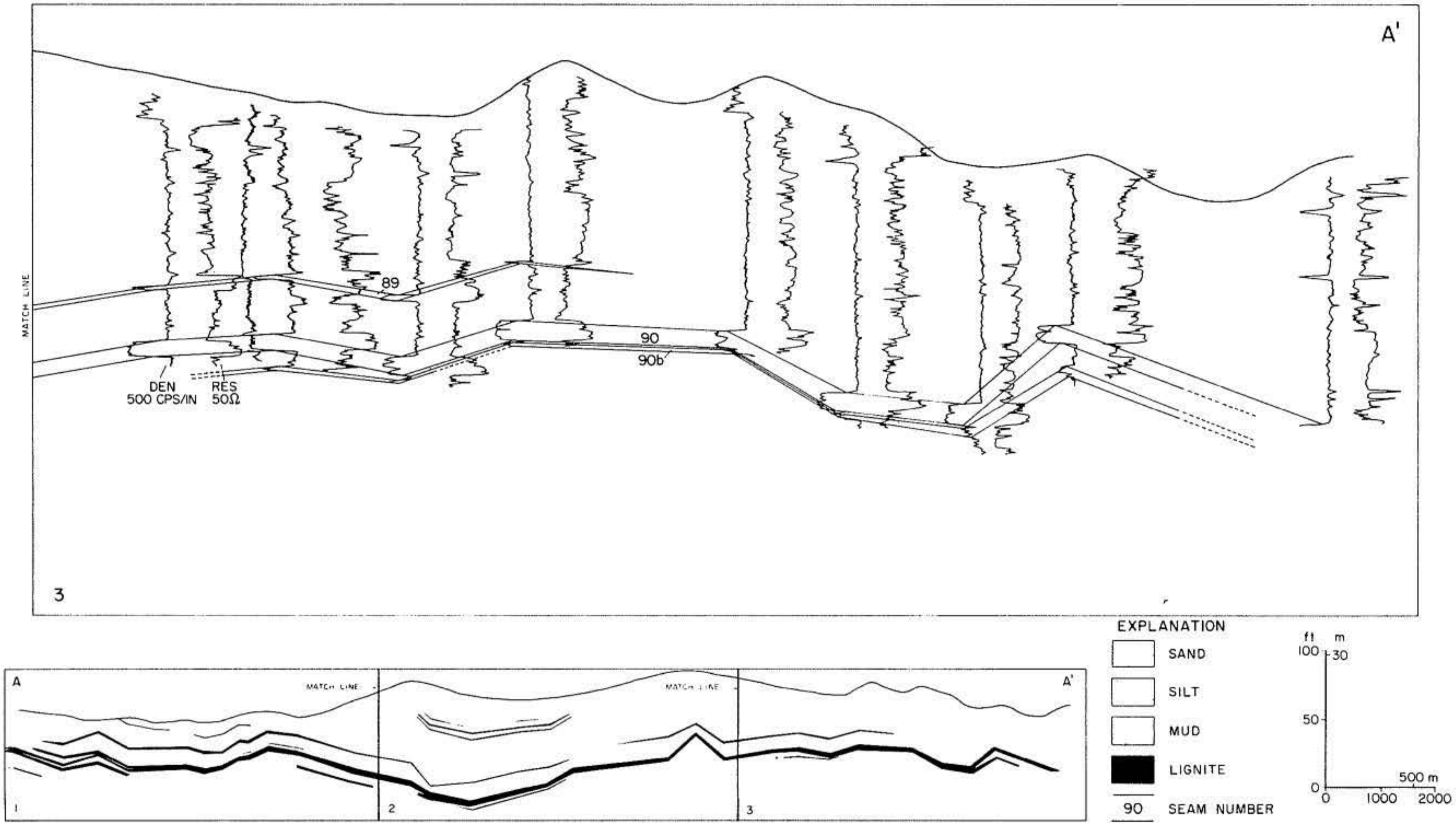


Figure 24. Strike-oriented cross section A-A′, Wilcox Group of east-central Texas.



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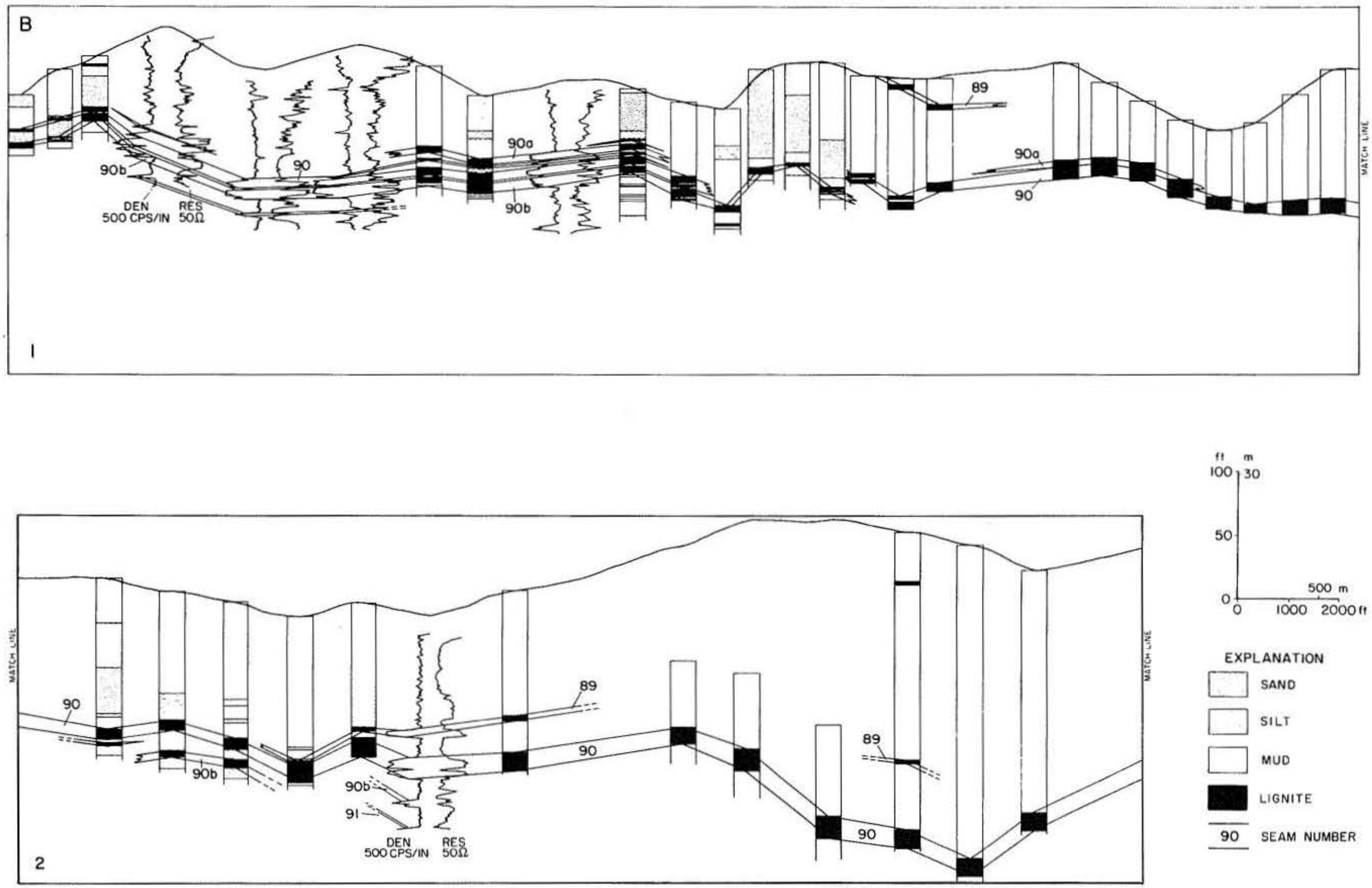
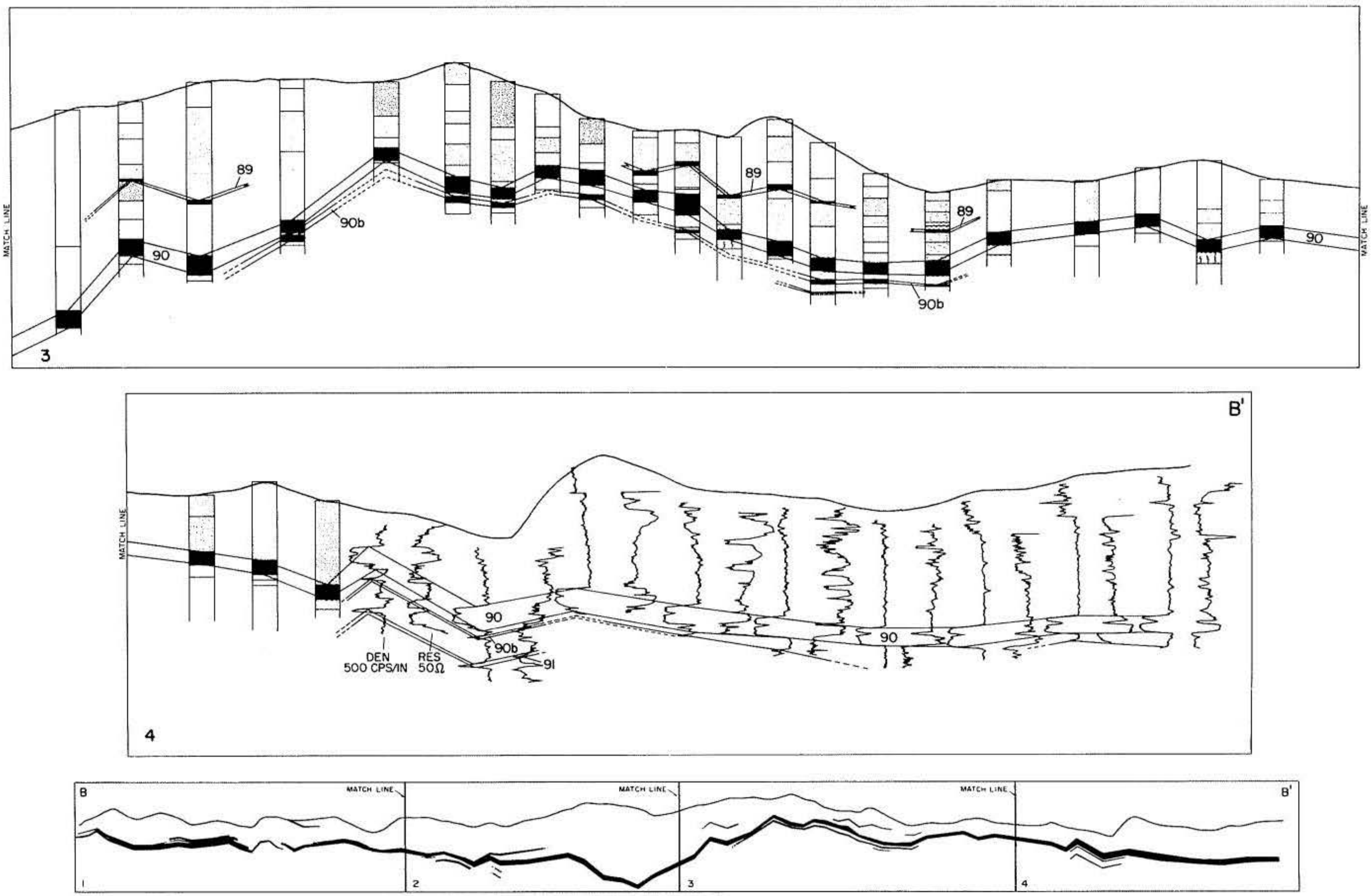


Figure 25. Strike-oriented cross section B-B', Wilcox Group of east-central Texas.



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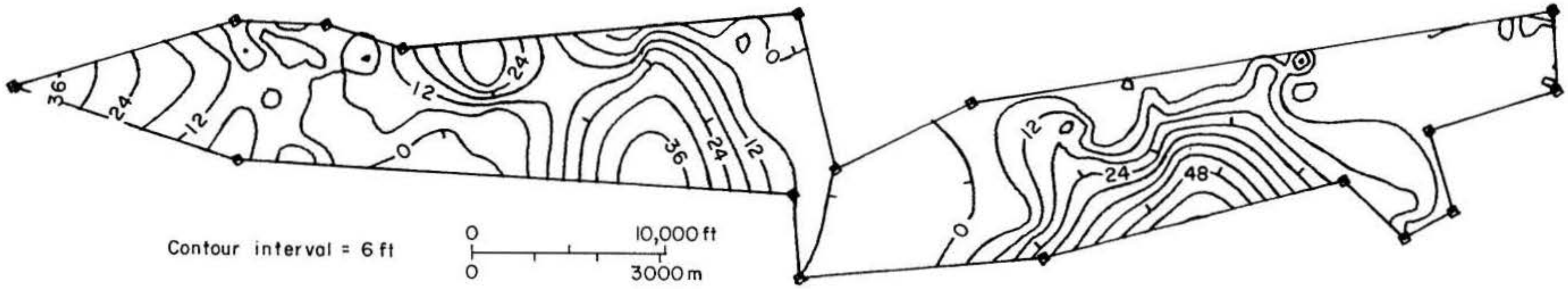


Figure 26. Isopach map of interburden thickness between seams no. 90 and 90b, Wilcox Group of east-central Texas.

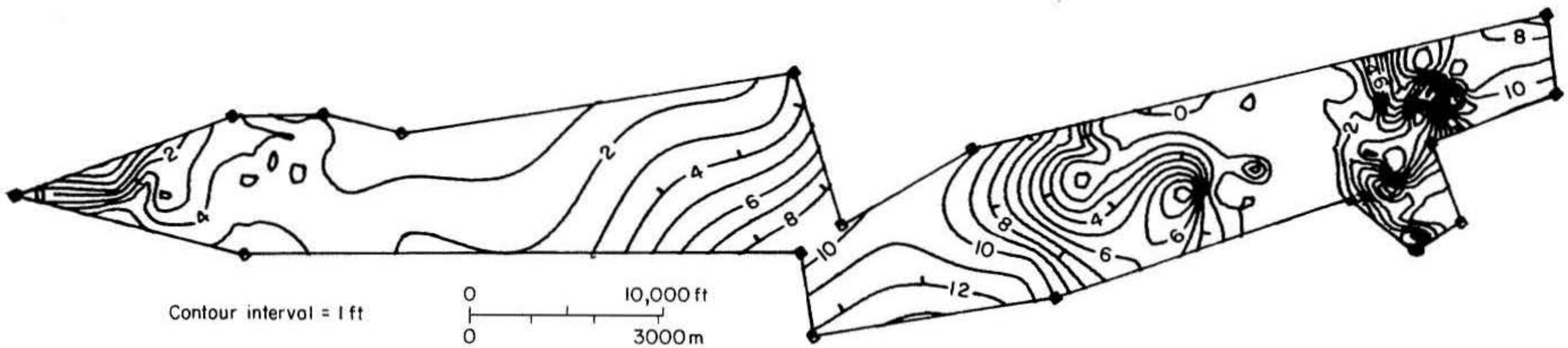


Figure 27. Isopach map of interburden thickness between seams no. 90 and 90a, Wilcox Group of east-central Texas.

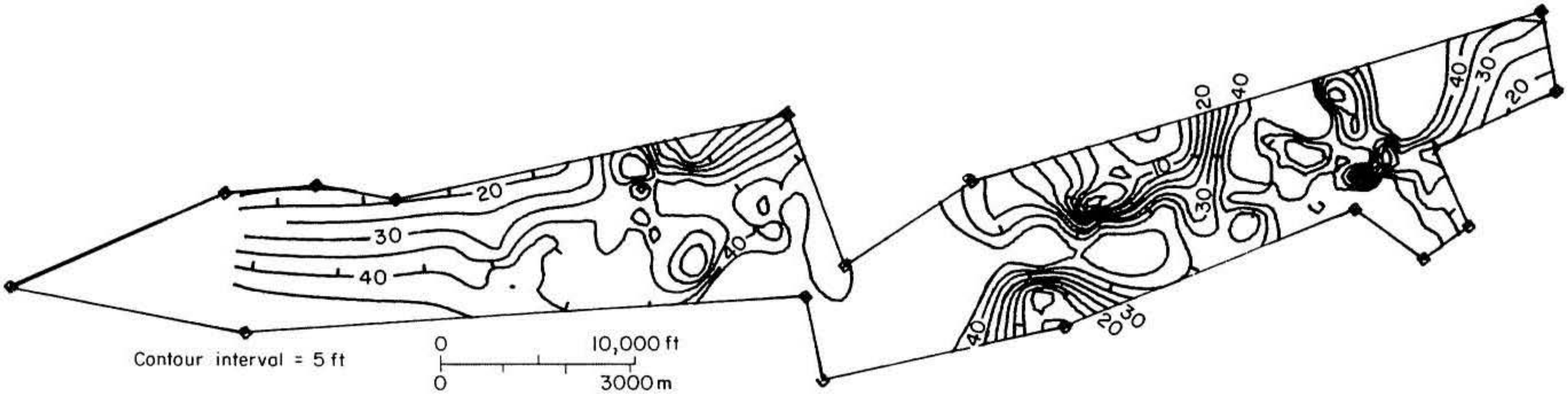


Figure 28. Isopach map of interburden thickness between seams no. 90/90a and 89, Wilcox Group of east-central Texas.

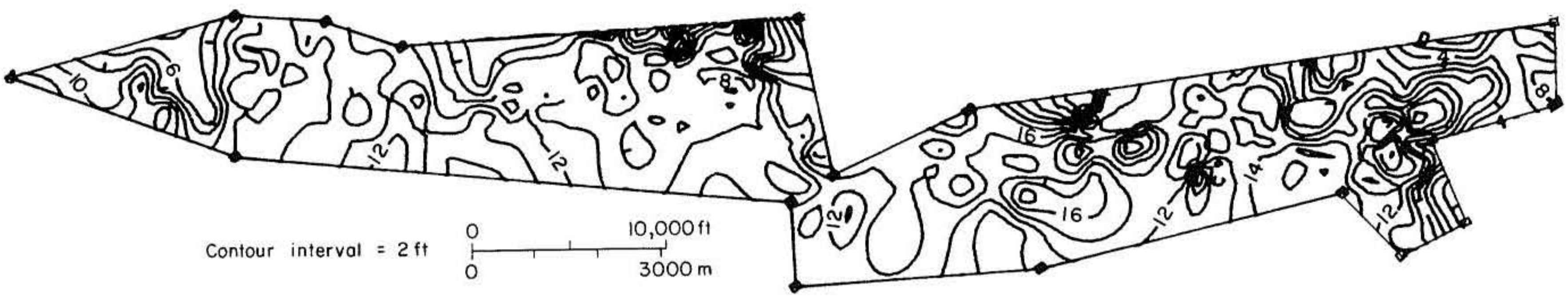


Figure 29. Isopach map of seams no. 90 and 90a, Wilcox Group of east-central Texas.

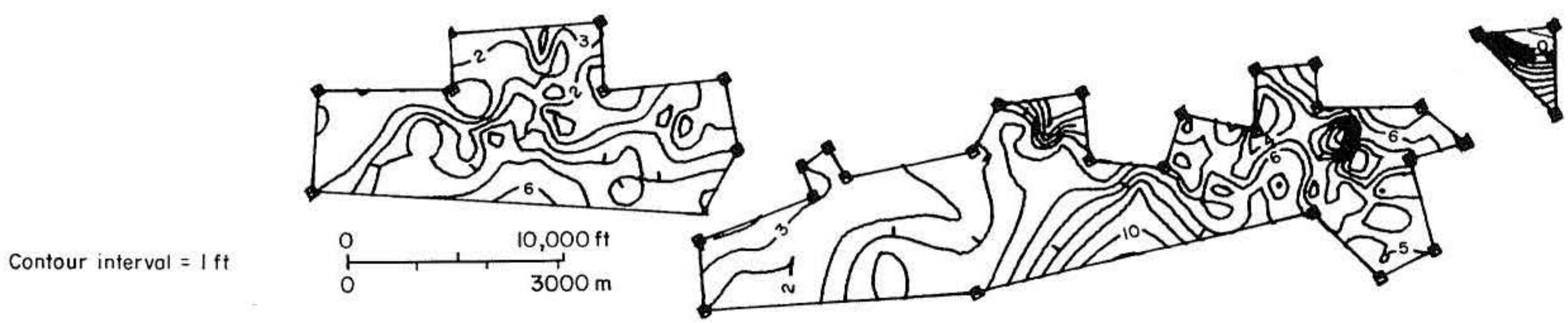


Figure 30. Isopach map of seam no. 89, Wilcox Group of east-central Texas.

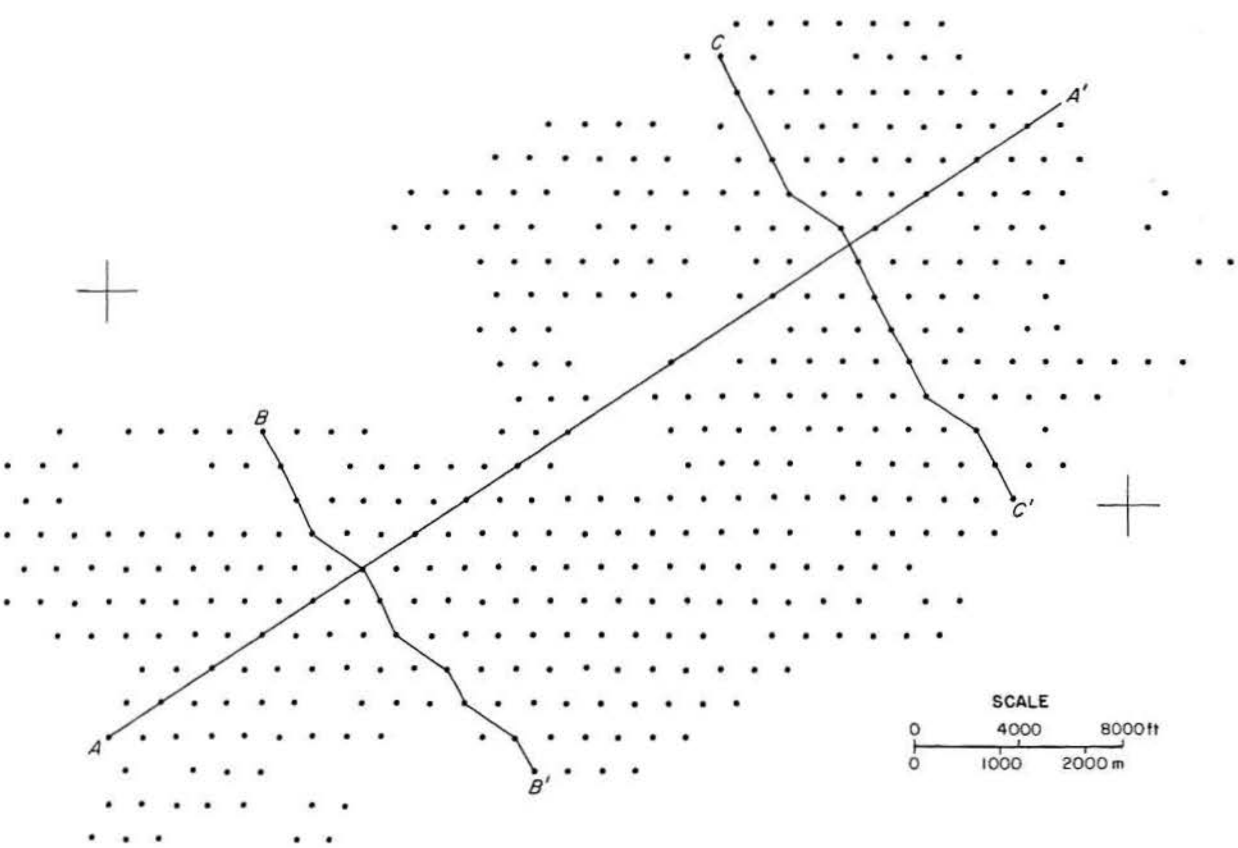


Figure 31. Locations of cross sections A-A', B-B', and C-C', and spatial arrangement of boreholes, lower delta plain deposit, Jackson Group of southeast Texas.

areas of splay are the last to be covered and, thus, become the areas of thinnest coal. The seam is generally continuous throughout the deposit, although at times there are minor reductions in seam thickness due to scouring of the seam by overlying channel sands. Thicknesses of this seam range from 1.5 to 5.2 m (5 to 17 ft). The discontinuity of seam no. 89 (fig. 30) is a function of the overlying channel sand that removed much of the lignite. A slightly lobate pattern is reflected in the thickness distributions, whereas only a weak correspondence exists between these features and those lobate features reflected in the underlying interburden map (fig. 28).

Summary of Geologic Features

The alluvial plain/delta plain transitional environment is characterized by fewer high sand-percent channels than are found in the alluvial plain setting of East Texas. Features of the transitional environment are thick seam continuity, fine-grained material overlying and underlying the thickest seam, possibly representing floodplain or interchannel deposits, and continuity of seam partings having a lobate areal distribution indicative of crevasse splays.

Depositional Setting—Lower Delta Plain

Introduction

The densely drilled deposit chosen for evaluation consists of 3,723 hectares (9,200 acres) situated along the Jackson lignite outcrop in southeast Texas. Five hundred seventeen boreholes with an average spacing of about 351 m (1,150 ft) and a limited number of chemical analyses, consisting of as-received Btu values, were available. The seams described in this deposit have been numbered from top to bottom: seam no. 4, seam no. 8, seam no. 3, seam no. 2, seam no. 7, seam no. 1, and seam no. 0.

Geologic Evaluation

Cross sections.—The most readily apparent feature of the cross sections (figs. 31, 32, 33, and 34) is the continuity of the thicker lignite seams. Thinner seams 0.3 to 0.6 m (1 to 2 ft) thick are markedly less continuous. Seam continuity imparts a high degree of certainty to seam-by-seam correlations over the area.

The two dip sections (figs. 33 and 34) also typify the multi-seam character of the deposit. Eight of the thicker seams and one thin seam were correlated and assigned seam numbers. A histogram of seam thickness versus the percentage of total seam population (fig. 35)

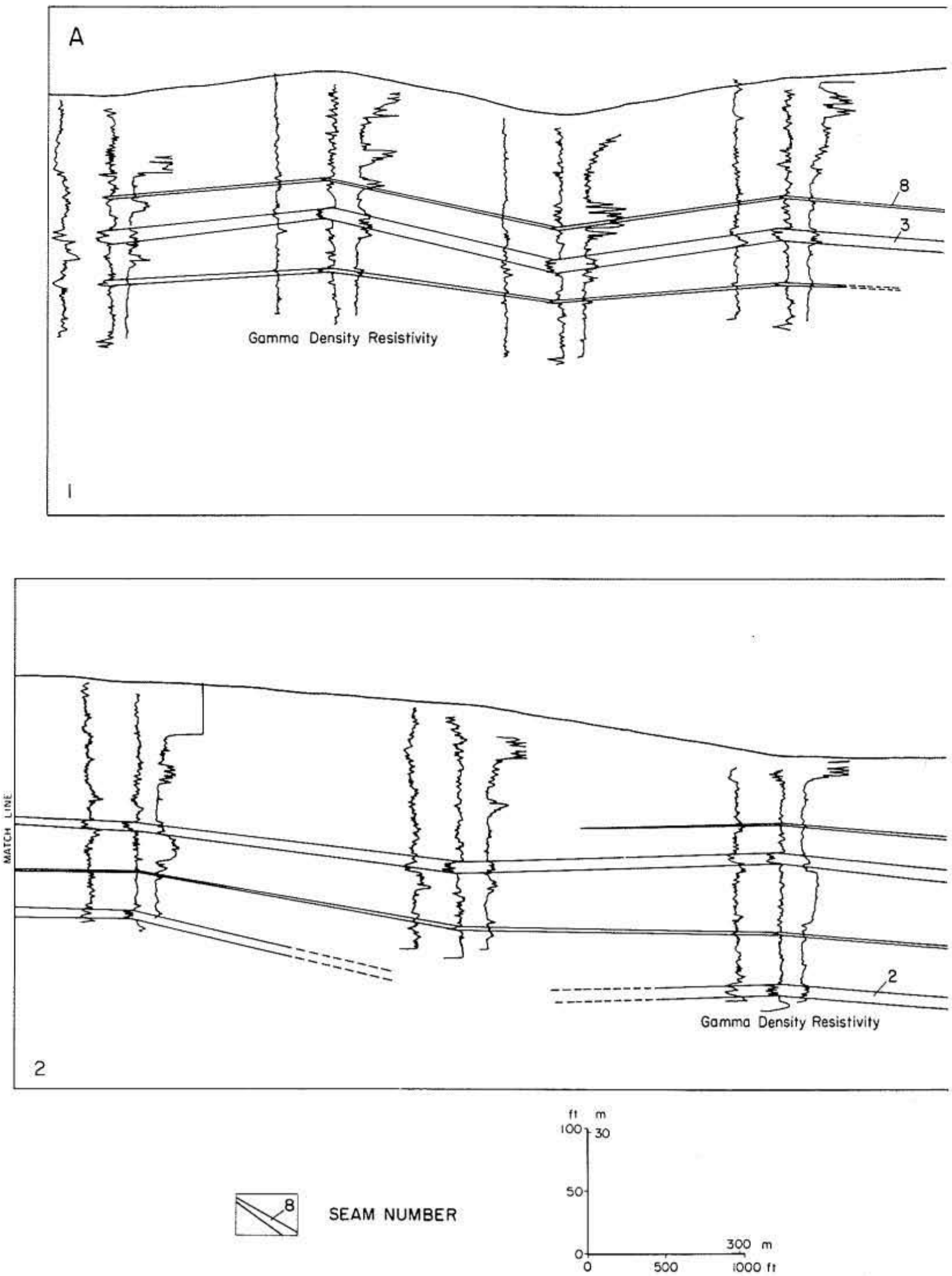
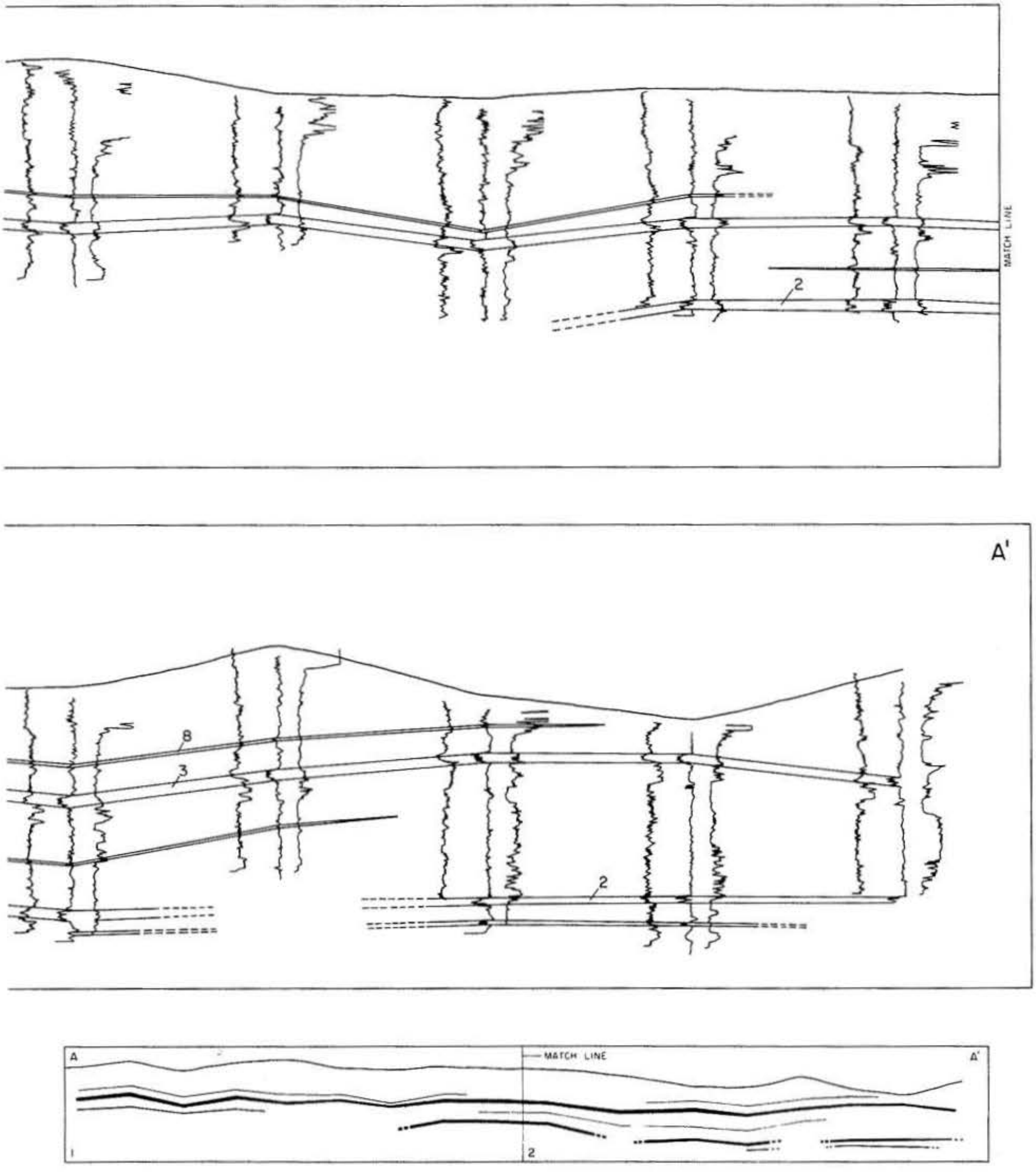


Figure 32. Strike-oriented cross section A-A′, lower delta plain deposit, Jackson Group of southeast Texas.



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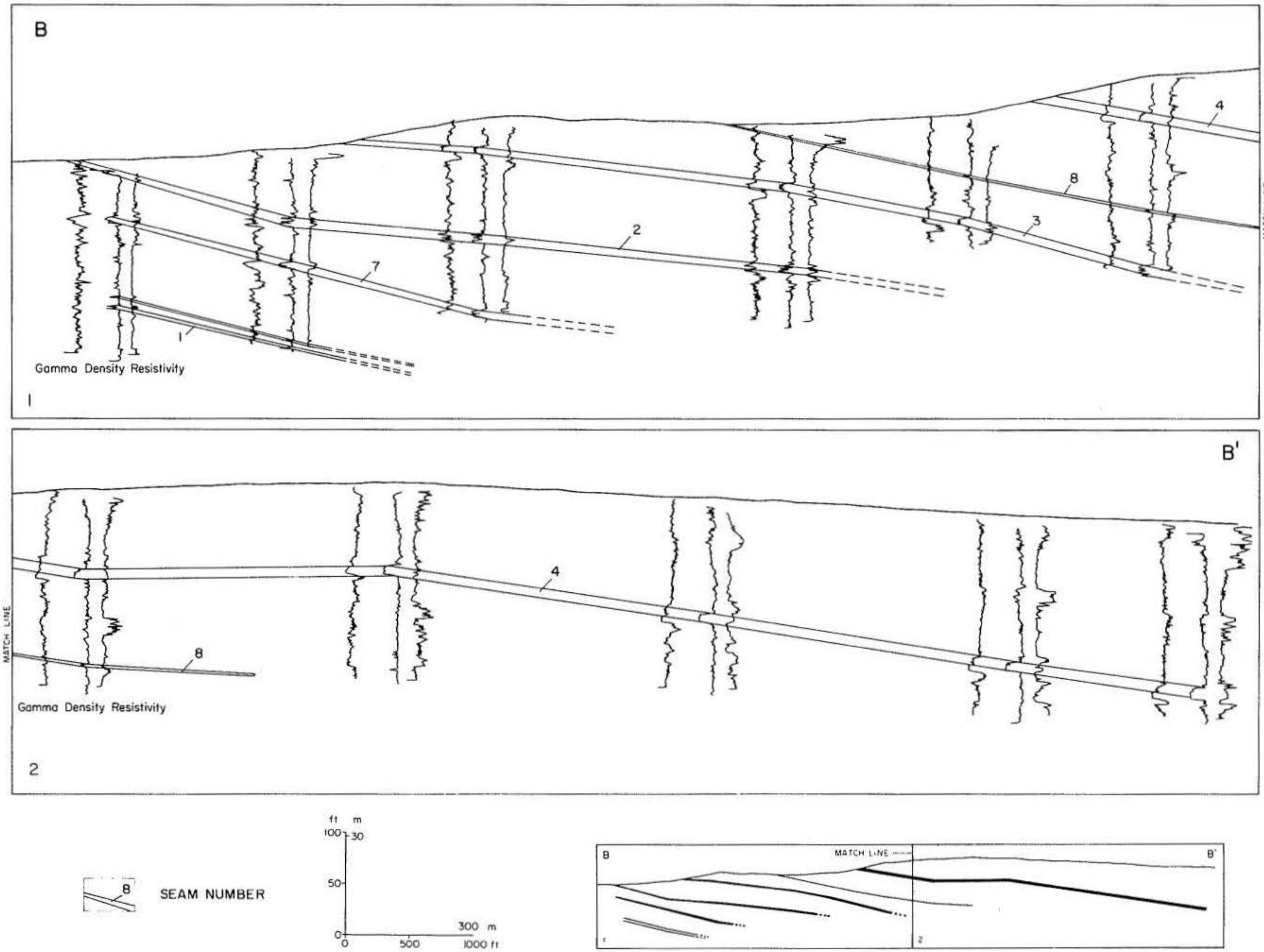


Figure 33. Dip-oriented cross section B-B′, lower delta plain deposit, Jackson Group of southeast Texas.

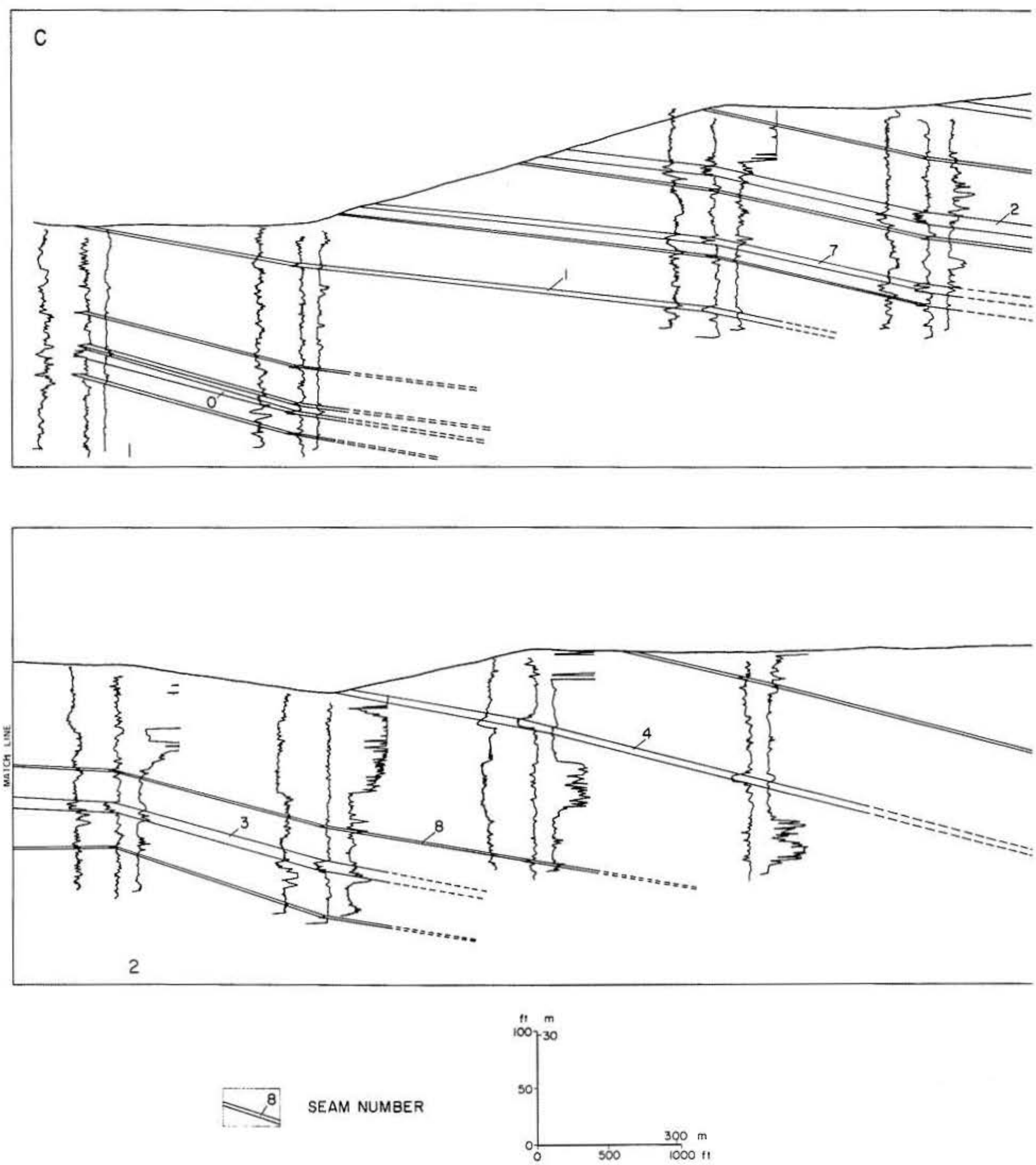
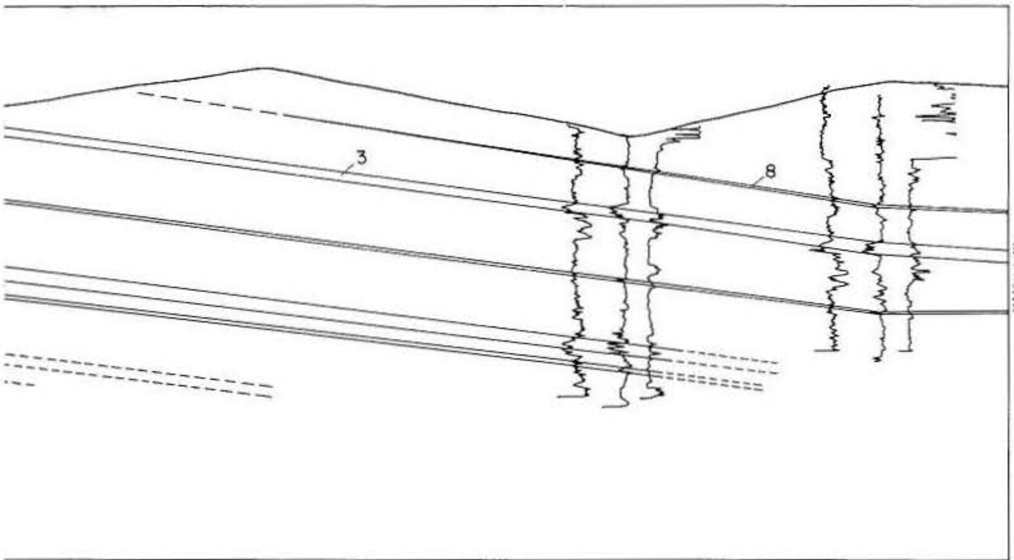
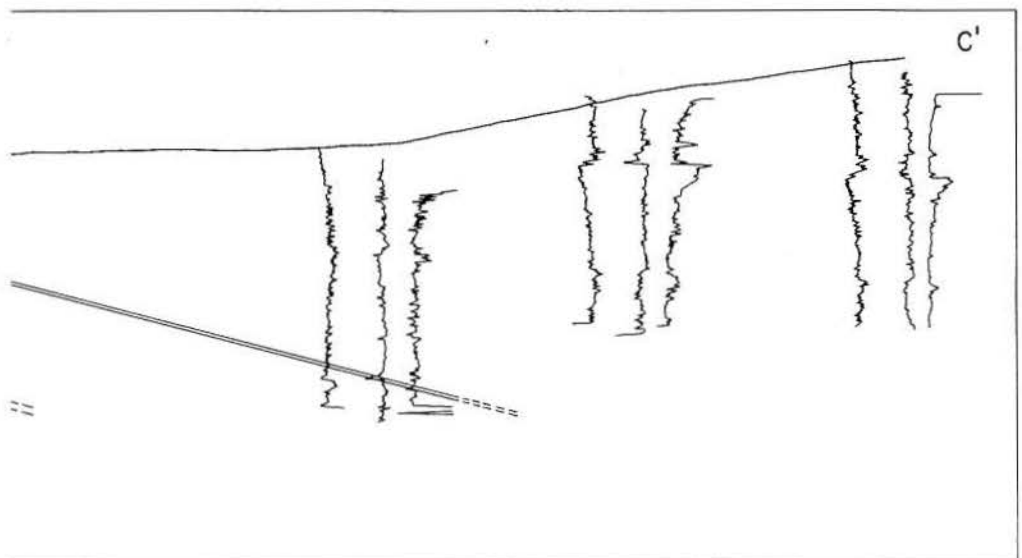
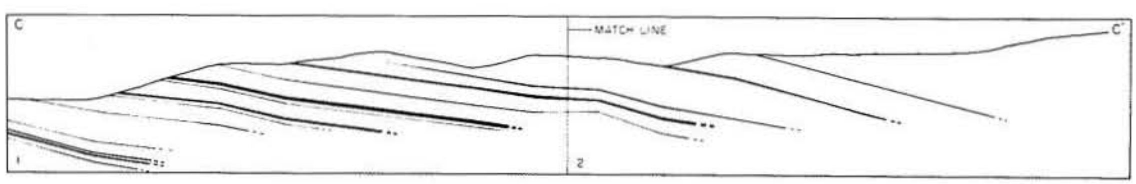


Figure 34. Dip-oriented cross section C-C', lower delta plain deposit, Jackson Group of southeast Texas.







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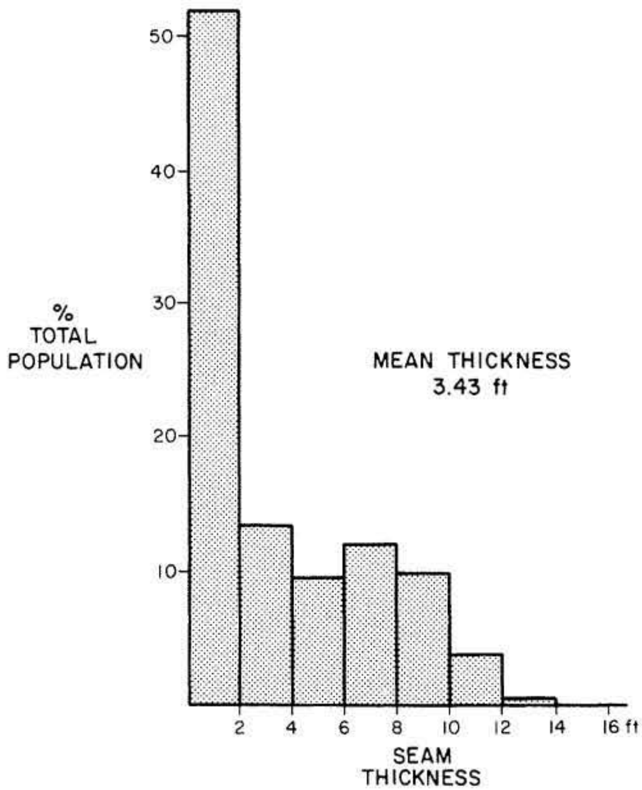


Figure 35. Histogram of seam thickness vs. percentage of total seam population, lower delta plain deposit, Jackson Group of southeast Texas.

demonstrates a bimodal population that is skewed toward the thinner seams. More than 50 percent of the lignite seams in this environment are less than or equal to 0.6 m (2 ft) thick. Closer inspection of the dip-oriented cross sections indicates that more and thinner seams are present in the lower or older part of the stratigraphic column than in the overlying section. In addition, seams no. 0, 1, and 7, which represent the older part of the column, contain more and thicker partings than the younger overlying seams.

The bimodal distribution of lignite seam thicknesses indicates two phases of lignite deposition. Thin seams represent deposition in small interdistributary areas. Sands present in these predominantly muddy intervals are very localized, not laterally continuous, and probably represent small distributary channels. In this type of environment, levees along distributary channels are small and more susceptible to overbank flooding and crevassing.

The thicker coals in the section appear to represent deposition of lignite during periods of abandonment of the delta lobe. The thicker coals are continuous, indicative of a blanket type of peat formation. These coals always occur directly above a thin mud interval that commonly overlies a sandy unit, and they apparently provided a medium for extensive plant growth. Also, the younger, thicker lignite seams contain considerably fewer partings, indicating a more stable environment, less affected by sediment influx. Much thicker and more laterally extensive sands are also present in the younger part of the section. These sands probably represent a series of distributary channel sands and mouth bars that continued their progradation over the more distal interdistributary system. These channel-mouth bars and delta-front sands eventually merged to form a single extensive sheet sand on which thick lignite seams could be deposited during periods of decreased sediment input or upon lobe abandonment. The cross sections imply progradation of the delta lobe through time.

Depositional setting of lignite seams.—Seam isopach maps were constructed for three thick seams (nos. 2, 3, and 4) and one thin seam (no. 8). Isopach maps for seams no. 2 (fig. 36), no. 3 (fig. 37), and no. 4 (fig. 38) indicate continuous lignite beds with thicknesses ranging from 0.6 to 3.4 m (2 to 11 ft), 1 to 3 m (3 to 11 ft), and 0.6 to 4 m (2 to 13 ft), respectively. In addition, figure 39 shows that the main axis for deposition of thicker lignite has remained constant for all three seams, which implies some type of control by underlying sediments on these seams. The decrease in lobate character of lignite thickness distributions in the upper part of the section indicates delta progradation and a more landward position of seam no. 4 on the delta plain than seam no. 2.

Lignite seam no. 8 (fig. 40) ranges in thickness from 0.2 to 0.6 m (0.5 to 2.0 ft). Seam no. 8, like the other thin seams in this deposit, is discontinuous and appears to represent deposition in a small interdistributary area during periods of contemporaneous deltation. The linear mud- and sand-filled features indicate contemporaneous scouring. Small, circular, no-lignite, mud-dominated areas represent nondeposition of lignite due to slightly greater water depth.

Depositional setting of host sediments.—Total parting thickness maps were constructed for lignite seams no. 2, 3, and 4 (figs. 41, 42, and 43, respectively). Trends presented in these three parting maps indicate that from older to stratigraphically younger seams, there is a decrease in the number of partings, total parting thickness, and lateral continuity of the partings. The direction of sediment source appears to have changed and suggests transition from a position on the lower delta plain, which is affected by sediment influx through tidal channels, to a position higher on the delta plain, which is less affected by marine sediment influx.

Thickness maps were constructed for mud intervals directly underlying seams no. 3 and 4 (figs. 44 and 45, respectively). In both cases, mud units completely underlie the lignites. Thicker lignite generally overlies thinner mud distributions. This may suggest that areas of thicker mud accumulation were watery areas that limited plant growth.

A sand-percent map (fig. 46) was constructed for the interval between seams no. 3 and 4. High sand-percent areas (up to 85 percent sand) were found to display a distinctly lobate, bifurcating pattern reflecting on a much

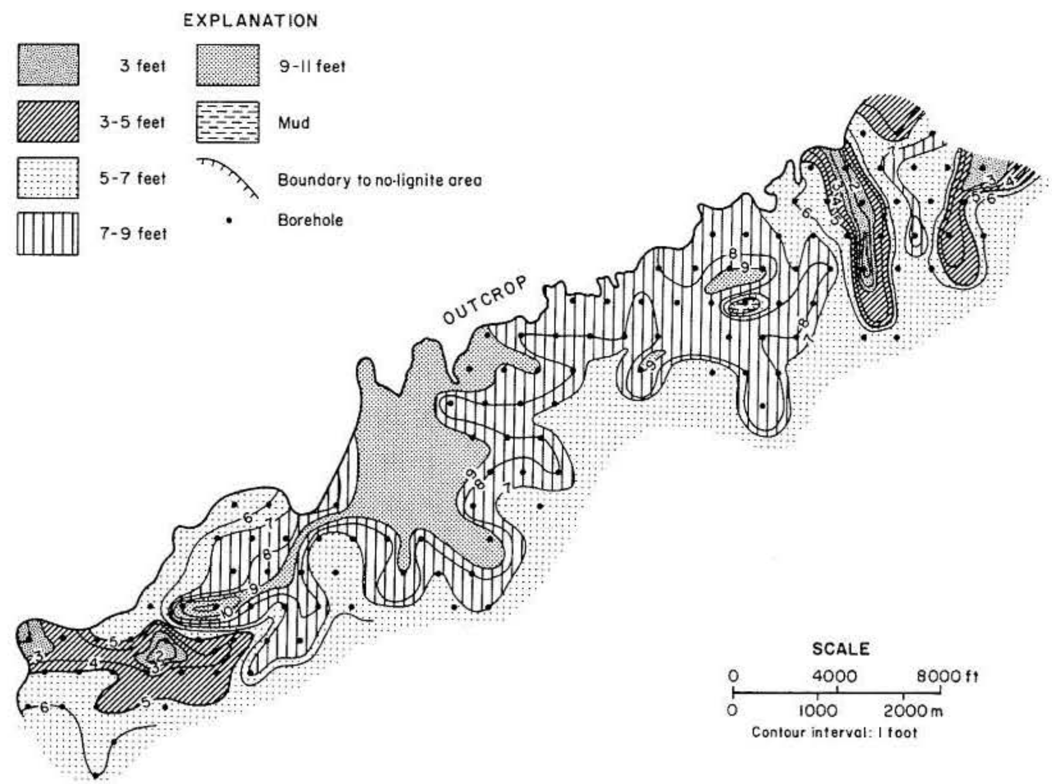


Figure 36. Isopach map of seam no. 2, lower delta plain deposit, Jackson Group of southeast Texas.

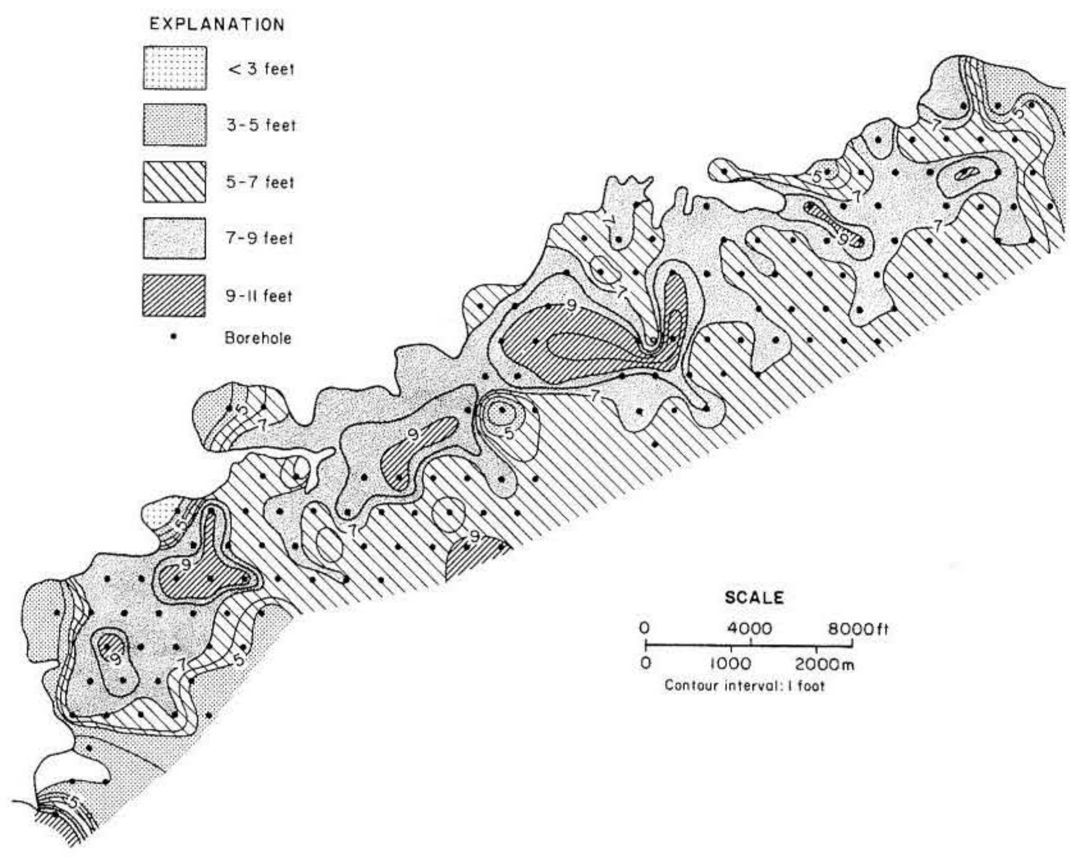


Figure 37. Isopach map of seam no. 3, lower delta plain deposit, Jackson Group of southeast Texas.

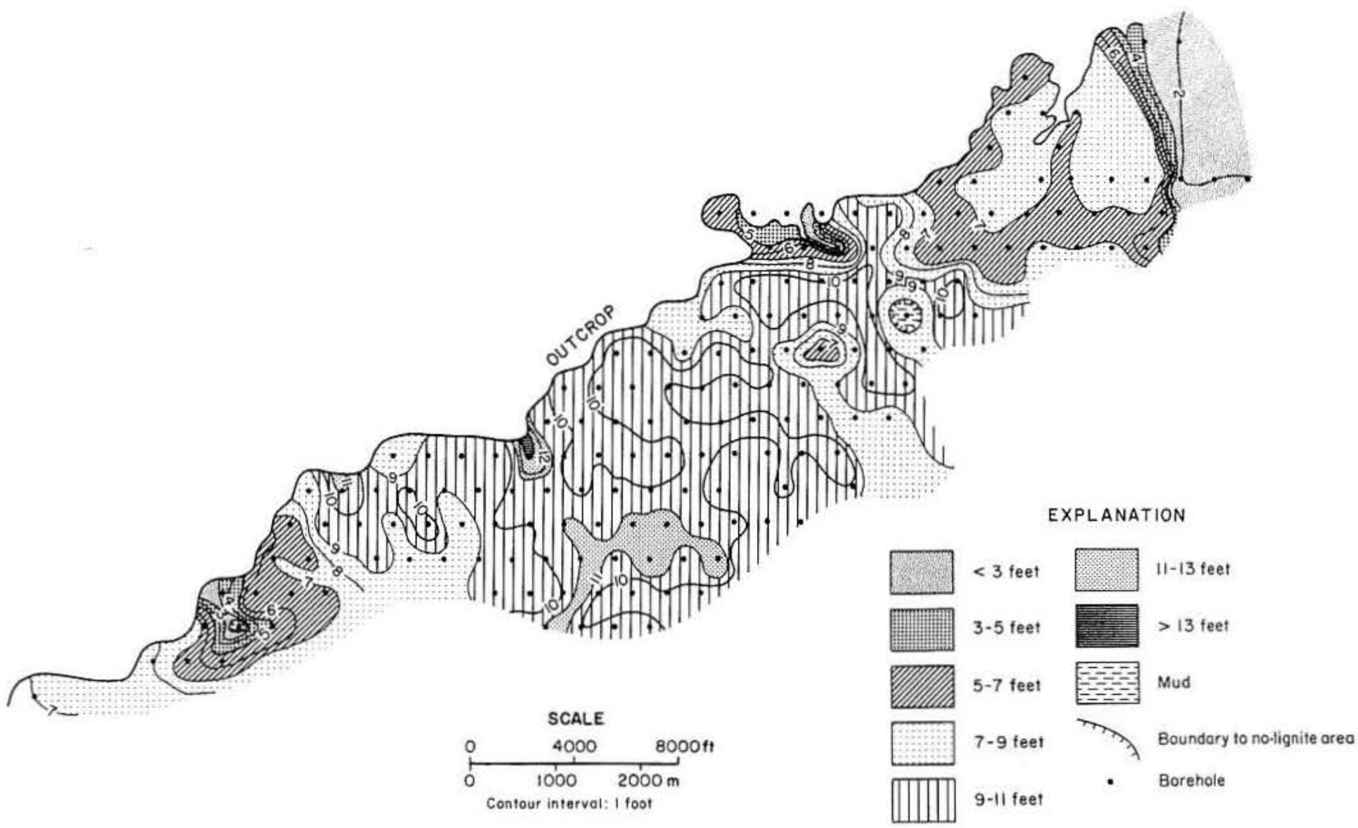


Figure 38. Isopach map of seam no. 4, lower delta plain deposit, Jackson Group of southeast Texas.

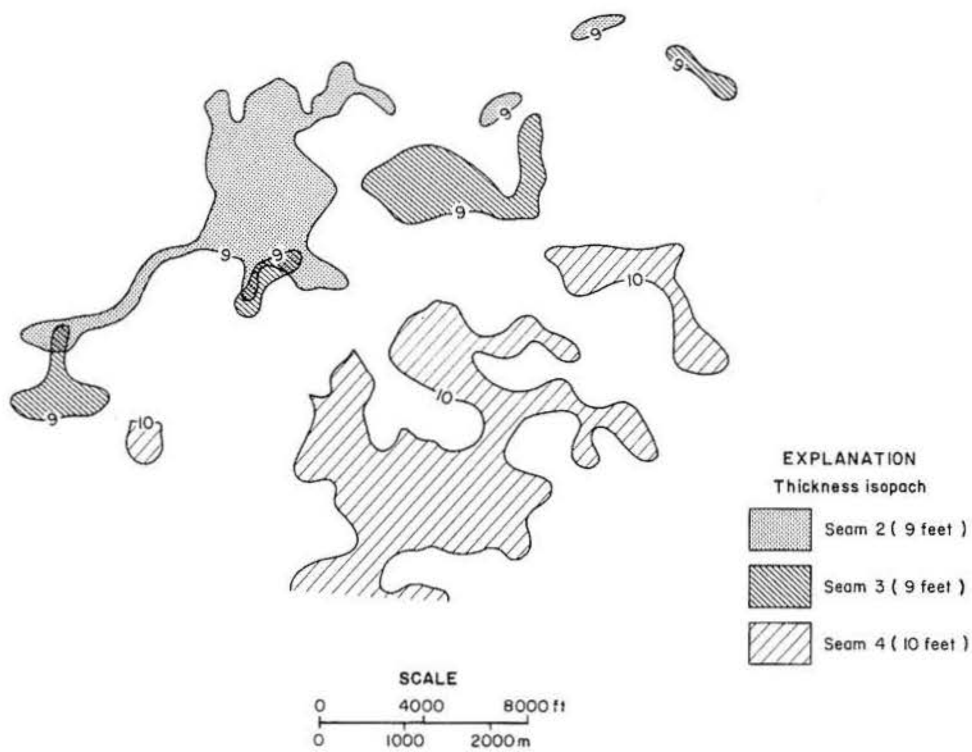


Figure 39. Comparison of locations of thickest lignites in seams no. 2, 3, and 4, lower delta plain deposit, Jackson Group of southeast Texas.

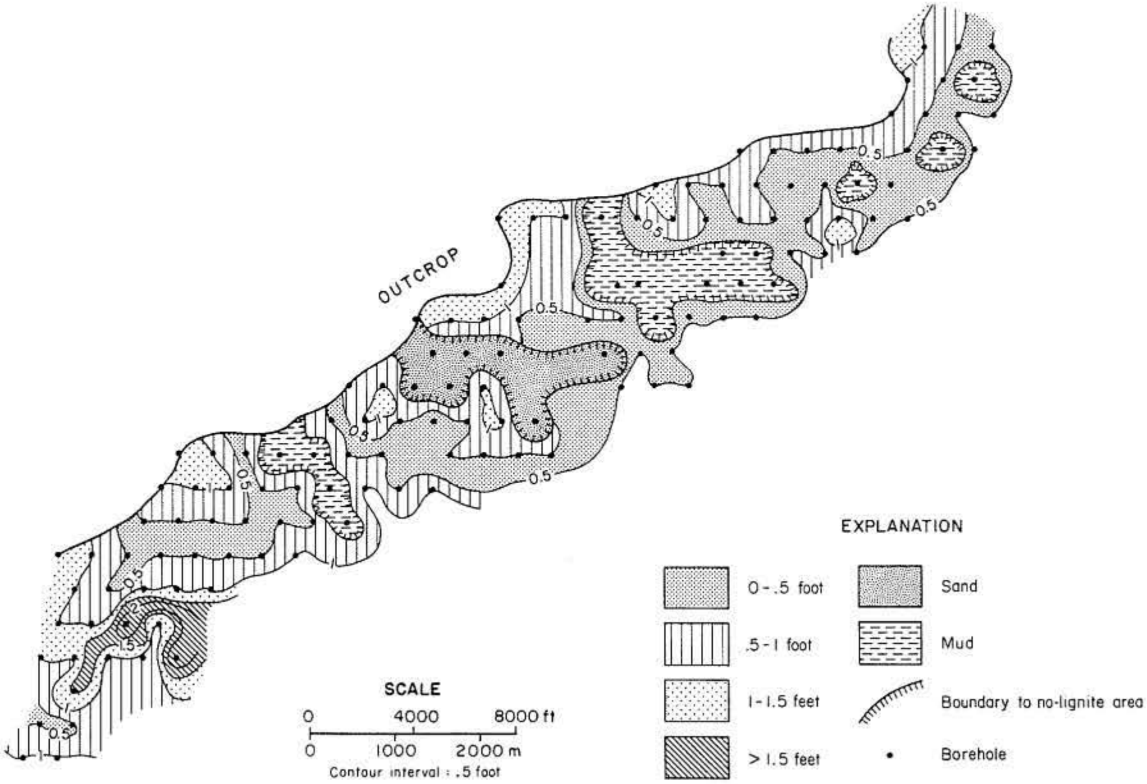


Figure 40. Isopach map of seam no. 8, lower delta plain deposit, Jackson Group of southeast Texas.

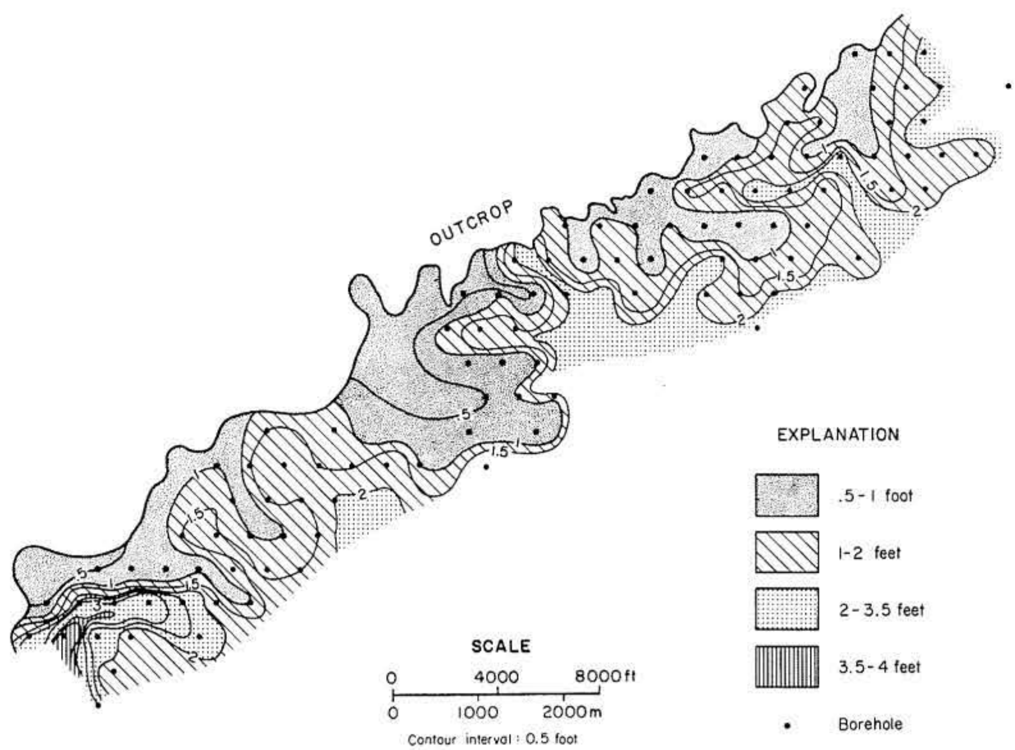


Figure 41. Isopach map of total partings, seam no. 2, lower delta plain deposit, Jackson Group of southeast Texas.

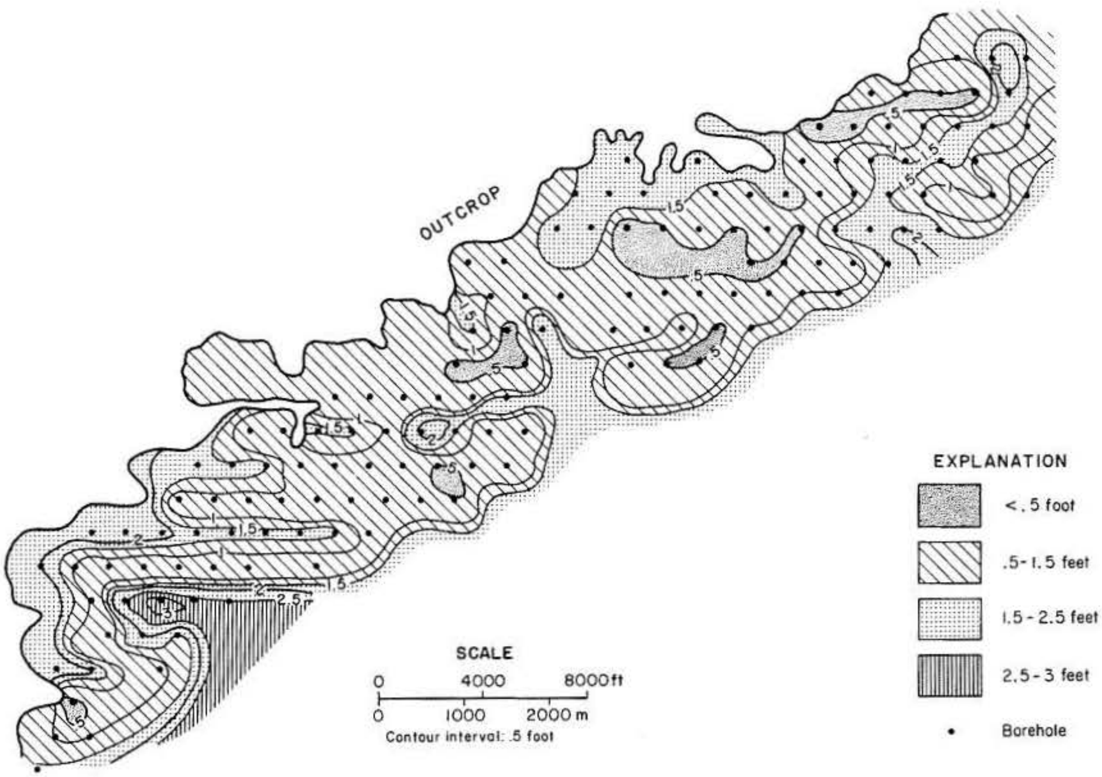


Figure 42. Isopach map of total partings, seam no. 3, lower delta plain deposit, Jackson Group of southeast Texas.

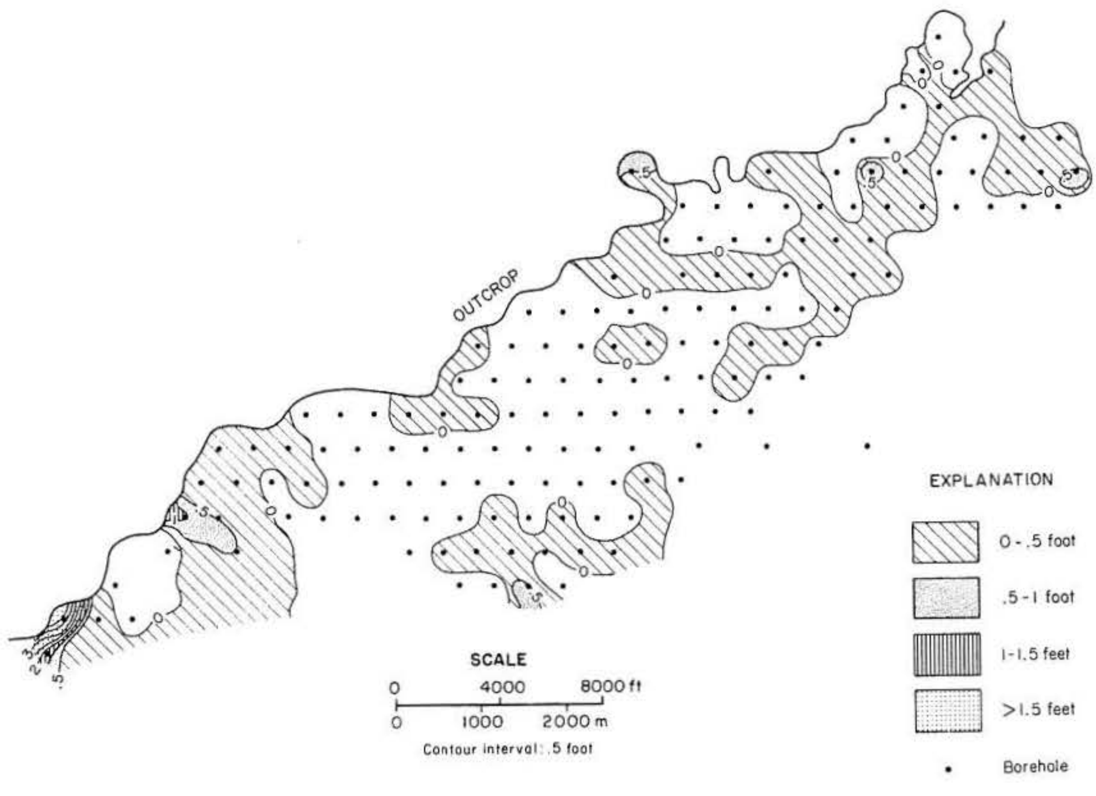


Figure 43. Isopach map of total partings, seam no. 4, lower delta plain deposit, Jackson Group of southeast Texas.

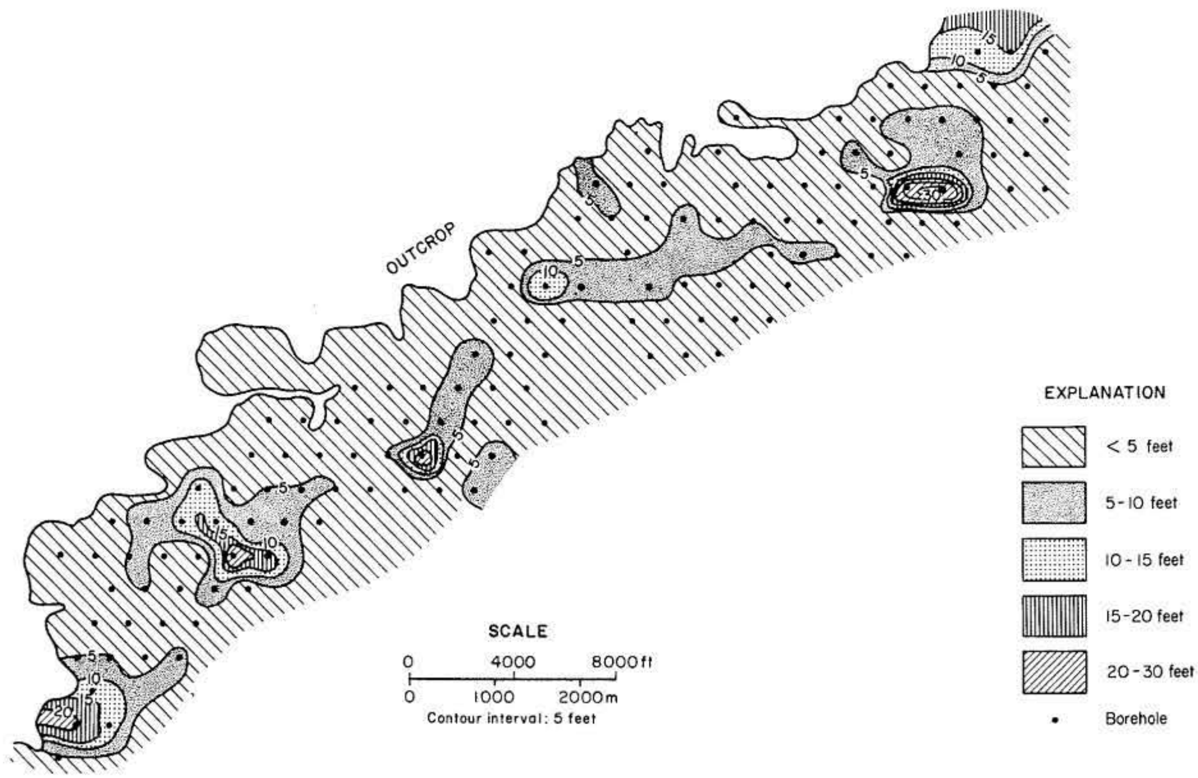


Figure 44. Isopach map of mud interval directly underlying seam no. 3, lower delta plain deposit, Jackson Group of southeast Texas.

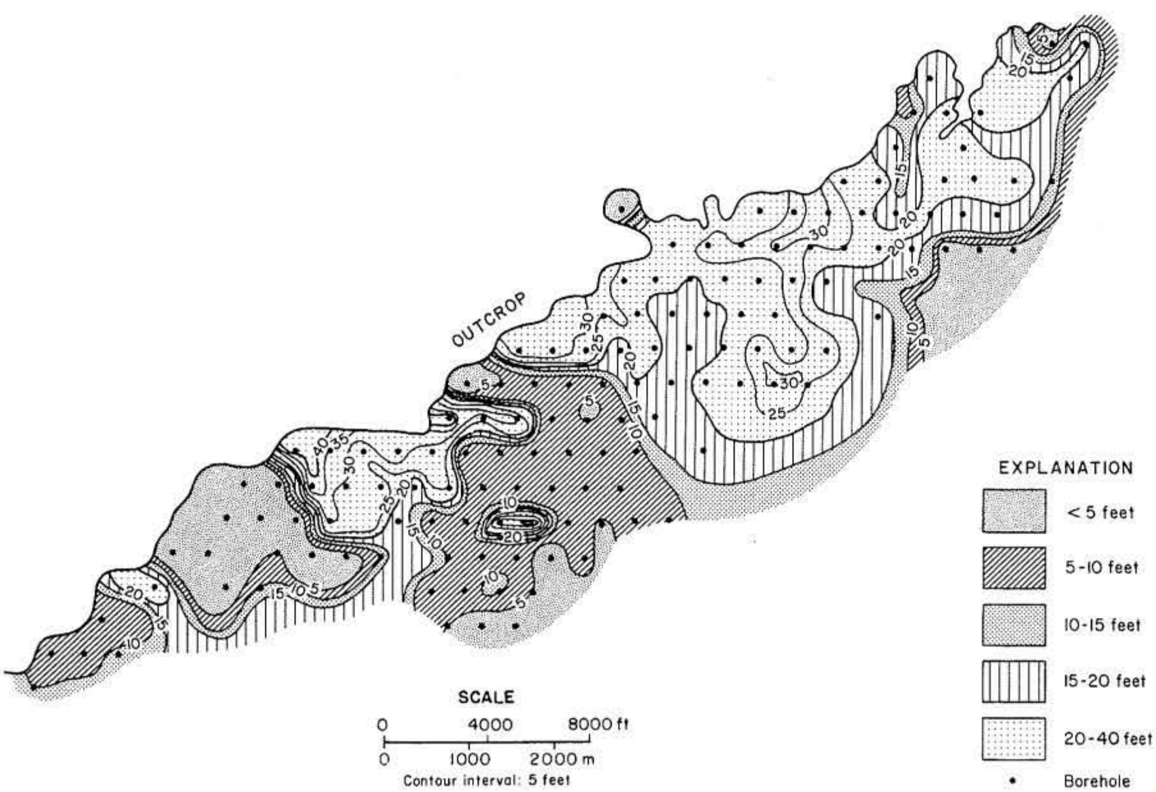


Figure 45. Isopach map of mud interval directly underlying seam no. 4, lower delta plain deposit, Jackson Group of southeast Texas.

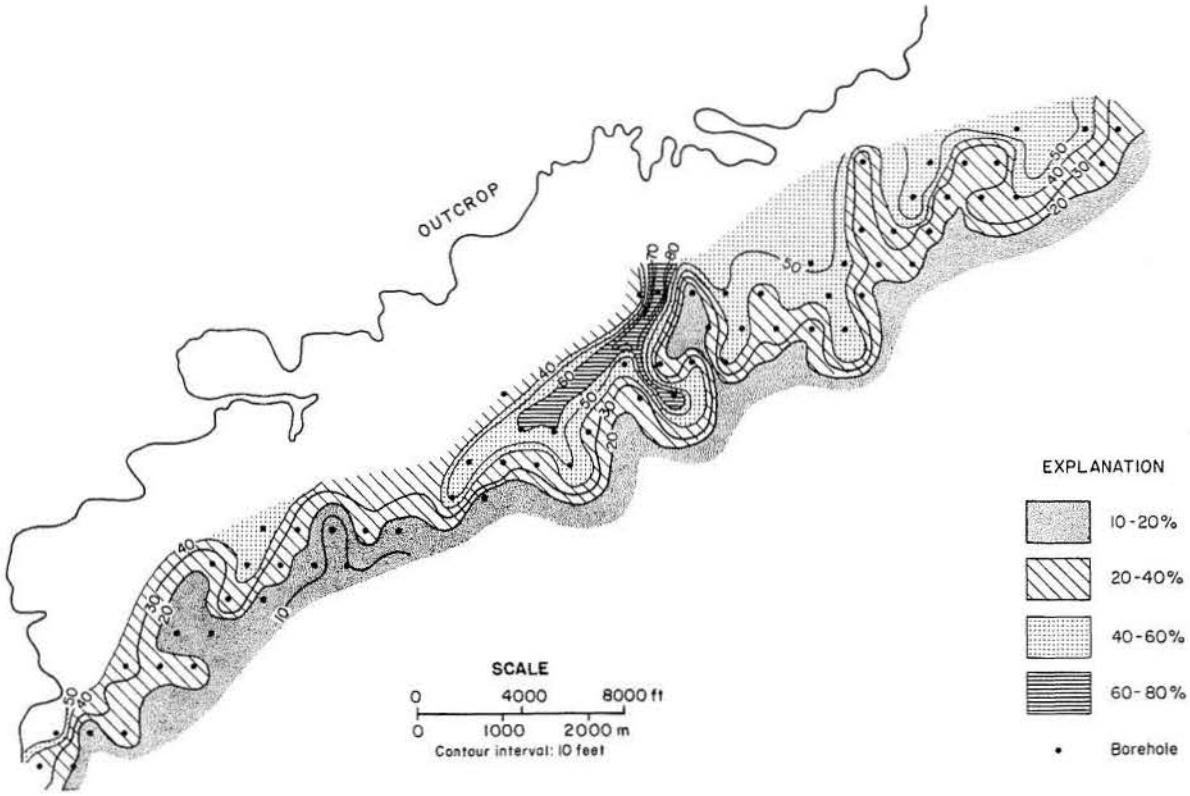


Figure 46. Sand-percent map of interval between seams no. 3 and 4, lower delta plain deposit, Jackson Group of southeast Texas.

smaller scale the overall lobate character or shape of the entire delta system as predicted by the regional model.

Lignite Quality Evaluation

Means and standard deviations for 136 Btu analyses are shown in table 4. Fifty analyses were from lignite seams stratigraphically below and including seam no. 2; 86 analyses were from all lignite seams stratigraphically above seam no. 2.

To determine whether differences between means and standard deviations of the "older" and "younger" seams were significant, the Kolmogorov-Smirnov test was applied to the two distributions. The probability that the two sample distributions came from different parent populations was greater than 0.95. The mean Btu value of the older seams is less than that of the younger seams and has a larger standard deviation. The older seams are thus interpreted as being generally poorer and more variable in quality than the younger seams. Btu values for this deposit tend to substantiate the geologic interpretation that there is a slight change in position on the delta plain from the older seams to the younger.

Summary of Geologic Features

Two distinct processes were involved in the formation of lignites in this lower delta plain environment. Thin, discontinuous lignite seams apparently formed in small interdistributary areas, which were frequently inundated by sediment during overbank flooding and crevassing. Thicker coal seams are laterally continuous and represent lignite deposition during periods of delta lobe abandonment. These thick seams represent blanket peats deposited on sand platforms.

Table 4. Statistical comparison of lignite seams—Jackson lower delta plain.

		All seams	Stratigraphically older seams	Stratigraphically younger seams
Btu (as-	Mean	4,956	4,704	5,103
received)	Std Dev	604	687	490

Depositional Setting—Strandplain/Lagoonal

Introduction

The lower Jackson strandplain/lagoonal deposit of South Texas covers approximately 11,655 hectares (28,799 acres). Available data consist of 255 unevenly distributed boreholes. Depth of the boreholes varies from 6 m (20 ft) updip near the lignite outcrop to 79 m (260 ft) along the downdip limit of drilling.

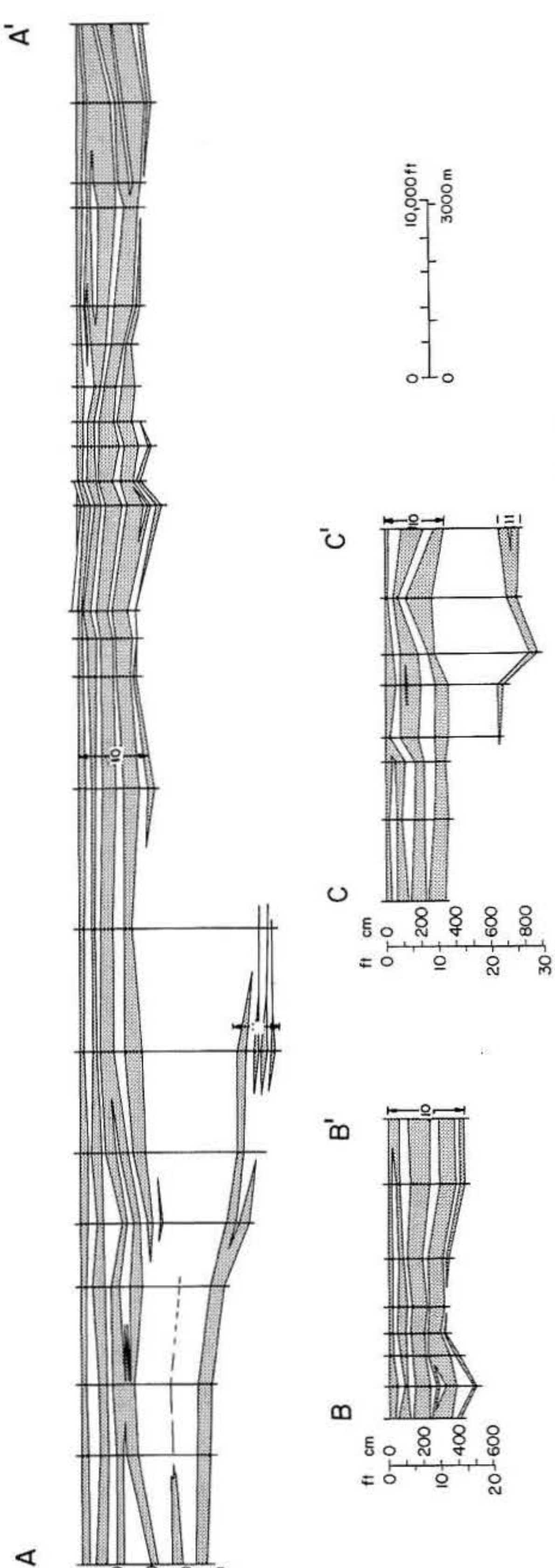


Figure 47. Strike-oriented cross section A-A', and dip-oriented cross sections B-B' and C-C', strandplain/lagoonal deposit, Jackson Group of South Texas.

Geologic Evaluation

Cross sections.—An approximately 4-m-(12-ft)-thick, laterally continuous lignite seam (seam no. 10), containing three to four persistent partings 0.15 to 0.30 m (0.5 to 1 ft) thick, is present throughout the deposit (fig. 47; see fig. 48 for section locations). Dip of the seam averages 0.5 degree southeast. A discontinuous seam occurs 2 m (7 ft) below seam no. 10, averages 0.6 m (2 ft) in thickness, and is present on the left-hand side of cross section A-A'. This seam splits and pinches out along strike (fig. 47).

Depositional setting of host sediments.—The contacts between seam no. 10 and its overlying and underlying sediments are gradational. Descriptions from driller's logs show that the sediments below seam no. 10 are predominantly blue-green, fine silts and clays. Descriptions of core samples of the interval record parallel, continuous laminations with occasional layers of gastropod and bivalve shells (Snedden, 1979). Grayish-tan silts and clays from the overlying interval are occasionally interrupted by thin lignitic zones, or less commonly, by a discontinuous sand body. Intense bioturbation and abundant root traces were reported by Snedden (1979) and are consistent with the strandplain/lagoonal setting established from the regional depositional model.

Seam no. 10 contains three to four partings that have an average combined thickness which varies from 0.8 to 1.20 (2.5 to 4 ft). A strike orientation of the partings is apparent (fig. 49). Partings increase in thickness toward the lower left of the figure; this suggests that the increased thickness represents sediment influx originating from dip-oriented channels of inferred tidal origin.

Depositional setting of lignite seams.—Seam no. 10 varies from 3 to 5 m (9 to 16 ft) in thickness (fig. 48). A strike orientation of the lignite is evident and is similar to that determined regionally for lower Jackson lignite (fig. 9) of South Texas. The total interval map displays a strong strike orientation of thickest areas located central to the mapped area (fig. 48). A linear basin of peat accumulation is suggested, perhaps a filled lagoon or abandoned strandplain broken by tidal inlets and channels. Modern analogs are found on the coast of South Carolina, Florida, and western Mexico.

Summary of Geologic Features

Strike orientations of thickness distributions in seam no. 10 and its associated partings correspond to the overall strike orientation of the strandplain environment for this area. Inferred from the regional model, seam dimensions are controlled by the maximum width and length of filled lagoons and abandoned strandplains.

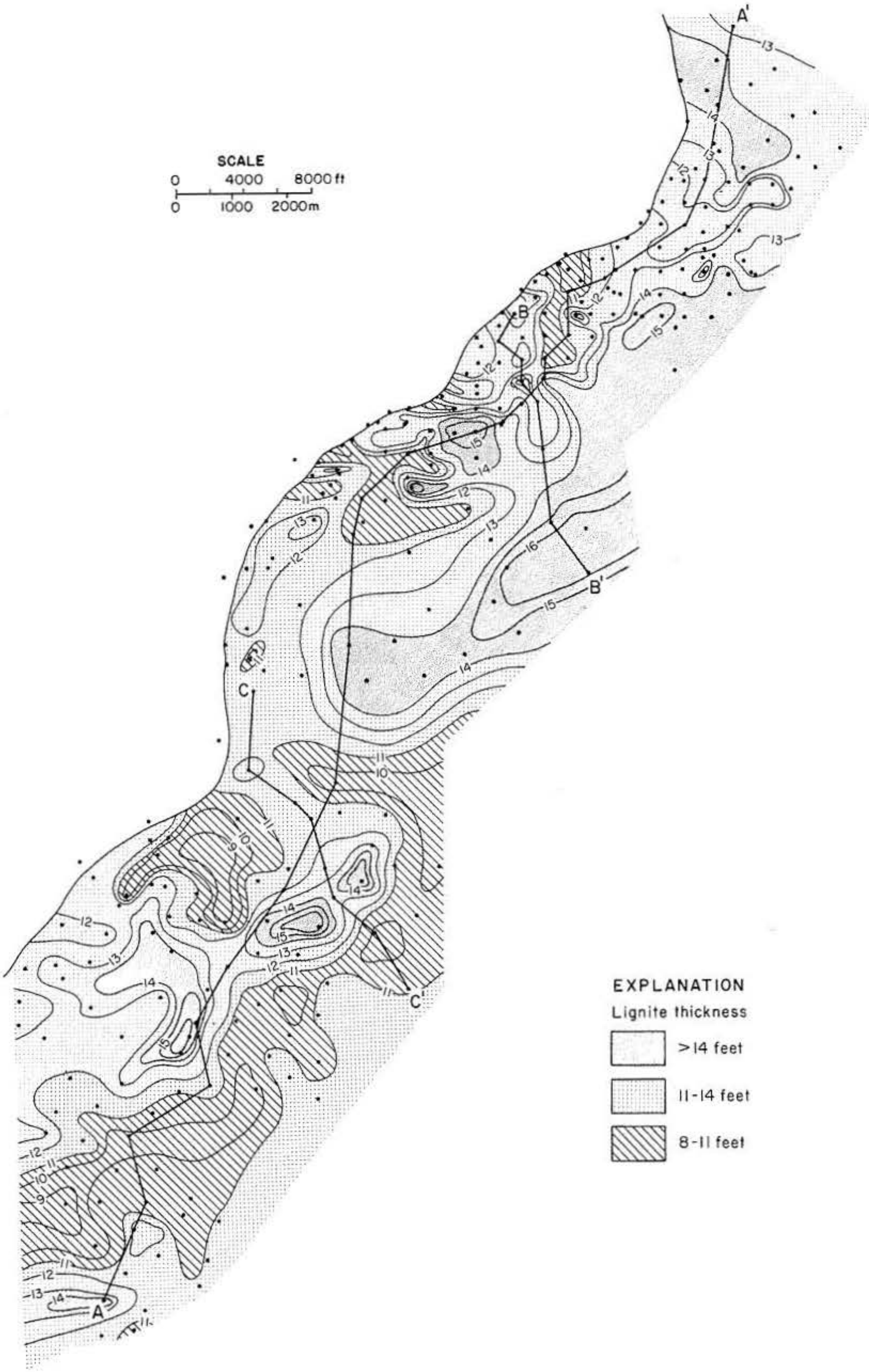


Figure 48. Isopach map of total lignite interval (lignite plus partings), strandplain/lagoonal deposit, Jackson Group of South Texas, showing locations of strike and dip cross sections.

Figure 49. Isopach map of total parting thickness, seam no. 10, strandplain/lagoonal deposit, Jackson Group of South Texas.

GEOLOGICAL UNCERTAINTIES

Geological uncertainties in resource evaluation are those uncertainties arising from variations in the depositional environment of coal formation. The most important geological uncertainties are those that affect lignite tonnages; they include seam thickness, areal distribution, and the number of seams. Aspects of seam thickness and seam distribution have been documented in all four deposits. However, the total areal distributions of lignite seams often are not fully delineated at the deposit scale. For example, only a small part of the total areal distribution is observed for Jackson seam no. 3 of the lower delta plain deposit, Jackson seam no. 10 of the strandplain/lagoonal deposit, and Wilcox seam no. 90 of the alluvial plain/delta plain transitional deposit. Knowledge of the regional depositional model can aid in defining seam distribution in these cases. A summary of the geological uncertainties associated with the four depositional environments is presented in table 5 with causes of geological uncertainty ranked as to their frequency of occurrence in the different environments.

Table 5. Geological uncertainties in different depositional environments.

Geological uncertainty	Alluvial plain setting	Upper delta plain setting	Lower delta plain setting	Strandplain/ lagoonal setting
1) Interruptions in seam continuity:				
a) due to postdepositional channeling	3	2	1	1
b) due to contemporaneous channeling	3	2	0	3
c) due to contemporaneous lakes or interdistributary bays	3	1	1	1
2) Variations in seam thickness:				
a) due to seam splitting	2	3	2	1
b) due to channel scour	3	2	1	1
c) due to unstable peat-forming conditions (i.e., water depth inhibiting vegetation)	1	1	2	1
3) Problems with seam correlation	3	2	1	1

Frequency of occurrence 3 = Abundant 2 = Common 1 = Rare 0 = Not present

QUANTITATIVE INVESTIGATION

Hand- and Computer-Calculated Resources

Introduction

To test the degree of uncertainty caused by variations in seam thickness, the numbers of boreholes considered in each deposit were progressively reduced and resources were calculated for each reduction in data. Various techniques of resource calculation (manual, computer, and geostatistical) were used. Classical statistics was the method used to determine the number of boreholes required to obtain resource estimates of individual seams within a given confidence interval under specified conditions. Geostatistical methods (variograms and kriging) were used to measure variability in resource estimates.

Effect of Data Reduction on Hand-Calculated Resources

Isopach maps were hand-contoured with knowledge of the depositional setting and then planimetered to determine resources. As illustrated in figures 50 through 58, mapping was done on 25 percent, 50 percent, and 100 percent of the data set. In all numerical investigations of this study, boundaries were arbitrarily set and maintained. These manual procedures were carried out for the alluvial plain, lower delta plain, and strandplain/lagoonal environments. Resources were calculated by computer only for the alluvial plain/delta plain transitional setting; results of those data reductions are presented under the computer method of resource estimation.

The hand-drawn isopach map for seam no. 6 in the alluvial plain setting using 100 percent of the data (fig. 50) documents the irregularities of the lignite seam. The contour map that results from reducing the data set by 50 percent shows the same general trend of the thickest lignite (fig. 51); however, many of the minor irregularities in seam thickness are omitted, and the boundary between the lignite body and barren area does not show the same degree of definition. Reducing the data set by 75 percent produces a map that still documents the northeast-southwest-trending thick lignite, but the boundary line shows very little definition, and its position has changed somewhat from the 100-percent and 50-percent contour maps (fig. 52). In addition, very few of the thickness

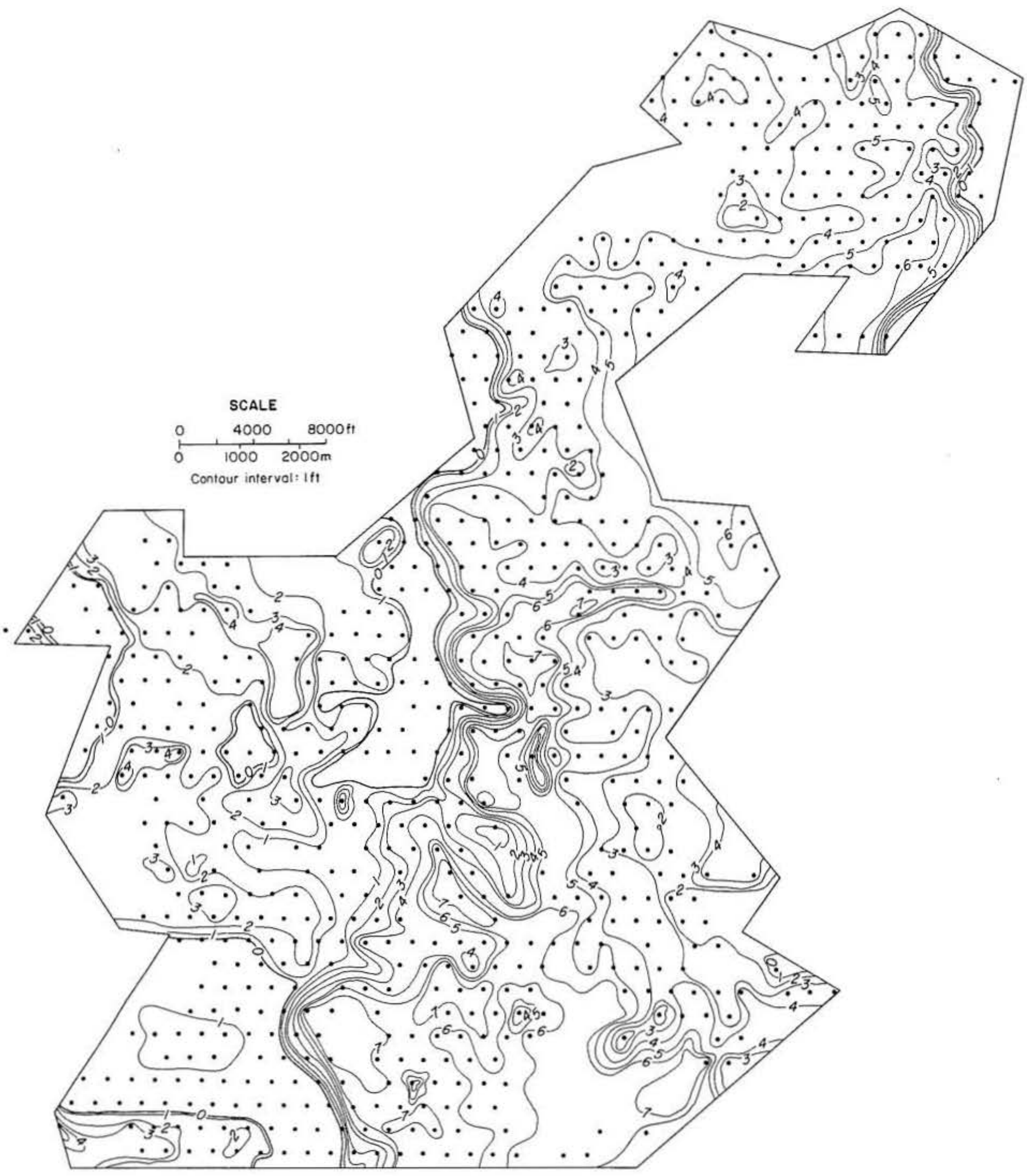


Figure 50. Isopach map of seam no. 6, 100 percent of available data, alluvial plain deposit, Wilcox Group of East Texas.

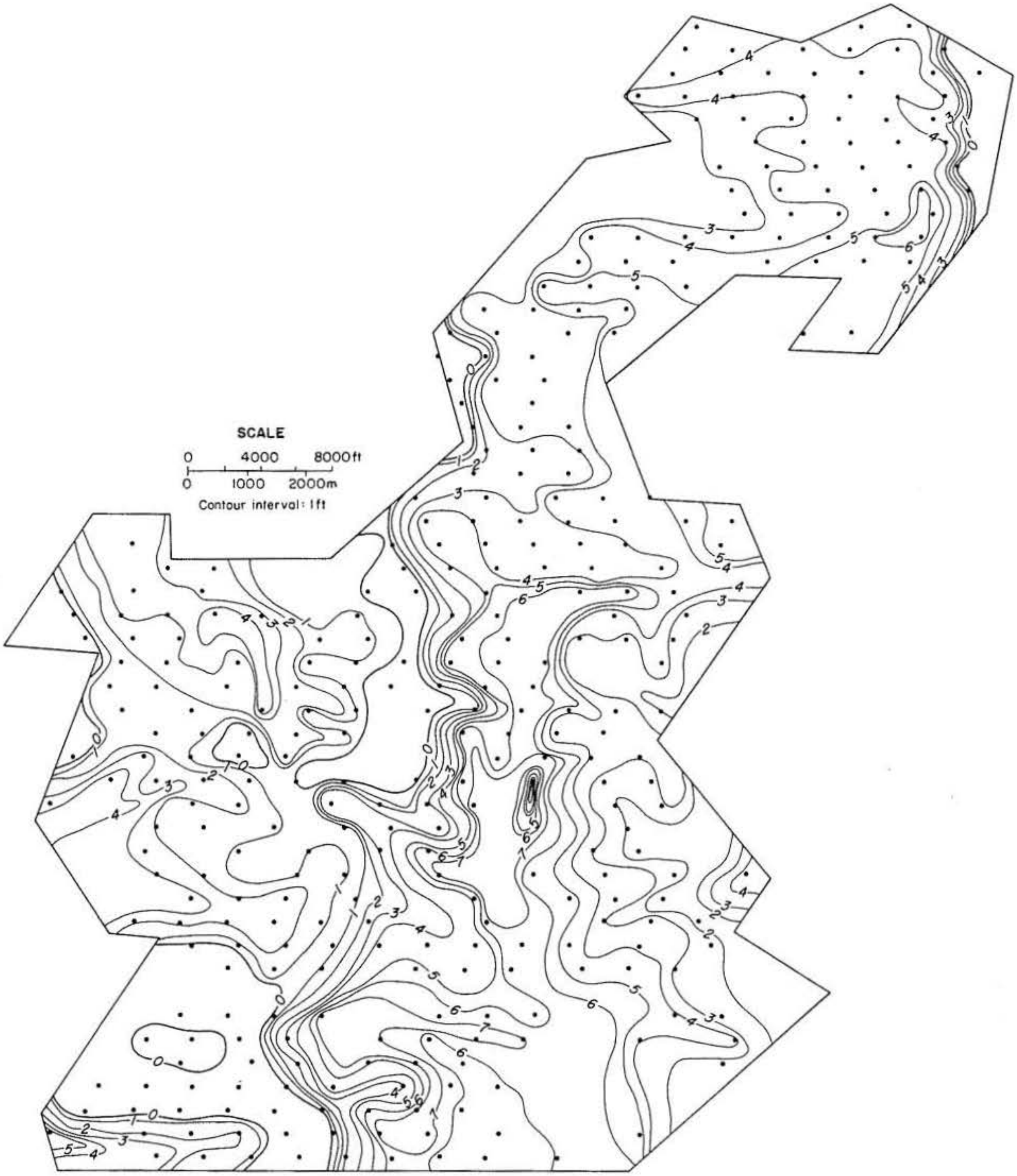


Figure 51. Isopach map of seam no. 6, 50 percent of available data, alluvial plain deposit, Wilcox Group of East Texas.

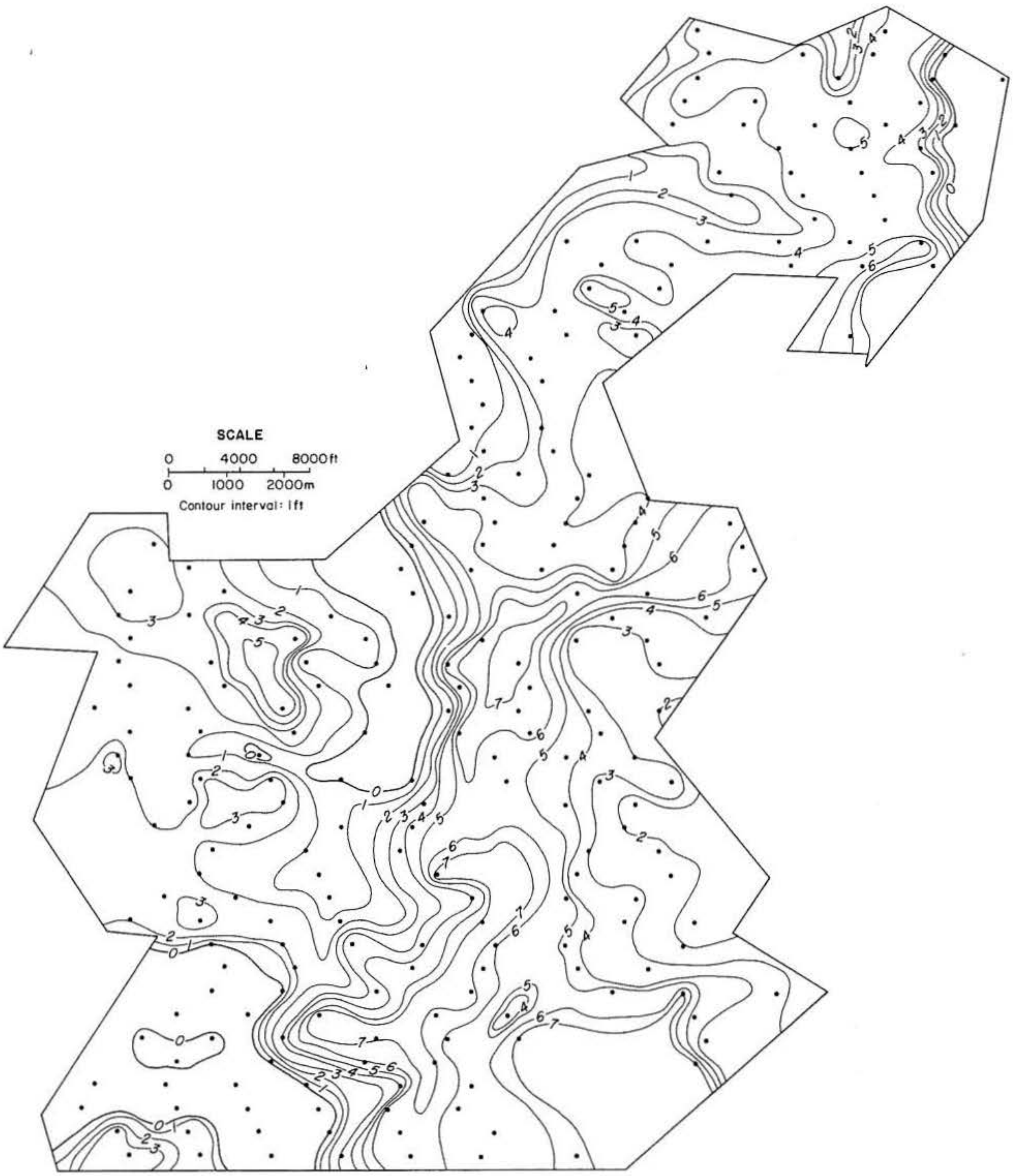


Figure 52. Isopach map of seam no. 6, 25 percent of available data, alluvial plain deposit, Wilcox Group of East Texas.

Table 6. Manually calculated resources for three depositional environments in millions of short tons.

Environment	Seam No.	100% of data	50% of data	25% of data
Alluvial plain	6	276	269	274
Lower delta plain	3	111	105	104
Strandplain/lagoonal	10	411	401	375

Table 7. Comparison of manually calculated to computer-calculated resources, seam no. 6—alluvial plain.

	100% of data	50% of data	25% of data
Manually calculated (short tons x 10^6)	276.8	269.3	274.2
Computer-calculated (short tons x 10^6)	261.1	259.0	260.9

Table 8. Computer-calculated resources for continuous seams.

	100% of data	50% of data	25% of data
Lower delta plain environment seam no. 3 (short tons x 10^6)	118.8	115.9	114.2
Strandplain/lagoonal environment seam no. 10 (short tons x 10^6)	429.0	418.0	429.0
Alluvial plain/delta plain seam no. 90 (short tons x 10^6)	287.2	288.1	292.5

Table 9. Computer-calculated resources for discontinuous seams.

	100% of data	50% of data	25% of data	12.5% of data
Alluvial plain environment seam no. 4	91.8	97.0	93.2	97.4
Lower delta plain environment seam no. 8	6.5	>6.2*	>5.0*	>4.6*

*Tonnages for fewer data are presented as a range instead of an exact value because of scarcity of data in particular areas, which prohibits certain polygons reflecting those areas from furnishing average thickness values. Thus, the total tonnages are artificially decreased as a result of limitations of the volume program utilized (CPS-1; Radian Corp., 1979).

irregularities within the lignite body are documented. The impact of this variation in seam geometry can best be tested by comparing the resources calculated from each of the maps. The tonnage figures are remarkably similar, with less than a 10-percent difference between the values (table 6).

Figure 53 represents the isopach map of seam no. 3 of the lower delta plain setting using 100 percent of the data. A roughly dip-oriented lobate pattern is apparent from the contouring. A 50-percent reduction in the data (fig. 54) still preserves the lobate trend; however, localized thickenings and thinnings become poorly defined. Overall, there is a smoothing or averaging effect. The isopach map (fig. 55) constructed with 25 percent of the available data preserves a subtle lobate trend; however, delineation of isolated patches of thinner and thicker lignite has been lost. Tonnages did decrease with a decrease in data (table 6), as could be predicted from the isopach maps, because of the omission of isolated patches of thicker lignite. However, these tonnages do not differ by more than 5 percent in any case.

Resource maps of total lignite (lignite less partings) constructed for seam no. 10 of the strandplain/lagoonal setting using 100, 50, and 25 percent of the available data are presented in figures 56, 57, and 58. The strike-trending pattern of this deposit persisted at each level of comparison; however, details of this trend diminished with data reduction. Comparison of the resource values (table 6) shows that the resources for seam no. 10 varied no more than 9 percent.

Effect of Data Reduction on Computer-Calculated Resources

A set of computer programs was used to store, update, and retrieve the data used in the project, with the aim of reducing error and allowing processing of large data sets. The stored borehole information included location data, stratigraphic data, and lignite quality data. The location information was obtained from maps using a digitizer. Primarily, data were stored for lignite seams, but some additional data were also included for important partings.

For this project, a mapping program (CPS-1; Radian Corp., 1979) was used to compute tonnages, using 100, 50, 25, and 12.5 percent of the data. The same data and boundaries used in the manually calculated resources were used in the computer evaluation.

Computer-generated contour maps of seam no. 6 in the alluvial plain setting using 100, 50, and 25 percent of the data (figs. 59, 60, and 61) equate visually with hand-drawn maps (figs. 50, 51, and 52). Minor differences do occur—the geologist manually draws the barren areas of seam no. 6 as linear features (that is, abandoned channels), whereas the computer represents them as isolated circular areas.

Hand-calculated and computer-generated tonnages are compared in table 7. The difference between these figures is less than 6 percent, which is well within the accepted definition of a measured resource (plus or minus 10 percent, for an accuracy of 20 percent).

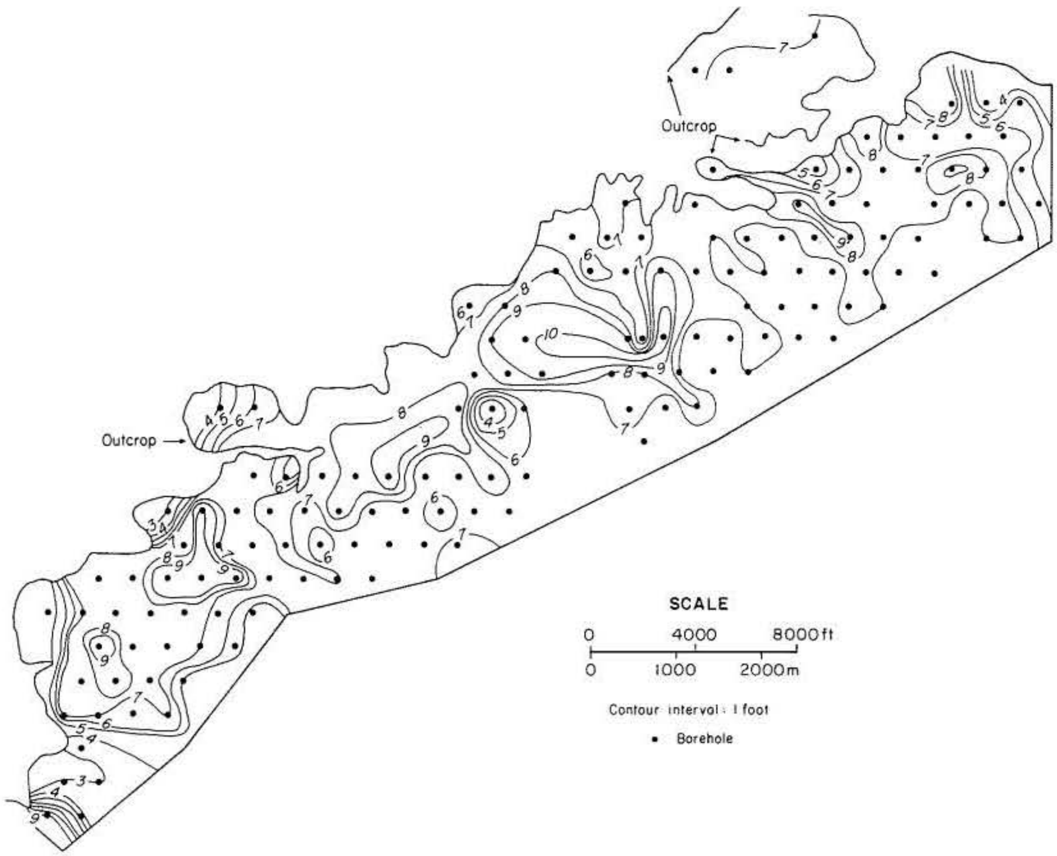


Figure 53. Isopach map of seam no. 3, 100 percent of available data, lower delta plain deposit, Jackson Group of southeast Texas.

To evaluate further the reliability of computer-drawn maps, resources were calculated (table 8) for seam no. 3 of the lower delta plain deposit, seam no. 10 of the strandplain/lagoonal deposit, and seam no. 90 of the alluvial plain/delta plain transitional deposit. The difference between manually calculated and machine-calculated resources was found to be no more than 10 percent overall.

Resources generated by the computer for two discontinuous seams from the alluvial plain and lower delta plain are shown in table 9. For seam no. 4, the differences between the tonnages are within 12 percent. Thus, the contention cannot be made that when discontinuous seams are analyzed, a reduction in the number of boreholes would result in marked variations in the tonnages.

Hand- and computer-calculated resources can be summarized as follows:

(1) Reproducible resource figures can be generated using fewer data.
(2) Variations of thickness within a lignite seam have little effect on the overall resources of that seam, given the level of data usually available.
(3) Minor irregularities in the definition of the boundary between a seam and a barren area have little effect on the overall resources of that seam.
(4) The recognition of a seam boundary and its position may have a major effect on the overall resources of that seam.

Geostatistically Calculated Resources

Introduction

Geostatistics is superior to other statistical approaches in that it uses the spatial dependency structure contained in the data. Spatial dependence simply means that observations taken near each other are expected to be more similar than those taken at some greater distance apart. Geostatistics captures this spatial dependency structure in the variogram.

The variogram is defined mathematically by:

$$\gamma(\underset{\sim}{\vec{h}}) = \tfrac{1}{2} E[Z(\underset{\sim}{X}) - Z(\underset{\sim}{X} + \underset{\sim}{\vec{h}})]^2 \qquad (1)$$

where $Z(X)$ is the observation at the point X, $Z(X + h)$ is the observation at the point $X + h$, $\|h\|$ is the distance from

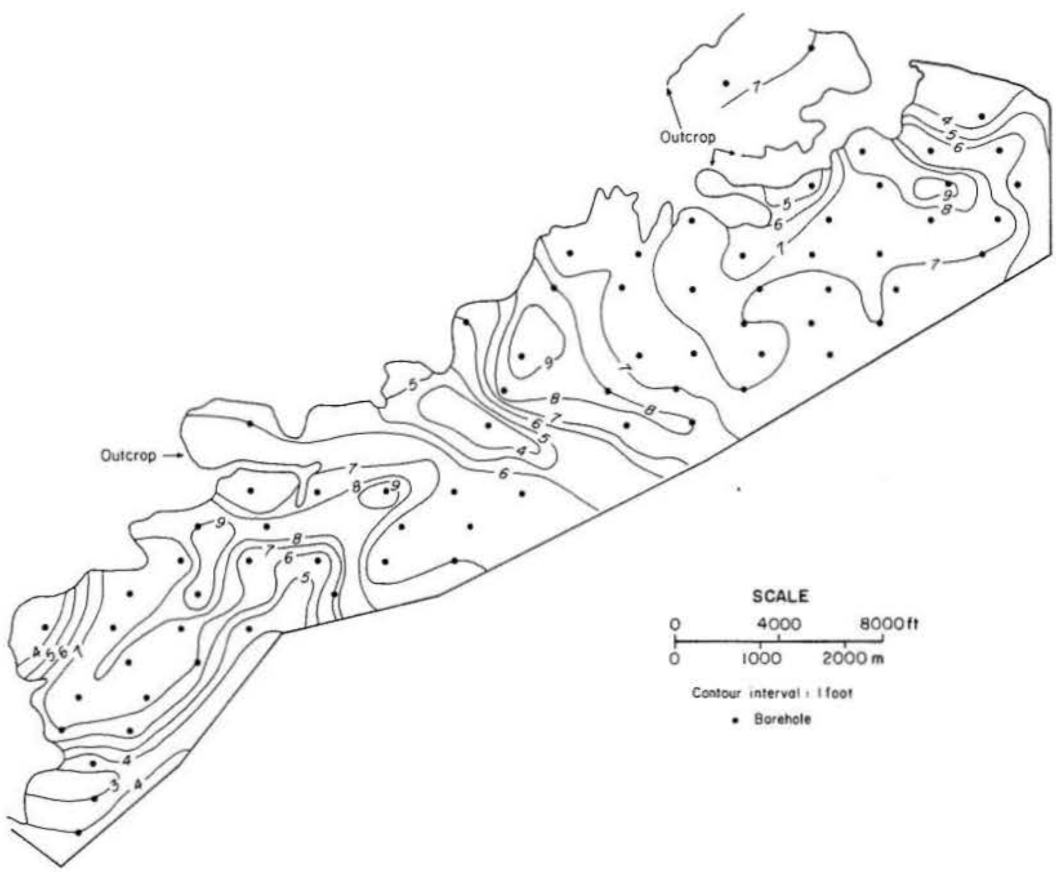


Figure 54. Isopach map of seam no. 3, 50 percent of available data, lower delta plain deposit, Jackson Group of southeast Texas.

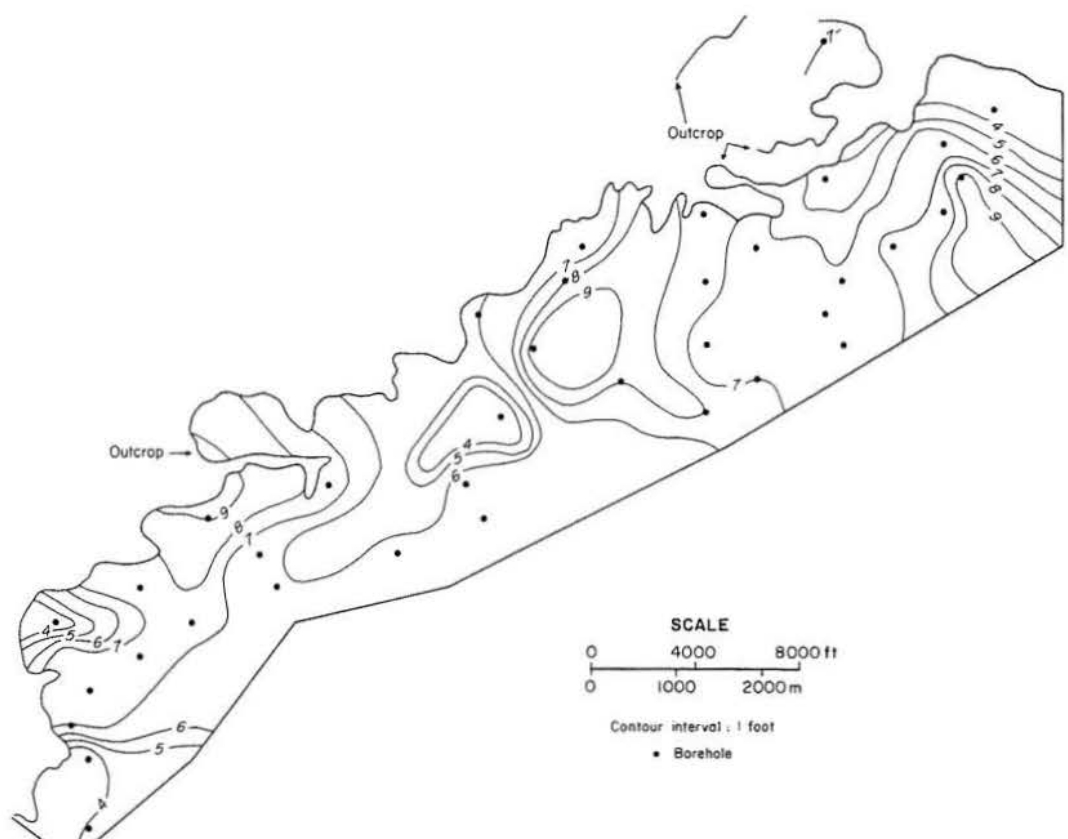


Figure 55. Isopach map of seam no. 3, 25 percent of available data, lower delta plain deposit, Jackson Group of southeast Texas.

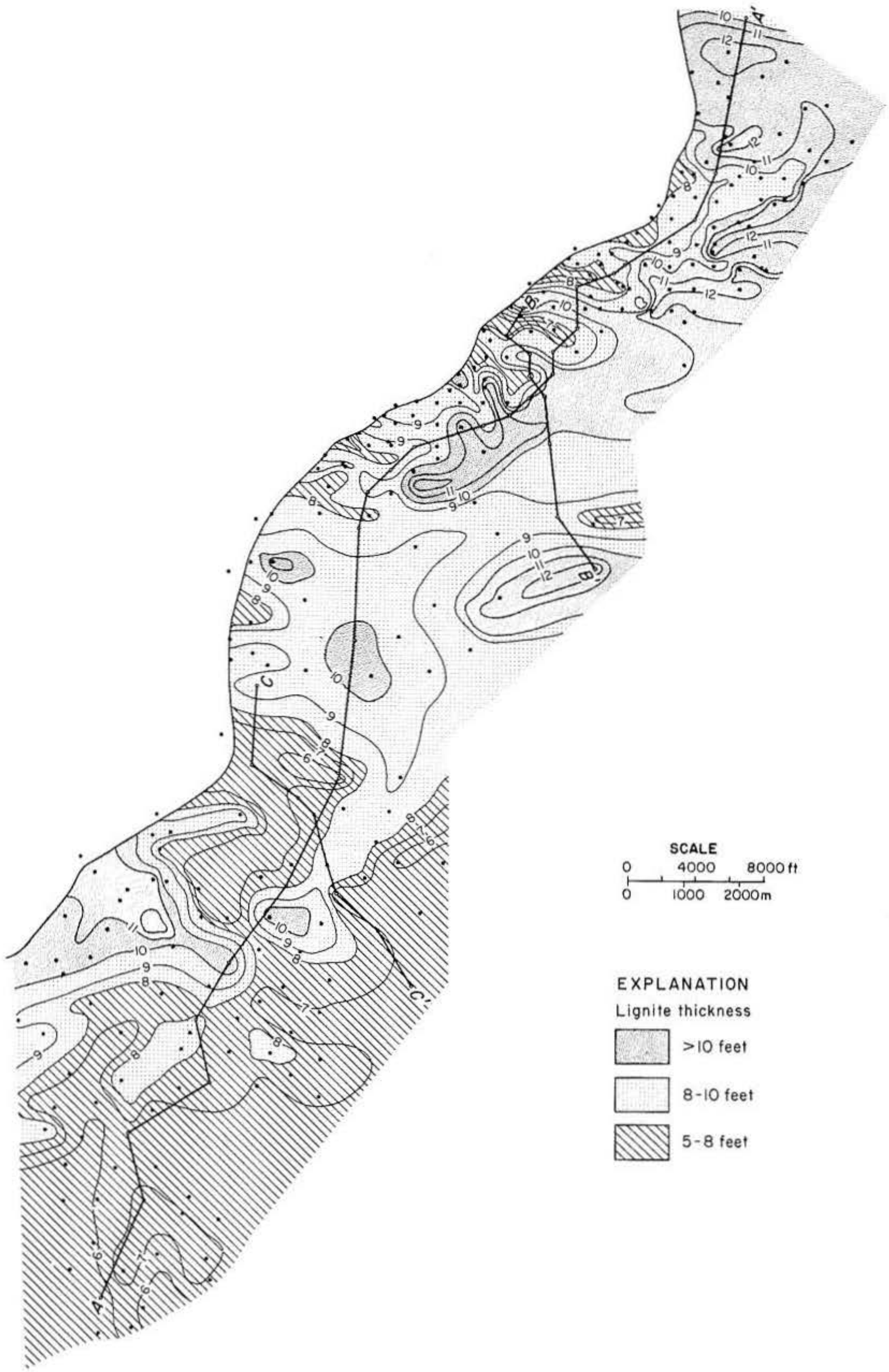


Figure 56. Isopach map of seam no. 10, 100 percent of available data, strandplain/lagoonal deposit, Jackson Group of South Texas.

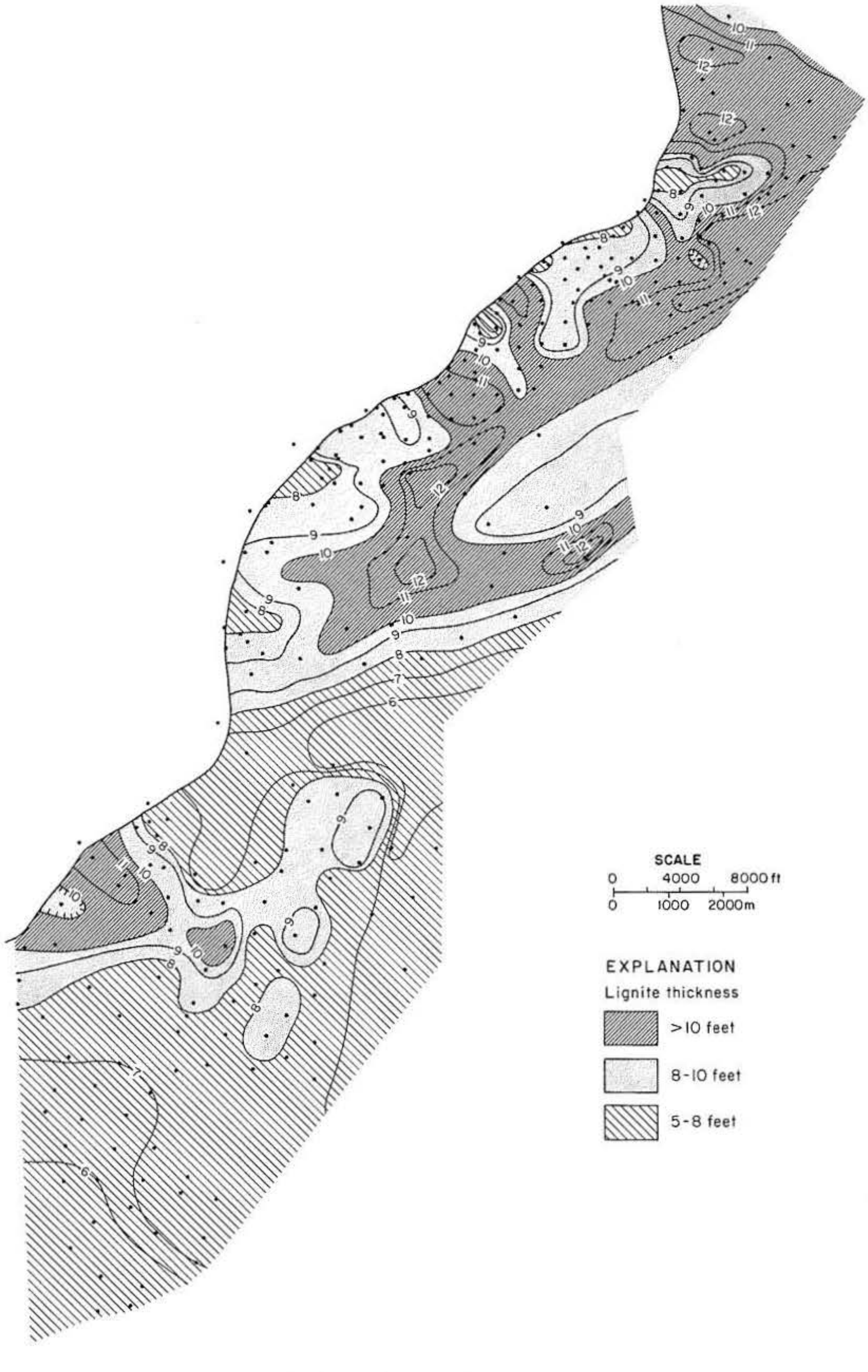


Figure 57. Isopach map of seam no. 10, 50 percent of available data, strandplain/lagoonal deposit, Jackson Group of South Texas.

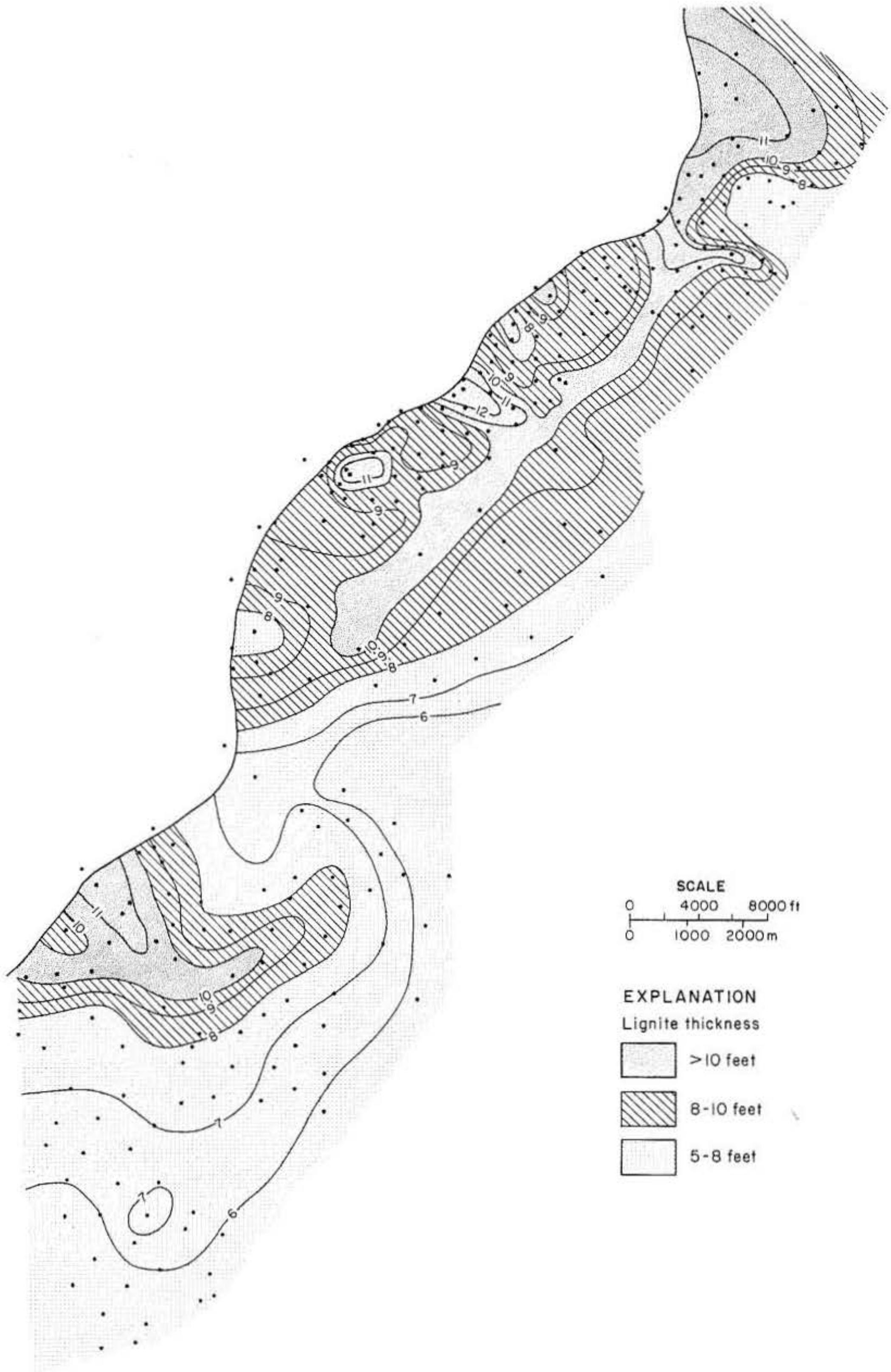


Figure 58. Isopach map of seam no. 10, 25 percent of available data, strandplain/lagoonal deposit, Jackson Group of South Texas.

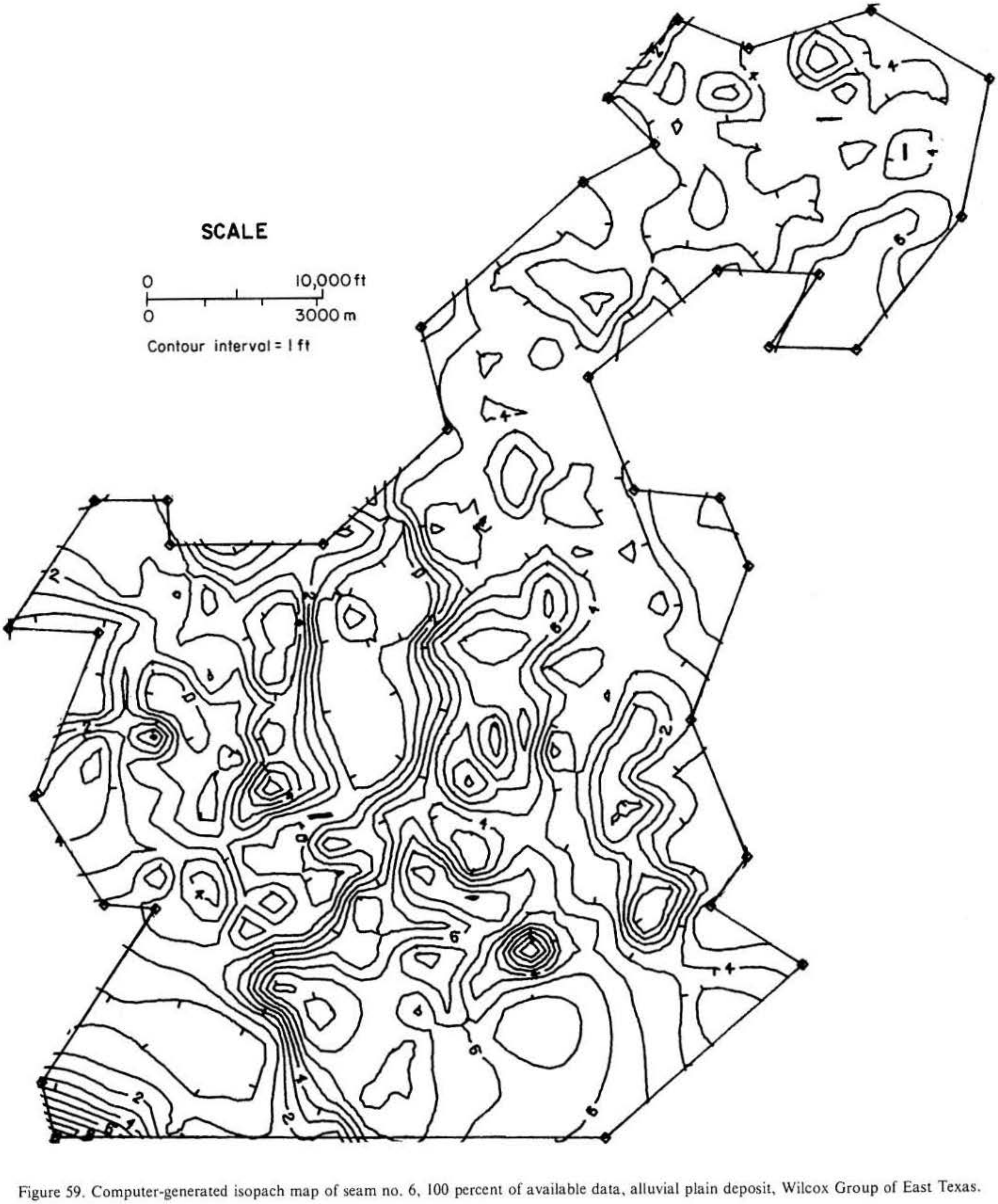


Figure 59. Computer-generated isopach map of seam no. 6, 100 percent of available data, alluvial plain deposit, Wilcox Group of East Texas.

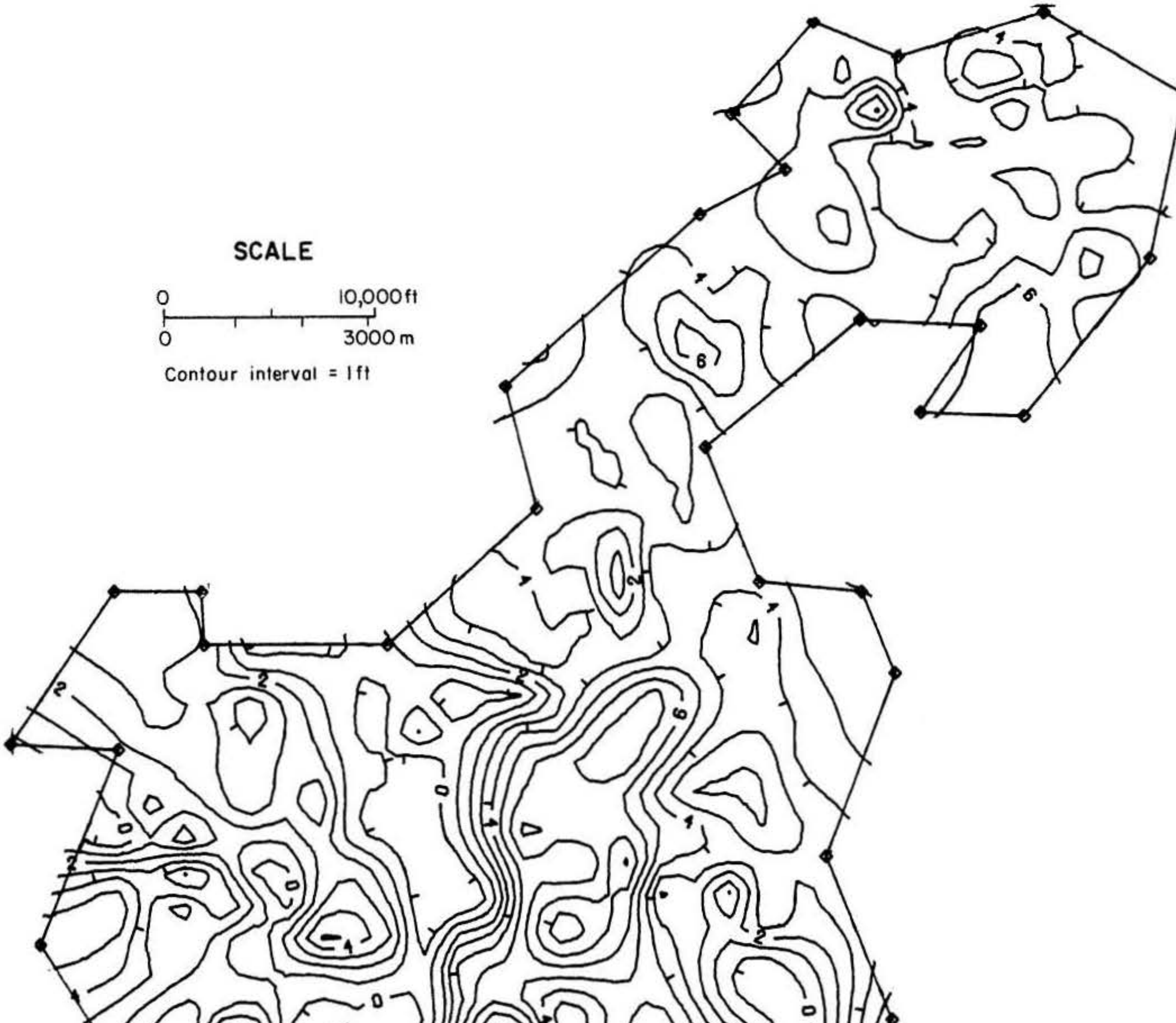


Figure 60. Computer-generated isopach map of seam no. 6, 50 percent of available data, alluvial plain deposit, Wilcox Group of East Texas.

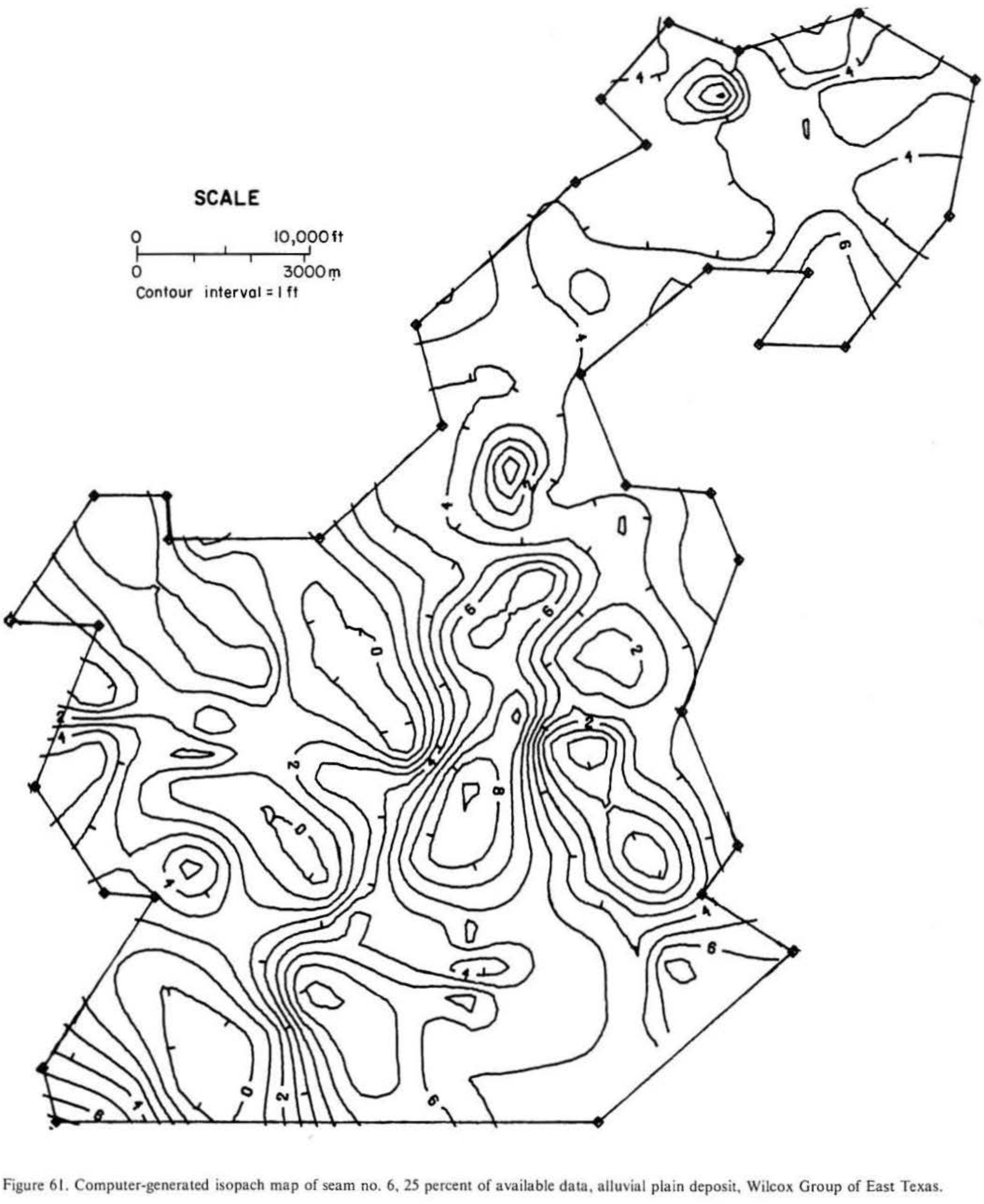


Figure 61. Computer-generated isopach map of seam no. 6, 25 percent of available data, alluvial plain deposit, Wilcox Group of East Texas.

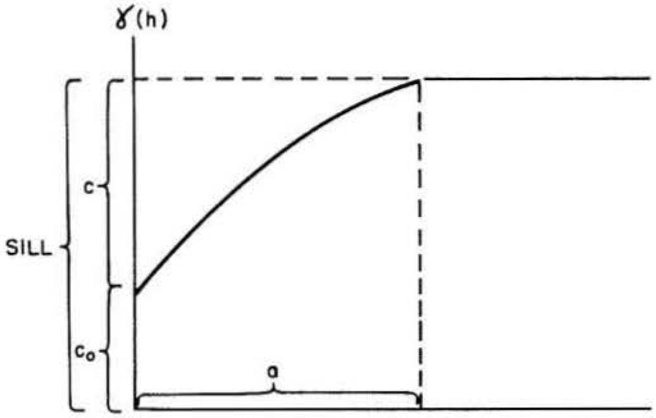


Figure 62. A spherical variogram.

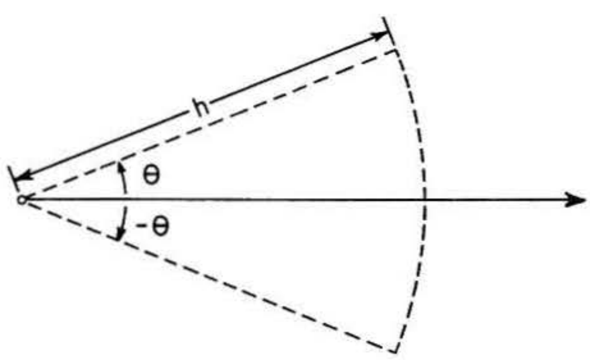


Figure 63. Angular sector with window θ and class size h; arrow indicates direction of variogram.

X to X + h in the direction of h, and E is the "expected value" or "averaging" operation. Generally, the variogram gives the average of the squared differences of the observations that are a specific distance apart in a specific direction. The variogram is a function of the direction h as well as the distance $\|h\|$. If the variogram calculated in a certain deposit is only a function of distance (that is, the variability is the same in every direction), the variogram is called isotropic, and the deposit is said to "possess no anisotropy." The variogram (1) is estimated by the formula:

$$\gamma(h) = \frac{1}{2N}\sum_{j=1}^{N}[Z(\underset{\sim}{X}j) - Z(\underset{\sim}{X}j+h)]^2 \qquad (2)$$

for a regular grid where all points a distance of $\|h\|$ apart contribute to the sum. If the drill holes are not located on a regular grid, formula (2) needs some modification. For example, all points lying between 0 and 100 m (0 and 328 ft) apart and lying within an allowed angular deviation from the specified direction would contribute to the computation of γ (100). Points lying between 100 and 200 m (328 and 656 ft) apart would contribute to γ (200), and so on.

Of the several kinds of theoretical variogram models, the spherical variogram model (fig. 62) has proved most applicable to this study. The mathematical definition of the spherical model for a fixed direction is given by:

$$\gamma(h) = C_0 + C\,[(^3/_2)\,^h/_a - (^1/_2)\,^{h^3}/_{a^3}] \qquad o<h<a$$

$$\gamma(h) = C_0 + C \qquad h \geqslant a$$

$$\gamma(h) = 0 \qquad h \equiv o$$

where "a" is the "range of influence," C_o is the "nugget effect," and $C_o + C$ is the "sill value."

The factor C_o arises naturally from random sources of error. After some distance "a," the range of influence, the variogram reaches a plateau with a value of γ(h), which is called the "sill value." That is, the observations more than "a" distance apart are not dependent.

The fitted spherical variogram obtained from the experimental variogram is important in estimating the mean value of the observations. The theoretical definition for the average of the observations Z (X) over a deposit "V" is given by the expression:

$$Z^* = {}^1/_V \int_V Z(\underset{\sim}{X})\, d\underset{\sim}{x} \qquad (3)$$

which is approximated by the weighted summation:

$$Z^* = \sum_{i=1}^{N} \lambda_i Z(\underset{\sim}{X_i}) \quad \left(\sum_{i=1}^{N} \lambda_i \equiv 1\right) \qquad (4)$$

If the true average of Z (X) over V is Z, this estimation will yield an error $Z^* - Z$. Hence the estimation variance is given by σ_E^2 which is the symbol for the variance of the error $Z^* - Z$.

Finding the weights λ_i that minimize σ_E^2 is a nonlinear optimization problem that can be converted to a problem of solving a linear system of equations. This estimation procedure (that is, finding the estimator Z^* that minimizes σ_E^2) is called "kriging" (Journel and Huijbregts, 1978).

This study focuses on the average thickness of a particular seam in a deposit and the estimation variance of that average. For this reason the variogram is confined to a single variable—thickness.

Continuous and discontinuous seams from the deposits were evaluated for spatial dependency. Kriging was performed on those seams for which a variogram was obtained to calculate resources. Seam no. 6 of the alluvial plain deposit is discussed in detail below to present the techniques used in this analysis.

Variogram

Wilcox Seam 6 (all direction)
Variogram (coal thickness of Wilcox Seam 6)

Direction = 0.
Window 90.
Class Size = 250.
Max. Distance = 5,000.

Data used in calculations
Mean = .363E+01
Variance = .427E+01
Std. Deviation = .207E+01

Logarithms — No
Relative variogram — No
No. of Samples = 565

Distance	No. Pairs	Drift	Gamma (H)	Moment Cent.	Aver. Dist.
250 - 500	1,169.	−.406E+00	.139E+01	.139E+01	433.0
500 - 750	643.	−.240E−01	.198E+01	.198E+01	721.3
750 - 1,000	1,396.	−.195E+00	.200E+01	.198E+01	847.9
1,000 - 1,250	2,086.	−.309E+00	.243E+01	.242E+01	1,154.6
1,250 - 1,500	1,661.	−.183E+00	.278E+01	.280E+01	1,417.1
1,500 - 1,750	1,643.	−.193E+00	.273E+01	.273E+01	1,612.5
1,750 - 2,000	2,180.	−.427E+00	.354E+01	.355E+01	1,842.0
2,000 - 2,250	2,906.	−.441E+00	.355E+01	.356E+01	2,117.6
2,250 - 2,500	2,298.	−.375E+00	.362E+01	.362E+01	2,377.2
2,500 - 2,750	2,978.	−.557E+00	.426E+01	.425E+01	2,607.4
2,750 - 3,000	3,298.	−.679E+00	.449E+01	.449E+01	2,897.5
3,000 - 3,250	2,537.	−.725E+00	.485E+01	.486E+01	3,154.9
3,250 - 3,500	3,065.	−.649E+00	.470E+01	.469E+01	3,351.7
3,500 - 3,750	3,593.	−.817E+00	.481E+01	.480E+01	3,637.9
3,750 - 4,000	2,581.	−.931E+00	.505E+01	.506E+01	3,878.4
4,000 - 4,250	3,629.	−.771E+00	.469E+01	.470E+01	4,095.1
4,250 - 4,500	3,764.	−.853E+00	.493E+01	.493E+01	4,384.8
4,500 - 4,750	3,065.	−.104E+01	.511E+01	.511E+01	4,641.5
4,750 - 5,000	3,178.	−.709E+00	.496E+01	.496E+01	4,872.6

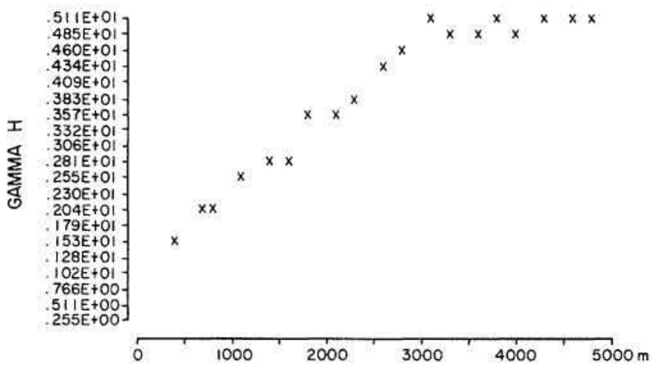


Figure 64. Sample variogram for seam no. 6, alluvial plain deposit, Wilcox Group of East Texas, class size 250.

Variogram

Wilcox Seam 6 (all direction)
Variogram (coal thickness of Wilcox Seam 6)

Direction = 0.
Window 90.
Class Size = 300.
Max. Distance = 6,000.

Data used in calculations
Mean = .363E+01
Variance = .427E+01
Std. Deviation = .207E+01

Logarithms — No
Relative variogram — No
No. of Samples = 565

Distance	No. Pairs	Drift	Gamma (H)	Moment Cent.	Aver. Dist.
300 - 600	1,173.	−.406E+00	.139E+01	.139E+01	433.2
600 - 900	1,704.	−.179E+00	.206E+01	.206E+01	788.6
900 - 1,200	1,672.	−.176E+00	.232E+01	.234E+01	1,076.8
1,200 - 1,500	2,406.	−.265E+00	.264E+01	.267E+01	1,356.5
1,500 - 1,800	2,150.	−.267E+00	.298E+01	.300E+01	1,653.4
1,800 - 2,100	2,949.	−.374E+00	.330E+01	.330E+01	1,934.5
2,100 - 2,400	2,570.	−.456E+00	.383E+01	.383E+01	2,219.3
2,400 - 2,700	3,888.	−.554E+00	.411E+01	.412E+01	2,537.7
2,700 - 3,000	3,746.	−.610E+00	.436E+01	.437E+01	2,875.7
3,000 - 3,300	3,332.	−.709E+00	.485E+01	.485E+01	3,183.2
3,300 - 3,600	3,189.	−.829E+00	.498E+01	.499E+01	3,437.1
3,600 - 3,900	4,270.	−.703E+00	.457E+01	.457E+01	3,720.3
3,900 - 4,200	3,994.	−.783E+00	.477E+01	.477E+01	4,042.3
4,200 - 4,500	4,384.	−.920E+00	.502E+01	.501E+01	4,362.5
4,500 - 4,800	3,635.	−.102E+01	.514E+01	.514E+01	4,662.2
4,800 - 5,100	4,067.	−.967E+00	.505E+01	.505E+01	4,951.4
5,100 - 5,400	3,987.	−.932E+00	.522E+01	.523E+01	5,252.7
5,400 - 5,700	4,194.	−.918E+00	.522E+01	.522E+01	5,547.2
5,700 - 6,000	3,710.	−.120E+01	.535E+01	.535E+01	5,834.9

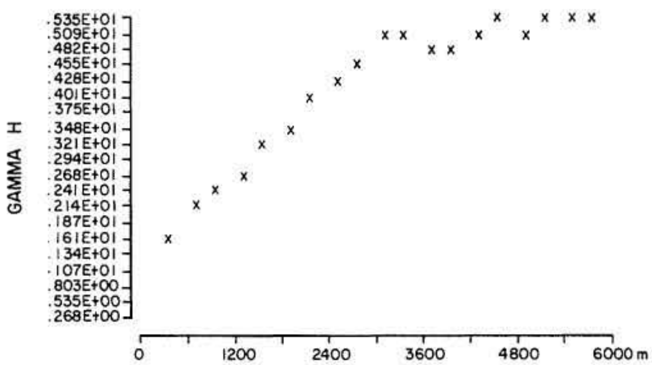


Figure 65. Sample variogram for seam no. 6, alluvial plain deposit, Wilcox Group of East Texas, class size 300.

Determination of Class Size and Subzones

To obtain the structure of seam no. 6 in the deposit, the east-west direction was chosen as the primary axial reference direction for the variogram computations. The term "window" is used to describe an allowable angular deviation from the specified direction within which points will be considered in variogram computation. Integer multiples of class size will take the role of h in γ (h). Figure 63 shows an angular sector in the case of a window θ and class size h.

Initially a 90-degree window was selected to ensure that all data points would be included. After considering the distance between drill holes in the alluvial plain deposit, several different class sizes from 200 to 1,000 m (660 to 3,300 ft) were selected. The sample variograms with class sizes between 250 and 400 m (825 and 1,312 ft) were quite similar both in appearance and in computed values of γ(h). Furthermore, the values for the range of influence and the sill were very close. The values vary from 4,500 to 5,000 m (14,850 to 16,500 ft) for range, from .06 to .1 m^2 (0.7 to 1.2 ft^2) for C_o, and from .45 to .50 m^2 (4.8 to 5.4 ft^2) for the sill. Plots of the sample variograms cited above are presented in figures 64 through 67.

Two conflicting criteria must be met in selecting the aggregation class size. The number of sample pairs in each class

Variogram

Wilcox Seam 6 (all direction)
Variogram (coal thickness of Wilcox Seam 6)

Direction = 0.
Window 90.
Class Size = 350.
Max. Distance = 7,000.

Data used in calculations
Mean = .363E+01
Variance = .427E+01
Std. Deviation = .207E+01

Logarithms — No
Relative variogram — No
No. of Samples = 565

Distance	No. Pairs	Drift	Gamma (H)	Moment Cent.	Aver. Dist.
0 - 350	2.	−.450E+00	.133E+00	.130E+00	336.0
350 - 700	1,214.	−.412E+00	.143E+01	.145E+01	442.4
700 - 1,050	2,012.	−.139E+00	.200E+01	.200E+01	813.4
1,050 - 1,400	2,654.	−.250E+00	.241E+01	.240E+01	1,197.5
1,400 - 1,750	2,716.	−.215E+00	.284E+01	.283E+01	1,551.2
1,750 - 2,100	3,456.	−.394E+00	.337E+01	.337E+01	1,912.7
2,100 - 2,450	3,384.	−.461E+00	.384E+01	.384E+01	2,269.5
2,450 - 2,800	3,593.	−.540E+01	.412E+01	.413E+01	2,589.6
2,800 - 3,150	4,336.	−.699E+00	.459E+01	.459E+01	2,945.9
3,150 - 3,500	4,493.	−.647E+00	.472E+01	.472E+01	3,307.7
3,500 - 3,850	4,675.	−.840E+00	.485E+01	.484E+01	3,676.2
3,850 - 4,200	4,508.	−.750E+00	.471E+01	.471E+01	4,022.9
4,200 - 4,550	5,047.	−.887E+00	.499E+01	.498E+01	4,383.9
4,550 - 4,900	4,426.	−.962E+00	.510E+01	.510E+01	4,744.8
4,900 - 5,250	4,660.	−.949E+00	.518E+01	.518E+01	5,081.7
5,250 - 5,600	4,651.	−.110E+01	.534E+01	.535E+01	5,423.9
5,600 - 5,950	4,679.	−.104E+01	.516E+01	.517E+01	5,762.2
5,950 - 6,300	5,251.	−.983E+00	.532E+01	.532E+01	6,130.1
6,300 - 6,650	4,551.	−.957E+00	.508E+01	.508E+01	6,490.7
6,650 - 7,000	4,763.	−.846E+00	.500E+01	.500E+01	6,840.0

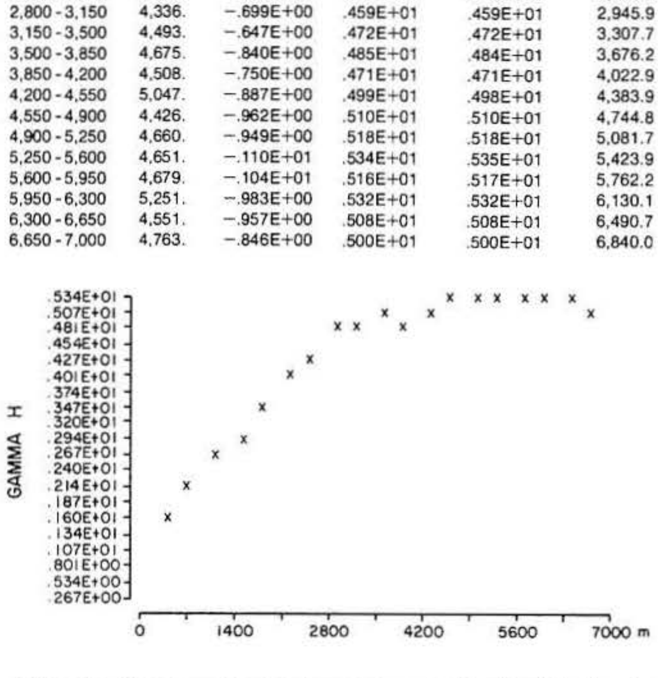


Figure 66. Sample variogram for seam no. 6, alluvial plain deposit, Wilcox Group of East Texas, class size 350.

Variogram

Wilcox Seam 6 (all direction)
Variogram (coal thickness of Wilcox Seam 6)

Direction = 0.
Window 90.
Class Size = 400.
Max. Distance = 8,000.

Data used in calculations
Mean = .363E+01
Variance = .427E+01
Std. Deviation = .207E+01

Logarithms — No
Relative variogram — No
No. of Samples = 565

Distance	No. Pairs	Drift	Gamma (H)	Moment Cent.	Aver. Dist.
0 - 400	142.	−.121E+01	.163E+01	.163E+01	388.0
400 - 800	1,970.	−.233E+00	.174E+01	.184E+01	584.1
800 - 1,200	2,437.	−.182E+00	.220E+01	.224E+01	1,003.9
1,200 - 1,600	3,082.	−.231E+00	.272E+01	.274E+01	1,403.8
1,600 - 2,000	3,147.	−.372E+00	.324E+01	.327E+01	1,780.1
2,000 - 2,400	3,846.	−.417E+00	.358E+01	.360E+01	2,157.7
2,400 - 2,800	4,407.	−.528E+00	.408E+01	.408E+01	2,559.7
2,800 - 3,200	4,709.	−.658E+00	.452E+01	.452E+01	2,963.4
3,200 - 3,600	5,039.	−.797E+00	.499E+01	.499E+01	3,367.9
3,600 - 4,000	5,255.	−.792E+00	.475E+01	.477E+01	3,766.1
4,000 - 4,400	5,543.	−.846E+00	.483E+01	.484E+01	4,173.7
4,400 - 4,800	5,485.	−.915E+00	.501E+01	.502E+01	4,590.3
4,800 - 5,200	5,322.	−.972E+00	.514E+01	.515E+01	4,997.0
5,200 - 5,600	5,443.	−.981E+00	.527E+01	.528E+01	5,395.3
5,600 - 6,000	5,193.	−.104E+01	.521E+01	.521E+01	5,783.1
6,000 - 6,400	5,292.	−.997E+00	.527E+01	.527E+01	6,167.7
6,400 - 6,800	5,410.	−.957E+00	.512E+01	.512E+01	6,565.2
6,800 - 7,200	5,540.	−.881E+00	.482E+01	.482E+01	6,979.1
7,200 - 7,600	5,047.	−.883E+00	.448E+01	.448E+01	7,383.8
7,600 - 8,000	4,992.	−.682E+00	.414E+01	.414E+01	7,780.7

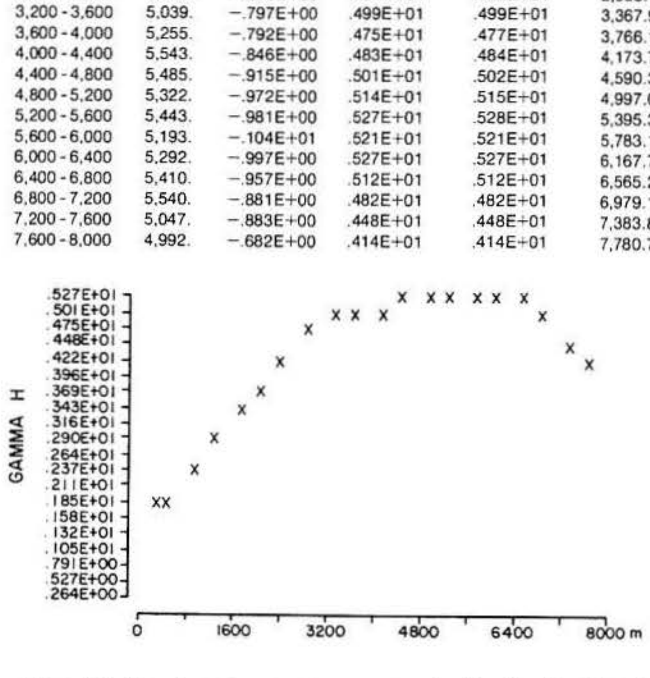


Figure 67. Sample variogram for seam no. 6, alluvial plain deposit, Wilcox Group of East Texas, class size 400.

size, particularly within the interval of primary interest, must be sufficiently large statistically. On the other hand, there is a possibility that the precise variation structure captured by the sample variogram will suffer or be completely lost when an unnecessarily large class size is chosen. Considering the above needs, it was subjectively concluded that a 300-m (984-ft) class size is preferable for seam no. 6. Figure 65 shows the possibility of a "drift" (Journel and Huijbregts, 1978) present in the data set. The amounts of drift were deemed to be unimportant because of their magnitude relative to the associated distances and because the isopach map (fig. 50) contradicts an assertion of significant drift. If a significant drift had been present, the analysis would have proceeded with more sophisticated methods (Journel and Huijbregts, 1978).

From the average sample variogram with a 90-degree window and a class size of 300 m (984 ft) the following estimates of theoretical (spherical) variogram parameters were obtained: 5,000 m (16,405 ft) for the range, 0.093 m^2 (1.0 ft^2) for C_o, and 0.48 m^2 (5.2 ft^2) for the sill. Having obtained the estimates of the theoretical variogram parameters, possible zonal and geometrical anisotropies of the deposit under study were investigated. The area was divided into two subareas called zone 1 and zone 2. Zone 1 is the lower two-thirds of the total deposit and zone 2 is the upper one-third.

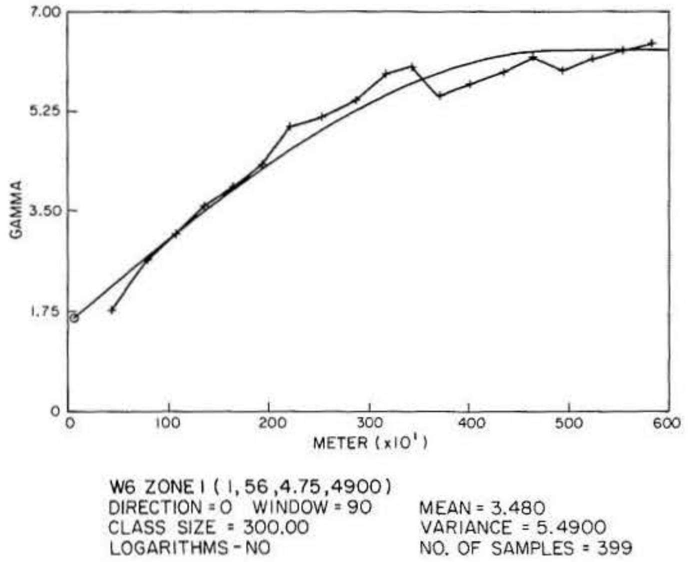


Figure 68. Variogram of zone 1 (theoretical variogram comes from least square and visual fitting methods).

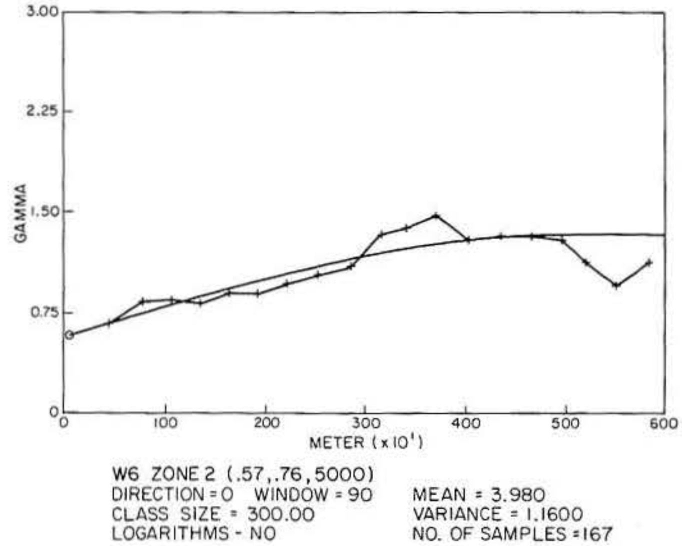


Figure 69. Variogram of zone 2 (theoretical variogram comes from least square and visual fitting methods).

Table 10. Results of verification procedures, Wilcox seam no. 6.

Parameter sets	Variogram parameters C_o	C	R	ANG	AFH	Data point Observed thickness, in feet HOLE 1 2.6 PT[1]	KV[2]	HOLE 2 2.2 PT	KV	HOLE 3 3.0 PT	KV	HOLE 4 3.4 PT	KV	HOLE 5 3.0 PT	KV	HOLE 6 6.4 PT	KV
R	1.56	4.75	4,900	0	1	2.86	.6617	2.07	.6638	2.18	.8969	2.77	.6511	2.54	.6793	6.69	.6499
A	1.45	4.86	4,400	0	1	2.86	.7136	2.09	.7156	2.13	.9540	2.77	.7029	2.52	.7333	6.70	.7020
B	1.45	4.86	5,400	0	1	2.86	.6139	2.07	.6159	2.18	.8329	2.77	.6041	2.54	.6302	6.69	.6029
C	1.65	4.66	4,400	0	1	2.86	.7177	2.07	.7194	2.17	.9693	2.77	.7059	2.54	.7365	6.69	.7046
D	1.65	4.66	5,400	0	1	2.86	.6184	2.05	.6222	2.22	.8491	2.77	.6097	2.56	.6359	6.68	.6081
E	1.65	4.50	5,200	0	1	2.86	.6199	2.05	.6236	2.22	.8507	2.77	.6111	2.56	.6374	6.68	.6096
F	1.65	4.50	5,500	0	1	2.86	.5958	2.04	.6000	2.23	.8210	2.77	.5878	2.56	.6130	6.68	.5862

[1]Predicted Thickness
[2]Kriging Variance

Variograms of both zones with windows of 90 degrees are presented in figures 68 and 69. The smooth curves are theoretical spherical variogram models corresponding to the variograms of the two zones. Both zones indicate about 5,000-m (16,405-ft) ranges of influence. The total variability of zone 2 is markedly smaller than that of zone 1 in the variograms for a window of 90 degrees. This indicates that a zonal anisotropy is present between zones 1 and 2. Therefore, it is appropriate to analyze the two different zones of this seam separately. Estimates of the theoretical variogram parameters, as illustrated in figures 68 and 69, are given as follows:

	Nugget (ft^2)	Sill value (ft^2)	Range (m)
zone 1	1.56	6.31	4,900
zone 2	0.57	1.33	5,000

Investigation of Geometric Anisotropy

Because multiple zones are necessary, variogram computations for both zones were performed along eight different directions using the 300-m (984-ft) class size and a window of 15 degrees. The eight different directions

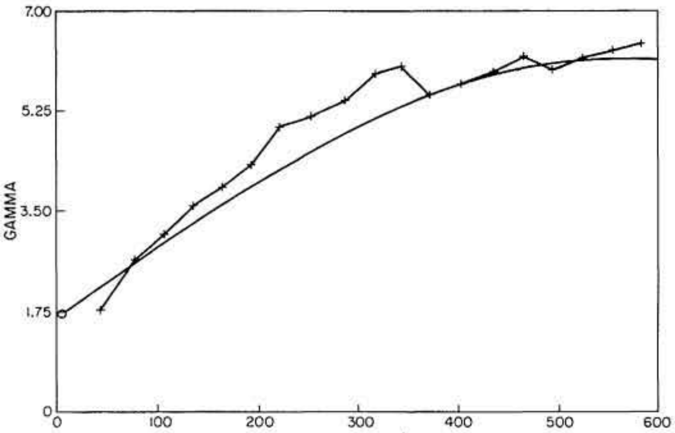


Figure 70. Variogram of zone 1 (theoretical variogram comes from verification procedure).

Table 10. (cont.)

Data point Observed thickness, in feet								
HOLE 7 3.7		HOLE 8 5.2		HOLE 9 6.4		HOLE 10 6.4		
PT	KV	PT	KV	PT	KV	PT	KV	WSE
3.91	.6677	5.37	.9422	4.9	.6377	5.68	1.0278	.45094
3.90	.7204	5.36	1.0282	4.88	.6850	5.68	1.1118	.46872
3.91	.6195	5.37	.8737	4.90	.5918	5.68	.9529	.45077
3.91	.7238	5.37	1.0238	4.90	.6905	5.68	1.1155	.45275
3.91	.6254	5.37	.8732	4.92	.5998	5.68	.9593	.43448
3.91	.6268	5.37	.8755	4.92	.6011	5.68	.9618	.43458
3.91	.6029	5.37	.8390	4.93	.5791	5.68	.9237	.42928

were 0, 23, 45, 68, 90, -23, -45, and -68 degrees from the east-west coordinate axis (measured counterclockwise). The ranges of influence for zone 1 from the above directions were bounded between 4,500 and 5,500 m (14,765 and 18,046 ft). This is very close to the value of the range of influence from the average variogram for all directions.

The directional variograms for zone 2 were not acceptable. The primary reason for this was the small number of data points in zone 2. However, the ranges of influence could be observed for several of the directions. The ranges of influence were all close to the average variogram for all directions. From these results, we concluded that no significant geometric anisotropies exist in either zone.

Verification of Spherical Variogram Parameters

Since the variogram is the most important and basic tool of geostatistics, a verification procedure is needed in the selection of the theoretical variogram.

Our verification method (Knudson and Kim, 1978, 1979) uses ten data points selected at random from different regions of zone 1. For each set of parameter values, each of the ten points' thicknesses was predicted, and the error between the prediction and the observed value was recorded. The quantitative measure of these errors was computed as the *weighted squared error* (WSE) defined by:

$$\mathrm{WSE} = \frac{\sum_{i=1}^{10} \frac{1}{\sigma_i^2}(e_i)^2}{\sum_{i=1}^{10} \frac{1}{\sigma_i^2}} \qquad (5)$$

where e_i is the error for point i, and σ_i is the kriging variance for point i.

Table 10 shows verification results for zone 1, labeled as parameter set "R," which was obtained from the least-squares fitting method (regression). As shown in figure 68, the fit using the parameter set appeared to be good. Hence, a simple neighborhood searching technique was applied about the nugget and range of influence of set R, resulting in parameter sets A, B, C, and D (table 10). Slight reductions of WSE were observed in the parameter sets B and D, which have larger ranges of influence than those of R, A, and C. When comparing D with B, the larger nugget effect produces the smaller WSE. It was concluded, therefore, that the "true" nugget value and the range of influence are greater than the parameter values that were obtained by regression. In figure 68, the fitted sill value appeared greater than the experimental values. Therefore, two more parameter sets whose sill values were less than the parameter set R were added (table 10). Parameter set F yielded least WSE; however, the difference between the WSE's of parameter sets R and F is less than 5 percent. Furthermore, from a graphical viewpoint, the theoretical variogram of parameter set F, as shown in figure 70, does not appear to be better than that of set R.

It could be contended that the choice of ten drill holes might affect the weighted squared error. If this error were to cause a significant bias of the estimate, some safety sampling device for testing the selected drill holes would be needed. Alternatively, a sufficiently large number of

Table 11. Analysis of Wilcox seam no. 6 using UGAMM, UKRIG, and ESTVAR.

Data used (%)	Zone	Fitted Spherical Variogram Parameters CO	C	a	ANG.	AFH.	Kriged thickness	Estimation variance	95% confidence interval for mean thickness Lower bound	Upper bound	Arithmetic mean
100	zone 1	1.56	4.75	4,900	0	1	3.35	0.0301	3.00	3.69	3.48
	zone 2	0.57	0.76	5,000	0	1	3.81	0.0107	3.60	4.01	3.98
	mean and variance of zone 1 and 2						3.51	0.0143	3.27	3.74	----
50	zone 1	1.09	5.54	5,100	0	1	3.56	0.0381	3.18	3.95	3.50
	zone 2	0.64	0.73	4,800	0	1	3.83	0.0151	3.59	4.07	3.99
	mean and variance of zone 1 and 2						3.65	0.0186	3.38	3.92	-----
25	zone 1	.829	5.96	4,950	0	1	3.46	0.0455	3.04	3.88	3.55

sample holes could be used to offset this problem. However, such an approach would greatly increase the computational burden of the technique. Fortunately the kriged estimates of the average thickness were 1.02007 m (3.34667 ft) and 1.02070 m (3.34875 ft) when parameter sets R and F were used, respectively. Therefore, the noticeable difference in the appearance of the two variograms did not produce a comparable difference in the resulting estimates. The difference was less than 0.07 percent, which is negligible. This implies that in this specific case the choice of either theoretical variogram R or F is not of serious consequence. This may be one reason why visual variogram fitting approaches are widely used by other researchers.

Kriging

The modeling process for the theoretical variogram is subjective, whereas the kriging process is objective. As mentioned previously, kriging is the optimization procedure of finding weights of selected or neighboring drill holes that minimize the estimation error. This nonlinear optimization procedure is converted into a linear system using Lagrange multipliers (Journel and Huijbregts, 1978).

The kriging technique was applied to 3,000-m (9,843-ft)-wide square blocks in zone 1 and zone 2. Results of kriging for zone 1 and zone 2 are shown in figure 71 with the map of the kriged blocks. The estimated thickness of seam no. 6 in zone 1 and zone 2 is 1.12 m (3.69 ft) and 1.22 m (4.01 ft), respectively. These values were calculated from the mean value of the 28 and 13 kriged blocks, respectively.

In zone 2, five blocks were not kriged since no data points were contained within the range of influence. When 25 percent of the data points were used, no spatial dependency structure, or pure nugget effect, was obtained in zone 2. Hence, the result obtained for 25 percent of the data is reported only for zone 1 (table 11).

Estimation Variance

Table 11 shows the fitted spherical variogram parameters, the mean thicknesses, the estimation variances, and the approximate 95-percent confidence interval for thickness of Wilcox seam no. 6. These numbers were obtained from our analysis using the computer programs UGAMM, UKRIG, and ESTVAR (Knudson and Kim, 1978) with 100, 50, and 25 percent of the data. These results are different from the arithmetic mean thicknesses in the last column of table 11, which were obtained by applying classical statistics. However, each arithmetic mean thickness value is contained in the corresponding 95-percent confidence interval. The use of the approximate 95-percent confidence interval has been suggested by Journel and Huijbregts (1978).

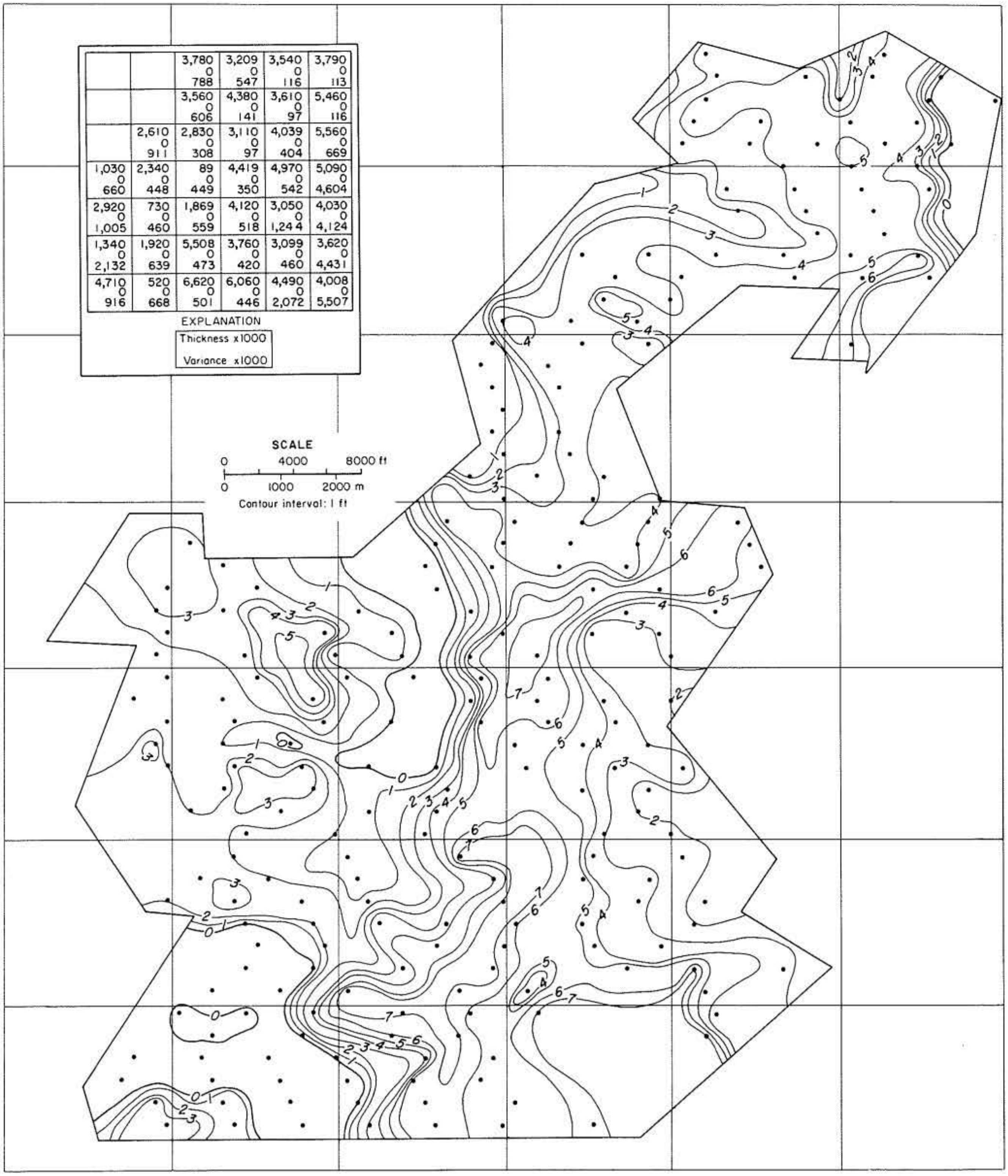
The weighted mean and variance of zones 1 and 2 were computed based on the assumption of independence for both zones. Since both zones have different underlying structures, this assumption is reasonable. Because of this independence, the following equations can be used:

$$E\left[\sum_{i=1}^{n} C_i X_i\right] = C_i \sum_{i=1}^{n} E[X_i] \qquad (6)$$

$$\mathrm{Var}\left[\sum_{i=1}^{n} C_i X_i\right] = \sum_{i=1}^{n} C_i^2 \,\mathrm{Var}[X_i] \qquad (7)$$

In the two equations above, C_1 and C_2 are the percentages of the total area that are present in zone 1 and zone 2, respectively.

Changes in all of the estimates occur when differing amounts of data are available. Notice particularly that the estimation variance tends to increase when the data availability is reduced (table 11). The method of data reduction deserves mention. From a statistical standpoint, data points to be deleted should be selected at



		3,780 0 788	3,209 0 547	3,540 0 116	3,790 0 113
		3,560 0 606	4,380 0 141	3,610 0 97	5,460 0 116
	2,610 0 911	2,830 0 308	3,110 0 97	4,039 0 404	5,560 0 669
1,030 0 660	2,340 0 448	89 0 449	4,419 0 350	4,970 0 542	5,090 0 4,604
2,920 0 1,005	730 0 460	1,869 0 559	4,120 0 518	3,050 0 1,244	4,030 0 4,124
1,340 0 2,132	1,920 0 639	5,508 0 473	3,760 0 420	3,099 0 460	3,620 0 4,431
4,710 0 916	520 0 668	6,620 0 501	6,060 0 446	4,490 0 2,072	4,008 0 5,507

Figure 71. Manually contoured isopach of seam no. 6, alluvial plain deposit, Wilcox Group of East Texas, overlain by kriged blocks with kriged results.

Table 12. Analytical results of eight seams using UGAMM, UKRIG, and ESTVAR.

Setting	Seam no.	Data used (%)	Subzone	Fitted Spherical Variogram Parameters CO	C	a	ANG.	AFH.	Kriged thickness	Estimation variance	95% Confidence Interval Lower bound	Upper bound	Arithmetic mean
			Zone 1	1.376	3.954	4,160	0	1	3.49	0.0456	3.07	3.91	3.76
Wilcox—	3	100	Zone 2		Nugget				-----	0.0137	2.40	2.86	2.63
Alluvial			Combined		----				3.11	0.0169	2.86	3.36	3.38
Plain		100	-----	1.0	1.2	2,500	0	1	1.51	0.0045	1.38	1.64	1.59
	4	50	-----	0.6	2.1	6,300	0	1	1.66	0.0104	1.46	1.86	1.65
		25	-----	0.9	1.7	6,500	23	2	1.56	0.0133	1.34	1.79	1.70
	11	100	-----	0.824	0.494	4,470	0	1	1.66	0.0151	1.42	1.90	1.70
	12	100	-----	3.214	3.637	4,680	0	1	3.16	0.0718	2.64	3.69	3.32
Wilcox—			Region 1		Nugget				-----	0.036	10.972	11.715	11.343
Alluvial/		100	zone 2		Nugget				-----	0.226	12.964	14.827	13.896
Delta Plain	90		zone 3	5.366	5.830	1.740	0	1	10.945	0.185	10.582	11.308	11.1
Transition			Combined		-----				11.908	0.035	11.543	12.273	11.6
Jackson—Strandplain/Lagoonal	10	100	-----		Nugget				-----	0.038	9.793	10.558	10.176
Jackson—	3	100	-----	2.0	0.7	2,200	0	1	7.65	0.0169	7.40	7.91	7.76
Delta		50	-----	1.7	0.9	5,500	0	1	7.90	0.0264	7.58	8.21	7.84
Plain	8	100	-----	0.07	0.13	3,200	0	1	0.72	0.0012	0.65	0.79	0.616
		50	-----	0.05	0.1	3,200	0	1	0.69	0.0015	0.61	0.76	0.619

random. To do so, however, would defeat the principle of having data points (drill holes) fairly equidistant. Consequently, it is felt that any bias contributed to the statistics is justified due to the maintenance of the dependency structure representative of the underlying deposits.

Geostatistical Evaluation of Additional Seams

The same procedural approach, as described earlier, was applied to additional seams: Wilcox seam nos. 3 and 4 from the alluvial plain deposit, Jackson seam nos. 3 and 8 from the lower delta plain deposit, Jackson seam no. 10 from the strandplain/lagoonal deposit, and Wilcox seam no. 90 from the lower alluvial plain/delta plain transition deposit.

Seam data are discussed in detail here, and the results, including the parameters of the fitted variogram models, are summarized in table 12.

Alluvial Plain Deposit

Wilcox seam nos. 3 and 4 share the same 400 km^2 (988 mi^2) region as Wilcox seam no. 6. The variograms of both seams, with a window of 90 degrees, showed very good dependency structures. As in the analysis of seam no. 6, seam nos. 3 and 4 were both divided into two zones. Zone 1 is the southern part of the deposit and zone 2 consists of the northern part of the deposit.

For seam no. 3, the variogram from zone 1 revealed a fairly good dependency structure, but zone 2 possessed only random structure. Clearly, seam no. 3 has a strong zonal anisotropy. No geometric anisotropy was found in zone 1. Hence, the spherical model was applied to zone 1 and the nugget effect model to zone 2. No anisotropies were found in seam no. 4.

In addition, variograms were obtained for two Wilcox seams, 11 and 12, from another deposit in the alluvial plain setting and revealed good dependency structures. No anisotropy was found in either seam (table 12).

Lower Delta Plain Deposit

Jackson seam nos. 3 and 8 occur in a relatively long and narrow area with an average width of 3 km (1.5 mi). In practice, the extreme limit of reliability of an experimental variogram is one-half the width, or in this case about 1,500 m (4,921 ft). This effect, combined with the comparatively low density of data, created difficulties in obtaining variograms. In the verification step of the variogram model (using the point kriging techniques described previously), there were relatively large discrepancies between the true thickness and kriged thickness compared to other well-behaved seams such as Wilcox seam no. 6. This indicates that a pathological location of drill-hole data can affect any modeling of a structural function.

The variogram of seam no. 3, with a window of 90 degrees, revealed almost random structure. The parameters of the fitted spherical variogram (table 12) for seam no. 3 showed that the difference between the sill value and the nugget value is very small, and the kriged thickness is close to the corresponding arithmetic mean.

The variogram of seam no. 8 showed a fairly strong dependency structure up to 2,000-m (6,561-ft) distances. The variogram was highly variable beyond this range, and difficulties were encountered in fitting a curve with "good" statistics.

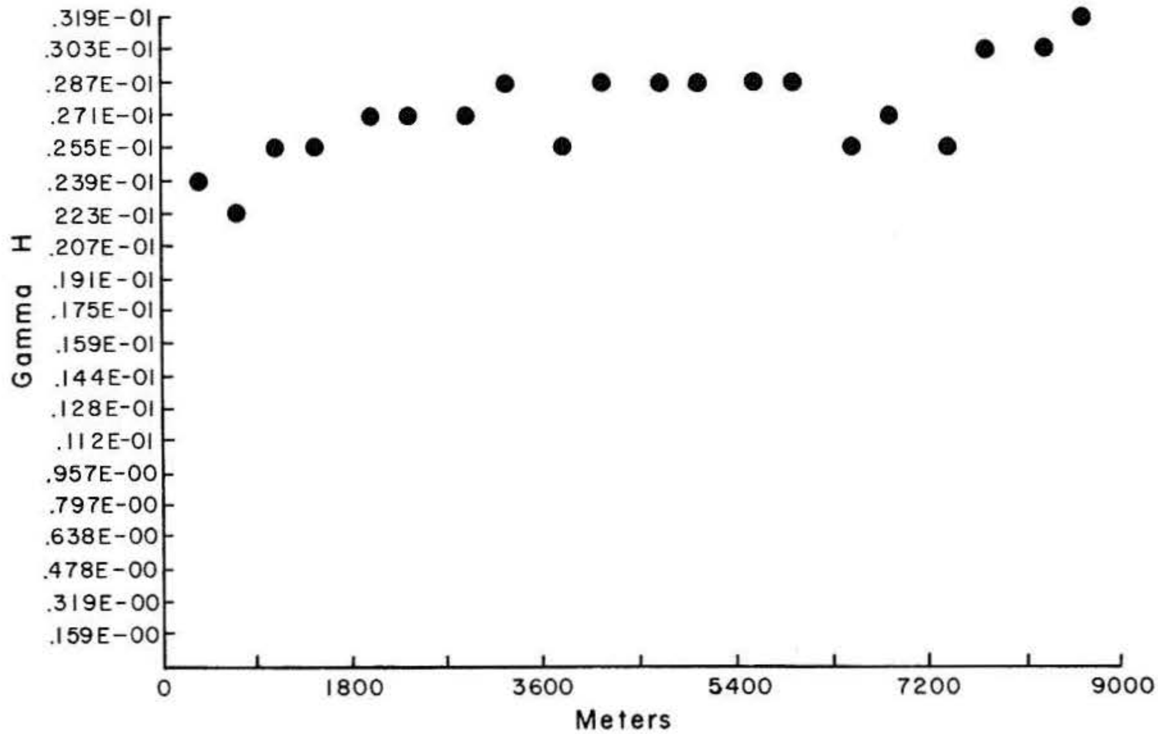


Figure 72. Experimental variogram of seam no. 3 (delta plain deposit, Jackson Group), showing 1,500-m limit of variogram reliability.

Strandplain/Lagoonal Deposit

Jackson seam no. 10 exhibits a boundary shape and orientation similar to the previously discussed seams of the lower delta plain deposit, and similar difficulties in obtaining a variogram were encountered. The experimental variogram as shown in figure 72 with a window of 90 degrees showed almost random structure. After additional investigation, it was concluded that the nugget effect model is appropriate for this deposit.

Lower Alluvial Plain/Delta Plain Transitional Deposit

The distribution of borehole data for Wilcox seam no. 90 led to the division of the entire area into two regions, named 1 and 2, which are shown in figure 73. The variogram of Region 1 revealed an almost purely random structure. The variogram of Region 2 showed a fairly strong dependency structure, but exhibited two plateaus. This structure might be caused by zonal anisotropies in Region 2. Therefore, Region 2 was divided into zone 2 and zone 3. Zone 3 has 185 boreholes and zone 2 has 63 boreholes. The total areas of both zones are similar. The variograms of the zones are different. No dependency structure was found in zone 2, but zone 3 had a slight dependency structure with no geometric anisotropy (table 12).

Summary

In the analysis of lignite seams, the spherical and nugget effect models have been appropriate. Three variations of these two models were encountered. The first is a spherical variogram, as shown in figure 68. The second is a nugget effect model, as shown in figure 72. The third type of variogram (fig. 69) falls between these two and has a nugget effect slightly less than the sill value and reaches its sill value gradually.

Resources calculated by kriging for seams with dependency structures are shown in table 13. The resource estimates are similar to those obtained by previous methods.

Number of Holes Required to Characterize Resources of a Seam

The degree of certainty of a resource is expressed as a percentage. For example, measured resources are those resources with a tonnage known to within a confidence limit of 20 percent. If the boundary of a seam is known with certainty, as is commonly the case with individual leases, it is possible to use statistical methods to indicate the amount of drilling necessary to determine the average thickness to within a given percentage. The density of drilling, and the relative location and number of holes are important in

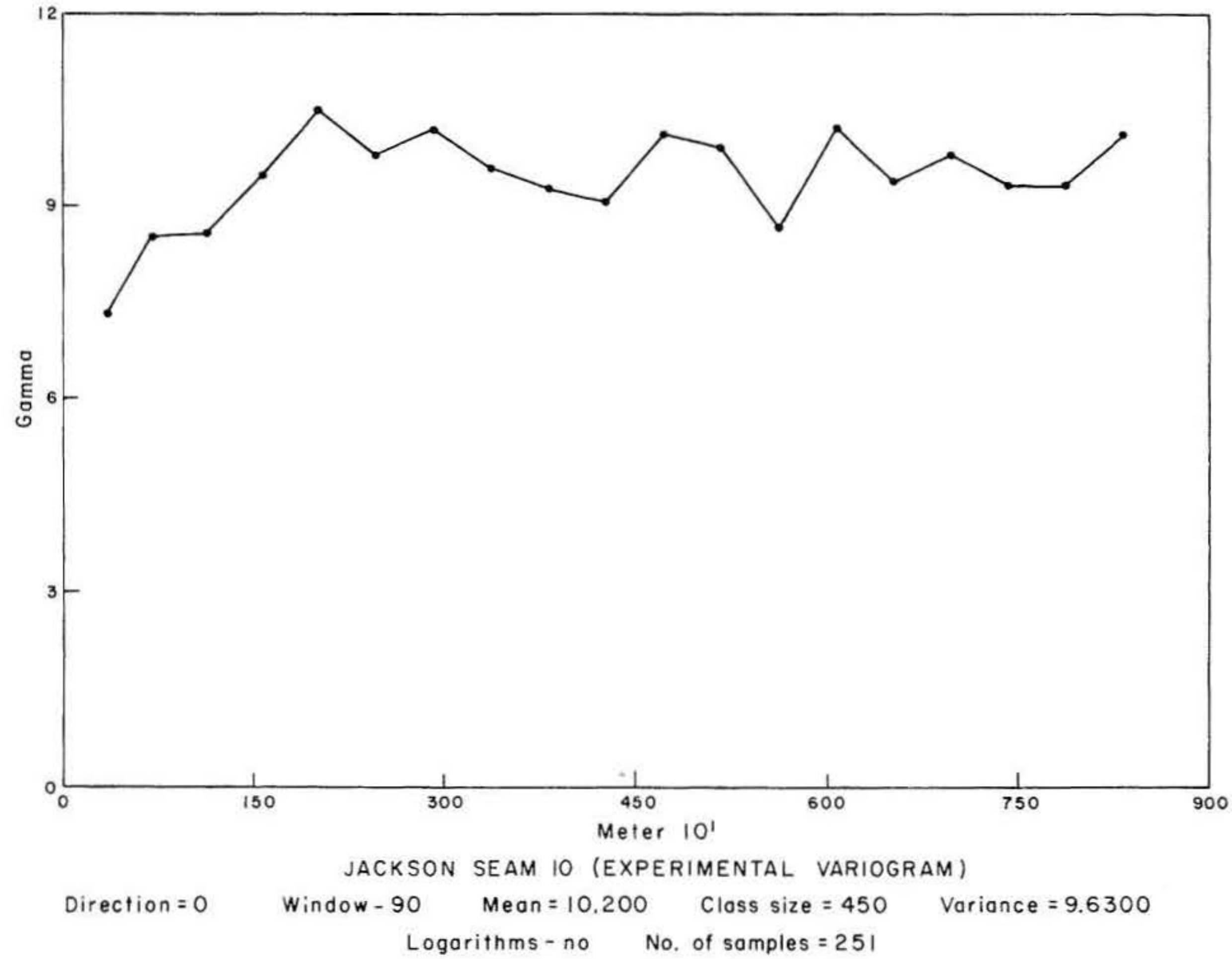


Figure 73. Experimental variogram for seam no. 10, strandplain/lagoonal deposit, Jackson Group.

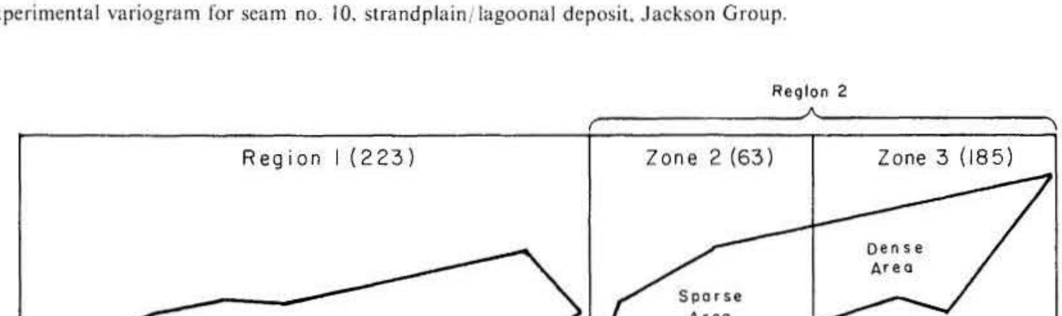


Figure 74. Division of seam no. 90 into zones, alluvial plain/delta plain transitional deposit, Wilcox Group.

determining the average seam thickness to a given percentage degree of certainty. Other important factors are the dependency structure and coefficient of variation of the seam thickness (that is, the standard deviation as a proportion of seam thickness).

Presence of a dependency structure can improve the estimate, provided samples are independent statistically. A moderate number of regularly spaced holes (depending on the coefficient of variation) is sufficient to characterize the tons per acre in a deposit to within a range of confidence, for example, within 20 percent. A statistically based measure of seam variability in terms of number of holes is derived and used for comparison in the following discussion.

Table 13. Comparison of resource tonnages using different methods of calculation (short tons x 10^6 [tonnage factor 1,750 short tons/acre ft]).

Method % of data set	Alluvial plain seams		Lower delta plain seams		Strandplain/ lagoonal seam	Lower alluvial/ upper delta plain transition seams
	no. 6	no. 4	no. 3	no. 8	no. 10	no. 90 and 90a
Hand-calculated tonnage						
100	276.8	96.2	111.2	6.3	411.1	
50	269.3		105.1		400.5	
25	274.3		104.8		375.2	
Computer-calculated tonnage						
100	261.1	91.8	118.8	6.5	428.8	287.2
50	259.0	97.0	115.9	6.2	417.9	288.1
25	260.9	93.2	114.2	5.1	428.7	292.5
12.5	229.4	97.4	109.4	4.6	428.2	300.8
Geostatistically calculated tonnage						
100	260.1	84.9	123.1	6.6		
50	265.9	93.5	127.1	6.3		
25	270.9	87.9	—	—		

Assume a deposit of area A, drilled with n boreholes; assume further that the n holes are drilled on a regular square grid of side d. Since each hole is at the center of a square block of area d^2, then approximately:

$$n = \frac{A}{d^2} \tag{8}$$

Suppose further that a spherical variogram model has been adopted to describe the spatial dependency, with nugget effect C_o, sill $C + C_o$, and range "a." If the average thickness of the deposit is estimated as the average of the thicknesses of the n blocks, with each block estimated from the value of the central borehole, it is possible to arrive at an expression for the variance of the resulting estimate. Certain assumptions are made, following a method used by Knudson and Kim (1978, p. 190) and discussed in Journel and Huijbregts (1978). First, the variance of the estimate due to estimating a block by a borehole at its center is computed as:

$$\sigma_L^2 = C_O + r(\tfrac{d}{a}) \times C \tag{9}$$

where $r(\frac{d}{a})$ is a multiplicative factor between 0 and 1 that depends on d. This formula takes into account geostatistical theory and assumes correlation of sample values within a block. It may be assumed that the error for one block is independent of errors for the other blocks, which is true to a first approximation (Journel and Huijbregts, 1978, p. 414). Then the variance of the estimate for the whole deposit can be approximated by:

$$\sigma_D^2 = \frac{\sigma_L^2}{n} = \frac{C_O + r(\frac{d}{a}) \times C}{n} \tag{10}$$

Table 14 gives approximate values for the function r, showing that for d>6a, $r(\frac{d}{a})$ approximates 1 (Knudson and Kim, 1978, p. 190). In that case, equation (10) simply becomes:

$$\sigma_D^2 = \frac{\sigma_L^2}{n} = \frac{C_O + C}{n} \tag{11}$$

which is the statistical formula for the variance of the mean of n independent samples with individual variance σ^2.

Normal distribution theory predicts that the average value of n borehole thicknesses will lie in 95 percent of all cases in the interval given by:

$$\left(\mu - \frac{2\sigma_L}{\sqrt{n}},\ \mu + \frac{2\sigma_L}{\sqrt{n}}\right),$$

where μ is the true mean of the borehole thicknesses. The figure of 95 percent is chosen arbitrarily to represent an

Table 14. Values of the multiplicative factor, r, for borehole thickness variance as a function of the ratio between grid square size and geostatistical range.

ratio	a	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	2	3	4	5	6
factor	r	0.039	0.075	0.12	0.16	0.19	0.24	0.28	0.32	0.37	0.41	0.80	0.91	0.95	0.97	0.99

acceptable degree of confidence. To calculate how many holes are necessary to achieve an interval of $\pm 100p$ percent (where $0<p<1$), n must be large enough that

$$\frac{2\sigma_L}{\sqrt{n}} < p\mu$$

$$\text{that is, } n > \frac{4}{p^2}\frac{\sigma_L^2}{\mu^2} \qquad (12)$$

Here $\frac{\sigma_L}{\mu}$ is the coefficient of variation (the standard deviation divided by the mean).

Combining equations (8), (10), and (12) yields:

$$n > \frac{4}{p^2}\frac{\left[C_0 + r\left(\frac{1}{a}\sqrt{\frac{A}{n}}\right)C\right]}{\mu^2}$$

$$\text{that is, } n > \frac{4C_0}{p^2\mu^2} + \frac{4C}{p^2\mu^2}\, r\left(\frac{1}{a}\sqrt{\frac{A}{n}}\right) \qquad (13)$$

The assumption by the theory of normality for the distribution of average seam thickness is clearly justified by reference to figure 75, where the distribution of thicknesses of the thicker seams is shown to be close to normal. The distribution of the thinner seams appears to be exponential. In the absence of any dependency structure, equation (13) becomes:

$$n > \frac{4\sigma^2}{p^2\mu^2} \qquad (14)$$

Equations (13) and (14) assume that individual block estimation errors are independent statistically, which is true to a first approximation if each block is estimated from its own data. The availability of large borehole data sets for each of the deposits means that good estimates (fig. 75) of the mean and standard deviation of thickness were obtained. Equations 13 and 14 must however be applied with caution where the underlying assumptions may be violated. The use of the number, n, is to provide a relatively simple comparative measure of variability whereby different deposits may be compared.

Estimates of σ and μ are available for most of the seams studied. Table 15 shows the values of n derived from equation (14) using these estimates and assuming a 20- and 10-percent precision level. The required number of boreholes is considerably less than is currently considered necessary for resource evaluation. Table 15 shows that to achieve a 10-percent level of precision, that is, to double the precision, four times the number of holes are required. In all cases it is assumed that the holes are spaced regularly throughout the deposit. The numbers in table 15 assume that the average thickness and variance of seam intersections do not change from place to place within the deposit.

Equation 14 implies that no matter how large the area A is, provided that it remains "homogeneous," a fixed number of regularly spaced drill holes will suffice to characterize the seam thickness within percentage bounds. However, a geologist is normally not prepared to infer data from an area beyond a certain distance from the nearest control point. This possibly reflects a belief that the homogeneity will be likely to disappear as A becomes larger. The crucial question then becomes: for how great a distance can we expect statistical homogeneity to extend? This question remains for further investigations.

As an example of the influence of an underlying dependency structure, it may be noted that if a nugget effect of $0.09\ m^2$ ($1.0\ ft^2$), a sill of $0.37\ m^2$ ($4\ ft^2$) and a range of 5,000 m (16,404 ft), similar to the average values found for Wilcox seam no. 6, are applied using equation (13) of this section, with a value for the area A of 17,010 hectares (42,031 acres), the value of n obtained is 15 holes, compared to 33 obtained by classical methods. In other words, with knowledge of the dependency structure in this case the same precision can be predicted from approximately 55 percent fewer holes than would be needed if no dependency structure was considered.

Table 15. Number of holes, n, required to characterize thickness on the basis of classical statistics.

Seam	No. of holes available	μ ft	σ ft	n (20%)	n (10%)
Alluvial plain					
Seam 4	594	1.59	1.52	92	366
Seam 6	568	3.63	2.06	33	129
Lower delta plain					
Seam 3	147	7.76	1.63	5	18
Seam 8	121	0.62	0.41	44	175
Strandplain/lagoonal					
Seam 10	250	8.41	2.20	7	27
Alluvial plain/delta plain transition					
Seam 90	471	11.57	3.42	9	35

FREQUENCIES OF SEAM THICKNESSES

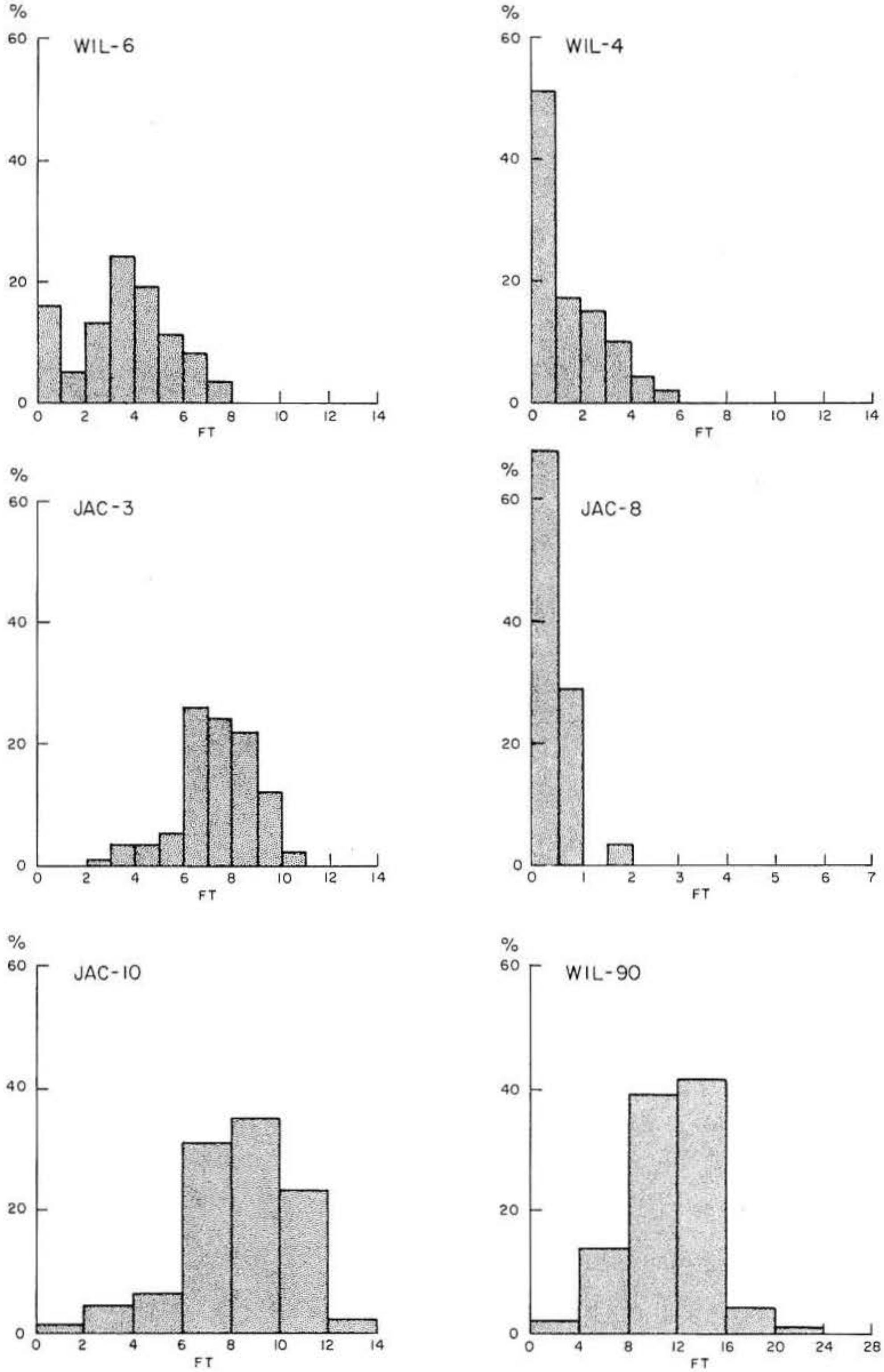


Figure 75. Frequency histograms of thicknesses for thick seams: Wilcox seam no. 6, Jackson seam no. 3, Jackson seam no. 10, and Wilcox seam no. 90; and thin seams: Wilcox seam no. 4 and Jackson seam no. 8.

Introduction

There are many instances when resource estimates are desired for a relatively large geographic area, or in other words, at a regional level. Data at the regional level of evaluation consist of boreholes of different depths and highly variable spacing. Accurate seam correlation is generally not possible; therefore resource calculation is limited to the sum of all seams in each borehole (total coal). In contrast, the deposit level of evaluation assumes the existence of identifiable coal seams persisting throughout the study area, except where the seams are naturally bounded or where geological processes have removed them. Some methods of resource investigation used at the deposit level are not necessarily transferable to the regional level; therefore, alternative methods that take into account the inability to correlate seams and the variable spacing of boreholes must be developed for use at the regional level. These methods should also provide an estimate of the uncertainty of the final tonnage figure. Three approaches are explored: geostatistical, alternate statistical, and geologic. The common aim in all these methods is to reduce the uncertainty in the final estimate by exploiting inherent information. At the same time, the methods should continue to perform well when lesser amounts of data are available.

The outcrop of the Wilcox Group in east-central Texas, an area approximately 249 km (150 mi) long and 3 to 20 km (2 to 12 mi) wide, was selected for developing these methods of evaluating regional resources. Data from 1,382 boreholes were obtained from geophysical logs and included the location of the borehole, the number of lignites encountered, the top hole elevation, the total borehole depth, and the depth and thickness of each lignite seam.

Geologic Setting

The Wilcox Group in east-central Texas has been divided into three formations (Calvert Bluff, Simsboro, Hooper) and is bounded by the Midway Group below and the Carrizo Sand above. The Calvert Bluff is the major lignite-bearing unit; it conformably overlies the Simsboro Formation. The Simsboro, which contains few lignites, is a massive sand that unconformably overlies the Hooper. Lignite occurs as a persistent zone in the lower part of the Calvert Bluff Formation just above the Simsboro Formation and again in the upper part of the Calvert Bluff. Northward toward the Trinity River, the Simsboro Formation is a facies equivalent of the Calvert Bluff, and lignites in the Simsboro occur at this transition. Hooper lignites are most numerous and thickest in the upper part of the formation just below the Simsboro (Kaiser and others, 1978).

Knowledge of the depositional setting and geologic features in regional studies is beneficial in understanding the uncertainties that are associated with tonnage estimates. The Calvert Bluff, Simsboro, and Hooper Formations of the Wilcox Group in east-central Texas contain sands that form complex channel networks displaying straight, dendritic, and bifurcating trends characteristic of fluvial and deltaic depositional systems. The areal distribution of lignite in the Wilcox of east-central Texas occurs in elongate concentrations roughly parallel to the paleoslope and primarily in sand-deficient interchannel areas (Kaiser and others, 1978).

Geostatistical Methods

The following discussion presents an analysis of the difficulties inherent in a geostatistical resource estimation of the Wilcox Group in east-central Texas. Geostatistical coal resource estimation can be divided into two categories, deposit and regional. Deposit estimation is concerned with the best estimators of the underlying true statistics of a regionalized variable over a relatively small area. The areal dimensions of deposit estimations are generally smaller than the dimensions of the quasi-stationary (homogeneous) zones. Estimation at the regional level considers distances larger than the limits of quasi-stationarity and, thus, in some cases contains various heterogeneous deposits.

Only the variogram is required for application of the kriging estimation technique. If this variogram is known over an entire region, the regional estimators can be obtained. The assumption of regional stationarity is rarely met. Furthermore, over a large region, seam boundaries and discontinuities will interfere with information about seam thickness variation. Even if the condition of regional stationarity is satisfied, it is difficult to construct a kriging system and then to solve the resulting system. A large regional data set presents difficulties both in terms of computer storage and computer execution time. For these reasons the entire region is rarely kriged directly. Instead kriged estimates of small areas are usually combined to form a regional estimator. Such a process typically follows these three steps: (Journel and Huijbregts, 1978):

Step 1. Divide the region into kriging blocks of reasonable size.

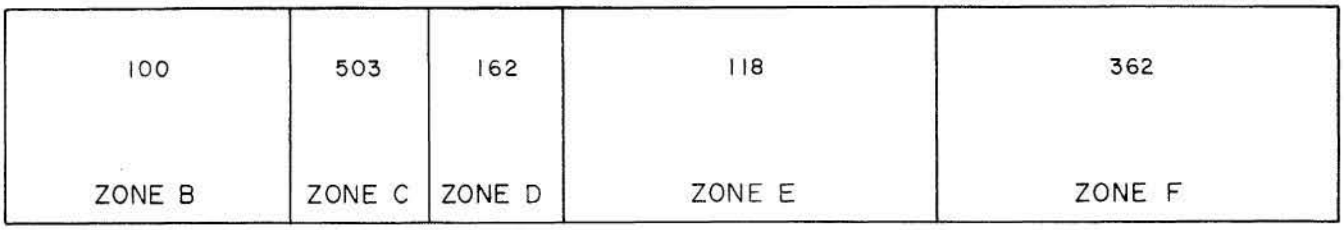


Figure 76. Division of the areal distribution of the Texas regional dataset into zones, indicating number of boreholes in each.

Step 2. Find the kriged estimates of each block.

Step 3. Combine the kriged estimates of the blocks.

One method of combining the kriged estimates is to form a weighted linear combination of the estimators of the component blocks. If the number of kriging blocks is very large, this approach commonly requires lengthy computing time, especially for computing estimation variance. To reduce required computing time, a method of combining statistical sampling and kriging of small blocks has been suggested (Starks and others, 1980). In all cases, it is assumed that the variogram is available.

The data set for the Wilcox Group of east-central Texas contains 1,382 boreholes spread over an area of about 10,000 km^2 (3,861 mi^2). Because of the narrowness of the study area in east-central Texas, the limit of the reliability of the variogram is remarkably small. Even within the reliable range of the variogram, the experimental variogram cannot give dependable information about the underlying dependency structure of the region due to the inconsistency of the distances between drill-holes.

The study area was divided into five zones to allow investigation of the variogram of total lignite thickness throughout the region (fig. 76). Except for zone C, no reliable dependency structures were found.

Considering the results obtained from the seam-by-seam analysis in the deposit studies, a dependency structure may well exist in every seam of the region. However, the spatial distribution of the data set presents difficulties in finding those dependency structures. Furthermore, the summation of thicknesses of different coal seams strongly affects attempts to find the dependency structure of the region. That is, even though each seam has a good dependency structure, the combined seam data may not reveal any dependency structure.

Alternate Statistical Methods

Analysis of Borehole Data

Data from the 1,382 boreholes were placed in the computer system. The data included the location of the hole, the number of lignites encountered, the top hole elevation and the total depth of the borehole, and for each lignite seam intersected, a record of the depth and thickness of the seam. This information was measured as before from the geophysical log traces. In the study area nearly half the boreholes are densely clustered in the southwestern part.

The total borehole data set has been analyzed statistically in several ways. Figure 77 shows frequency histograms of individual seam thickness, total lignite thickness per borehole, and the number of seams per borehole. It is possible, as shown in figure 77, to fit an exponential model with a mean of 1 m (3.42 ft) to the distribution of seam thicknesses greater than two feet. A Kolmogorov-Smirnov Test (Breimann, 1973) does not reject this fit at 5 percent significance. The deviation from exponential among very thin seams is possibly explained by the difficulty of detecting or measuring thin seams on the geophysical logs. Figure 77 shows that the number of seams per well has an appearance similar to the Poisson distribution.

A correlation and regression computation was made to determine whether variation in total lignite thickness is related statistically to variation in some other measured factors. For this purpose, the boreholes were grouped by 7.5-minute quadrangle, and average statistics for the set of boreholes in each quadrangle were computed. Each quadrangle was treated as an observation for the regression. None of the factors measured had a major influence on the total lignite except the average seam thickness and the number of lignites (their product approximates total lignite). A statistically significant predictive relationship (.001 significance level) between total lignite and hole density was observed, as well as between total lignite and the downdip location of the 7.5-minute quadrangle, but neither had a large predictive value (regression coefficient). Table 16 shows the factors used and the matrix of correlation coefficients obtained in the regression.

Resource Evaluation Methodology

Because dependency structures cannot be identified for the entire region, an alternative statistical

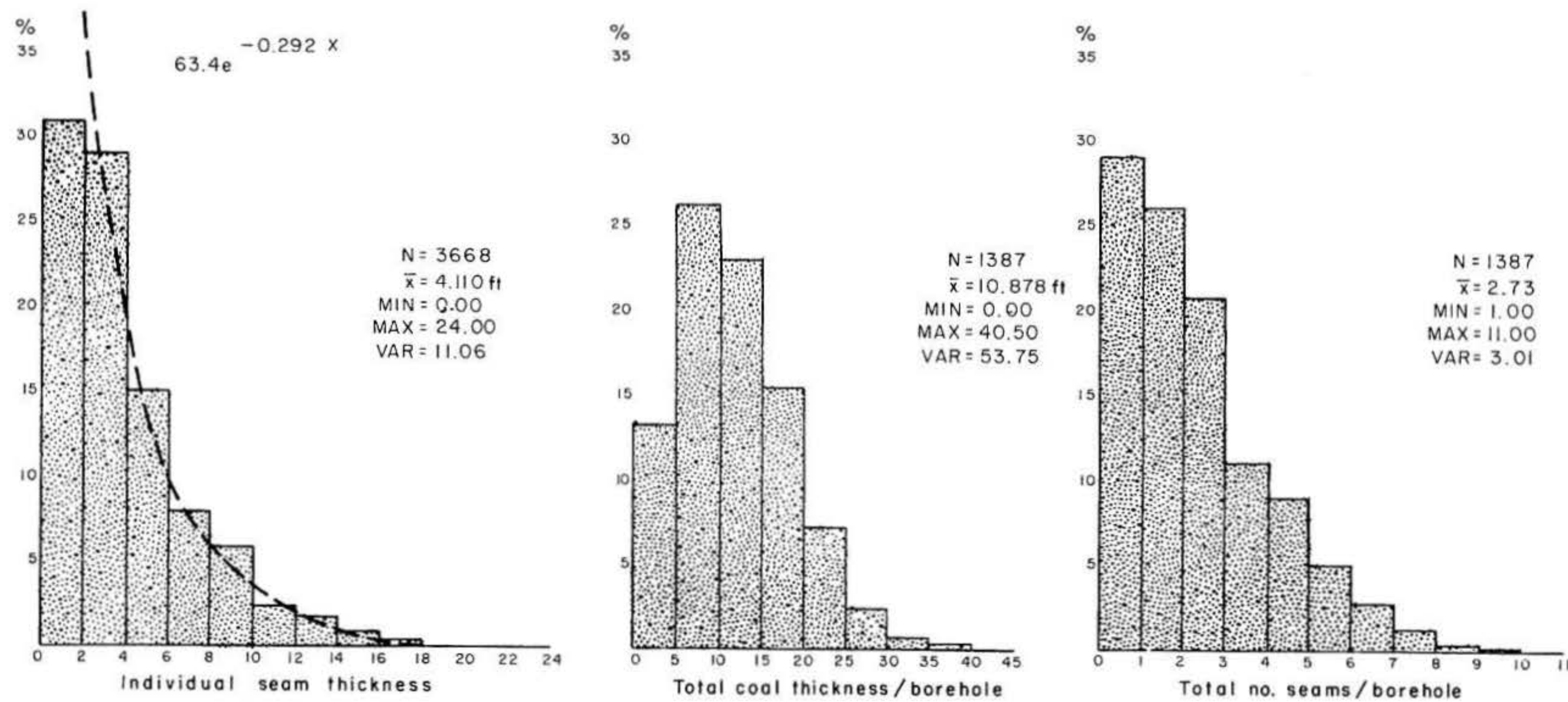


Figure 77. Frequency histograms and statistics for regional data for the Wilcox Group of east-central Texas, showing the exponential model fitted to seam thicknesses.

Table 16. Correlation coefficients: average values by quadrangle.

	NWELLS	X	Y	THPFT	SMPFT	AVESMTH	AVEPTTH	SDTH	SDNSMS	SDSMTH
X	-.39173									
Y	-.11080	.36046								
THPFT	.13345	-.51561	-.32454							
SMPFT	-.22129	-.26858	-.44348	.82026						
AVESMTH	.71049	-.56425	-.10446	.54868	.02170					
AVEPTTH	-.29075	.37166	.49003	-.38793	-.23495	-.44117				
SDTH	.22900	-.62433	-.34849	.57210	.36631	.47704	-.33539			
SDNSMS	.09257	-.40323	-.47381	.64102	.60618	.24359	-.52268	.74298		
SDSMTH	.51173	-.41782	-.07547	.54636	.12918	.76473	-.36366	.47182	.43631	
SDPTTH	-.03615	-.23709	-.04868	.06760	.18126	-.08313	.35028	.17265	-.00304	.06728

Explanation: NWELLS = well density; X = location along strike; Y = location downdip; THPFT = average coal thickness per foot of well; SMPFT = average number of seams per foot of well; AVESMTH = average seam thickness; AVEPTTH = average parting thickness; SDTH = standard deviation of parting thickness; SDNSMS = standard deviation of number of seams per well; SDSMTH = standard deviation of seam thickness.

methodology can be used. In all the methods to be discussed, attention is directed to estimating the average total lignite thickness. Tons may then be computed by multiplying this figure by the area and tonnage factor (1,750 tons per acre foot for lignite). In all cases the area is known or set.

Equal Weighting

Equal weighting of holes is a commonly used procedure. As an example, for n holes, where the total thickness of coal in the i^{th} hole is X_i feet, then an estimate for average thickness is given by:

$$\bar{X} = \frac{1}{n} \sum_{1}^{n} X_i \qquad (15)$$

and the variance of the estimate is given by:

$$\text{var}(\bar{X}) = \frac{1}{n} \text{var}(X_i)$$

$$= \frac{1}{n(n-1)} \sum_{1}^{n} (X_i - \bar{X})^2 \qquad (16)$$

These equations are only strictly applicable when a pure nugget effect model is determined, so that borehole values are statistically independent. In this case the equations yield estimates and variances of estimates coinciding with those derived by geostatistics; that is, the sample mean and variance are the same as the spatial mean and variance (Journel and Huijbregts, 1978, p. 312). These conditions are not likely to be met over an entire region; nevertheless, this method was tested. Application of the equations to the whole data set yields a mean of 3.3 m (10.9 ft) and a variance of .01 m^2 (0.039 ft^2). This is equivalent to the 95 percent confidence interval of 3.3 ± 0.1 m (10.9 ± 0.39 ft), which implies an uncertainty of only 7.2 percent. However, because of the known concentration of drilling in areas of thick lignite, the mean value of 10.9 ft cannot be accepted with confidence.

Grid Method

This method consists of laying a grid over the borehole location map so that each borehole lies inside (or on the boundary of) some grid cell. Only those grid cells which have two or more boreholes assigned to them are considered for further analysis (see fig. 78). The average thickness of the total lignite in a cell is estimated from all the boreholes in the cell by equation 15, and the variance of the estimate is computed from equation 16; that is, the method of equal weighting is applied to each cell separately. If there are M cells, and the estimate of the i^{th} cell is $\bar{x}_i$ ft, and the variance of the estimate is var ($\bar{x}_i$) ft^2, then the estimate of average thickness of all cells combined is given by:

$$\bar{\bar{X}} = \frac{1}{M} \sum_{1}^{M} \bar{X}_i \qquad (17)$$

and the variance of this estimate is given by:

$$\text{var}(\bar{\bar{X}}) = \frac{1}{M^2} \sum_{1}^{M} \text{var}(\bar{X}_i) \qquad (18)$$

Grid cells are weighted equally to produce the final result. The equations are based on the assumption that

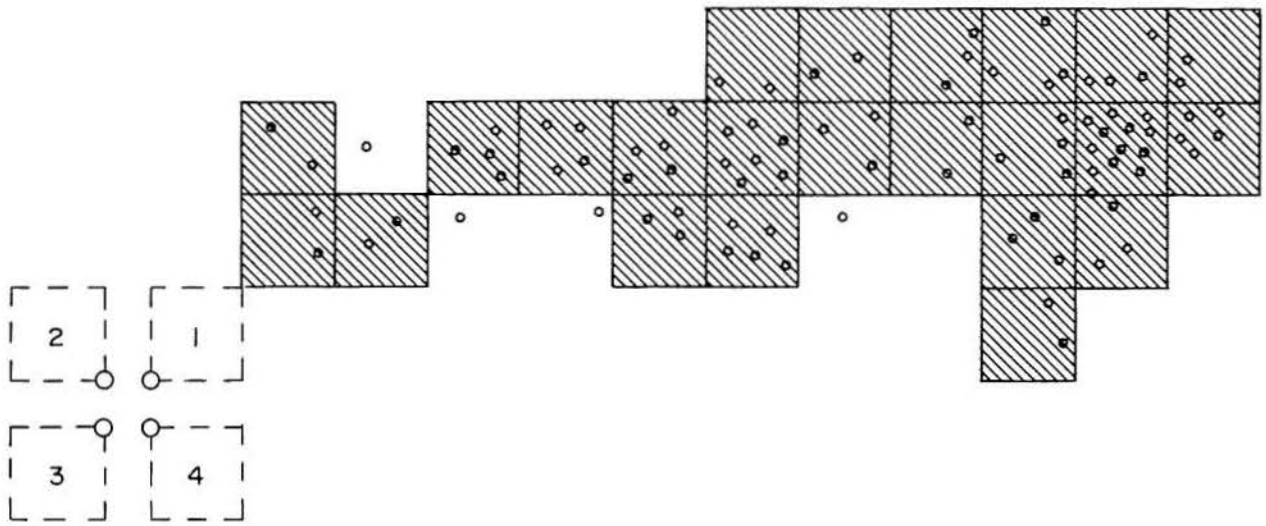


Figure 78. Grid method: grid cells shown are determined by the position of cell 1.

the average thickness and variance of the estimate in each cell can be adequately estimated by an equal weighting technique, that is, a separate pure nugget effect is applicable in each cell, and that cell means are statistically independent of each other. Earlier results have shown that dependency structures in individual lignite seams have a range not greater than approximately 5,000 m (16,000 ft) so a grid size of 5,000 m was chosen for the application of the method to ensure statistical independence of cell means. The grid was applied four times with different origins, to test the stability of the results (see fig. 78). The results are shown in the first part of table 17. The second part of table 17 shows similar results for grids of 10,000 m. Both grids yield the same estimate of mean thickness (7.9 ft) but the variances of the larger grid computed from equation 18 are about 50 percent higher.

Both grids also produce a computed estimate that is 73 percent of that obtained from equation 16 using equal weighting for the whole data set. This estimate of regional resources may be regarded with more confidence than the overall equal weighting model, because the breaking up of the area into cells clearly makes greater allowance for the local differences in mean and variance that may be expected in a study of regional total coal.

Using the sample variance of repeated estimates, which was obtained by shifting the origin of the 5,000 m grid, considerable confidence can be placed in the estimate of 2.4 ± 0.14 m (7.9 ± 0.47 ft) of total coal for the region, equivalent to an uncertainty of 11.9 percent. However, it is clear that the grid method will fail progressively as data levels are reduced or as cell sizes decrease, since more and more grid cells will fail to meet the requirement of having two data points. Reduction in grid size also risks the independence of cell means. The area being estimated is the sum of all the cells. The grid method can be regarded as a quick way of getting a good estimate if the data are plentiful and are already stored in a computer. The uncertainty in the estimate may be assessed by simulating different grids as above, though it should be remembered that the results from the different grids are not statistically independent.

Homogeneous Block Method

A method has been developed which can be applied to intermediate levels of data availability. The general method is to partition the study area into a set of blocks, of any shape, such that the blocks have some internal homogeneity. The mean total thickness and the variance of estimate of individual blocks will be calculated by equally weighting all the data in the block. Thus, the internal homogeneity sought is such that any errors introduced by assuming a pure nugget effect model are minimized. If a block is known to possess a dependency structure other than a pure nugget effect, the structure should be used to obtain a better estimate and variance of estimate for that block.

Suppose that the area has been partitioned into M blocks, and that the estimate of mean and variance of estimate for the i^{th} block are $\bar{x}_i$ and var $(\bar{x}_i)$, respectively. The mean of the whole study area will be estimated by a weighted sum of the block means. Let a_i be the weight applied to the i^{th} means, with the a_i's summing to unity. Then the overall mean $\bar{\bar{x}}$ is calculated from:

$$\bar{\bar{X}} = \sum_{1}^{M} a_i \bar{X}_i \qquad (19)$$

Table 17. Means and variances of estimates from varying grids (Texas).

Case	Grid Size	Origin	Holes	Estimated Mean (ft)	Variance of Estimate (ft^2)
1	5000 m	0,0	1348	7.92	0.0373
2	"	-2500,0	1350	7.53	0.0363
3	"	-2500,-2500	1359	8.05	0.0348
4	"	0,-2500	1345	8.15	0.0354
1 - 4	Summarized			7.91	0.036*
5	10,000 m	0,0	1378	7.54	0.0420
6	"	-5000,0	1379	7.60	0.0479
7	"	-5000,-5000	1374	8.22	0.0580
8	"	0,-5000	1374	8.33	0.0753
5 - 8	Summarized			7.92	0.056*

*The summarized variance is the mean of the four variances.

and the variance of estimate by:

$$\text{var}(\bar{\bar{X}}) = \sum_{1}^{M} a_i^2 \text{ var}(\bar{X}_i) \tag{20}$$

There are several possible weighting schemes for combining blocks to form an overall estimate: weighting by number of samples, by inverse variance (which minimizes the total variance, formula 20) or by the area of the blocks. The first was not used because it produces the same estimate as the equal weighting method. The second would be the best method if all blocks could be regarded as independent estimators of the same average thickness. This applies only if there is no trend over the region, which cannot be assumed without extensive analysis. The third method was adopted, in which the weight given to a block is proportional to the area of the block. The homogeneous block method can thus be seen as a generalization of both the grid method (the special case where all the blocks have equal area and shape) and the equal weighting method (the special case of only one block for the whole region). For simplicity, all data points in a homogeneous block were used, although it might be more realistic in terms of the nugget effect model to randomly sample from areas of locally dense drilling.

To apply the method, the region must be partitioned into blocks which have a measure of internal similarity or homogeneity. The boundaries of the blocks and also the number of blocks to be used must be decided. Three primary methods of block selection have been considered: cluster analysis, contour mapping, and geologic mapping. Cluster analysis assigns basic units to larger groups on the basis of similarity of attributes. A cluster analysis was carried out on data averaged by 7.5-minute quadrangles using a computer program (Davis, 1973). The criterion for clustering was the total thickness in each quadrangle of coal in the following three categories: thin seams (less than 2 ft), medium seams (2 to 6 ft), and thick seams (greater than 6 ft). The cluster program assigned the quadrangles to six main groups, each characterized by the relative proportions of thin, medium, and thick seams. The first group contained a predominance of thin seams, the fourth a predominance of thick seams, and the rest a predominance of medium seams, but the groups differed in the relative proportion of thin and thick seams. The results are shown schematically in figure 79, wherein topographic quadrangles are shaded according to the group to which they were assigned by the cluster program. The criterion for clustering in this case depends on the probability distribution of seam thicknesses, which is of exponential type over much of the range and is therefore close to being described by a single parameter, namely average thickness. This therefore suggests that essentially similar results could be obtained from contour maps of average seam thickness, and for this reason, this particular cluster technique was not pursued further. In another approach to clustering, using the single linkage technique with individual boreholes as elements, it proved difficult to constrain the clusters to compact subregions except by overemphasizing coordinate values to the point where geological factors made little or no difference.

The contour method of block assignment involves the use of contour maps to suggest areas of internal homogeneity. Four possible basic techniques were considered. The rationale for the first method (overlay technique) is derived from the observation that the

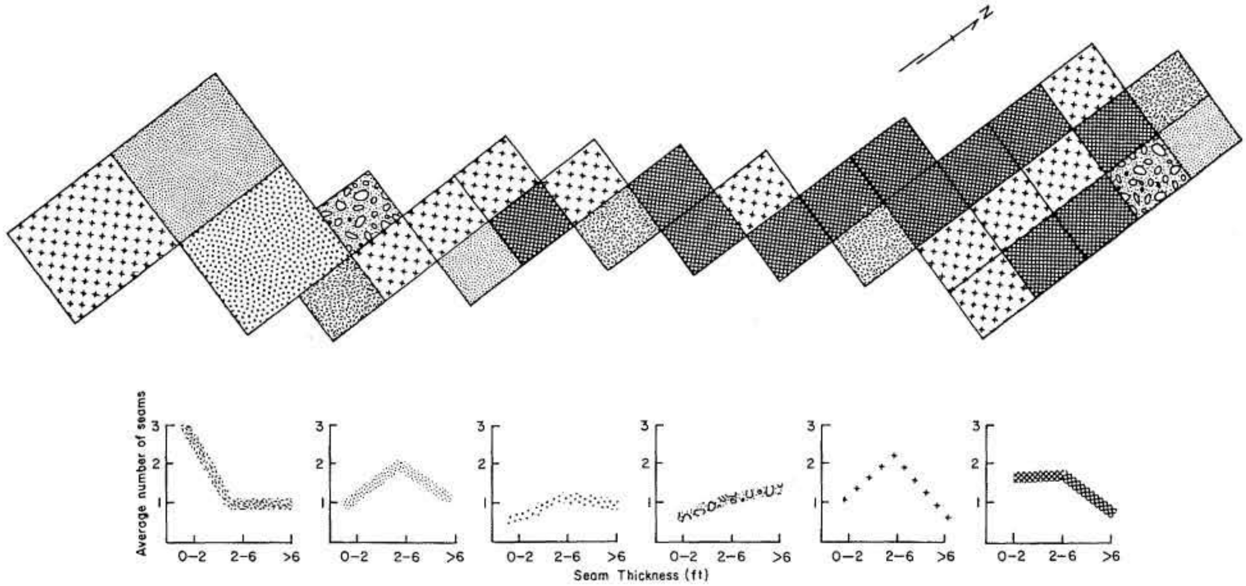


Figure 79. Clusters of east-central Texas topographic quadrangles, based on the proportion of thin (0 to 2 ft), medium (2 to 6 ft), and thick (over 6 ft) seams represented in the quadrangle.

distributions of average seam thickness and number of seams (fig. 77) are simply characterized by their averages, and that the average total lignite in an area is the product of the average number of seams and the average seam thickness. Homogeneity in the product (total lignite) will thus be assured by homogeneity in both average thickness and number of seams. The two contour maps are overlaid, thus providing more information in the selection of blocks than if one map were used. The second technique was to use a single contour map of the total lignite thickness (total coal). The third technique was to use a contour map of the average borehole density, and the fourth was to contour a mathematical function measuring precision of estimate, which was computed using the local mean and variance of total lignite thickness as well as the number of holes in an area. The function measures the precision with which the coal can be locally estimated; the formula is similar to that used to determine the number of holes required to estimate comparative lignite thickness variability, as discussed previously. In the fourth technique the number of boreholes is known and it is the precision, P, which must be estimated. The rationales for the third and fourth techniques were to test blocks which would be homogeneous in terms of borehole density and precision of estimation, respectively; such blocks should be well estimated by the equal weighting method.

The contour maps were produced by the computer using the CPS-1 program on data averaged over 5 km^2 (1.9 mi^2) cells. The resulting contours were smoothed, making the choice of block boundaries easier. The maps were shaded to highlight areas of above-average and below-average values and the boundary of the total region was drawn. Blocks were then chosen which appeared to enclose homogeneous areas (fig. 80). With the first technique (overlaid contours) the blocks are areas in which both maps show high values, or both show low values, or one showed high and the other low.

For the total lignite and hole density maps (second and third techniques), the area was divided into above-average and below-average categories. In the second technique, the contours of equal total lignite define areas of internal similarity. In the case of the precision function map (the fourth technique), four distinct value classes were considered (0 to 10 percent, 20 to 50 percent, 50 to 100 percent, and greater than 100 percent). Contour maps were evaluated as in other techniques. For ease of computation, all the techniques used only rectangular blocks.

Results of the four techniques for selecting homogeneous blocks are summarized in table 18. For each technique, two results are given, first for the full number of blocks chosen, and then for a few large blocks, chosen by combining all original blocks of the same type into one, regardless of contiguity. For example, all blocks of less than average total coal were combined into one area, the mean and estimation variance of which were then reestimated using the equal weighting method.

The results in table 18 are compared graphically with the results of the grid and other methods in figure 81. The grid method is used as a reference; the dotted vertical lines in the figure show the 95 percent confidence interval obtained from the grid method. Using this reference, the other techniques are ranked according to whether the

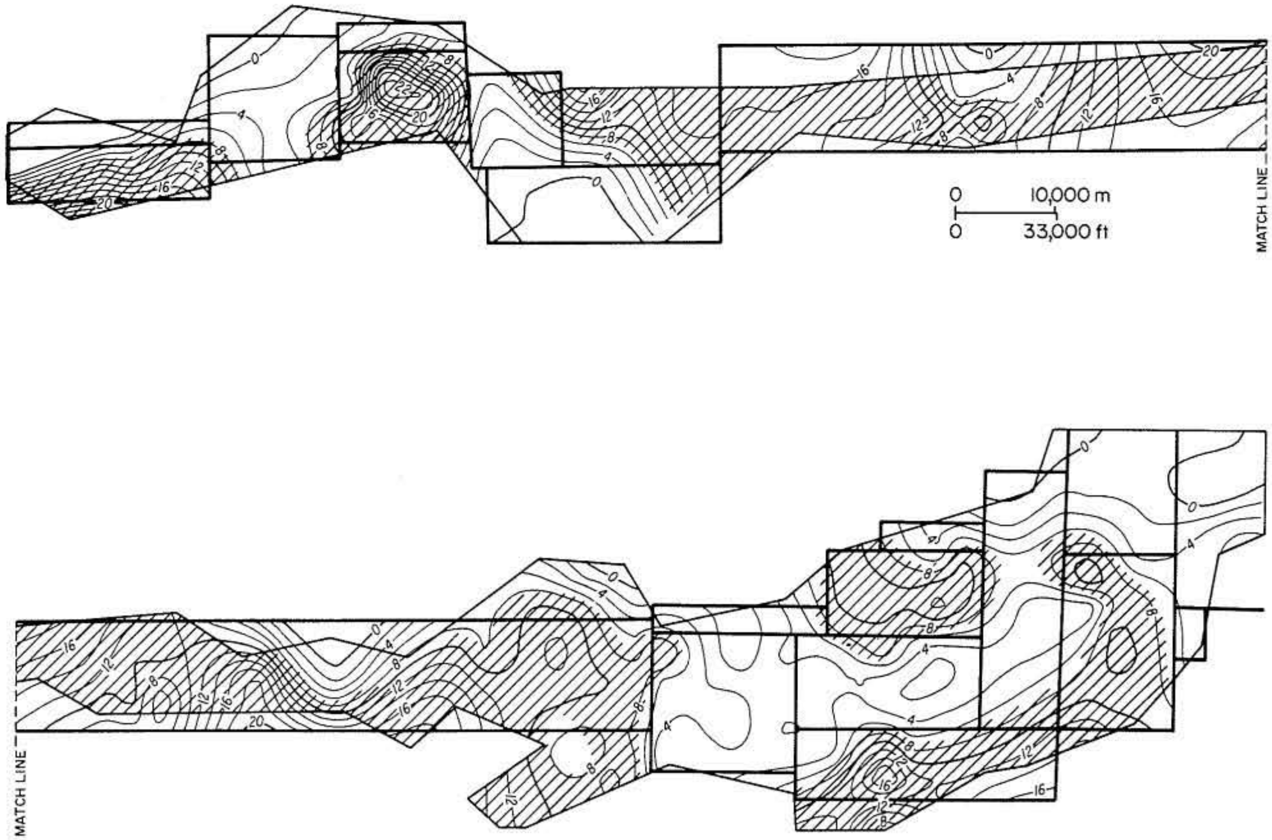


Figure 80. Homogeneous blocks (shown by thick line) selected on the basis of smoothed contours of total coal (second technique) in the Wilcox Group of east-central Texas. Thinner line is the boundary used by computer for tonnage calculations. Shaded areas contain total coal thicker than average.

Table 18. Results of contour method for homogeneous blocks in east-central Texas.

Description	No. of Blocks	Estimated Mean (ft)	Variance of Estimate (ft^2)	Standard Deviation
First technique				
Overlay basic	28	7.7	0.0278	0.17
Overlay combined	4	8.6	0.0220	0.15
Second technique				
Total coal basic	19	8.1	0.0328	0.18
Total coal combined	2	8.8	0.0255	0.16
Third technique				
Hole density basic	27	8.6	0.0526	0.23
Hole density combined	2	8.6	0.0502	0.22
Fourth technique				
Precision basic	46	8.2	0.0425	0.21
Precision combined	4	9.6	0.0492	0.22

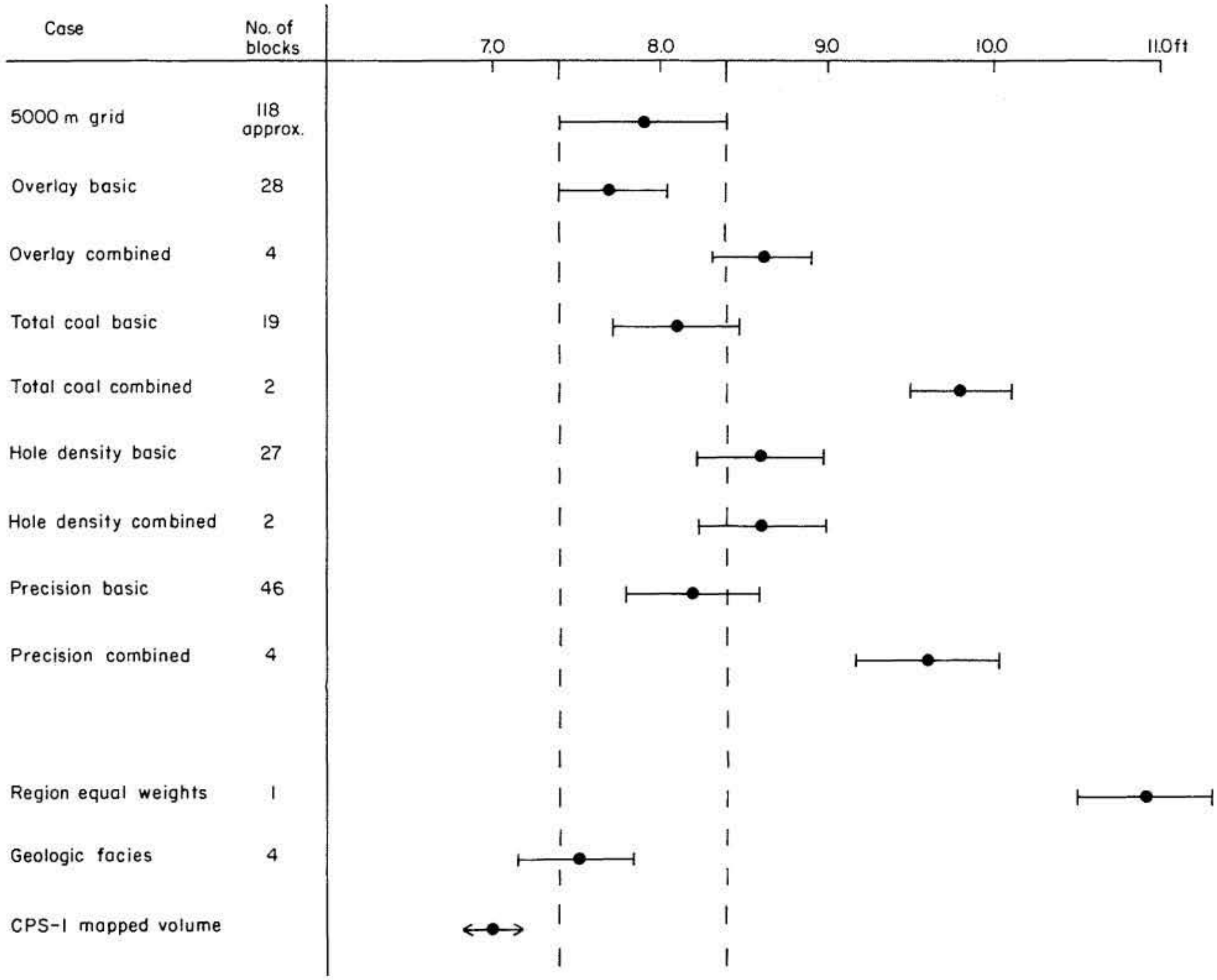


Figure 81. Estimates of total coal thickness per borehole and 95-percent confidence limits for various methods. Solid dots represent means and the bars represent confidence limits for total coal in the Wilcox Group of east-central Texas.

estimate lies within the dotted line (best), or the estimate is outside but the confidence limits intersect the dotted line (good), or finally the estimate and its confidence limits lie outside the reference limits or dotted lines (bad). The equal weighting method is bad. The best results are given by the overlay methods, except the one based on hole density, which is considered good. Computed confidence intervals do not depend on the number of blocks, although it is clear from figure 81 that the resulting estimate of the contouring method does depend on the number of blocks chosen. In general more blocks lead to greater precision. However, the overlay and total lignite techniques achieved substantially the same precision as the grid method but use one-quarter to one-fifth the number of blocks, and have a smaller estimation variance. The overlay technique appears the more stable of the two. Its computed variance is 0.0278 ft^2 compared with an average of 0.0360 ft^2 from the 5,000-m (16,404-ft) grid, a reduction of 22 percent. Because one of the chief factors affecting the estimation variance is the number of boreholes, it can be inferred that the overlay technique will do as well as the grid method with about 80 percent of the holes and with less computational effort because of fewer blocks, always provided that the homogeneous blocks are reasonably modeled by a pure nugget effect.

The third method used for choosing homogeneous blocks is geologic facies mapping. Geophysical logs of boreholes were used to construct regional cross sections (locations shown on figure 82) of the near-surface Wilcox Group (figs. 83, 84, and 85). Even though seam-by-seam correlation was not possible with the number and spacing of boreholes available, recognizable sedimentary units or facies were traceable across the area.

Cross section A-A′ (fig. 83) shows three discernible facies: Simsboro, Simsboro-equivalent, and lower Calvert Bluff. The Simsboro facies in the central and southern part of the area is identified on the cross section by "blocky" resistivity patterns (interpreted as massive fluvial sands) and occasional lignites. In a northerly direction these massive sands thin, break up, and interfinger with finer grained sediments to constitute the second mappable facies, the Simsboro-equivalent facies.

Lignites become more abundant with the break up of the sands. The Simsboro-equivalent facies is identified on the cross section by thinner "blocky" resistivity patterns, inverted "Christmas tree" resistivity patterns (interpreted as coarsening-upward sequences), and straight resistivity and density traces (interpreted as mud). Overlying the Simsboro is the lower Calvert Bluff, the third mappable facies, a sequence comprised of occasional sands and numerous lignites. The facies is identified on cross section A-A′ (fig. 83) by common inverted "Christmas tree" resistivity patterns with capping low density and high resistivity peaks, "straight" resistivity and density traces, and occasional "blocky" and "Christmas tree" resistivity patterns (interpreted as fining-upward sequences). The lower Calvert Bluff facies is mappable over the entire area.

The lower Calvert Bluff is overlain in certain areas by a lignite-barren zone, the middle Calvert Bluff facies, consisting of sand, mud, and silt (figs. 84 and 85). This fourth facies has geophysical log patterns similar to lower Calvert Bluff patterns except for the absence of lignite. Overlying the barren zone is the upper Calvert Bluff (figs. 84 and 85), the fifth mappable facies in the area. It is a fine-grained succession with occasional sands and numerous lignites. This facies has geophysical patterns similar to those of the lower Calvert Bluff.

For the geologic mapping method, a sample of 392 boreholes was taken from the 1,382 available holes. The sampling plan involved placing a 2,000-m (609-ft) square grid over the borehole location map and randomly sampling a maximum of three boreholes from each grid square. Sampling reduced the number of boreholes evaluated and also resulted in a more homogeneous distribution over the area. The stratigraphic section penetrated by each borehole was divided according to the defined facies. Outcrops of the five facies were taken as the homogeneous blocks within which equal weighting was applied. The blocks were then combined using equations 19 and 20. Two sets of results were obtained, one for thickness of lignite per 100 ft, and one for measured total thickness. The Simsboro outcrop represents an additional area not included in the previous methods since little or no data were previously available for this area; therefore the results are stated in table 19 with and without the inclusion of the Simsboro outcrop. The table shows a large variance of estimate when the Simsboro is excluded, which reflects the fact that only 474 samples were taken into account in the computation. Total coal, excluding the Simsboro, was plotted on figure 81 with the variance normalized to 1,382 holes [.003 m^2 (.0326 ft^2), equivalent to a standard deviation of .05 m (0.18 ft)] and falls into the "best" class. The geologic facies method makes more use of each individual well log, and requires fewer homogeneous blocks than do other methods. On the other hand, a geologic study of the region is a prerequisite, and considerably more data

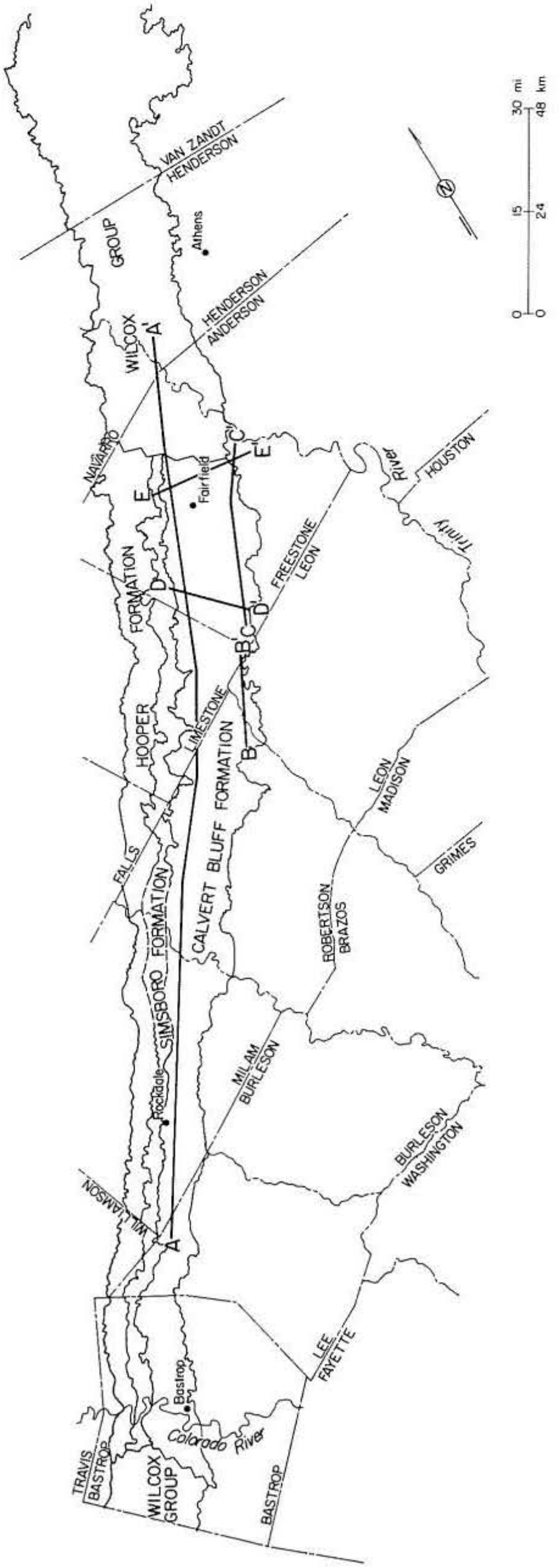


Figure 82. Locations of cross sections, Wilcox Group of east-central Texas.

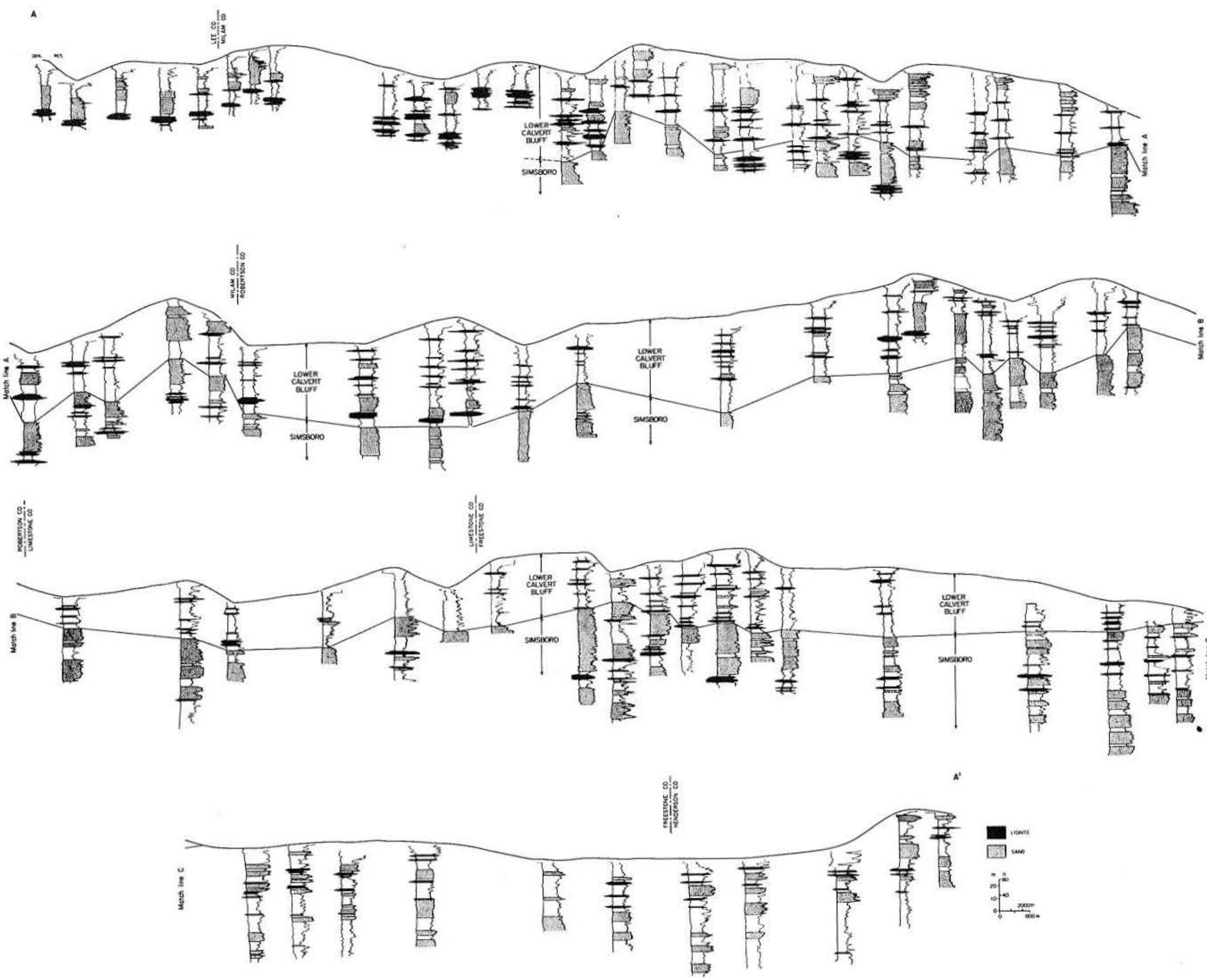


Figure 83. Strike-oriented cross section A-A′, Wilcox Group of east-central Texas.

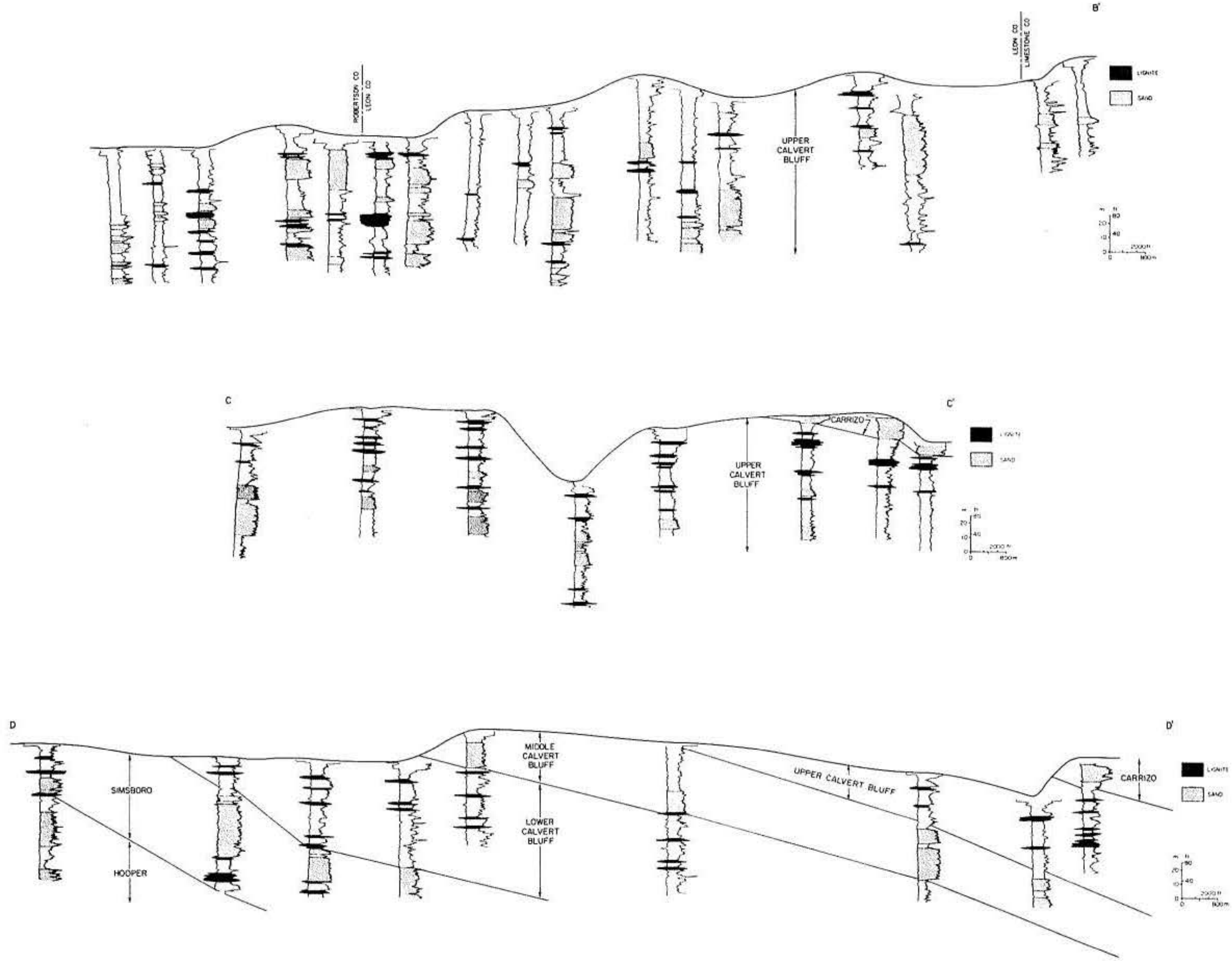


Figure 84. Strike-oriented cross sections B-B′ and C-C′ and dip-oriented cross section D-D′, east-central Texas.

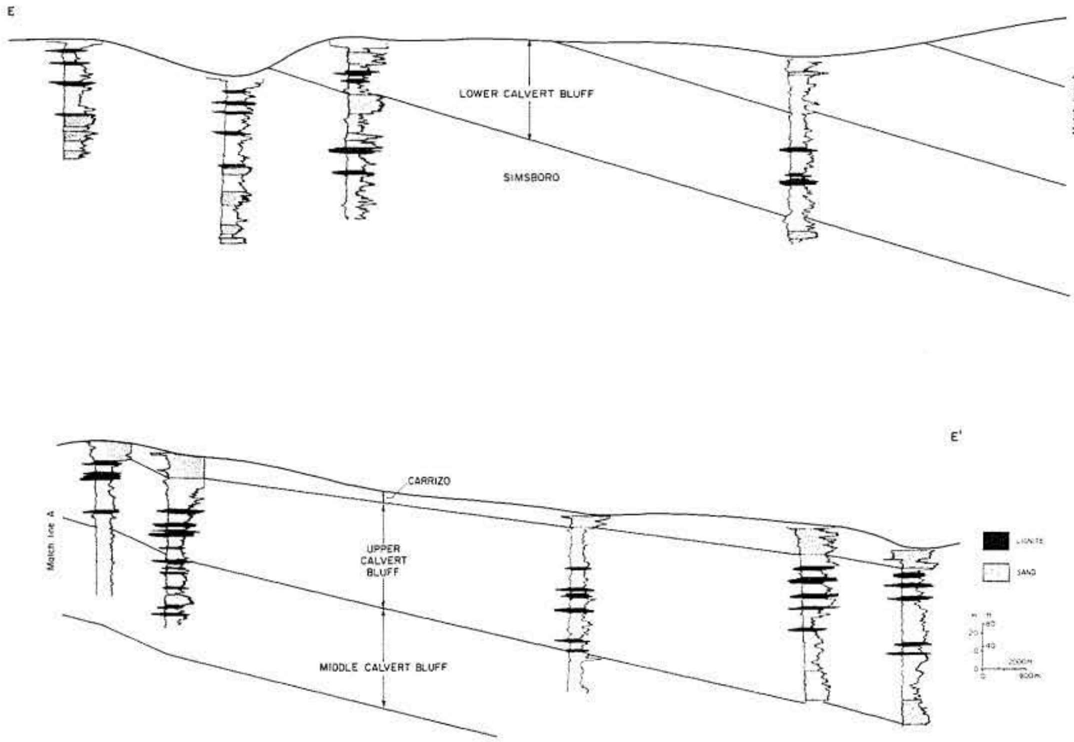


Figure 85. Dip-oriented cross section E-E', east-central Texas.

Table 19. Results of geologic facies mapping method in Texas.

Case	No. of Blocks	Mean (ft)	Variance of Mean (ft^2)	Standard Deviation
1. Feet of coal per 100 ft	5	3.022	.0130	0.228
2. Feet of coal per 100 ft excl. Simsboro	4	4.243	.0280	0.334
3. Total coal (ft)	5	5.809	.0565	0.475
4. Total coal (ft) excl. Simsboro	4	7.488	.0952	0.617

processing is required to separate the seams into facies designated by the geologist.

Computer Mapping Method

The CPS-1 program was used to provide another estimate of the total lignite tonnage in the Wilcox of east-central Texas. A tonnage figure of 9.4 billion metric tons (10.3 billion short tons) was obtained over an area of 337,837 ha (834,796 acres). This represents a region enclosing all the data points. Since the tonnage factor is 1,750 tons per acre-foot, this corresponds to an average total coal thickness of 2.1 m (7.0 ft) (see fig. 81). No measure of the error of the estimate is available from the CPS-1 program, but if the grid method result is taken as correct, the CPS-1 estimate is in error by .3 m (0.9 ft), or 13 percent.

Depositional-Model Method

Depositional models at the regional scale (Kaiser and others, 1978) can be used to identify potential coal-

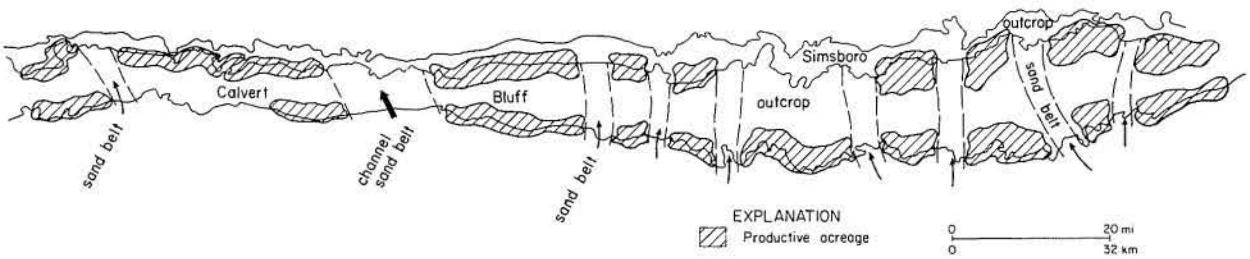


Figure 86. Productive acreage in the Wilcox Group of east-central Texas, using the regional depositional model.

bearing lands. Resources can also be calculated using these models, but calculations represent a first approximation and should not be expected to compare exactly with calculations using large amounts of data.

Evaluation of seams at the deposit level has demonstrated trends of continuity and thickness similar to those predicted by the regional depositional models. Tonnage factors (tons per acre) derived from the deposit studies were modified and used with the depositional models to calculate resources. Productive acreage, or acreage underlain by lignite, was outlined by projecting subsurface areas deficient or high in sand (dependent on the depositional environment) to the outcrop. Resources were calculated by multiplying respective acreages and tonnage factors.

In east-central Texas lignite occurs mainly in the lower and upper parts of the Calvert Bluff Formation; therefore two bands of productive acreage, broken by the updip projections of mapped channel-sand belts, were outlined. Overlap into the Simsboro outcrop allows for possible Simsboro lignite, whereas extension into the subcrop allows for lignite in the uppermost part of the Calvert Bluff (fig. 86). Widths of the acreage blocks reflect regional dip and widen northward as dip decreases from 2 to 0.5 degrees. The tonnage factor calculated for the lower alluvial/upper delta plain deposit in east-central Texas was considered large and not representative of the whole region and was used in the vicinity of the deposit, but reduced northward along the outcrop. Logs were chosen at random from the regional data and a net thickness of lignite was calculated to arrive at appropriate tonnage factors. Using this method, resources for the Wilcox Group of east-central Texas were found to be 5,655 million metric tons (6,234 million short tons).

A similar method of resource evaluation utilized depositional models only for basic understanding of the area and projection into areas of sparse or no data. Kaiser and others (1980) utilized available proprietary geophysical data and using an unweighted average method of calculation reported resources in three degree-of-certainty categories. Total resources for the Wilcox of east-central Texas were determined in this manner to be 5,880 million metric tons (6,481 million short tons).

U. S. Geological Survey Method

The term "coal resource" as defined by the U.S. Geological Survey (USGS) includes identified and hypothetical resources. Identified resources are broken down into measured, indicated, and inferred categories. These categories are based on increasing distances from observation points for the coal bed(s) concerned.

Although the USGS recognizes that the spacing of observation points needed to demonstrate the continuity of a coal bed varies from region to region, in most cases, data points are on the order of 0.8 km (0.5 mi) apart. Therefore, the outer limit of a block of measured coal will be 0.4 km (.25 mi) from the last observation point (or roughly one half the distance between observation points).

Indicated coal is computed partly from data points and partly from geologic projection. If the measured coal blocks have indicated good bed continuity, then indicated coal will extend as much as 0.8 km (1/2 mi) out from measured coal (fig. 87).

Inferred coal is calculated only where geologic evidence warrants projection from the indicated coal. There are few, if any, actual bed measurements. Inferred coal extends as much as 3.6 km (2-1/4 mi) out from indicated coal. Hypothetical coal can extend beyond inferred coal areas if geologic evidence warrants projection (fig. 87).

The resource categories (measured, indicated, and inferred) are reported in specific thickness categories for various coal ranks. The thickness categories originally had economic implications, which may or may not be relevant at present. The category limits are retained so that new estimates can be compared to older work. For example, lignite resources are reported in three thickness categories: 0.7 to 1.5 m (2.5 to 5 ft), 1.5 to 3 m (5 to 10 ft), and greater than 3 m (10 ft).

The resources of the Wilcox Group of east-central Texas were evaluated by USGS methods on their computer system. Total resources for the region were determined to be 29,160 million metric tons (29,629 million short tons). Approximately 79 percent of this figure arose from the inferred resource category, which is

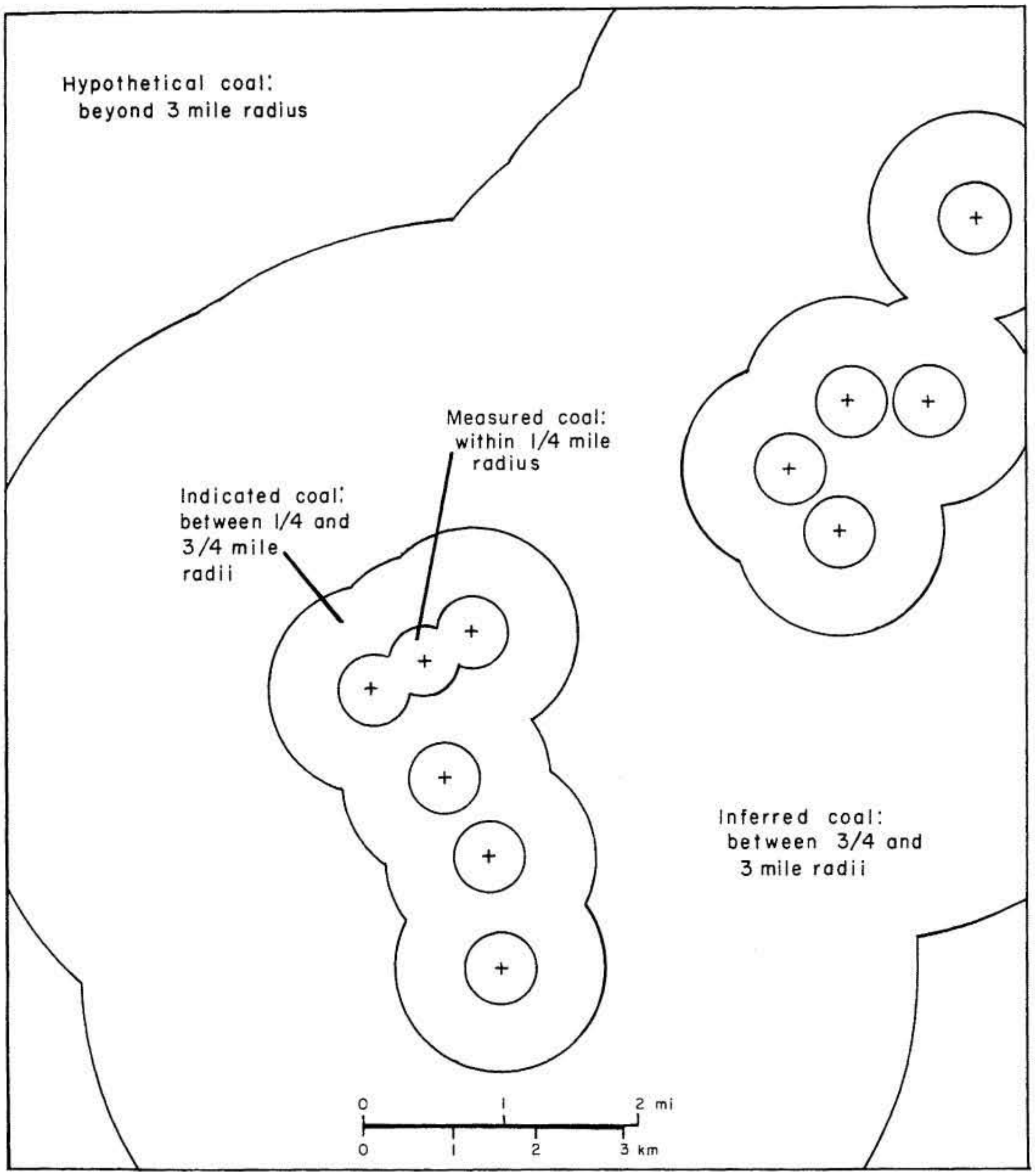


Figure 87. USGS criteria for resource categories; measured, indicated, inferred, and hypothetical.

the least geologically certain. Resources are currently being recalculated for this area because of a revision in the method of data selection using the USGS computer system.

Summary of the Methodology Developed in Texas

In resource studies at the regional scale, limited data normally preclude the use of the methodologies developed for seam-by-seam analysis. For the Wilcox Group of east-central Texas we were unable to delineate dependency structures using geostatistics. The summation of many lignite seams with different dependency structures resulted in an inability to find a regional dependency structure. In addition, the distribution of the data in a narrow belt along the outcrop would reduce the reliability of a variogram if one were obtained. Various alternative statistical methods of evaluating regional resources were investigated. These are the equal weighting method, the grid method, and three homogeneous block methods based on cluster analysis, contouring, and geologic facies mapping. The equal weighting method applied to the whole region probably overstates the lignite resources by 38 percent while giving a misleading impression of precision. By contrast, the gridding method is found to give a reliable and easily

Table 20. Results of regional resource evaluation for the Wilcox Group of east-central Texas.

Method	Data Constraints	Acreage	Ave. Total Coal Thickness[1] (ft)	Short Tons (millions)
Computer Mapping CPS-1	Depth: 0-300 ft Thickness: ≥ .5 ft	834,796	7.0	10,300
Grid Method (5,000 m)	as above	928,000	7.9	12,800
Homogeneous Block Method (overlay technique)	as above	1,056,000	7.7	14,200
Regional Depositional Models	Depth: 0-200 ft Thickness: ≥ .5 ft	383,000	9.3	6,200
Geological Eval. (unweighted average)	Depth: 20-200 ft Thickness: ≥ 3 ft			
Measured		326,400	6.1	3,450
Indicated		239,360	5.7	2,450
Inferred		66,560	5.1	580
Total		632,320	5.8	6,480
USGS Computer	Depth: 0-300 ft Thickness: ≥ 2.5 ft			
Measured and Indicated		351,030	10.6	6,530
Inferred		758,470		23,100
Total		1,109,500	15.2	29,630

[1]Derived by dividing tons by acreage and 1,750 tons per acre-ft

obtainable estimate, provided that large amounts of data cover most of the study area. The precision of the grid method can be assessed by varying the grid position. If data decrease, or if they are not stored in a computer, the method of selecting homogeneous blocks from contour maps shows promise. Two techniques gave good results for the Wilcox Group: overlaying contours of average seam thickness and number of seams, and direct use of total thickness contours. The first technique appears more stable and marginally more precise. Where a geologic facies analysis of the region can be done, homogeneous blocks can be selected according to the different facies. This method makes better use of fewer boreholes by exploiting vertical as well as horizontal homogeneities. Another advantage of the geologic facies mapping method over the other methods is that estimates can be made of the lignite in the entire Wilcox succession by projecting the appropriate facies into areas of limited data. However, the geologic facies method requires good geologic knowledge of the region, and thus is not transferable to other basins. The grid method and the two contour techniques mentioned above will be transferred to other basins. They are not dependent on geologic assumptions concerning depositional environment and could be applied in any coal area, although the relative advantages of the various methods may change as a result of less or more heterogeneous data.

Knowledge of the regional depositional models of a formation has been used to generate first approximations of resources in areas of limited data. Resources calculated solely by depositional models should be classified as indicated or inferred. They should not be expected to compare exactly with measured resources calculated using large amounts of data. Two other regional resource methods (the USGS computer method and the unweighted average/geologic method) were also applied in east-central Texas.

Table 20 examines the variation between the regional resource estimates of the Wilcox Group of east-central Texas for most of the methods discussed in this section. Differences exist between data constraints for the methods, such as depth and seam thickness and the acreage involved in the resource calculation, which lead to differences in final resource estimates. Because constraints differ, the resource estimates cannot be directly compared. However, the table does display the uncertainties associated with resource estimates contributed by data selection as well as method of evaluation.

Geologic Evaluation

Introduction

Sand dendroids and belts and associated lignites of the Wilcox Group of East Texas resemble the reported sand-body geometries and coal associations found in the Fort Union Formation of the Powder River Basin. Therefore, the Powder River Basin area was chosen to test the transferability of the methodology developed in Texas.

The Powder River Basin located in northeastern Wyoming and southeastern Montana (fig. 88) is

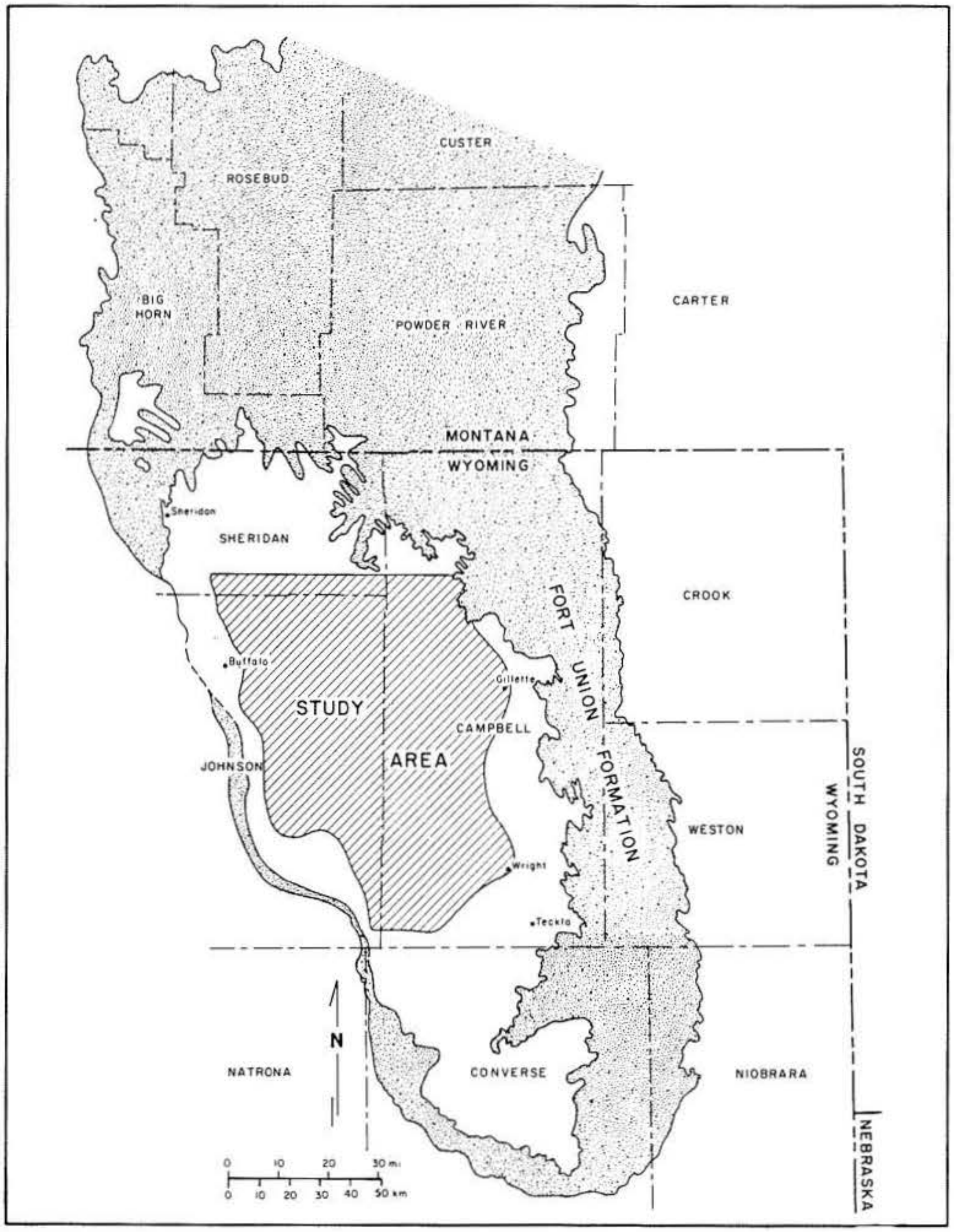


Figure 88. Location of the study area in the Powder River Basin. Modified from Love and others (1955) and Ross and others (1955).

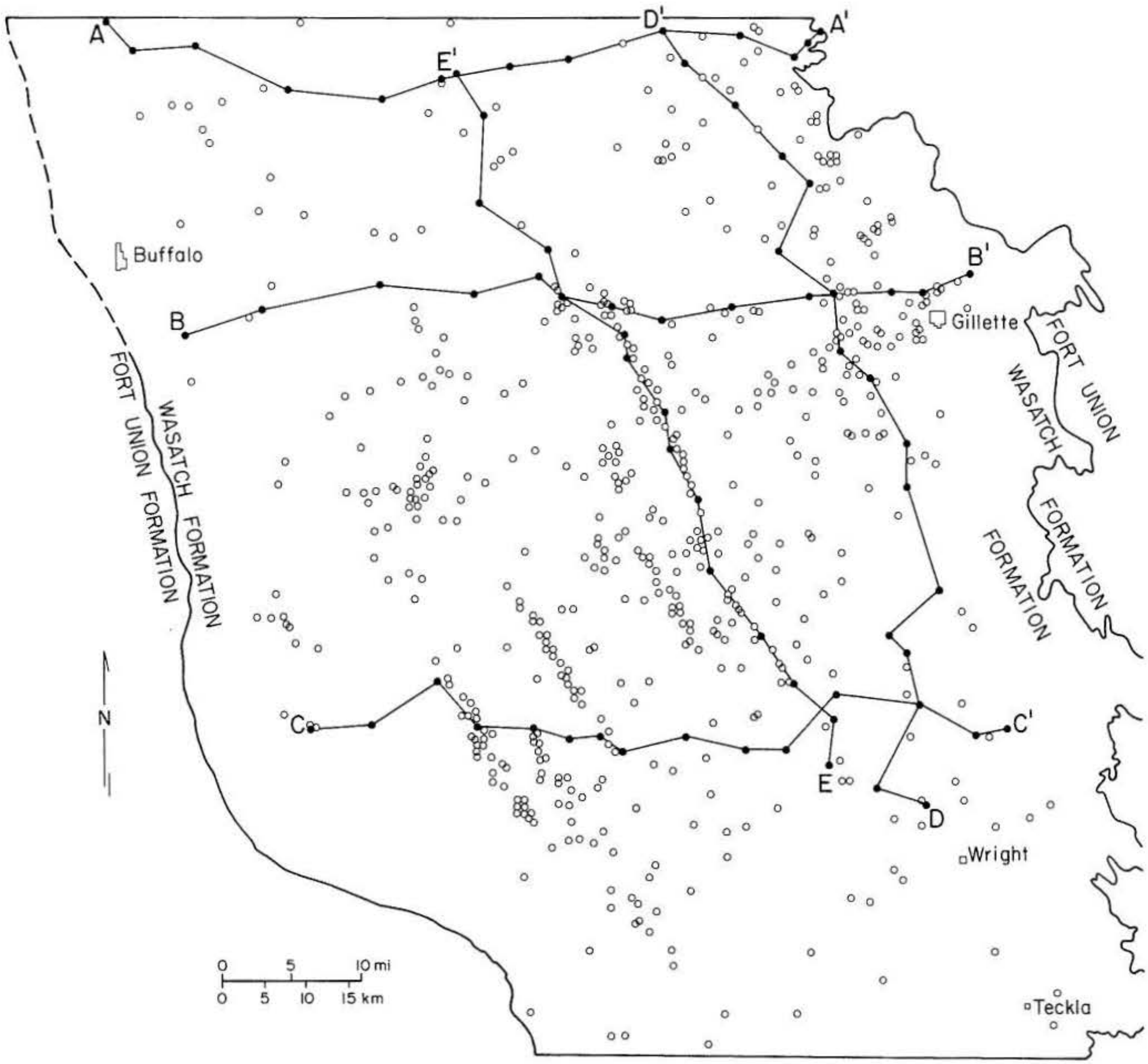


Figure 89. Location of well control and cross sections, Powder River Basin.

structurally asymmetrical. Strata along the eastern flank of the basin dip approximately 1 degree to the west near the town of Gillette, Wyoming; the dip on the western flank is 10 to 25 degrees to the east.

The Paleocene Fort Union Formation, the major coal-bearing unit in the basin, contains more than 558 billion metric tons (614 billion short tons) of subbituminous coal occurring in thick, laterally continuous seams. Production from strip mines along the eastern margin of the basin was approximately 26 million metric tons (29 million short tons) in 1978 (Glass, 1980) and is steadily increasing as new mines open. The basin has also been the site of two in situ gasification tests.

Previous Work

Sharp and Gibbons (1964) characterized the depositional facies of the Fort Union Formation in the southern Powder River Basin as components of a mixed-load fluvial system. In a later study of the same area, Galloway (1979) described north-south-trending mixed-load to bed-load channel sands that interfingered laterally and downslope to the north into mixed-load and suspended-load systems. Contemporaneous peat swamps were inferred by Galloway to have occupied the floodplains and interfingered with overbank, crevasse splay, and lacustrine deposits. Flores (1979) described a similar system in the northern segment of the basin, along the Powder River.

The fluvial depositional systems described by these authors are similar to the Wilcox Group of Texas (Kaiser and others, 1978). Sharp and Gibbons (1964, p. 19) described the Paleocene Fort Union landscape in the Powder River Basin as ". . . a swampy, forested lowland threaded by shallow, shifting streams." In such an environment it appears unlikely that stability would be maintained long enough to form thick, laterally continuous coals.

Methods of Study

Because the Powder River Basin is a mature oil and gas province, a large number of geophysical well logs were available for use in this study. Approximately 600 well logs were chosen for the Wyoming portion of the basin at an average density of one well per 6 mi^2. The study area and the well control are shown in figures 88 and 89. In addition, three dip sections and two strike sections (figs. 90, 91, 92, 93, and 94) were constructed to determine lithostratigraphic boundaries and facies boundaries. These cross sections demonstrate the lateral continuity of the thick seams. The type log shown in figure 95 indicates the manner in which the Paleocene Fort Union Formation and its members were defined. For this study only the coal-bearing Tongue River Member of the Fort Union Formation was mapped. The base of the Tongue River Member was chosen at the base of the first coarsening-upward sequence above the shaly Lebo Member. The top of the Tongue River Member is defined by a persistent, thick coal seam and is further distinguished by a marked decrease in resistivity of the overlying strata.

Coal seams proved to be easily recognizable on the resistivity logs, as seen on figure 95. Whenever possible a gamma-ray log was also used in conjunction with the electric log to verify the presence of coals.

The thicknesses and depths of all coals in the Tongue River Member were recorded from the logs and coded for computer storage. In addition, the top of the Tullock Member was recorded to provide a datum for a structure contour map. The thickness of the Tongue River Member (a genetic unit, as described earlier) was recorded. Within the Tongue River Member all sands were measured and

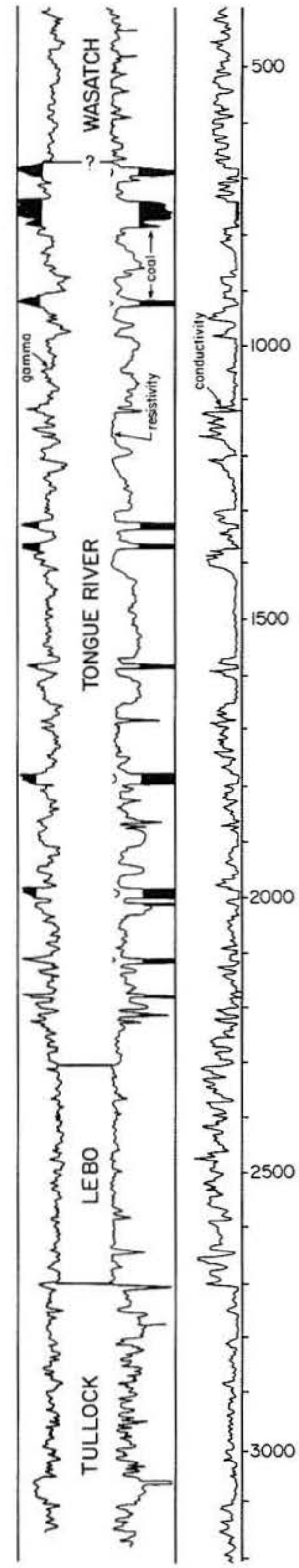


Figure 90. Composite type log of the study interval, Powder River Basin.

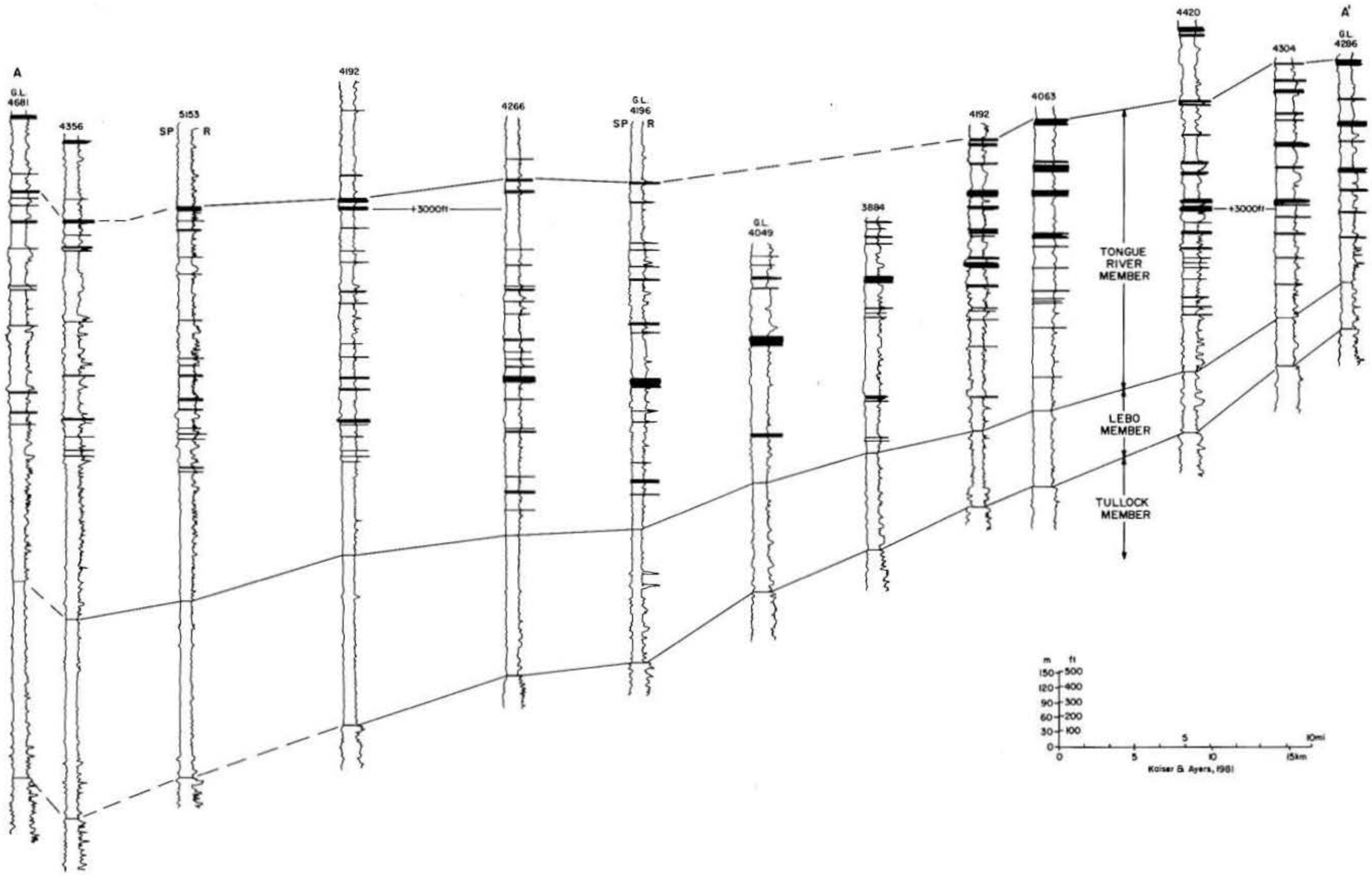


Figure 91. Dip section A-A′, Powder River Basin. Datum is sea level.

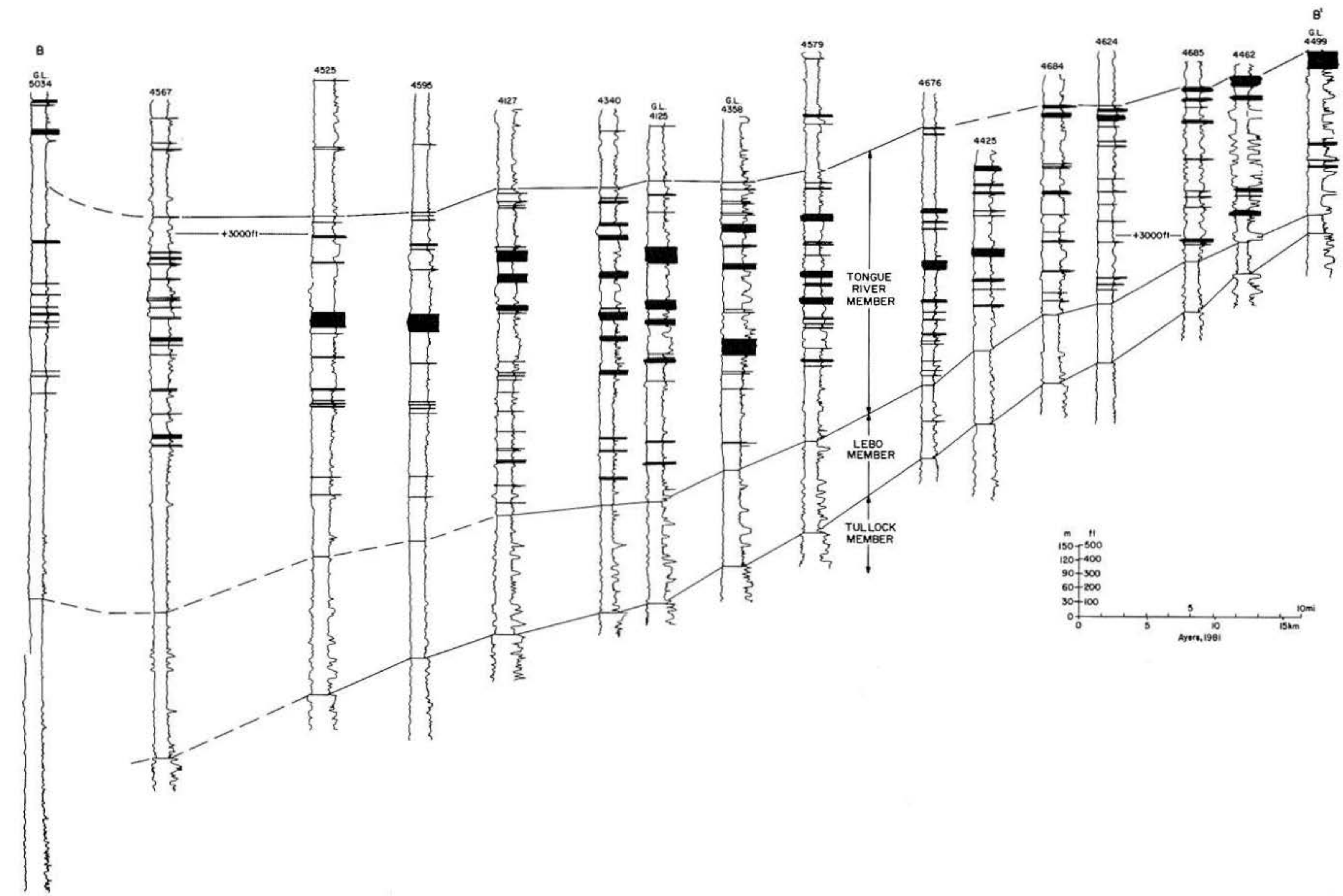


Figure 92. Dip cross section B-B', Powder River Basin. Datum is sea level.

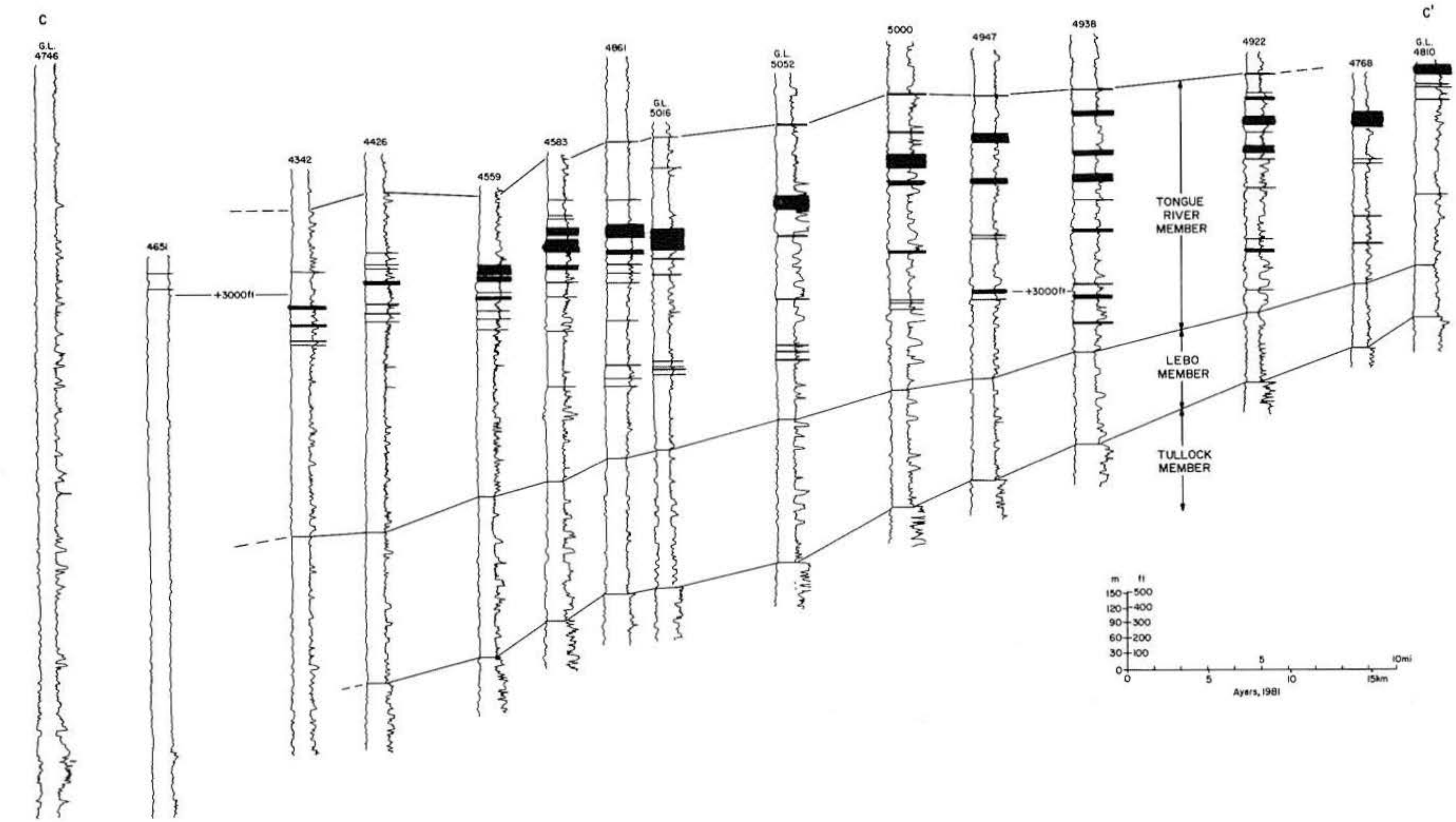


Figure 93. Dip cross section C-C', Powder River Basin. Datum is sea level.

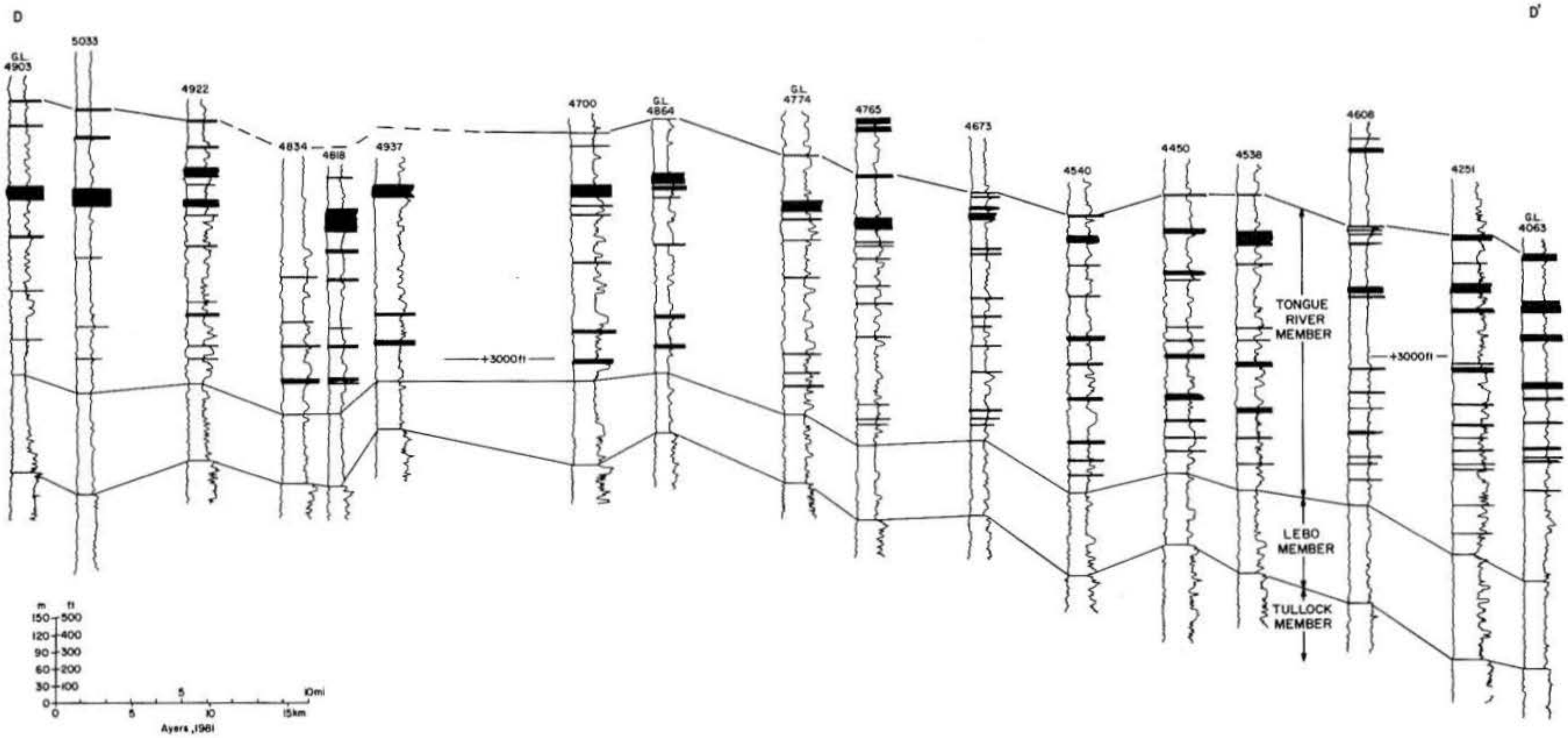


Figure 94. Strike cross section D-D′, Powder River Basin. Datum is sea level.

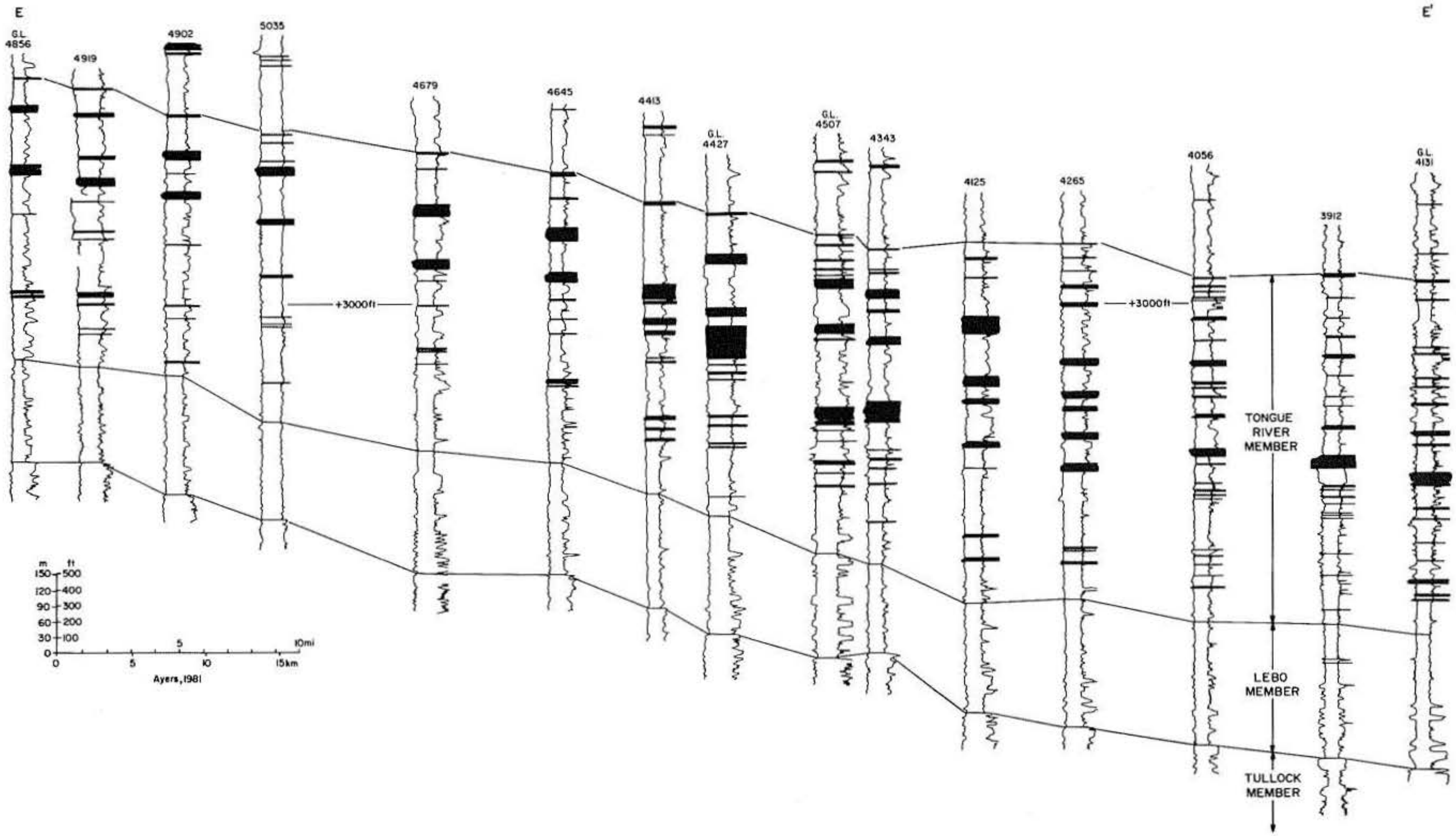


Figure 95. Strike cross section E-E′, Powder River Basin. Datum is sea level.

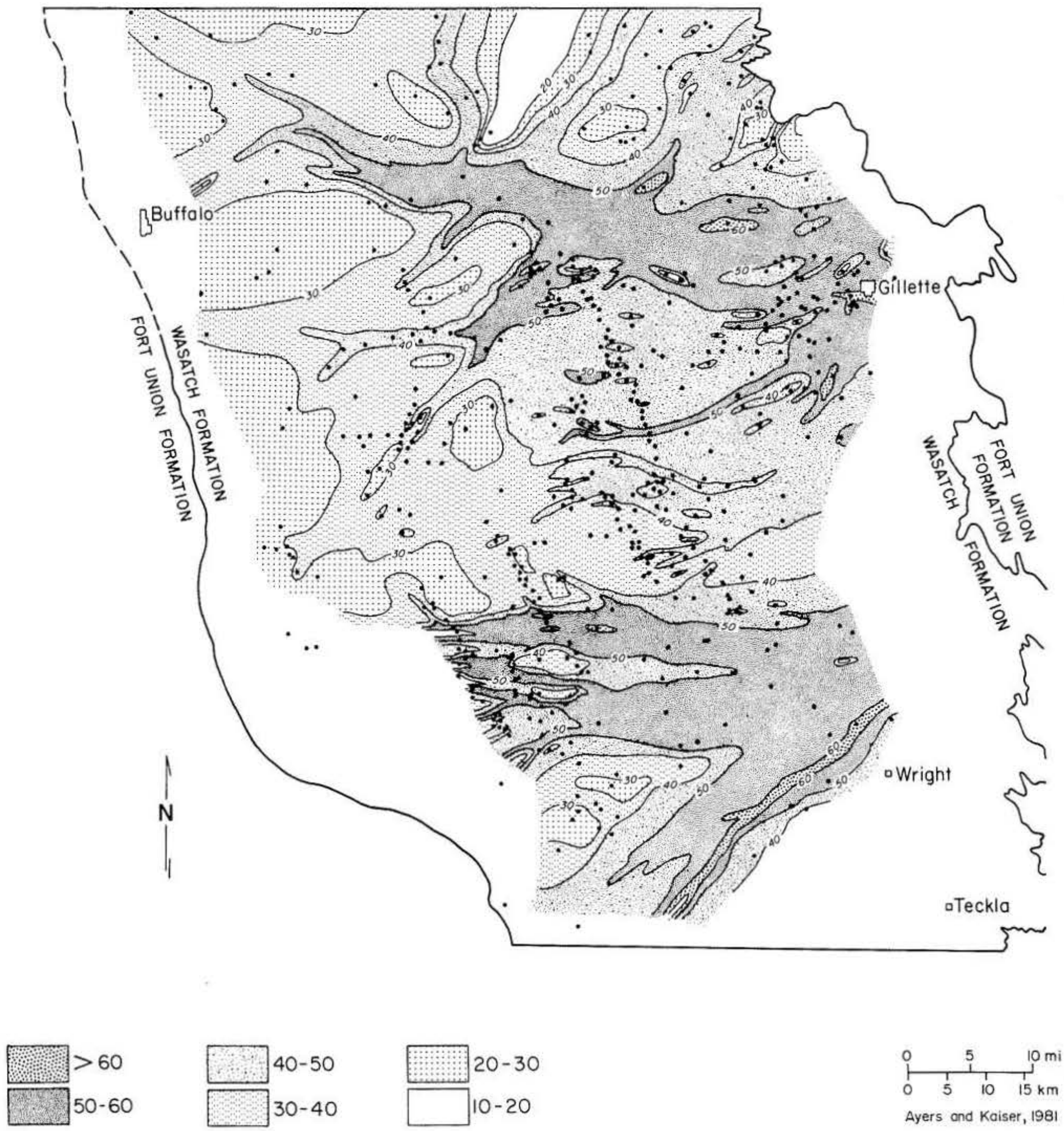


Figure 96. Sand-percent map of the Tongue River Member, Powder River Basin.

their thicknesses totaled to calculate a sand percentage for the interval. In addition, the thicknesses of all sands greater than 12.2 m (40 ft) were summed and considered to comprise major sands. Sand-percent values could then be generated and posted by the computer for contouring to determine geometry and orientation of sand bodies.

Sand Maps

The sand-percent map (total sand divided by the interval thickness) and the major-sand-percent map (total of sands greater than 12.2 m (40 ft) in thickness divided by the interval thickness) were used to define the

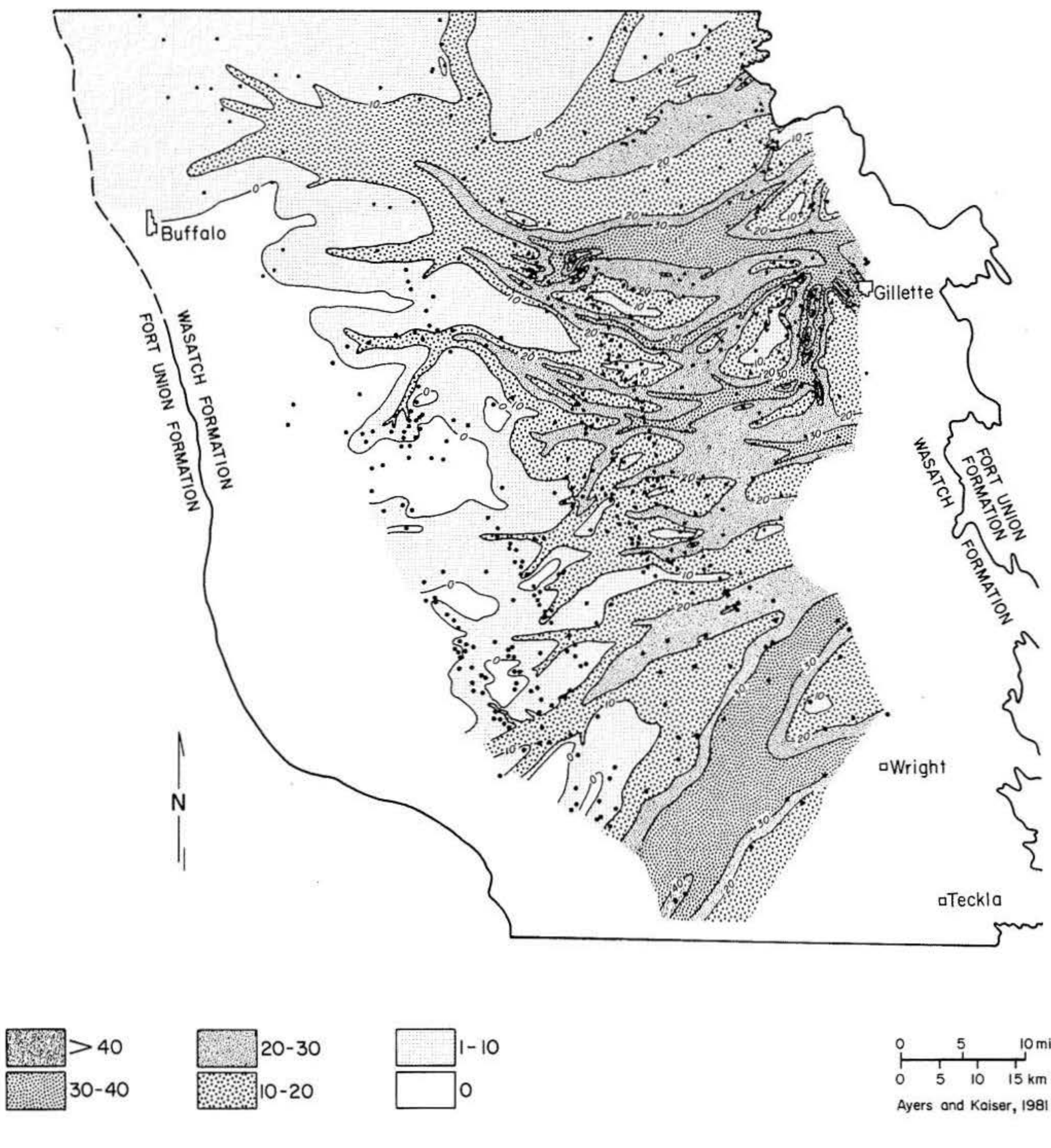


Figure 97. Major sand-percent map of the Tongue River Member, Powder River Basin.

depositional setting of the Tongue River Member (figs. 96 and 97, respectively). This member is characterized by low sand-percent values (20 to 25 percent) along the western margin of the basin. High sand-percent values (50 to 60 percent) are present in two locations along the eastern margin of the basin. The decrease in sand percentage and bifurcation of sand bodies westward, combined with the progradational character of the lower Tongue River Member, suggest that the central part of the basin was filled by two deltaic lobes which were supplied sediment from an eastern source in the ancestral Black Hills. The northern (Gillette) lobe built westward,

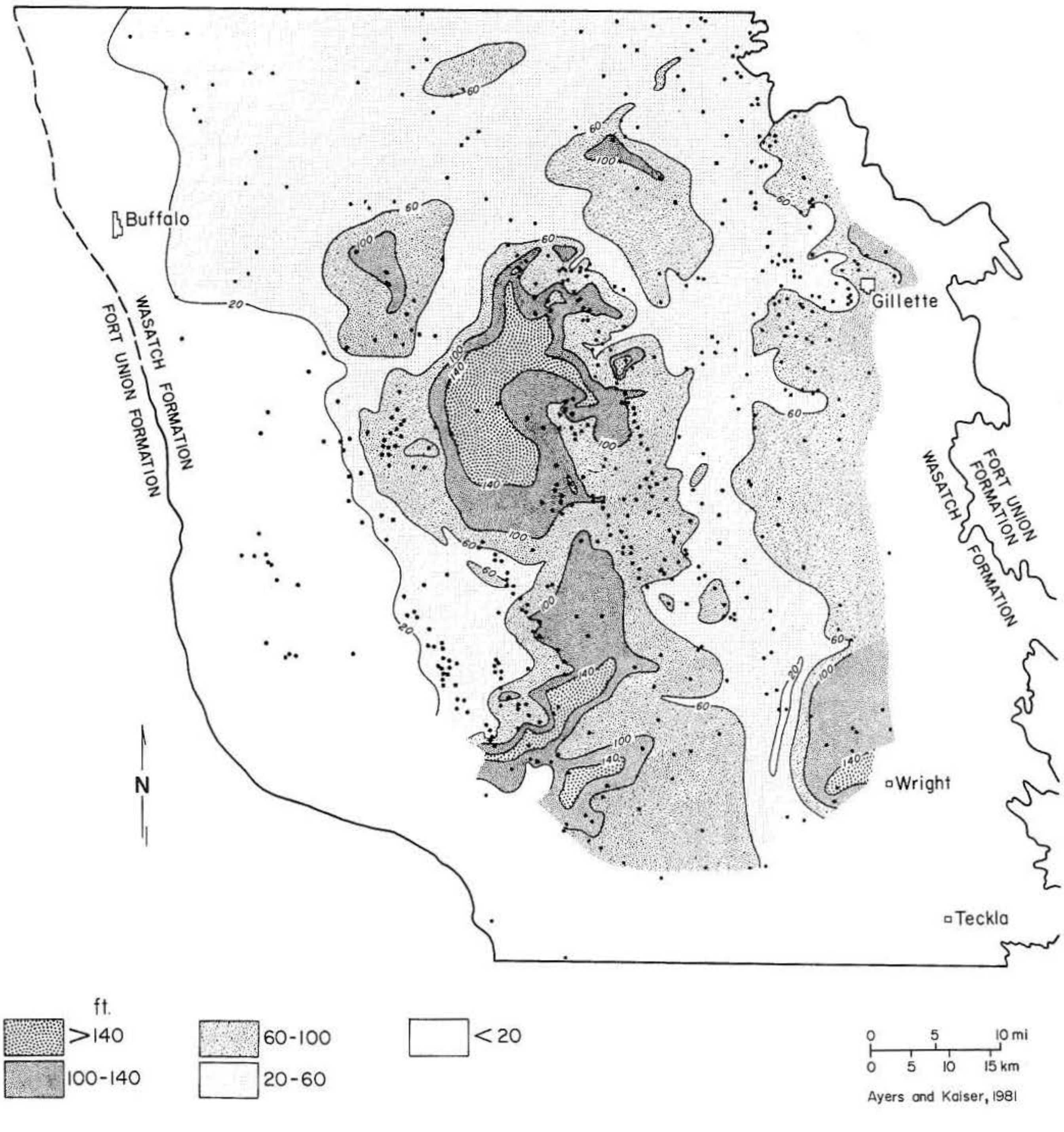


Figure 98. Maximum coal map of the Tongue River Member, Powder River Basin.

while the southern (Wright) lobe prograded to the west and southwest, toward the basin axis.

Coal Maps

The maximum coal map (fig. 98) was constructed by contouring the values for the thickest coal recorded from each geophysical well log. Comparison of the maximum coal and structure contour maps (figs. 98 and 99) indicates no structural control on the distribution of the thickest coals. Major coals (seams more than 18.3 m (60 ft) thick) are located in two areas which parallel the structural axis of the basin. Coals in the first area occur

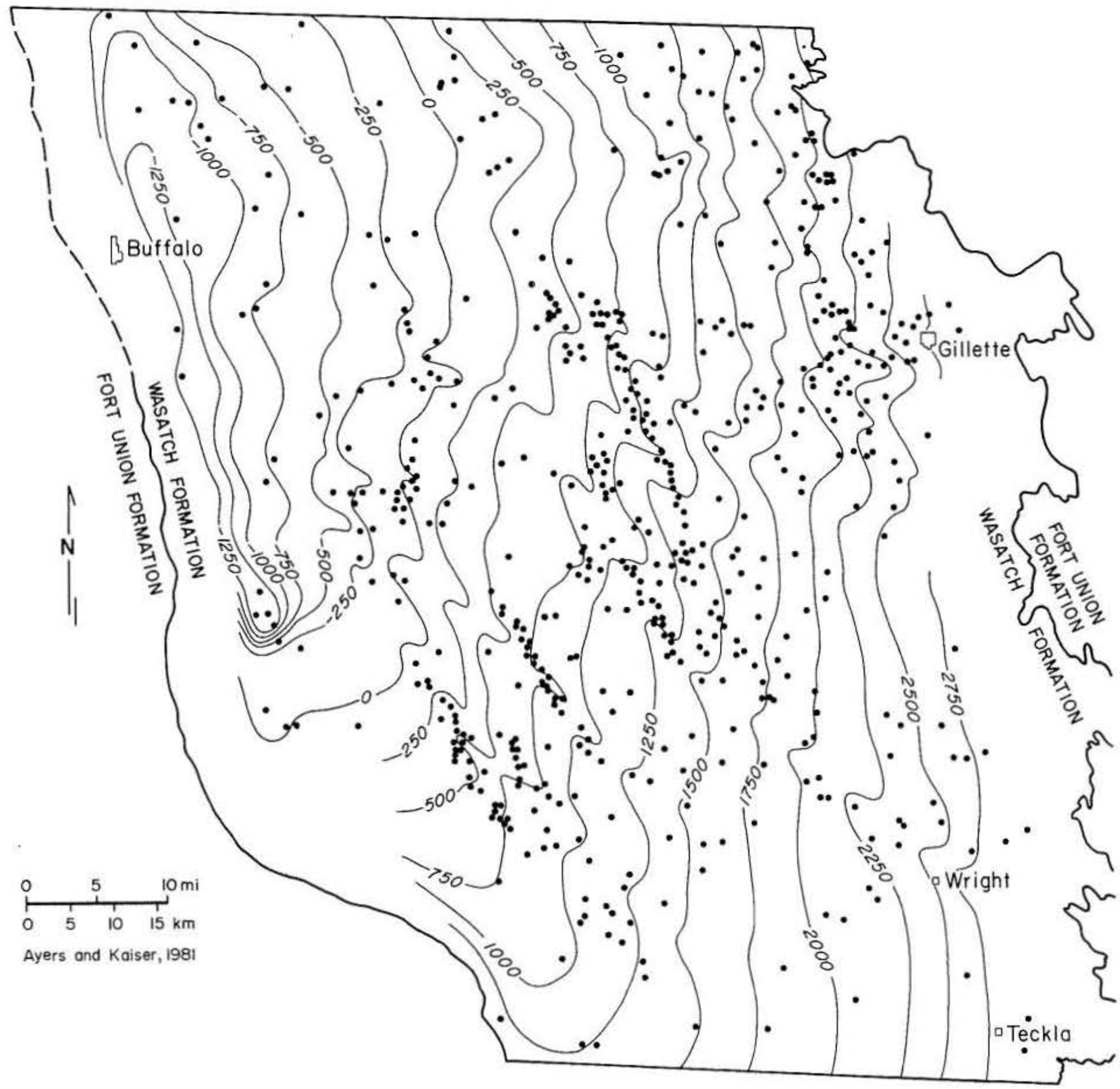


Figure 99. Structure map drawn on top of the Tullock Member, Powder River Basin. Datum is sea level.

along the eastern margin of the basin. These coals split and thin into the basin (figs. 91 and 92). Their actual eastern boundary is difficult to define because of the lack of shallow geophysical borehole data. In the second region the major coals split and thin toward both the west and the east (figs. 91 and 92).

An isopach map of total coal in seams greater than .6 m (2 ft) (fig. 100) indicates that the greatest thickness of coal occurs in the north-central part of the basin. Comparison of the total coal isopach and isopleth maps (figs. 100 and 101) reveals that the coal in the northern part of the basin occurs in many (14 to 27) comparatively thin (<10-m or 30-ft) seams, while coal in the central part of the basin occurs in fewer (10 to 12) seams of greater thickness. Values for numbers of seams and total coal thickness were smallest along the western margin of the basin. These trends are also apparent on the cross sections (figs. 93 and 94).

Proposed Depositional Model

The scarcity of shallow geophysical well logs along the eastern margin of the basin precluded a complete evaluation of the thick coals in that region. Therefore, the

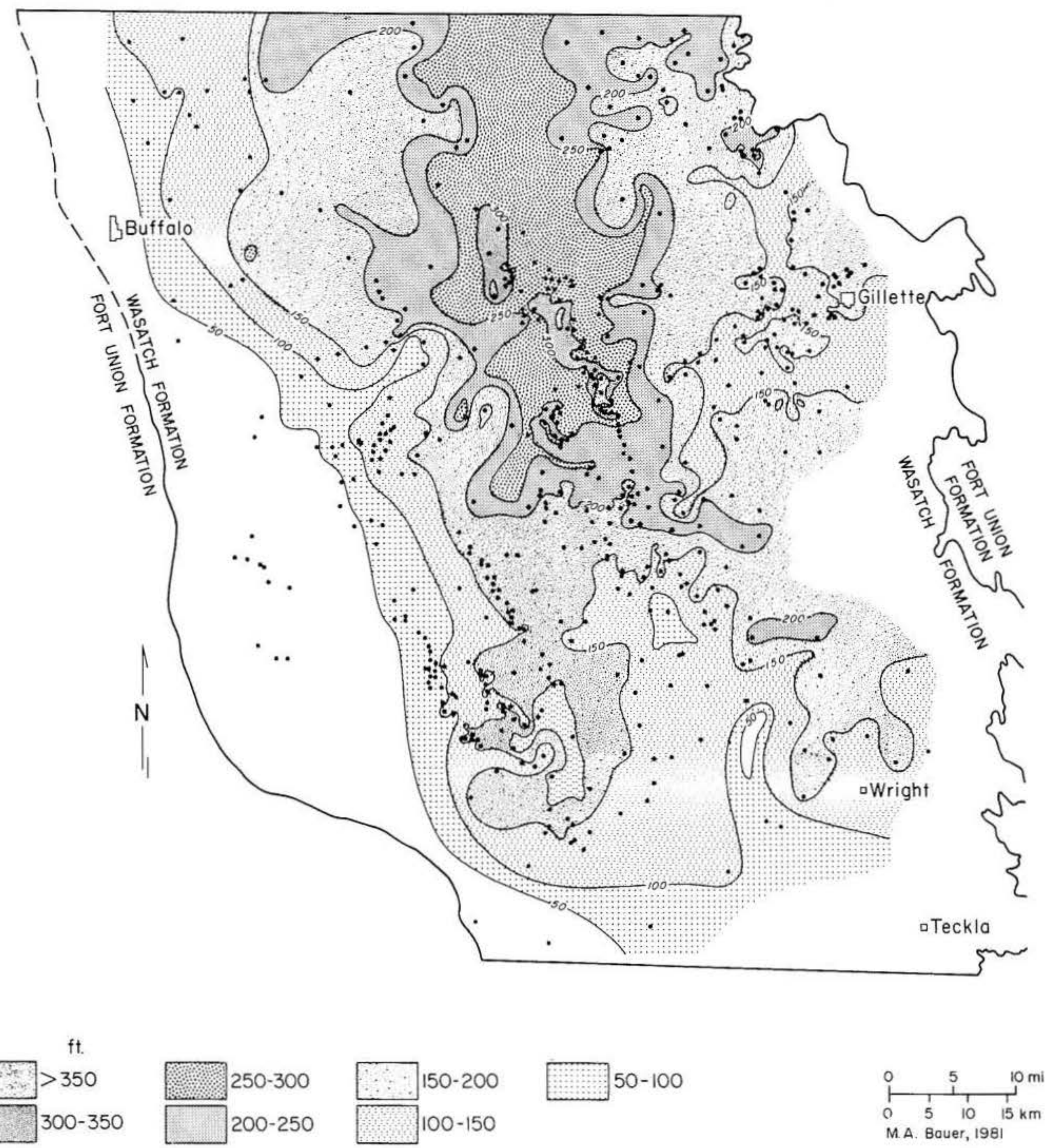


Figure 100. Isopach map of coal seams greater than 2 ft thick on the Tongue River Member, Powder River Basin.

depositional model is based on the study of the coals of the deep basin.

In the center of the Powder River Basin, the Tongue River Member of the Fort Union Formation is interpreted as consisting of two broad deltas (fig. 96) which prograded westward into the basin. Superposition of the maximum coal and sand-percent maps (fig. 102) shows that major coals occur across the delta plain. Periodic abandonment of individual deltas allowed swamps, which had formed in interdeltaic areas flanking active deposition, to spread across the foundered lobes. Thus, swamp expansion resulted in the formation of

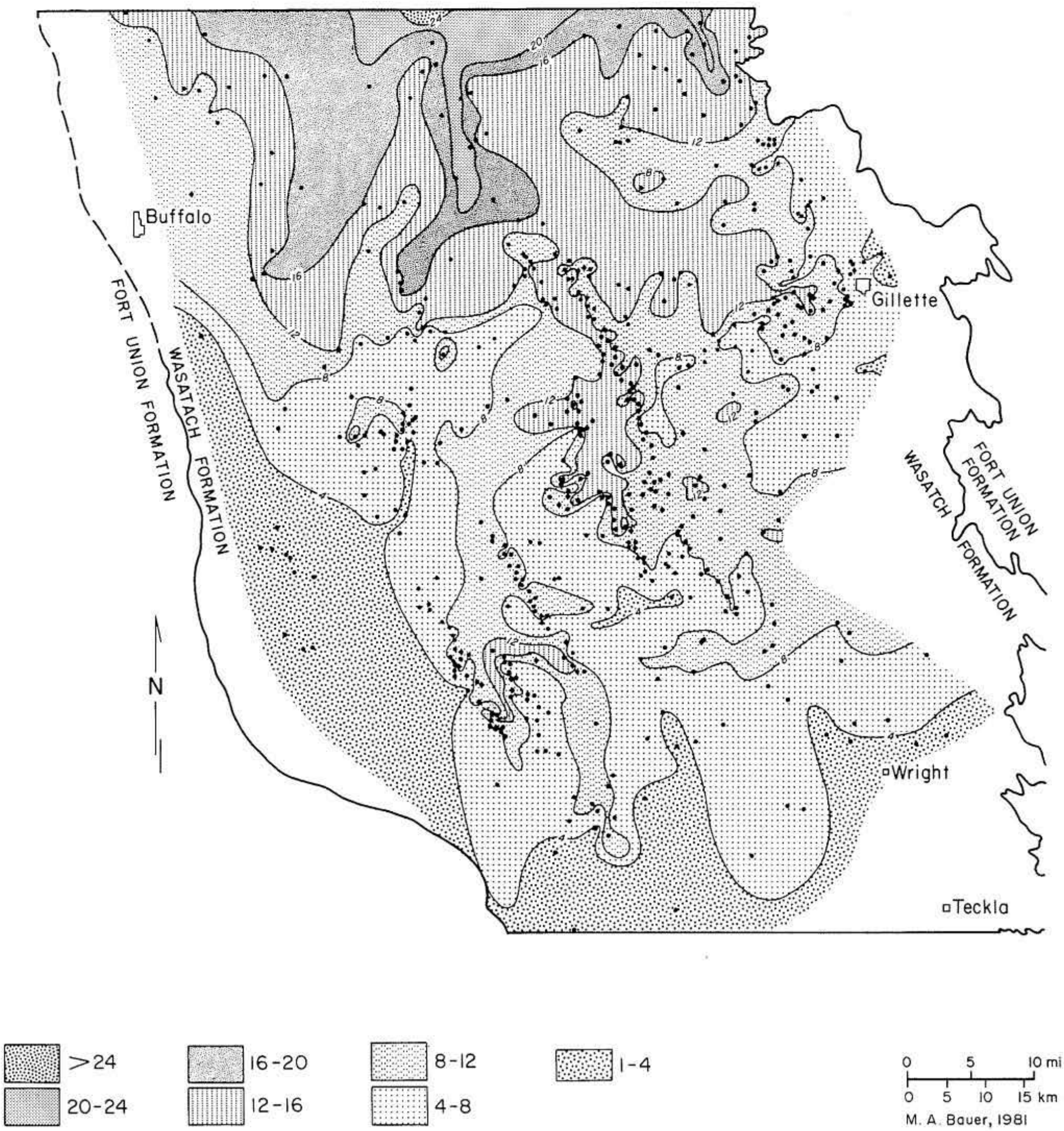


Figure 101. Isopleth map of coal seams of the Tongue River Member, Powder River Basin.

laterally continuous peats. The diminishing thickness and splitting of the thick coals toward the west correspond to decreased sand percentages and attest to the importance of a platform of long-term stability for the accumulation of thick peat. Thinning and splitting of the coals eastward reflects the updip limits of optimum swamp conditions.

A delta plain model elucidates the origin of the Powder River Basin coals. This model, unlike the fluvial models described earlier, is compatible with the development of laterally continuous peats; however, as yet no explanation can be suggested for the development of such great thicknesses.

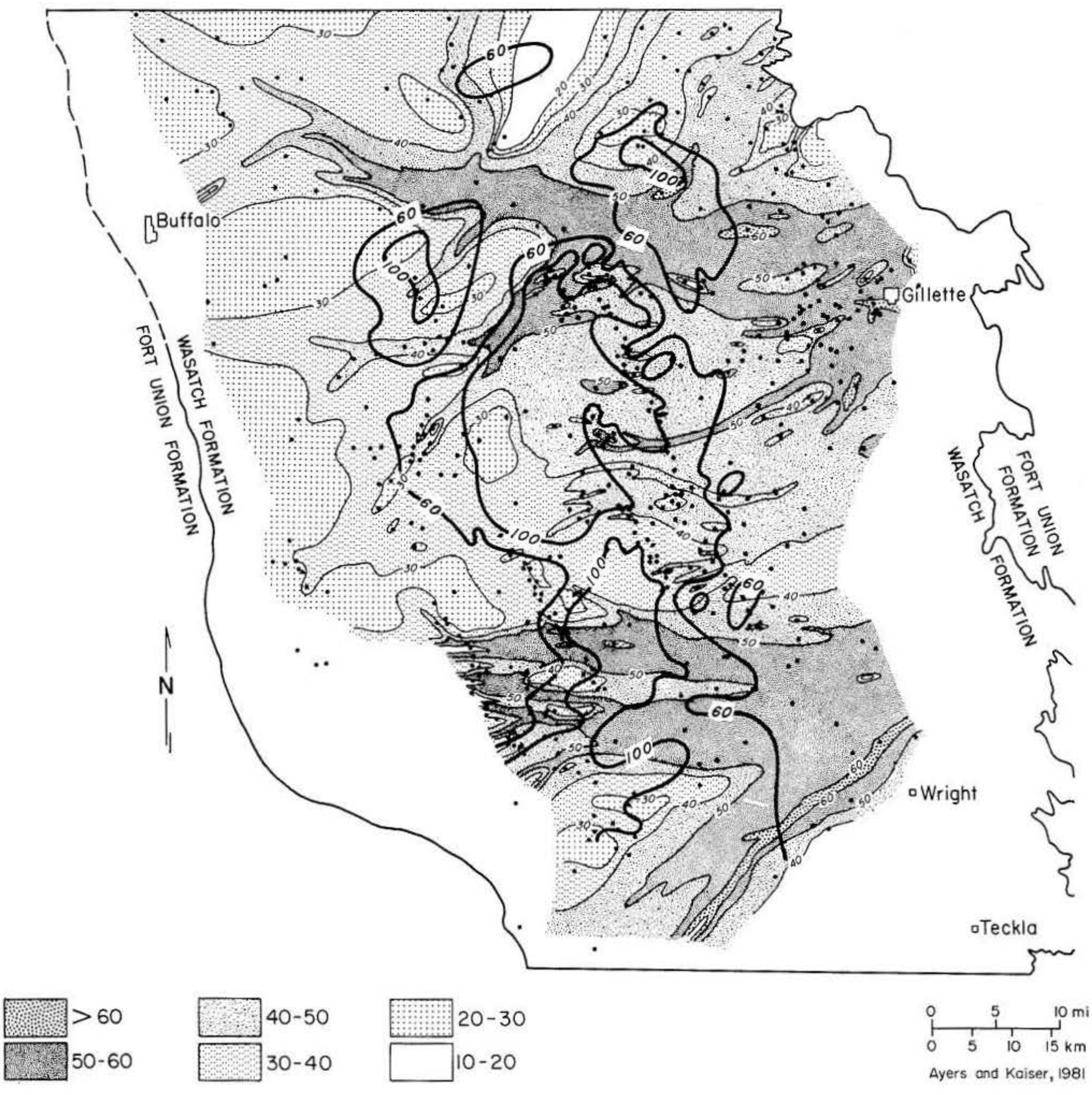


Figure 102. Superposition of deep-basin major coals (from maximum coal map) and sand-percent map, Powder River Basin.

Quantitative Investigation

Introduction

Data from 577 boreholes were stored in the computer system. The boreholes are uniformly distributed over the area, except for some local concentrations of drilling. Coals were not correlated between boreholes, precluding a seam-by-seam evaluation, therefore the investigation concentrated upon the total coal thickness present in the interval.

Geostatistical Methods

Two data sets were analyzed by geostatistical methods: total coal (all seams) and major coal (seams thicker than 18.3 m (60 ft)). Analysis of total coal revealed no dependency structure. The major coal region, shown in figure 103, exhibited a strong dependency structure.

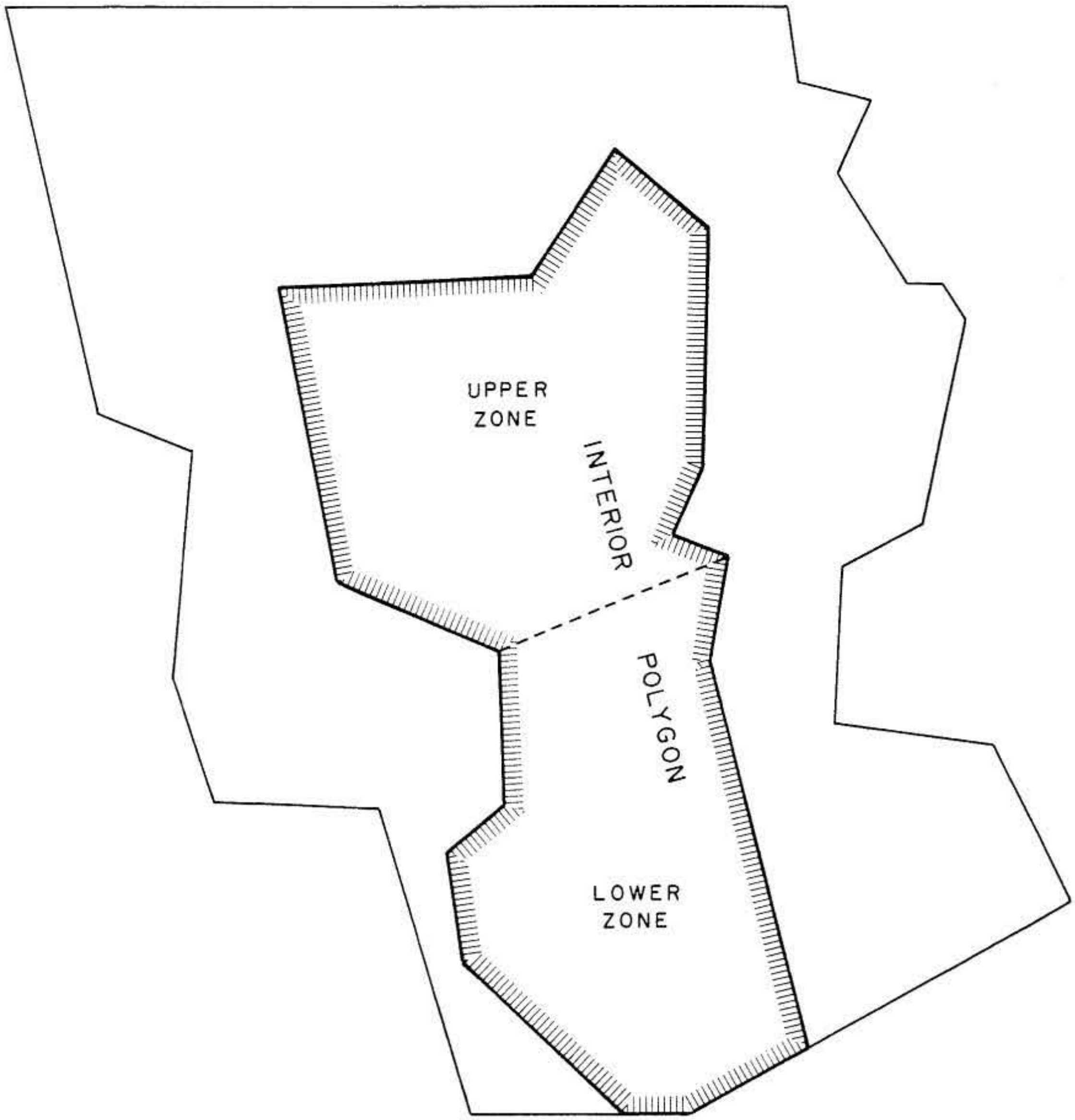


Figure 103. Division of the major coal area into zones, Powder River Basin.

The experimental variogram is shown in figure 104. For zonal studies, the major coal area was divided into two subzones based on the location of the deltas in the subsurface (fig. 103). Both zones exhibited dependency structures and revealed zonal anisotropies as illustrated in figures 105 and 106. The major coal analysis resembled some of the single seam analyses performed in Texas, although over a much larger area. Although individual seam correlations were not made, in general there was only one seam in each borehole that was a major coal (thicker than 18.3 m (60 ft)). It is possible that the same seam was thus selected in enough boreholes that the geostatistical analysis revealed a dependency structure. Because dependency structures were observed only in the major coal, alternative techniques were used to calculate total coal resources of the Tongue River Member.

Alternate Statistical Methods

Figure 107 presents the histograms of individual seam thickness, total coal thickness per hole, and the number of seams per hole. It is not possible to fit an exponential distribution to the tail of the distribution of seam thicknesses, as was done with the Texas lignites.

The statistical methods developed for regional evaluation of Texas lignites as described earlier were

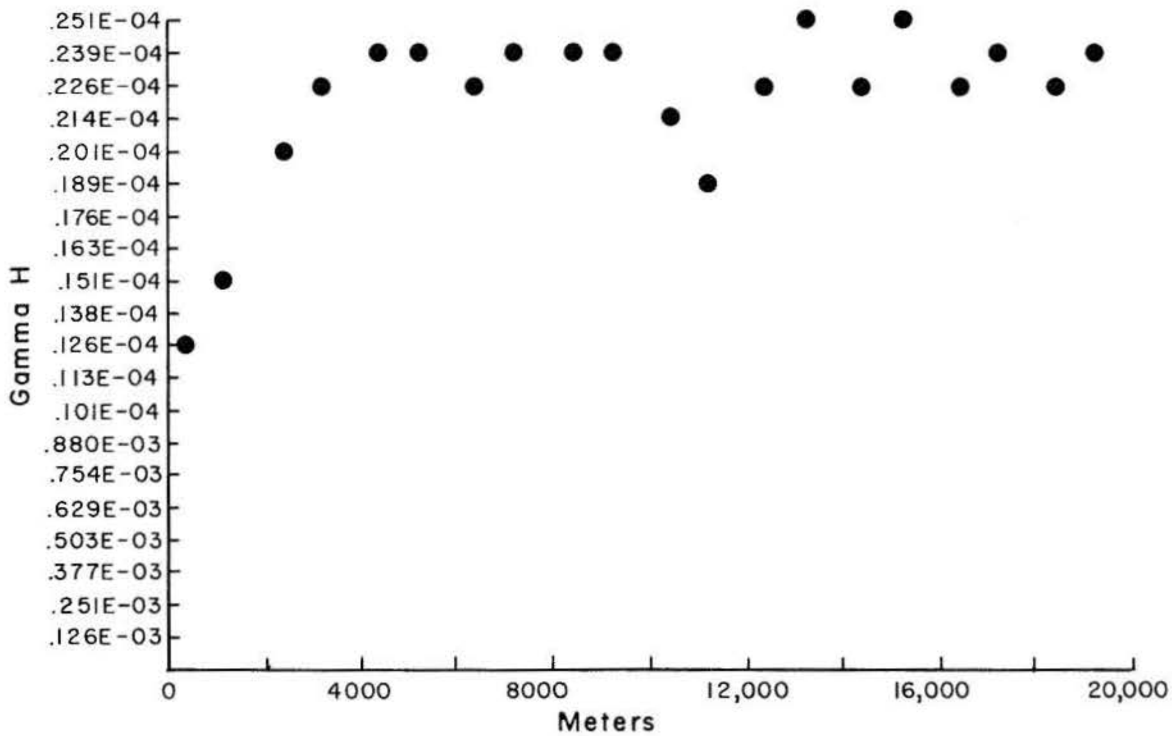


Figure 104. Experimental variogram for entire major coal area, Powder River Basin.

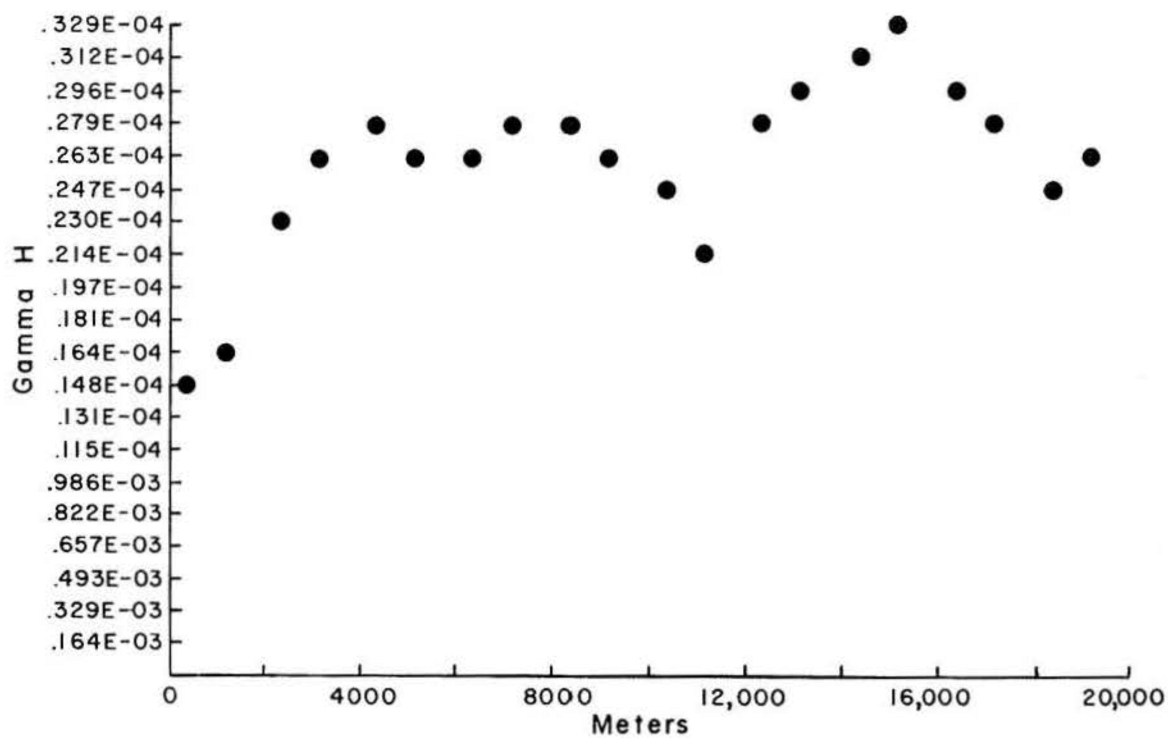


Figure 105. Experimental variogram for upper zone of major coal area, Powder River Basin.

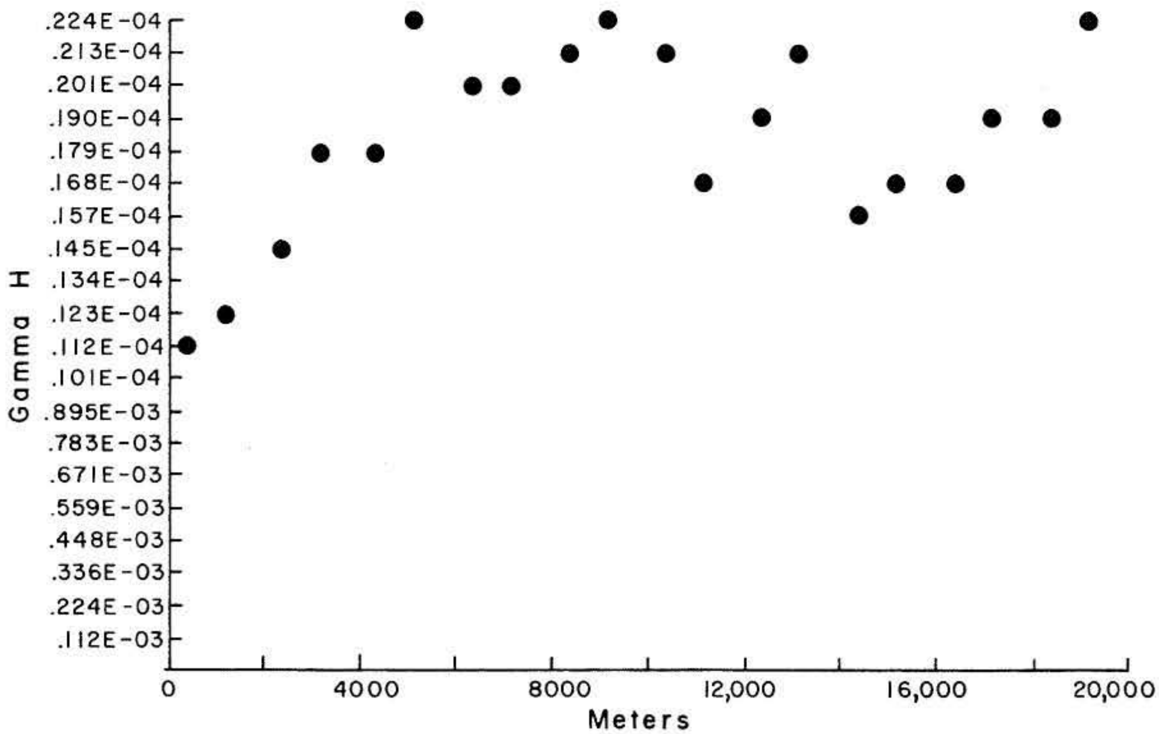


Figure 106. Experimental variogram for lower zone of major coal area, Powder River Basin.

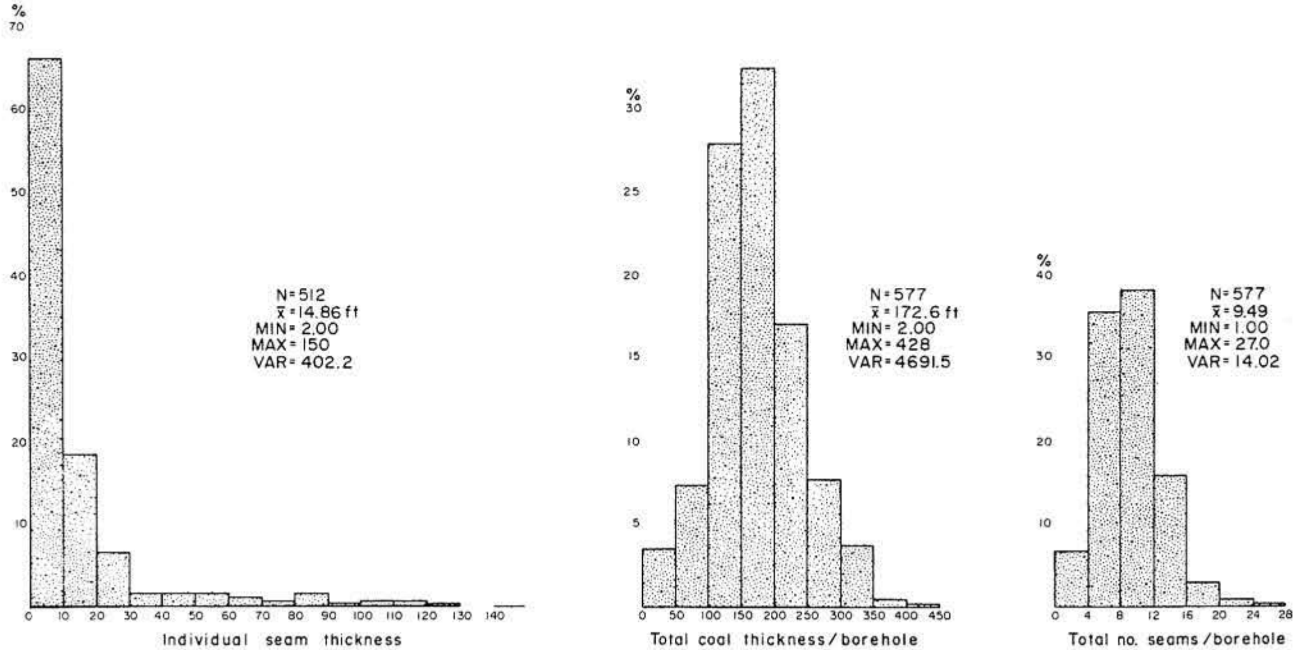


Figure 107. Frequency histograms for regional data, Powder River Basin. Thickness in feet.

Table 21. Means and variances of estimates from varying grids (Powder River Basin).

Case	Grid Size	Origin	Holes	Estimated Mean (ft)	Variance of Estimate (ft^2)
1	10,000 m	0,0	555	166.0	4.101
2	10,000 m	-5,000,0	556	166.0	3.593
3	10,000 m	-5,000,-5,000	556	163.5	3.132
4	10,000 m	0,-5,000	564	166.8	3.548
1 - 4	Summarized			165.6	3.6*

*The summarized variance is the mean of the four estimation variances.

Table 22. Results of contour and facies methods (Powder River Basin).

Description	No. of Blocks	Mean (ft)	Variance of Mean (ft^2)	Standard Deviation
First Technique				
Overlay basic	10	165.8	6.668	2.58
Overlay combined	4	169.2	4.202	2.05
Second Technique				
Total coal basic	14	166.5	4.177	2.04
Total coal combined	2	171.4	4.478	2.12
Facies Technique				
Coal thickness partition	2	166.1	7.219	2.69

applied. Equal weighting of all boreholes gives an estimate of average total coal thickness of 52.7 m (173 ft), with variance of 0.9 m^2 (8.13 ft^2). This is equivalent to a 95 percent confidence interval of 52.7 ± 1.7 m (173 ± 5.7 ft) of coal.

The grid method of evaluation was applied using 10 km- (6.2 mi-) square cells, to obtain a total of between 68 and 76 cells. The results of four grids using these cells and four different origins are displayed in table 21. It can be seen that the sample average of the four grids is 50 m (166 ft). The contour method was applied utilizing contour maps generated by CPS-1 based on averaged values for a 10 km (6.2 mi) grid. The overlay technique (overlaying maps of average seam thickness and number of seams) resulted in 10 homogeneous blocks and 14 blocks for the total coal technique. These blocks were combined as described in the section on Texas lignites. Since the Tongue River Member was not stratified, the geologic facies method could not be transferred. Instead, the whole area was partitioned according to the presence or absence of seams greater than 60 ft thick; this method resulted in two blocks. All the above results are summarized in table 22 and figure 108. The CPS-1 program was also used to obtain another estimate. Using a subbituminous coal tonnage factor of 1,768 tons per acre-ft, a figure of 558 billion metric tons (614 billion short tons) was obtained in an area of .9 million ha (2.24 million acres). This corresponds to an average coal thickness of 47 m (156 ft).

Although this study excluded considerable thick coal along the eastern margin of the basin and was confined to an analysis of only the Tongue River Member in the study area, the calculated resource number is approximately six times that reported for the entire Wyoming part of the Powder River Basin 100 billion metric tons (110.2 billion short tons: Glass, 1980). This larger value reflects primarily the delineation of thick, continuous deep basin coals, made possible by the large number of closely spaced wells.

Summary of Classical Statistical Methods

When figure 108 is compared with the results for Texas (fig. 84), there is a remarkable similarity. In

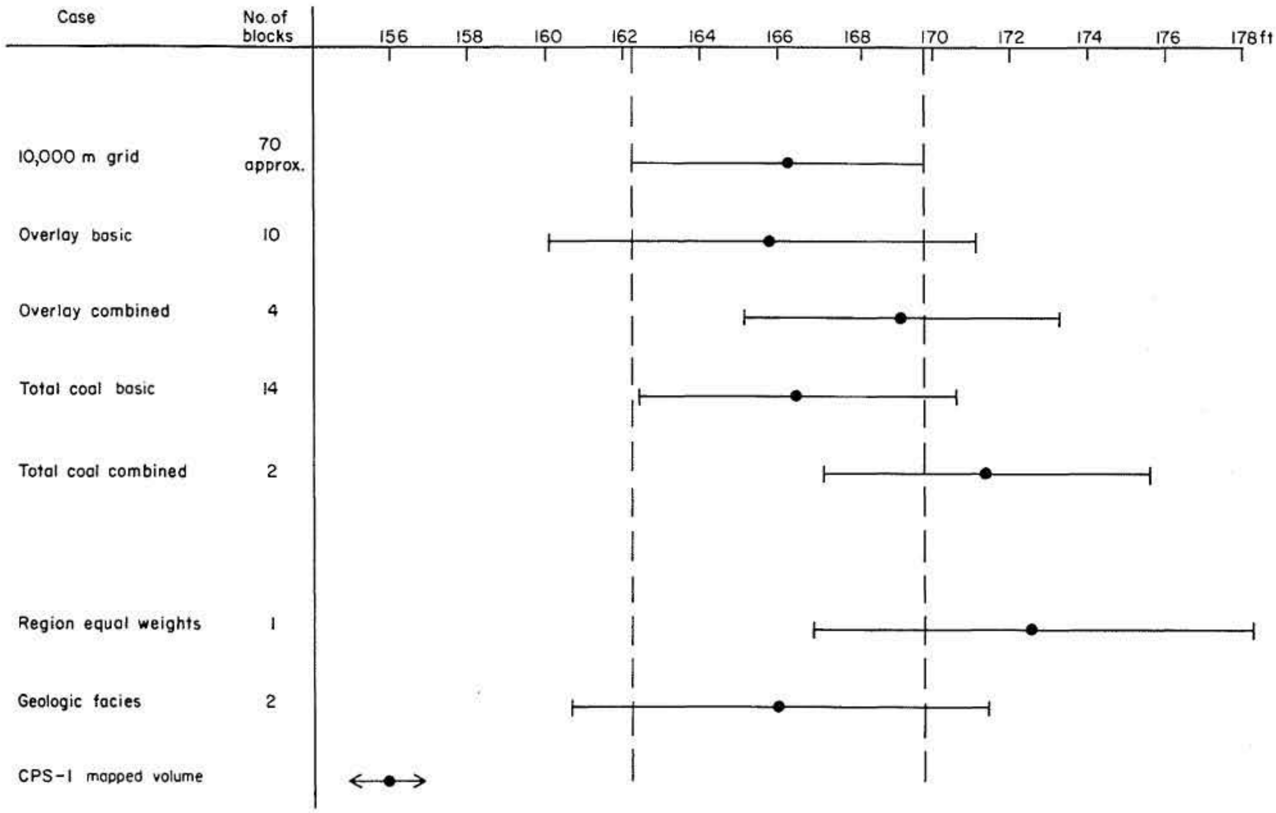


Figure 108. Estimates of total coal thickness and 95-percent confidence limits for various methods, Powder River Basin. Solid dots represent means, bars represent confidence limits.

particular, the same methods and techniques fall into the best class, as defined earlier. The highest and worst estimate comes from the equal weighting technique and the lowest from CPS-1. However the range of results, as a percentage of the grid method result, is only 10 percent for the Powder River data, as opposed to 50 percent for the Texas data. Generally all the methods required the use of fewer homogeneous blocks in Texas. These results may be attributed to the uniformity and distribution of the Powder River data relative to the Texas data, which are extremely heterogeneous in both areal distribution and origin. In particular, the geologic subdivision based on the presence or absence of seams over 18.3 m (60 ft) has produced an accurate result using only two blocks. Another feature of the Powder River Basin results is the size of the confidence limits relative to the spread of the means (fig. 108), which appears larger than in Texas (fig. 81). This may be attributed in part to fewer boreholes represented in the Powder River Basin data (577 versus 1,382 for Texas).

THE ALLEGHENY OF EASTERN OHIO

Geologic Evaluation

Introduction

The reason for choosing the Allegheny Formation of eastern Ohio as a test basin is its similarity in size and style of sedimentation to the Tertiary of the Texas Gulf Coast Basin. Allegheny Formation rocks are Pennsylvanian in age (fig. 109) and crop out along the west flank of the Allegheny Synclinorium (fig. 110). The dip of these rocks is toward the east at about 0.5 to 1 degree. Thickness of the formation varies from 57 to 88 m (188 to 290 ft) and generally thickens towards the southeast. The rocks

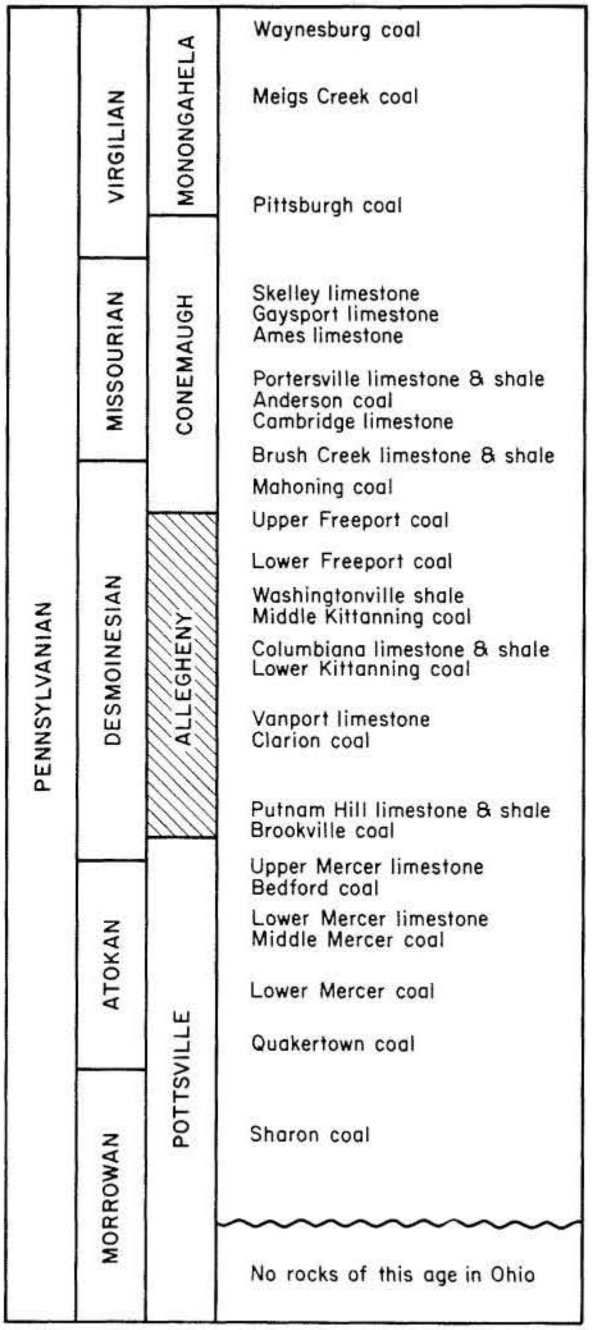


Figure 109. Stratigraphic occurrence of coals in eastern Ohio.

consist of a variety of sandstones, siltstones, shales, coals, "underclays," and limestones. Sandstones are more abundant in the south; shales, siltstones, and marine limestones and zones of marine-bearing fossils are more common toward the north. Coals are equally distributed throughout the succession. The significant coals in terms of production include, from top to bottom, the Upper Freeport (No. 7), Lower Freeport (No. 6A), Middle Kittanning (No. 6), Lower Kittanning (No. 5), Clarion (No. 4A), and Brookville (No. 4). Total Allegheny coal resources have been reported to be 37.8 billion tons (Brant, 1956; DeLong, 1957). In 1976, 41 percent of the coal produced in Ohio came from the Allegheny Formation, with 43 percent of that coming from the Middle Kittanning coal. On a regional basis the Upper Freeport and Lower Freeport coals are more variable in thickness and continuity than either the Middle Kittanning or Lower Kittanning coals.

Types of Data and Previous Work

Information on the Allegheny consists of numerous early reconnaissance, regional, county, economic, and general geologic reports published by the Ohio Geological Survey. Most of these (Stout, 1916, 1918, 1944; Stout and Schoenlaub, 1945; White and Lamborn, 1949; Lamborn, 1951, 1954, 1956; Brant, 1954; DeLong, 1957; DeLong and White, 1963; Couchot and others, 1980) are purely descriptive lists of estimated coal resources for different seams and do not discuss depositional environments of coal formation. A few publications (Ferm, 1962, 1964, 1970; Williams and Ferm, 1964; Bergenback, 1964; Flores, 1965) and unpublished dissertations (Webb, 1963; Flores, 1966; Zimmerman, 1966) present the genesis of the rocks in the area. We used all of these sources of information to provide a stratigraphic synthesis and genetic interpretation of the Allegheny Formation.

The Ohio Geological Survey's open files contain a large number of measured stratigraphic sections and driller's records for the Allegheny Formation. Measured stratigraphic sections and driller's records were used to compile three strike and two dip cross sections (figs. 111 through 115, with locations shown on fig. 110). Observations from these cross sections substantiate many of the interpretations made in the early works.

Ferm (1970) proposed a lithogenetic model for the Allegheny Formation. The model is a three-dimensional lenticular body composed mainly of detrital rocks that grade upward and landward from shales to sandstones and that are the result of deltaic progradation. The detrital sediments are completely or partially enclosed in a veneer of coeval chemically precipitated or indigenously formed peats (coals), root-penetrated clays (seat rocks), or carbonate sediments (limestone or ironstone). The chemically precipitated and non-detrital rocks were deposited on the offshore front or on marginal parts of the delta or accumulated on the delta-plain surface when it was no longer receiving appreciable sediment. Lateral shifts of sites of major detrital deposition resulted in an offset arrangement of progradational detrital wedges.

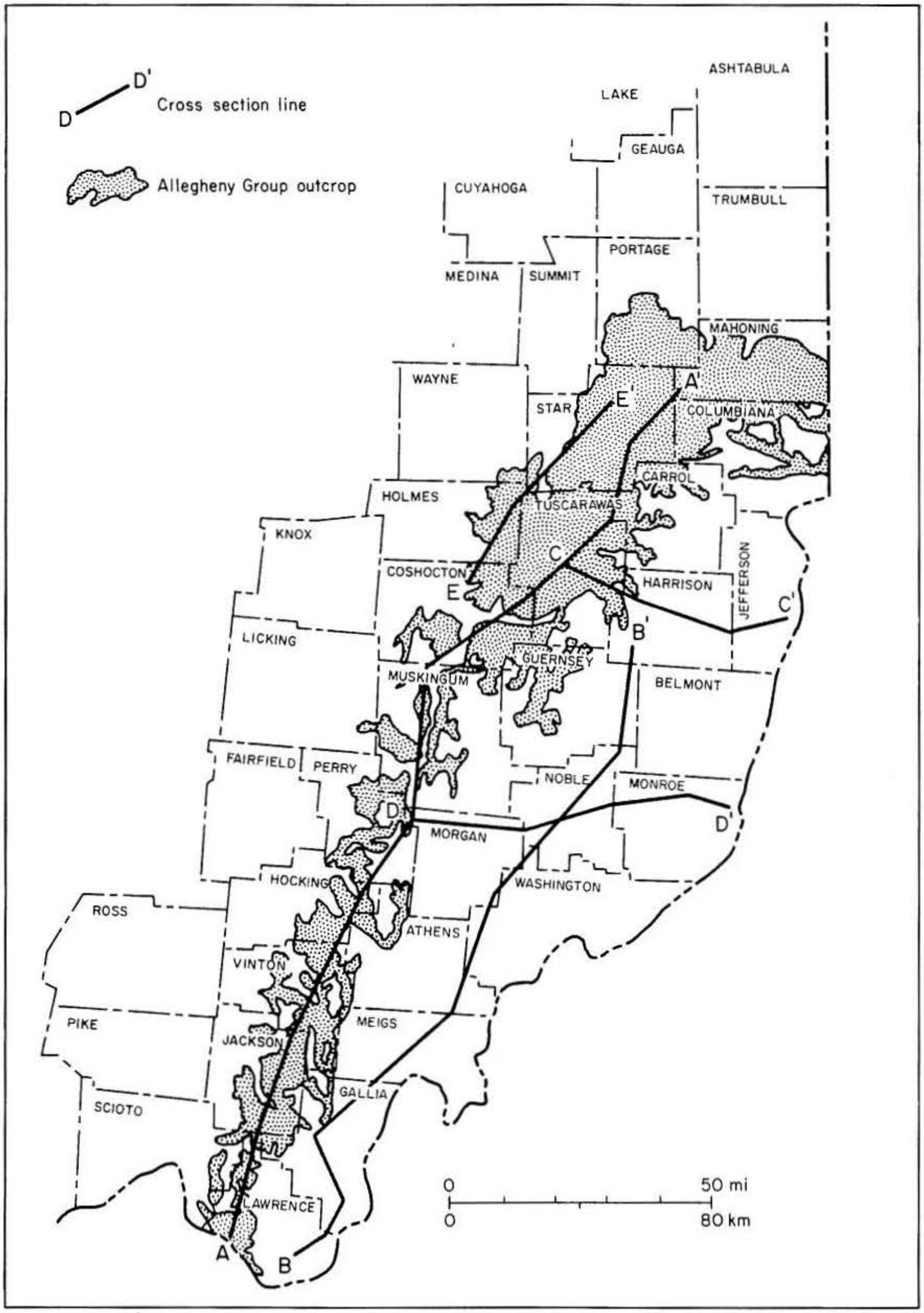


Figure 110. Map of eastern Ohio showing the coal-bearing Allegheny Formation and location of geologic cross sections.

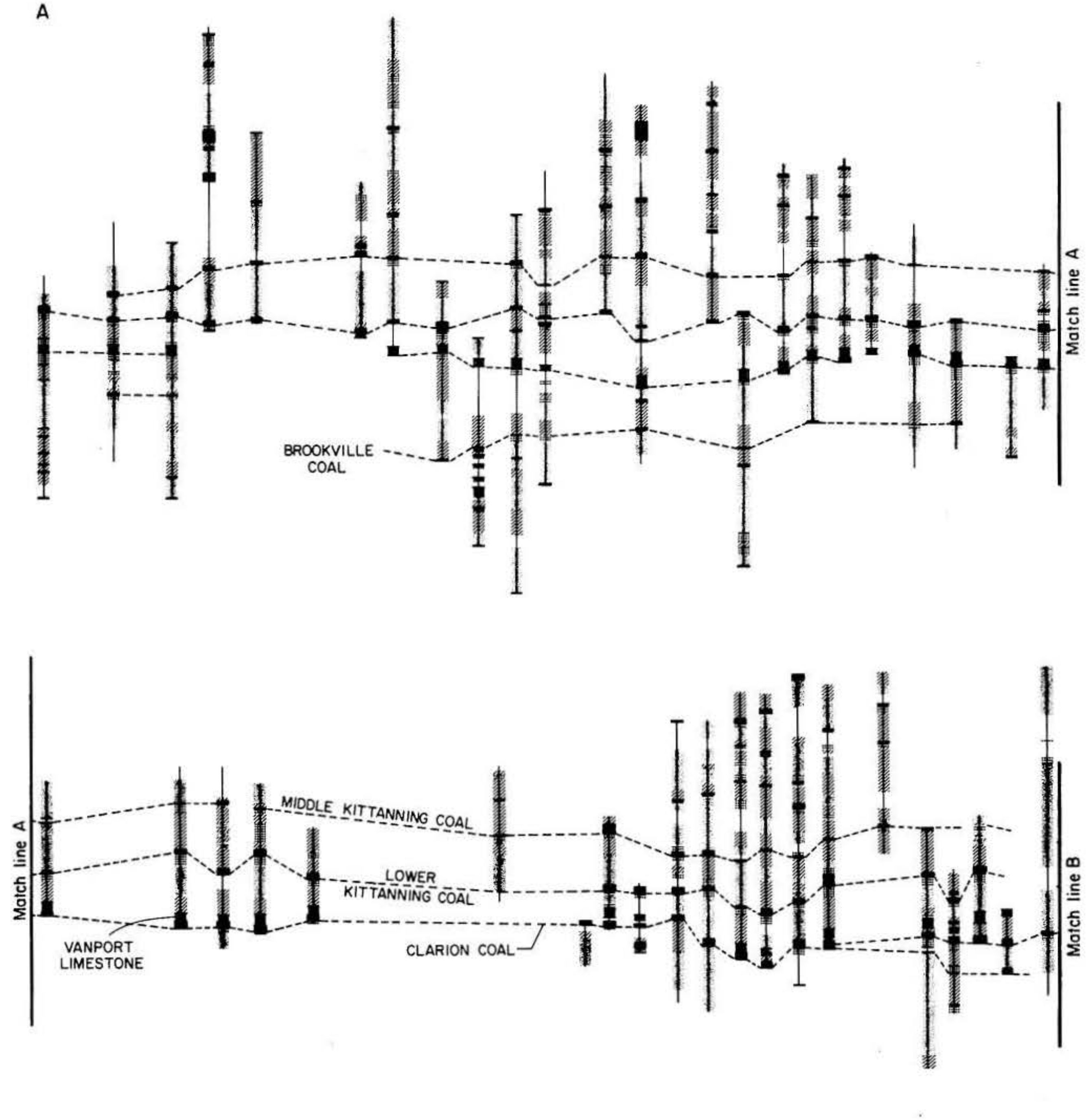


Figure 111. Strike-oriented cross section A-A′, Allegheny Formation.

In southern Ohio, Webb (1963) described two offset wedge-shaped sedimentary units overlain by a third. Webb attributed the offset and overlap relationships to deltaic progradation and shifting. The basal sedimentary unit recognized by Webb is documented on the extreme left-hand side of cross section A-A′ (fig. 111). It is a wedge-shaped body thickening to nearly 24 m (80 ft). The Brookville Coal forms the lower boundary and the Clarion Coal the upper boundary. Various rock types constitute the components of the wedge. Overlapping the basal unit from the north is a second sedimentary unit that appears similar in all respects to the first unit. It is wedge-shaped and pinches out in a southerly direction against a large underlying channel sandstone of the basal unit. The second unit is bounded at the base by the Ogan Coal and at the top by the coal and clay of the Vanport-Clarion interval.

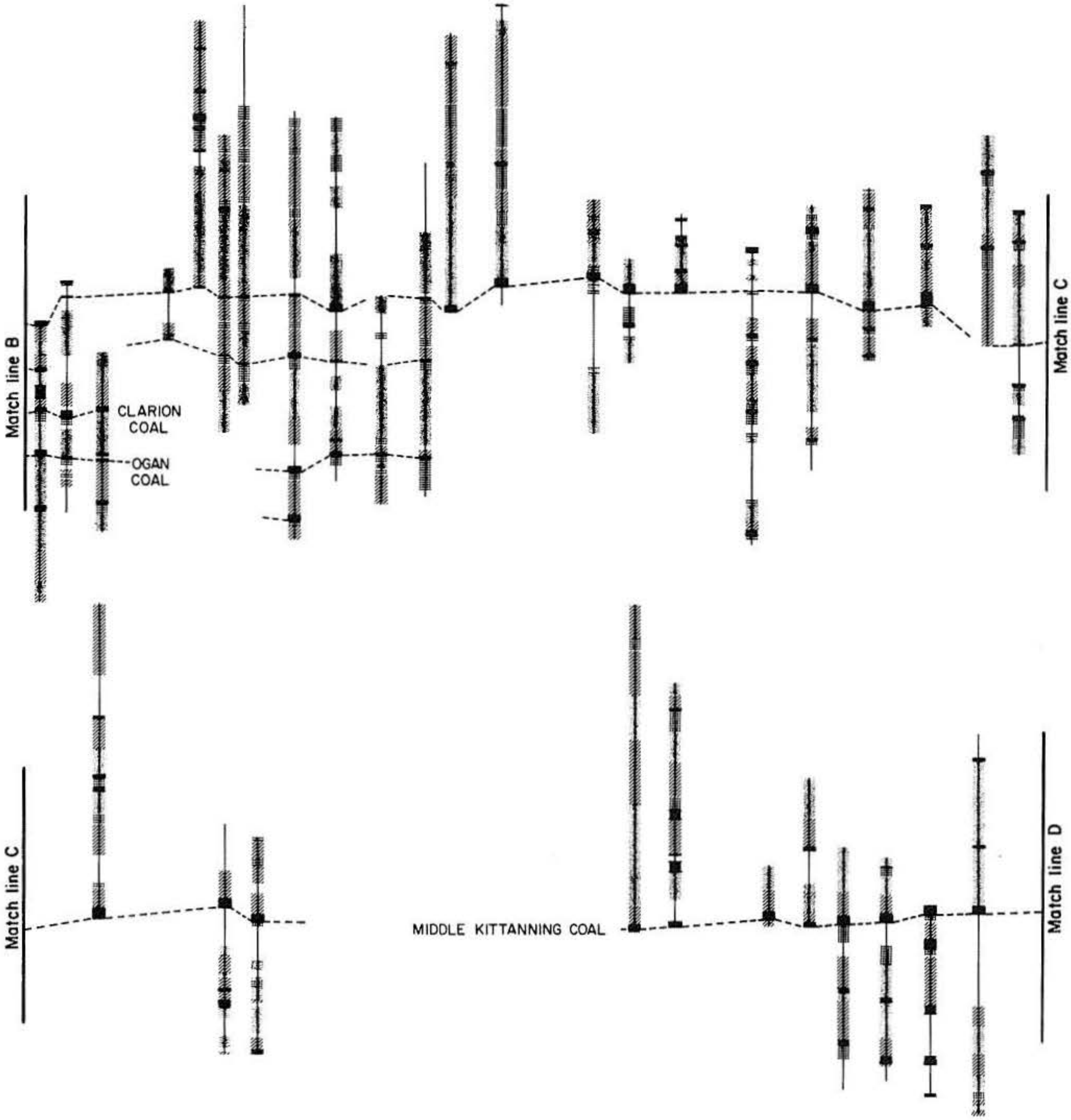


Figure 111 (cont.)

The detrital unit between the Vanport Limestone and the Lower Kittanning Coal (fig. 111) is similar in lithology to the underlying units. The sandstone content, however, is greater towards the southern part of the area. The sedimentary unit between the Lower Kittanning and overlying Middle Kittanning consists predominantly of a nonmarine sequence of shales, sandstones, and clays with occasional marine-brackish fossils in the northwestern part of the area (fig. 115). The Middle Kittanning Coal is the most persistent unit in the entire Allegheny succession.

The sedimentary units from the Middle Kittanning to the Upper Freeport are predominantly nonmarine. They consist of discontinuous coals, fireclays, fresh-water limestones, shales, siltstones, and sandstones, which dominate the succession (figs. 113 and 114). The channel

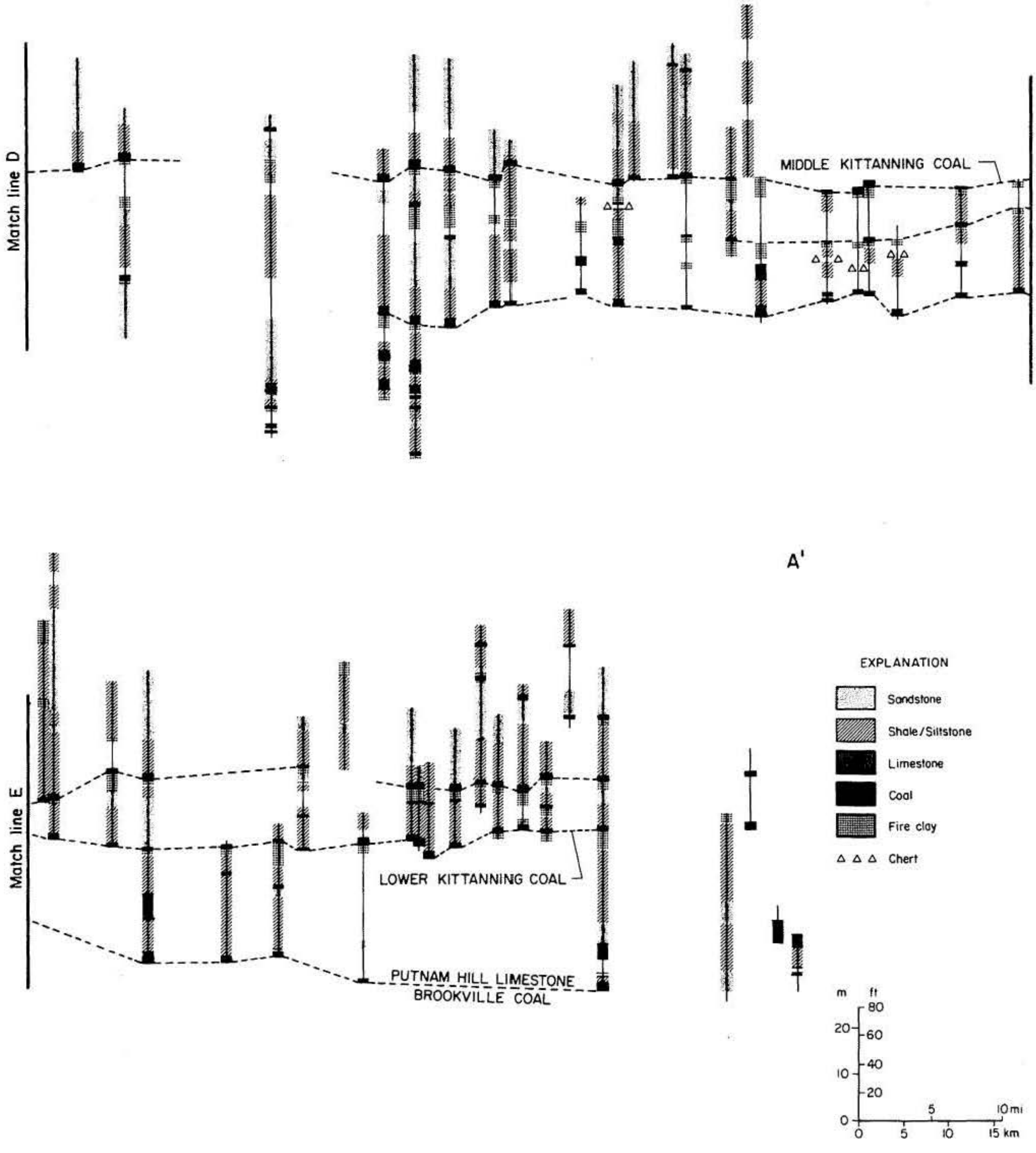


Figure 111 (cont.)

sandstones of these units are thicker and coarser grained than are the underlying units. Coals tend to drape over and interfinger with the large channel sandstones. Numerous coals occur scattered throughout this succession, but only two coals are of any significance, the Lower and Upper Freeport.

In summary, all units of the Allegheny Formation are partially or completely enclosed in veneers of coeval, chemically precipitated rocks or those formed in situ. The grain size of the sediments within units tends to increase upward. Units are arranged in an offset fashion, with coarse clastics of an overlying unit juxtaposed with finer sediments of a lower unit. From the Brookville Coal to the Lower Kittanning Coal, units are characterized by marine to brackish sediments (fossiliferous shales and limestones), whereas the overlying units (Middle

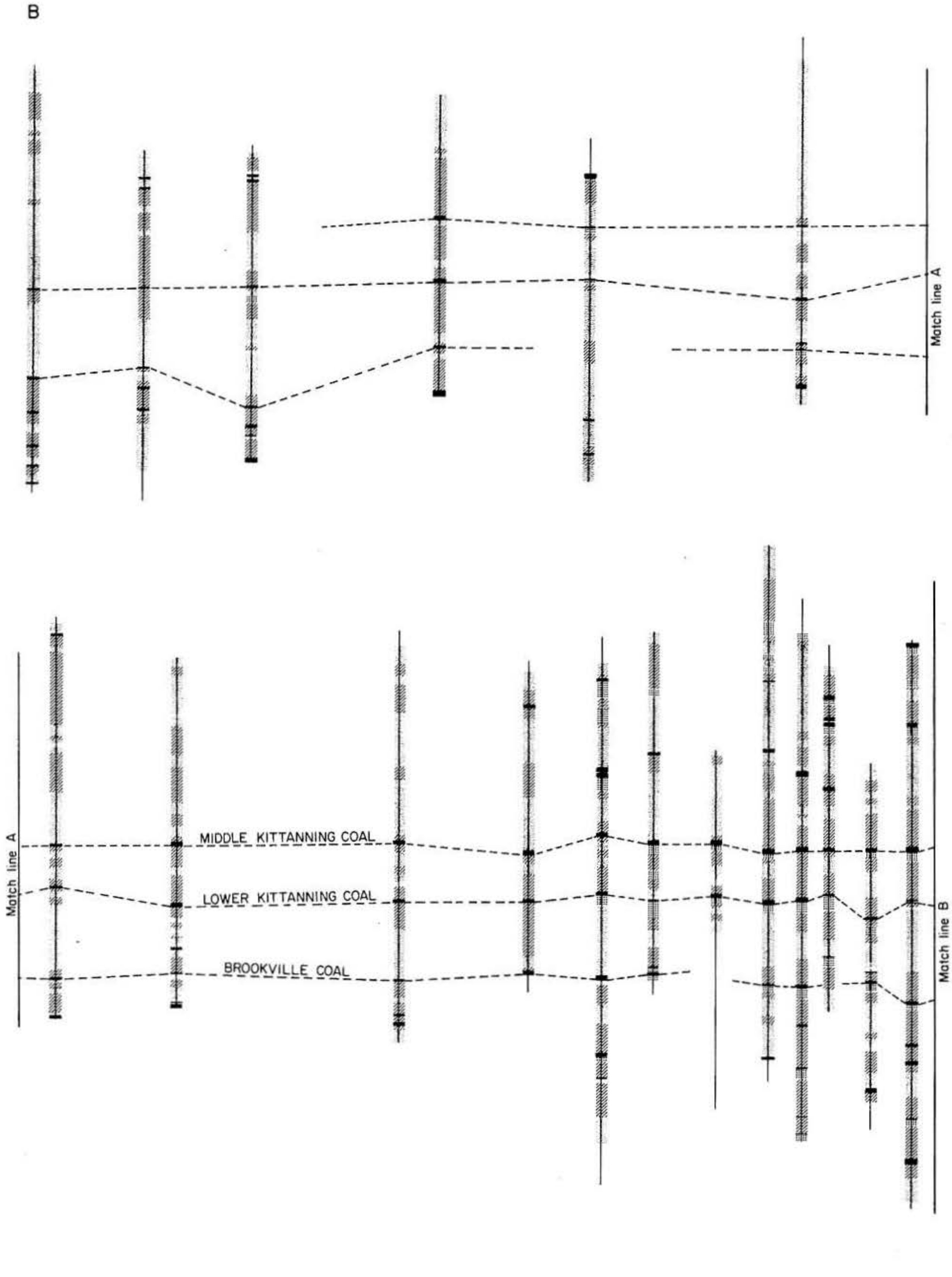


Figure 112. Strike-oriented cross section B-B', Allegheny Formation.

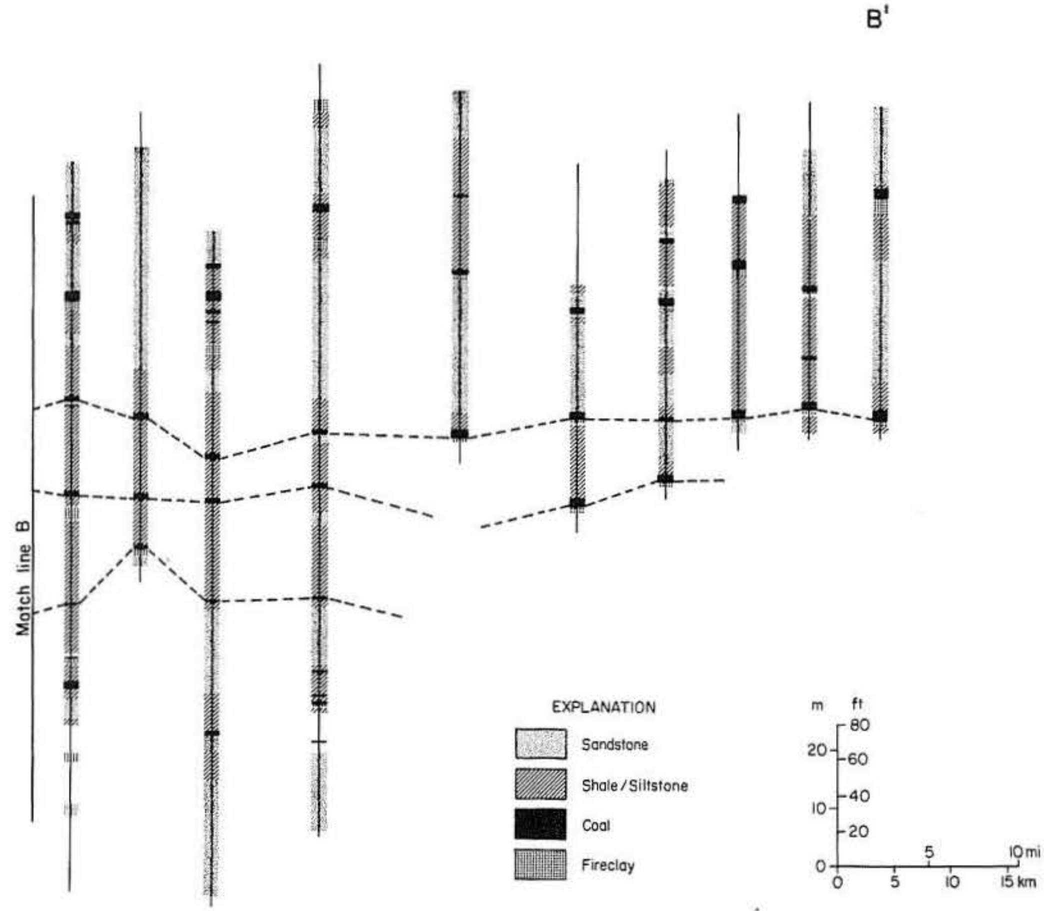


Figure 112 (cont.)

Kittanning to Upper Freeport) are dominated by nonmarine sediments. Marine sediments are occasionally found only in the northern part of the area. From north to south and from bottom to top the proportion of sandstone of the entire Allegheny succession increases.

Interpretations of the evolution of the Allegheny sedimentary units have been proposed by many workers (Zimmerman, 1966; Ferm, 1970). Zimmerman (1966) presented a series of paleogeographic maps depicting the geographic location of major delta progradational wedges for the lower Allegheny Formation (fig. 116).

As wedges of sediment prograded across the areas of open water, their upper surfaces merged with the inactive wedges of sediment to form the large platforms upon which the peat swamps formed. Delta progradation and abandonment continued through time, developing an extensive platform for Middle Kittanning coal formation. At that time the lower delta plain had advanced northward, giving way to an upper delta/alluvial-plain setting in the position of the present Allegheny outcrop.

Quantitative Investigation

Introduction

Since 1929 three separate resource appraisals have been compiled for the Allegheny of eastern Ohio. The most complete studies were done by Brant (1956) and DeLong (1957). Their resource figures for the Allegheny Formation on a seam-by-seam basis are as follows:

Upper Freeport (No. 7)	4,180,771,000
Lower Freeport (No. 6A)	2,446,278,000
Middle Kittanning (No. 6)	9,783,598,000
Lower Kittanning (No. 5)	9,913,989,000
Clarion (No. 4A)	715,637,000
Brookville (No. 4)	446,215,000
Total	37,863,439,000

The method used to compile these estimates included the compilation of maps upon which seam outcrops and

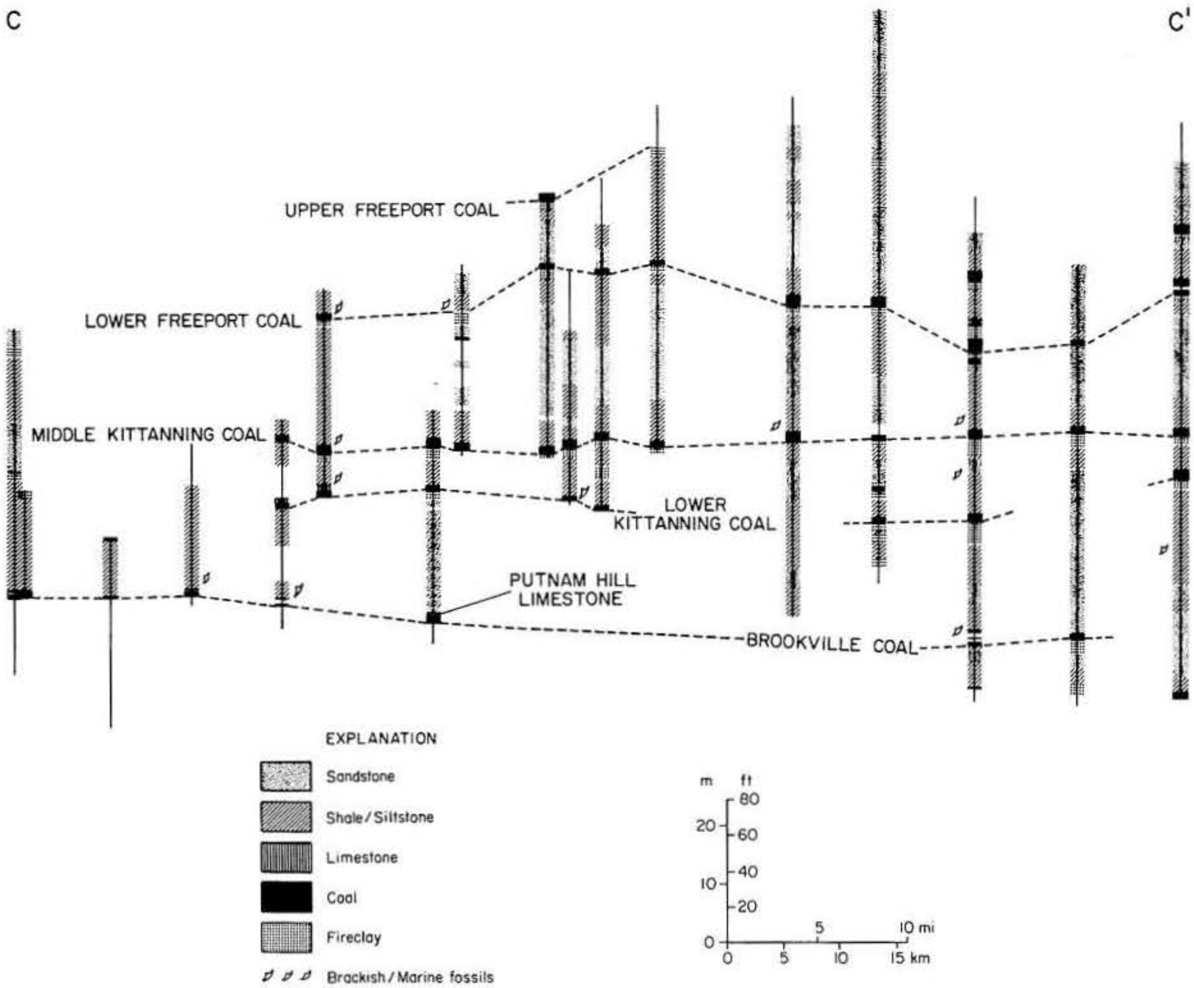


Figure 113. Dip-oriented cross section C-C', Allegheny Formation.

points of known coal thickness were plotted. Thickness contour lines were drawn by hand. Reliability arcs were cast around each point of information, as was done in the U. S. Geological Survey system described earlier. Planimeter measurements of each individual area were made and tons were calculated.

For this study, seam-by-seam resource analysis was restricted to the Middle Kittanning and Upper Freeport coals. This study gave us the first opportunity to investigate seam variability over a large area.

Technical Approach

Not all the available open-file data were entered in the computer. Only those boreholes and measured sections intersecting the Middle Kittanning were used. Since the Middle Kittanning Coal occurs approximately in the stratigraphic center of the Allegheny Formation, these boreholes should give a representative set of data for the entire Allegheny. A total of 1,042 boreholes and measured sections were coded and entered. About half these data points are clustered along the Allegheny outcrop belt. Most boreholes and measured sections had already been correlated, and the Middle Kittanning and Upper Freeport coals tagged; these correlations were used in this study.

One of the differences between the Allegheny and Wilcox of Texas is the outcrop pattern. The Allegheny outcrop pattern is very irregular because of the rugged relief in the area. The representation of the outcrop pattern used by the computer consists of straight line segments which, depending on the number used, approximates closely or generalizes the actual boundary. The degree of error in the calculations of coal volumes was investigated by increasing the generalization of the outcrop boundary. Three area calculations were made (table 23), each with a more generalized outcrop boundary (fig. 117). Since minor generalizing of the outcrop did not significantly affect the overall area

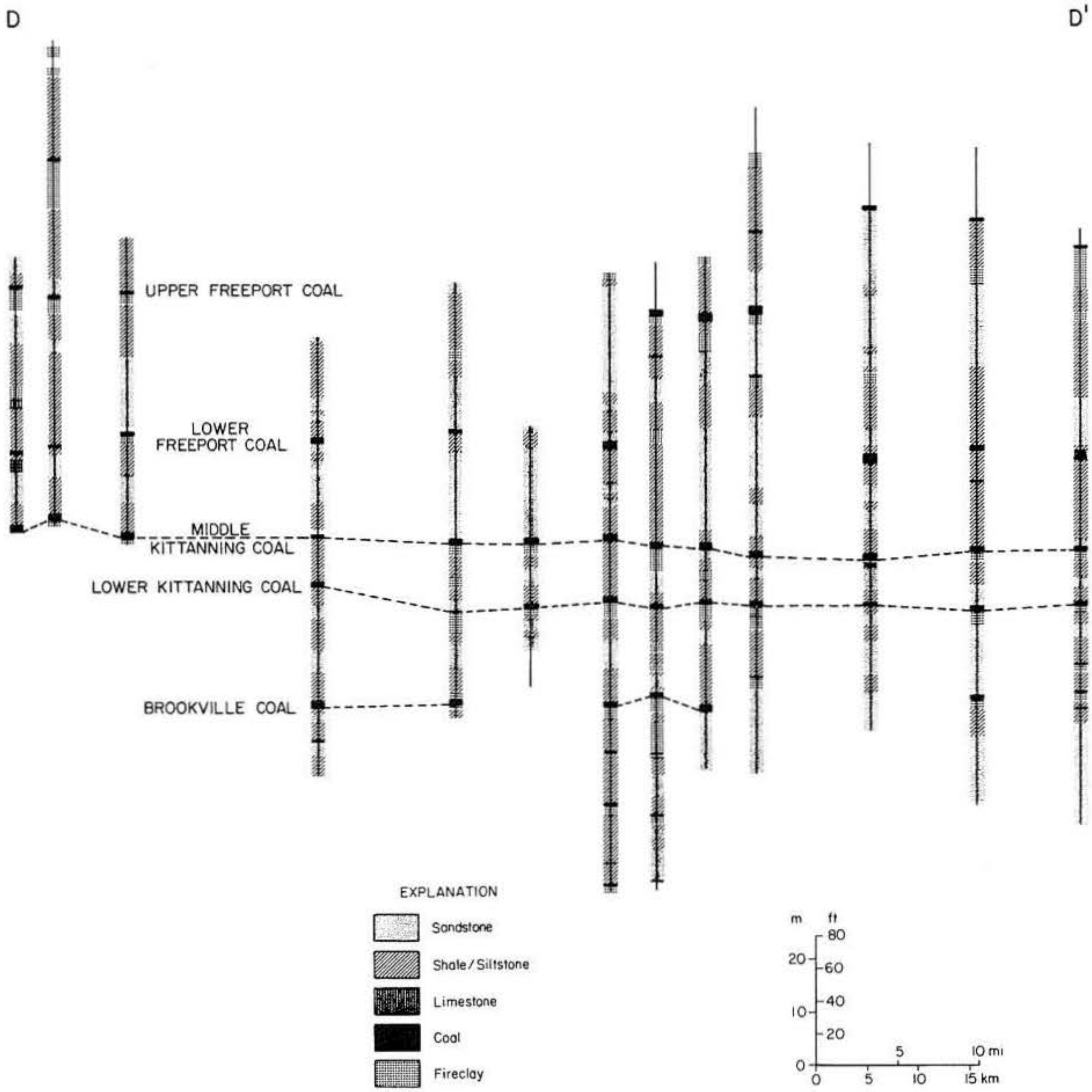


Figure 114. Dip-oriented cross section D-D', Allegheny Formation.

calculation, the procedure was repeated for maps covering the entire study area. For the resource calculation, small isolated outcrop areas beyond the major outcrop belt were ignored.

Geostatistical Methods

The Upper Freeport and Middle Kittanning coals were investigated for inherent dependency structures. Only 112 measurements of the Upper Freeport coal were available, whereas 877 Middle Kittanning measurements were used. The Upper Freeport data set was too small to detect any dependency structure. Figure 118, the experimental variogram of the Middle Kittanning, has a nugget value close to the sill value. Therefore no great decrease in estimation variance would result from the use of such a marginal dependency structure.

Alternate Statistical Methods

Seam Level Evaluation.—Figure 119 shows histograms of seam thickness for the Middle Kittanning and Upper Freeport seams. The unweighted mean thicknesses of these two seams are 0.9 and 0.6 m (2.97 and

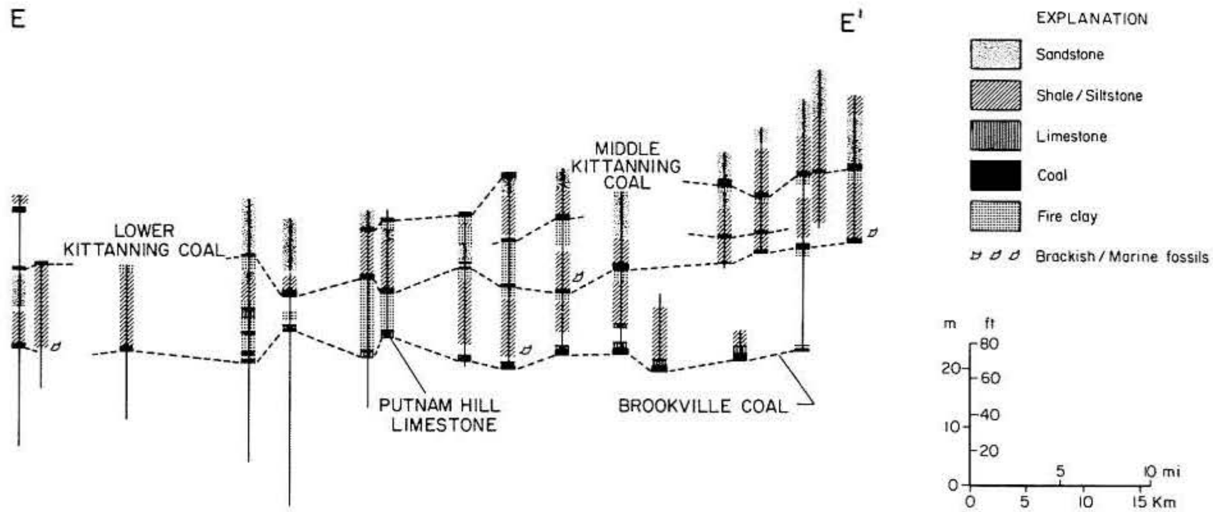


Figure 115. Strike-oriented cross section E-E', Allegheny Formation.

1.98 ft), respectively. Resource data were generated by computer (CPS-1) for the Middle Kittanning and Upper Freeport seams (table 24). The resources for these two seams are approximately double the official figures (Brant, 1956). One explanation is that in Brant's study resources were calculated for only those areas with available data. For example, resources were not calculated for much of the deep basin.

Using the seam methodology developed in Texas for both seams, we computed the number of holes required to obtain a precision of ±10 and ±20 percent on the resource estimate (table 24). Computer-calculated tonnages for various reductions in data (100, 50, 25, and 12.5 percent) were computed for both seams. Resource figures are remarkably similar for the Middle Kittanning seam; the Upper Freeport seam estimates have a greater variation.

Regional Level Evaluation.—Figure 120 is a histogram of total coal thickness for all seams per borehole with a mean of 1.2 m (3.90 ft). This distribution appears more lognormal than exponential. Figure 120 also shows the mean number of seams per data point and the mean thickness per seam to be 1.5 seams and .67 m (2.2 ft), respectively.

Total coal resources for the Allegheny Formation were computer-calculated by summing the coals in each borehole or measured section. Because of a situation similar to that occurring in Texas, where boreholes only partially intersect the entire stratigraphic interval, the total calculated resources of 44 billion metric tons (48.4 billion short tons) appears to be a conservative estimate. If all the available data were used and resources calculated on a seam-by-seam basis, it is anticipated that total coal resources might be much higher. If resource figures for the Middle Kittanning are any indication of how much larger this total resource figure could be, 64 billion metric tons (70 billion short tons) may be more appropriate.

Three alternative statistical methods for resource estimation developed in Texas were applied to the Allegheny data: equal weighting method, grid method, and homogeneous block method. The method of equal weighting of boreholes yielded an estimate of average total coal thickness of 1.2 m (3.90 ft) with a variance of .0002 m^2 (.0009 ft^2), equivalent to 1.2 ± 0.6 m (3.90 ± 0.19 ft). The grid method of evaluation was applied using 10 km (6.2 mi) square cells, which resulted in a total of between 135 and 144 cells. The results using four grids are presented in table 25, which shows an average total coal thickness of 1.26 m (4.15 ft).

The homogeneous block method was applied using average values of total coal, seam thickness, and number of seams for 10 km (6.2 mi) grid cells. The overlay technique resulted in 36 homogeneous blocks, and the total coal technique resulted in 24 blocks (table 26 and figure 121). For comparison, the CPS-1 estimate of calculated 44 billion metric tons (48.4 billion short tons) over an area of 2.1 million ha (5.8 million acres) results in an average seam thickness of 1.4 m (4.7 ft).

Figure 121 displays the relationships between the various methods used in Ohio. The relationships are similar to those that were seen in Texas and the Powder River Basin; the range of results is about 20 percent compared with 50 percent for Texas and 10 percent for the Powder River Basin. More blocks were required for both contour techniques than in either Texas or the Powder River Basin, in part because the study area in

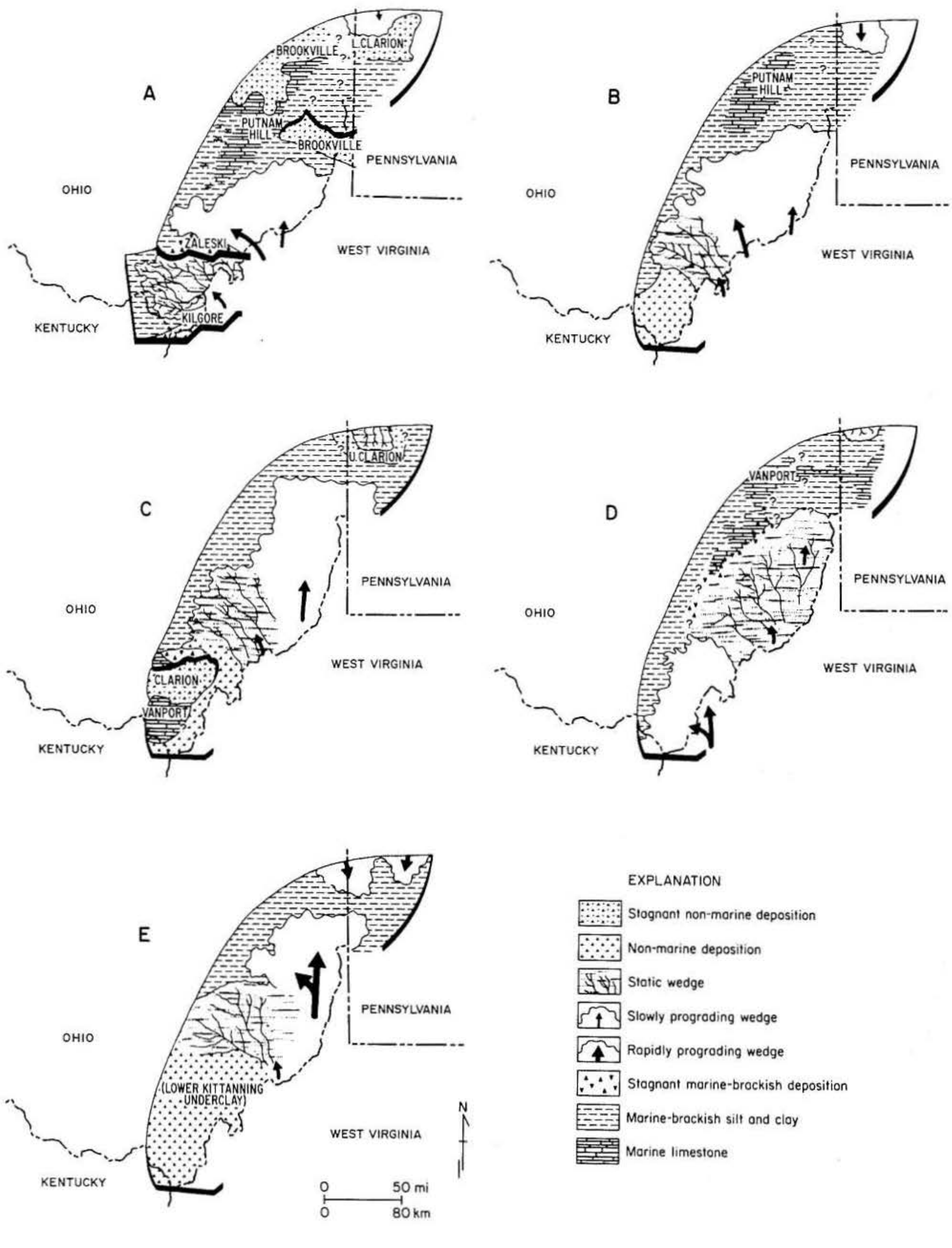


Figure 116. Early Allegheny paleogeography. After Zimmerman (1966).

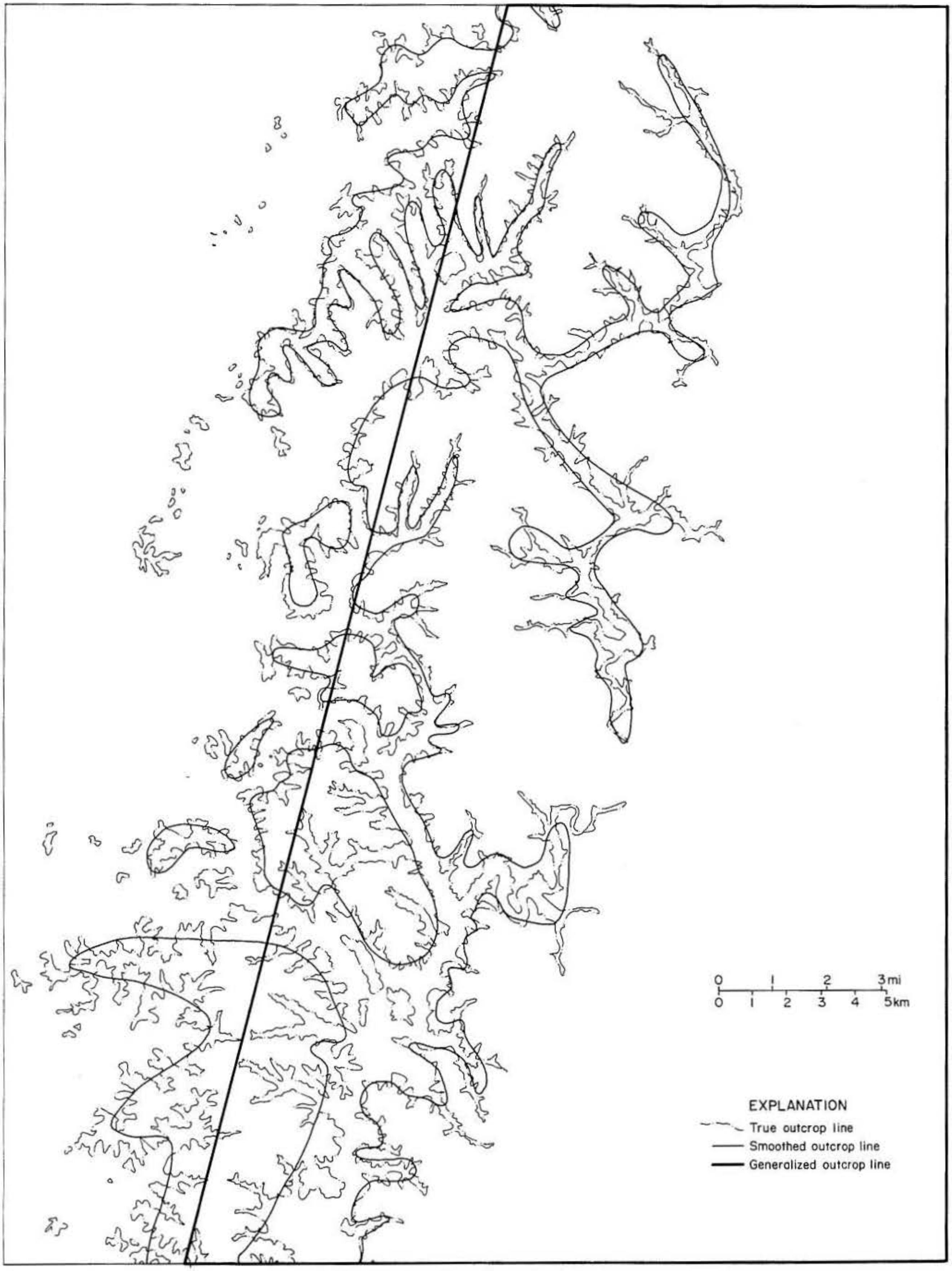


Figure 117. True and generalized outcrops of part of the Allegheny Formation.

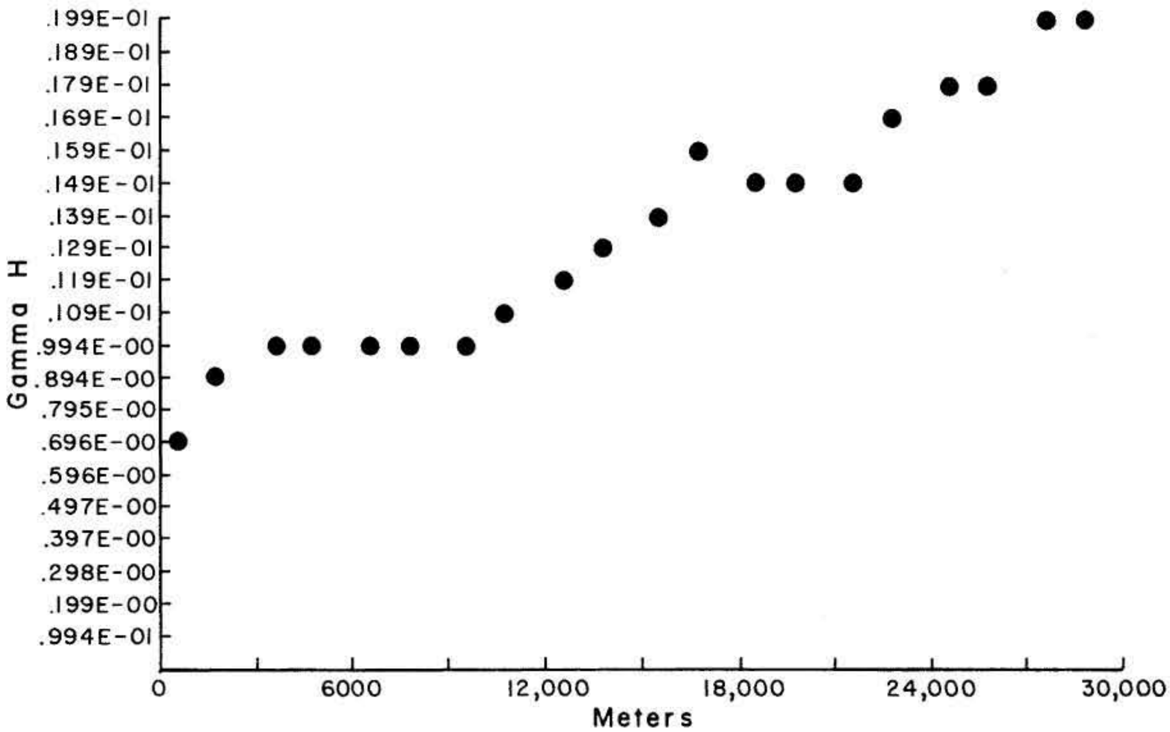


Figure 118. Experimental variogram of the Middle Kittanning seam, Allegheny Formation.

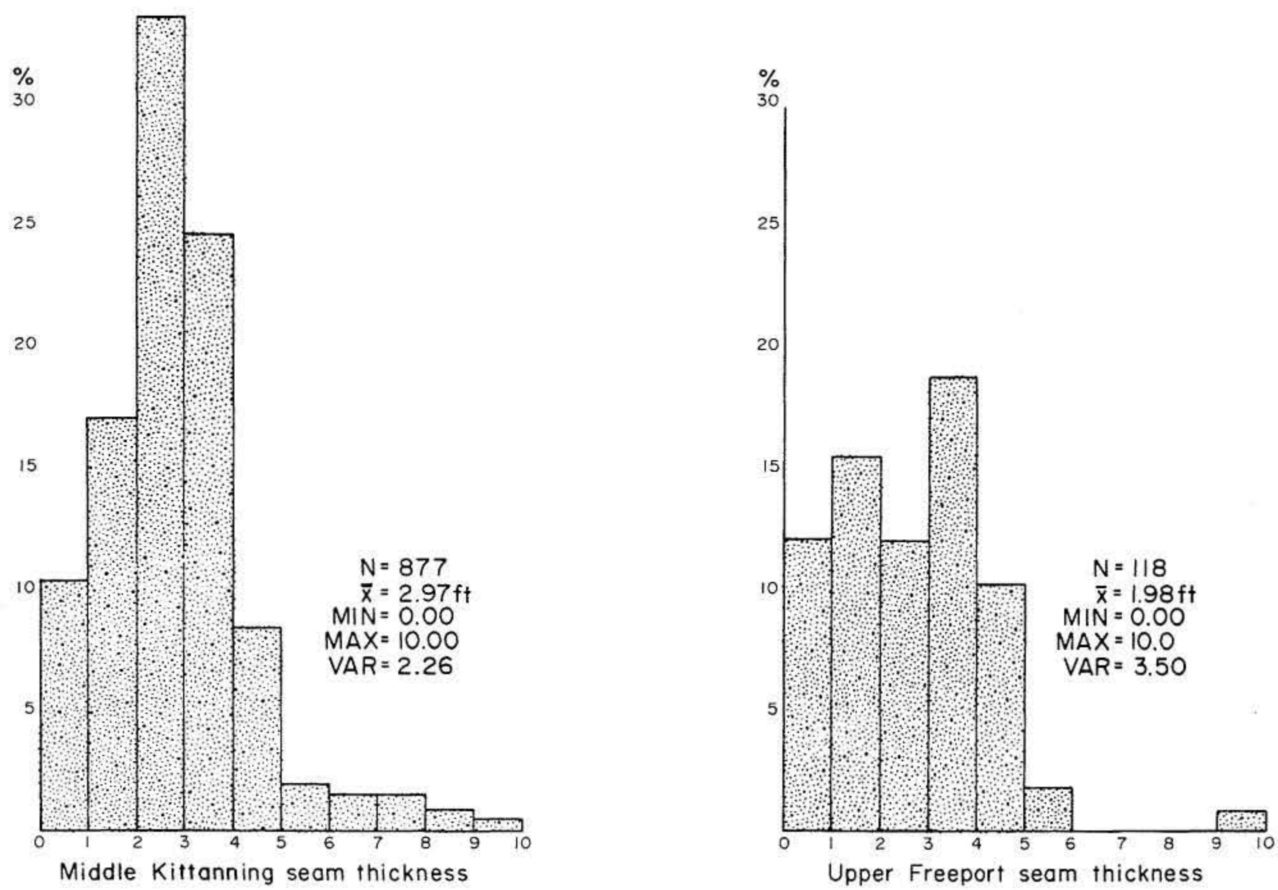


Figure 119. Frequency histograms of Middle Kittanning and Upper Freeport seam thickness, Allegheny Formation.

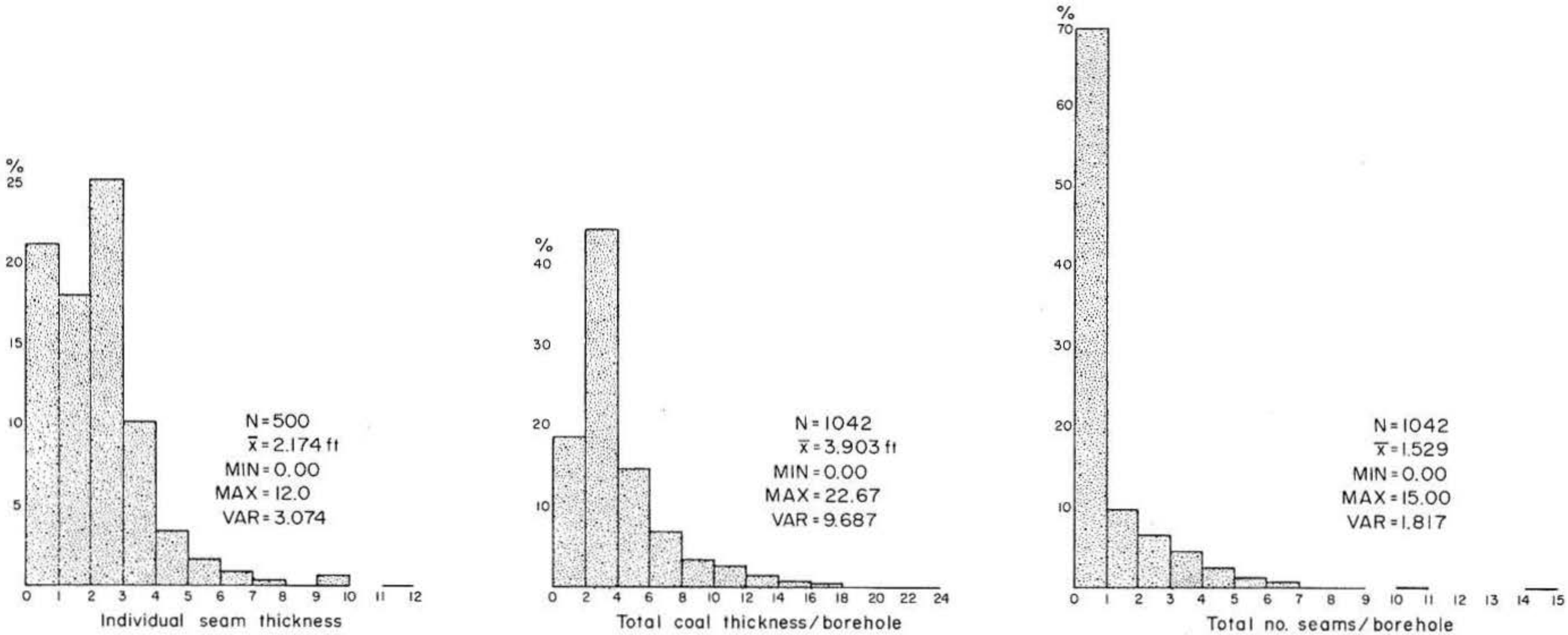


Figure 120. Frequency histograms for regional data, Allegheny Formation. Thickness in feet.

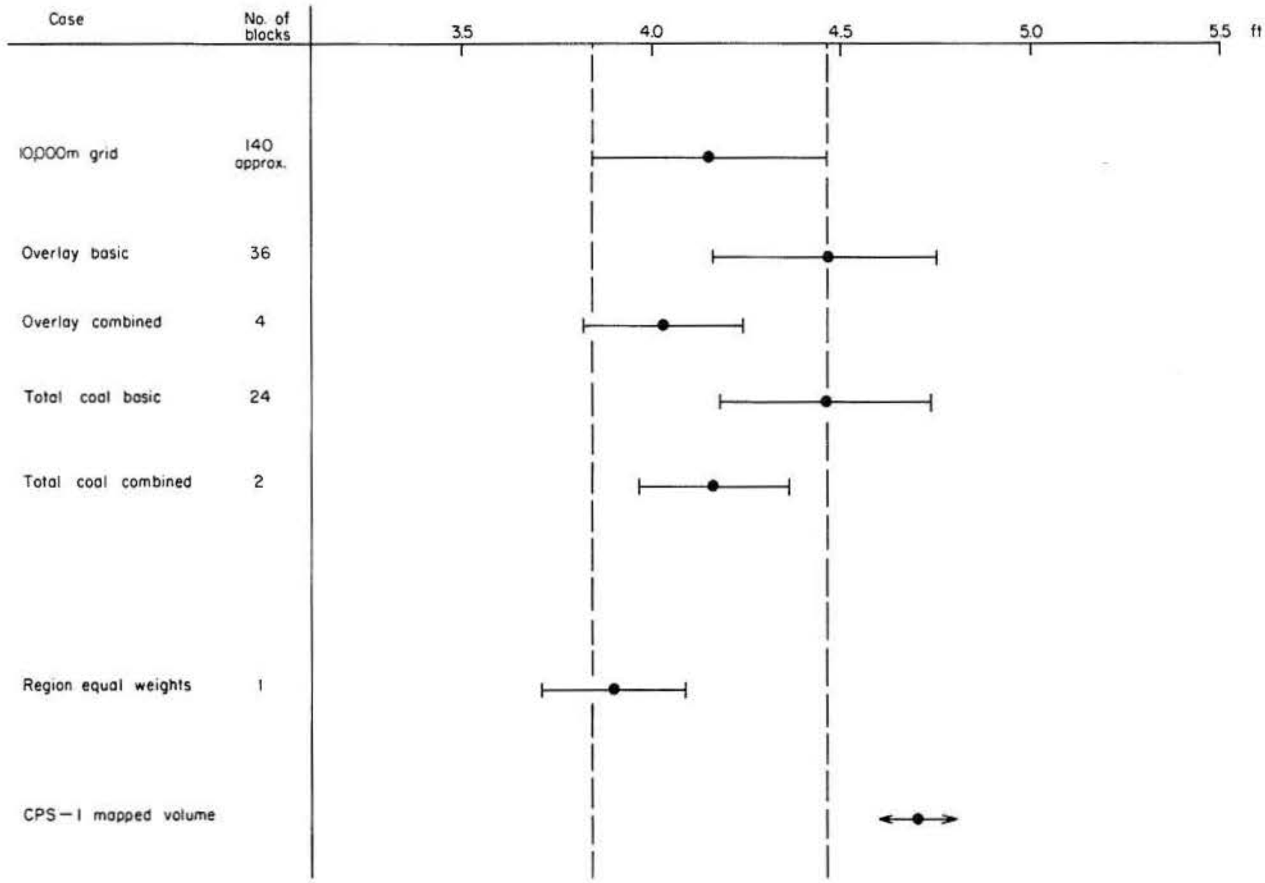


Figure 121. Estimates of total coal thickness and 95-percent confidence limits for various methods, Allegheny Formation. Solid dots represent means, bars represent confidence limits.

Table 23. Area calculations from actual and generalized outcrop boundaries in a test region.

Boundary	Area (sq. in.)	Difference in Area	Percent Difference
True outcrop	248.56	0.00	0.0
Smoothed outcrop	244.22	4.34	1.7
Straight line approximation	256.25	7.69	3.0

Ohio is much larger. The equal weighting method in Ohio gives the lowest value, whereas in Texas (fig. 81) and the Powder River Basin (fig. 108) it gave the highest. This can be explained by the concentration of data along the outcrop where fewer seams were intersected than in the basin subsurface. The CPS-1 mapping program yielded a higher estimate in Ohio as opposed to lower estimates in Texas and the Powder River Basin.

Table 24. Results of seam-level methodology (Allegheny Formation).

Seam	Middle Kittanning No. 6	Upper Freeport No. 7
Number of points	877	118
Mean thickness ft	2.97	1.98
Variance ft	1.50	1.87
$V = \sigma / \mu$	0.51	0.94
Number of holes for:		
±20% precision	26	88
±10% precision	104	353
Computer-calculated billion tons:		
100% of data	20.6	8.5
50% of data	22.9	11.4
25% of data	23.5	15.5
12.5% of data	25.8	12.1

Table 25. Means and variances of estimates from varying grids (Allegheny Formation).

Case	Grid Size	Origin	Holes	Estimated Mean (ft)	Variance of Estimate (ft^2)
1	10,000	0,0	995	4.05	.0131
2	10,000	-5,000,0	1004	4.25	.0166
3	10,000	-5,000,-5,000	1000	3.96	.0130
4	10,000	0,-5,000	1009	4.36	.0175
1 - 4	Summarized			4.15	.0151*

*The summarized variance is the mean of the four variances.

Table 26. Results of homogeneous contour methods (Allegheny Formation).

Description	Number of Blocks	Mean (ft)	Variance of Mean (ft^2)	Standard Deviation
First technique				
Overlay basic	36	4.46	.0215	0.15
Overlay combined	4	4.03	.0106	0.10
Second technique				
Total coal basic	24	4.46	.0197	0.14
Total coal combined	2	4,16	.0096	0.10

U. S. COAL RESOURCES

Introduction

Confusion surrounds the definitions of concepts such as reserves and resources. For instance, estimates made during the past decade of the amount of coal mineable in the United States have ranged from 20 to 3,200 billion short tons. The higher figure does not describe the same concept that the lower one does.

When considering regional or national estimates of coal resources in a country as vast as the United States, it is important to note that the geological work on which these estimates are based was carried out over many decades of changing geological concepts, and by numerous individual geologists with varying levels of competence and bias toward optimism or pessimism. In the United States, regional or national resource estimates are derived by summing data on many individual deposits and, therefore, reflect many different assumptions and varying degrees of accuracy. Another major difficulty in measuring coal resources is the unavailability and incompatibility of data from various sources.

USGS Resource Estimates

Estimated remaining coal resources of the United States as of January 1, 1974 (Averitt, 1974) are shown in table 27. The estimates of identified resources were obtained from summary reports on coals in the individual states. The state estimates are based primarily on mapped coal beds and on measurements of coal thickness along the coal outcrops, supplemented by information in mine workings and drill holes downdip from the outcrop. Most of this information is concentrated in the 0- to 305-m

Table 27. Estimated remaining coal resources of major coal-bearing states in the United States, January 1, 1974 (modified from Averitt, 1974).

(In millions (10^6) of short tons. Estimates include beds of bituminous coal and anthracite generally 14 in or more thick, and beds of subbituminous coal and lignite generally 2 1/2 ft or more thick, to overburden depths of 3,000 and 6,000 ft. Figures are for resources in the ground.)

Overburden 0-3,000 feet								Overburden 3,000-6,000 feet	Overburden 0-6,000 feet
	Remaining identified resources, Jan. 1, 1974								
State	Bituminous coal	Subbituminous coal	Lignite	Anthracite and semi-anthracite	Total	Estimated hypothetical resources in unmapped and unexplored areas	Estimated total identified and hypothetical resources remaining in the ground	Estimated additional hypothetical resources in deeper structural basins	Estimated total identified and hypothetical resources remaining in the ground
Alaska	19,413	110,666	[1]	[2]	130,079	130,000	260,079	5,000	265,079
Colorado	109,117	19,733	20	78	128,948	161,272	290,220	143,991	434,211
Illinois	146,001	0	0	0	146,001	100,000	246,001	0	246,001
Indiana	32,868	0	0	0	32,868	22,000	54,868	0	54,868
Kentucky:									
Eastern	28,226	0	0	0	28,226	24,000	52,226	0	52,226
Western	36,120	0	0	0	36,120	28,000	64,120	0	64,120
Missouri	31,184	0	0	0	31,184	17,489	48,673	0	48,673
Montana	2,299	176,819	112,521	0	291,639	180,000	471,639	0	471,639
New Mexico	10,748	50,639	0	4	61,391	65,556[3]	126,947	74,000	200,947
North Dakota	0	0	350,602	0	350,602	180,000	530,602	0	530,602
Ohio	41,166	0	0	0	41,166	6,152	47,318	0	47,318
Pennsylvania	63,940	0	0	18,812	82,752	4,900[4]	86,752	3,600[5]	90,352
Texas	6,048	0	10,293	0	16,341	112,100[6]	128,441	[6]	128,441
Utah	23,186[7]	173	0	0	23,359	22,000[8]	45,359	35,000	80,359
Virginia	9,216	0	0	335	9,551	5,000	14,551	100	14,651
Washington	1,867	4,180	117	5	6,169	30,000	36,169	15,000	51,169
West Virginia	100,150	0	0	0	100,150	0	100,150	0	100,150
Wyoming	12,703	123,240	[1]	0	135,943	700,000	835,943	100,000	935,943

[1]Small resources of lignite included under subbituminous coal.

[2]Small resources of anthracite in the Bering River field believed to be too badly crushed and faulted to be economically recoverable (Barnes, 1951).

[3]After Fassett and Hinds (1971), who reported 85,222 million tons "inferred by zone" to an overburden depth of 3,000 ft in the Fruitland Formation of the San Juan basin. Their figure has been reduced by 19,666 million tons as reported by Read and others (1950) for coal in all categories also to an overburden depth of 3,000 ft in the Fruitland Formation of the San Juan basin. The figure of Read and others was based on measured surface sections and is included in the identified tonnage recorded in table 2.

[4]Bituminous coal.

[5]Anthracite.

[6]Lignite, overburden 200-5,000 ft; identified and hypothetical resources undifferentiated. All beds assumed to be 2 ft thick, although many are thicker.

[7]Excludes coal in beds less than 4 ft thick.

[8]Includes coal in beds 14 in or more thick, of which 15,000 million tons is in beds 4 ft or more thick.

(0- to 1,000-ft) overburden category. Averitt (1974) estimated that, of the total identified resources, 91 percent lie within 305 m (1,000 ft) of the surface, 7.7 percent in the 305 to 610 m (1,000 to 2,000 ft) range, and 1.3 percent in the 610 to 915 m (2,000 to 3,000 ft) category. Based on available information the identified resources are minimum estimates and thus may increase in the future as mapping, prospecting, and development are continued.

Identified coal resources include the reliability categories measured, indicated, and inferred (already defined). Detailed analysis of the distribution of identified resources on a state-by-state basis provided evidence that unmapped and unexplored areas in known coal fields contain substantial additional resources, classified as hypothetical. The approximate magnitude of the additional hypothetical resources has been estimated

(Averitt, 1974) by a process of extrapolation from areas of identified resources (table 27). The estimated hypothetical resources given in table 27 are only an approximation, based primarily on extrapolation from the more reliable identified resources. Estimation of hypothetical resources constitutes an important part of the total resource that needs to be considered for future planning.

In most states containing coal, substantial areas of coal-bearing terrain were omitted because of a lack of data about occurrence and thickness (Averitt, 1974). For example, in Colorado 75 percent was omitted; in Washington, 66 percent; in Wyoming, 53.5 percent. The omissions were smaller in Montana, 9.3 percent, and in North Dakota, 1.7 percent.

Because most coal data in the United States are from areas concentrated along outcrops and in the near-surface (<305 m or <1,000 ft), the amount of detailed information on coal decreases rapidly away from these areas and in most coal basins is minimal at a distance of only a few miles from the outcrop. Only general information is available about coal in the centers of the large coal basins. In most coal basins identified resources are confined to a narrow zone a few miles wide parallel to the outcrop.

In remote or unexplored basins, mapping is of a reconnaissance nature. In such areas, points of information are widely spaced and confined to the thicker and better exposed beds. As a result, resource estimates tend to be small. Where correlations cannot be established, the estimated resources are restricted to the vicinity of known outcrops.

Experience gained from this study has shown that better use can be made of available data, especially oil and gas well data in areas of limited coal reconnaissance data. The use of this type of data could enable deep-basin coal resources (>305 m or >1,000 ft) to be identified and mapped. For example, in the Wyoming section of the Powder River Basin the official USGS identified coal resource estimate prepared by Berryhill and others in 1950 is 86.2 billion metric tons to 915-m depth (94.8 billion short tons to a depth of 3,000 ft). This figure includes all ranks of coal in both the Fort Union and Wasatch Formations. The method used by Berryhill and others (1950) included computing resources for individual coal beds. All available coal thickness data from coal outcrops, boreholes, and mines were used. The distribution of the data used by Berryhill (1950) was primarily along the outcrop belt of the Tongue River and Wasatch Formations. An area of 29,380 km^2 (11,341 mi^2) of the Powder River Basin was evaluated that was estimated to be approximately 97 percent of the coal-bearing land in the Wyoming part of the Powder River Basin (Berryhill and others, 1950).

Glass (1975, 1980) estimated 100 billion metric tons to a depth of 915 m (110.2 billion short tons of coal to a depth of 3,000 ft) for the Powder River Basin, an increase of only 15.3 percent over Berryhill's total. In our study, which was confined to the Tongue River Member, 558 billion metric tons (614 billion short tons) of coal resources down to a depth of 915 m (3,000 ft) were identified in a 9,075 m^2 (3,503 mi^2) section of Wyoming. Due to a lack of data, much of the shallow subsurface along the eastern part of the basin and part of the northern and southern sections (of the basin) were omitted from this study's estimate. Projecting from the areas of dense data into these three regions with knowledge of the depositional setting, a total of 909 billion metric tons (1 trillion short tons) of coal was estimated for the Tongue River Member in the Wyoming part of the Powder River Basin. This increase in tonnage resulted from thick relatively continuous coals occurring in the deeper part of the basin. The use of oil and gas data enabled accurate delineation of these seams beyond the depths of conventional coal exploration drilling.

Basin Resource Estimation

This study has also shown that better use can be made of depositional models to estimate coal resources, especially in areas of limited data. Petroleum explorationists have traditionally used depositional models to map non-tabular sedimentary reservoirs whose shape and internal properties are determined by sediment accumulation patterns. To develop a depositional model for a group of sedimentary rocks, one should determine, within the limits of the data, what the properties of these rocks are and then create the models using the available data. The depositional model approach for delineating coal-bearing terrain in the Gulf Coast Tertiary Basin will be presented here as an example.

In the Gulf Coast, lignite-bearing Tertiary sediments extend from Texas through Louisiana, Arkansas, Mississippi, Alabama, Tennessee, and Kentucky and eastward through Georgia and South Carolina. A total of 11.5 billion metric tons (12.6 billion short tons) of remaining identified resources of lignite to a depth of 1,000 m (3,000 ft) is the official USGS figure (Averitt, 1974).

Lignite occurs in three stratigraphic formations in the Gulf Coast, the Wilcox, Claiborne, and Jackson Groups and as components of fluvial, delta, and strandplain/lagoonal environments. The Gulf Coast is a mature oil and gas province, and depositional models have been developed from thousands of available electric logs. This information was used to construct maps showing the depositional environments for these three lignite-bearing formations (figs. 122, 123, and 124). The Texas studies enabled the formulation of average total

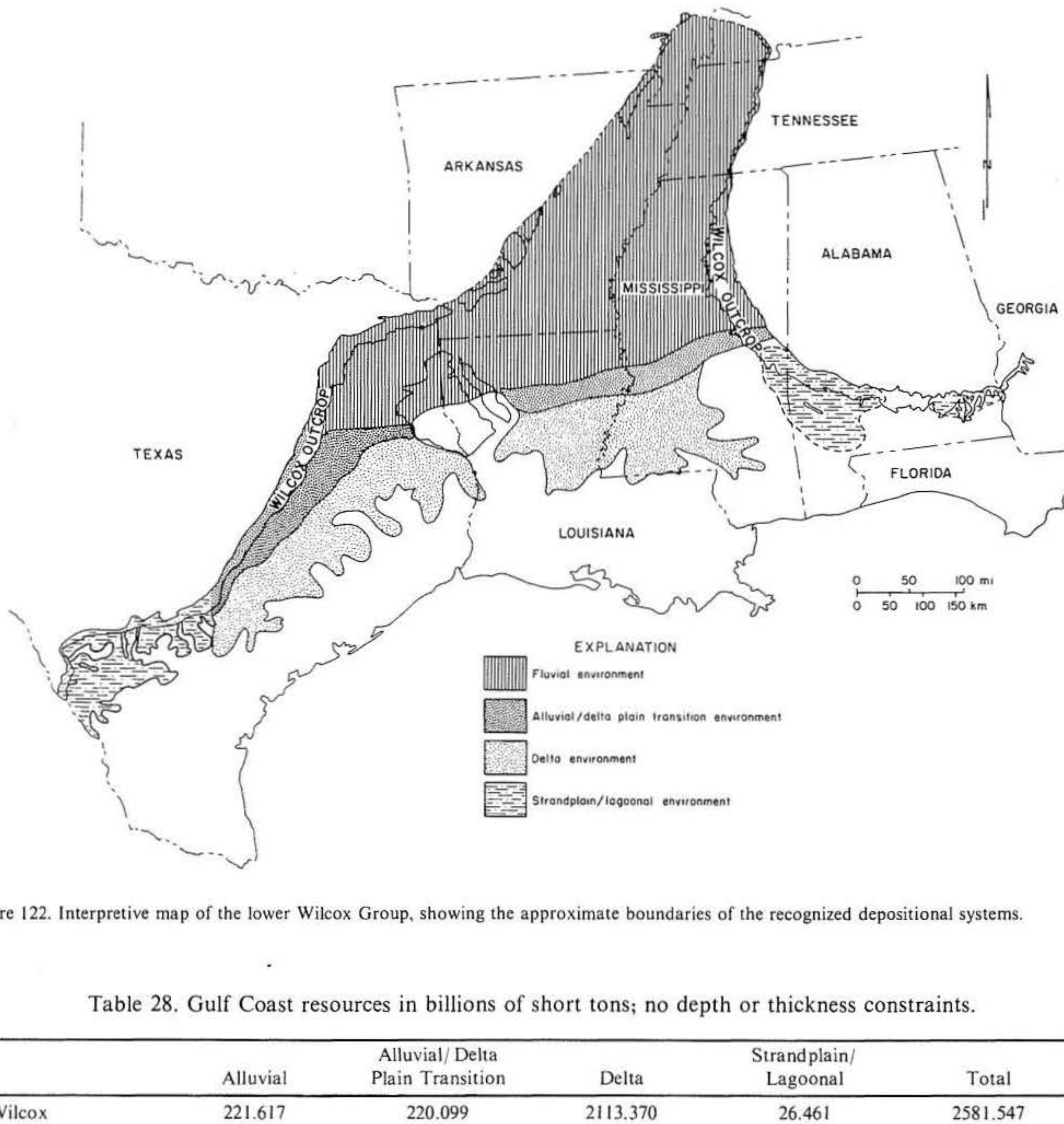


Figure 122. Interpretive map of the lower Wilcox Group, showing the approximate boundaries of the recognized depositional systems.

Table 28. Gulf Coast resources in billions of short tons; no depth or thickness constraints.

	Alluvial	Alluvial/ Delta Plain Transition	Delta	Strandplain/ Lagoonal	Total
Wilcox	221.617	220.099	2113.370	26.461	2581.547
Jackson	-----	-----	22.425	12.048	34.473
Yegua	15.394	16.425	18.589	-----	50.408
Total	237.011	236.524	2154.384	38.509	2666.428

lignite thicknesses for the different depositional environments, assuming that the deposits studied are truly representative of their environment. For example, in east-central Texas an average of 2.8 lignites per borehole gave an average total lignite thickness of 2.4 m (7.9 ft) for the near-surface Wilcox alluvial/delta plain transitional environment. Averages developed for the Texas Wilcox Group fluvial environment are 2.4 lignites and 1.3-m (4.2-ft) total thickness. The deltaic environment averages are 29.2 lignites and 25.1-m (82.4-ft) total thickness. The Jackson Group in South Texas averaged 1 lignite and 1.1-m (3.5-ft) total thickness, for the strandplain/lagoonal environment. Public data on lignite occurrence in the neighboring Gulf Coast states were used with the appropriate average total lignite thickness and area from the map to estimate resources (table 28).

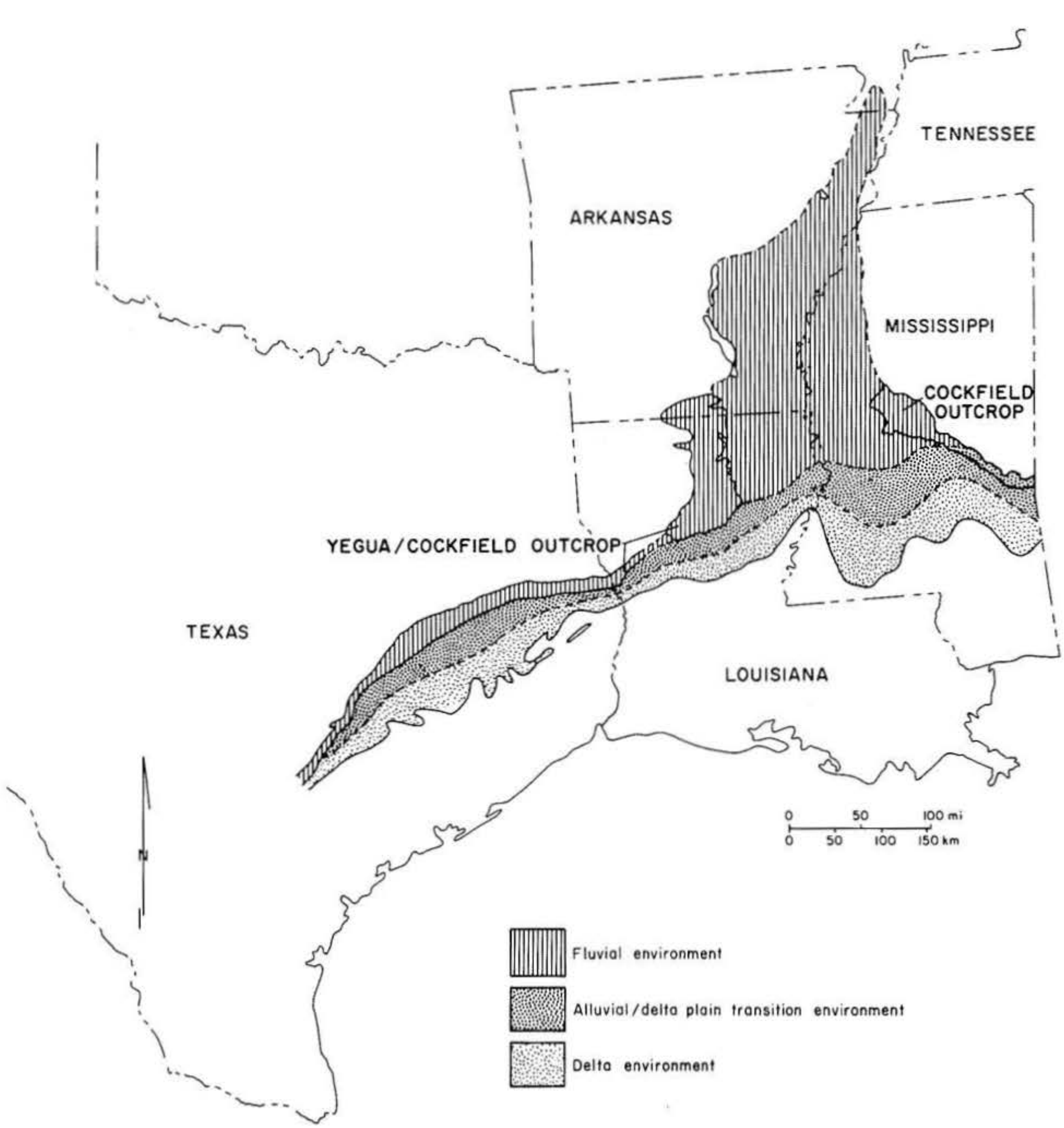


Figure 123. Interpretive map of the Yegua/Cockfield Formation, Claiborne Group, showing the approximate boundaries of the recognized depositional systems.

It should be pointed out that this figure of 2.7 trillion tons (table 28) is a first-step approximation with no depth or thickness constraints and it should not be expected to compare with measured resources calculated using large amounts of data. It is difficult to judge the accuracy of the depositional model approach. However, a comparison was made with the official resource figure for Texas (Kaiser and others, 1980) calculated using a 610 m (2,000 ft) depth limit (table 29). Most of the estimates for the Wilcox Group agree closely with these official estimates, except in east-central Texas, which can be partly attributed to differences in the acreage considered. Total estimates for the Jackson Group and Yegua Formation from this method were higher than official estimates, but are not considered overstated. The total resources to 610 m (2,000 ft) for Texas using this method are 83.7 billion metric tons (92.1 billion short tons).

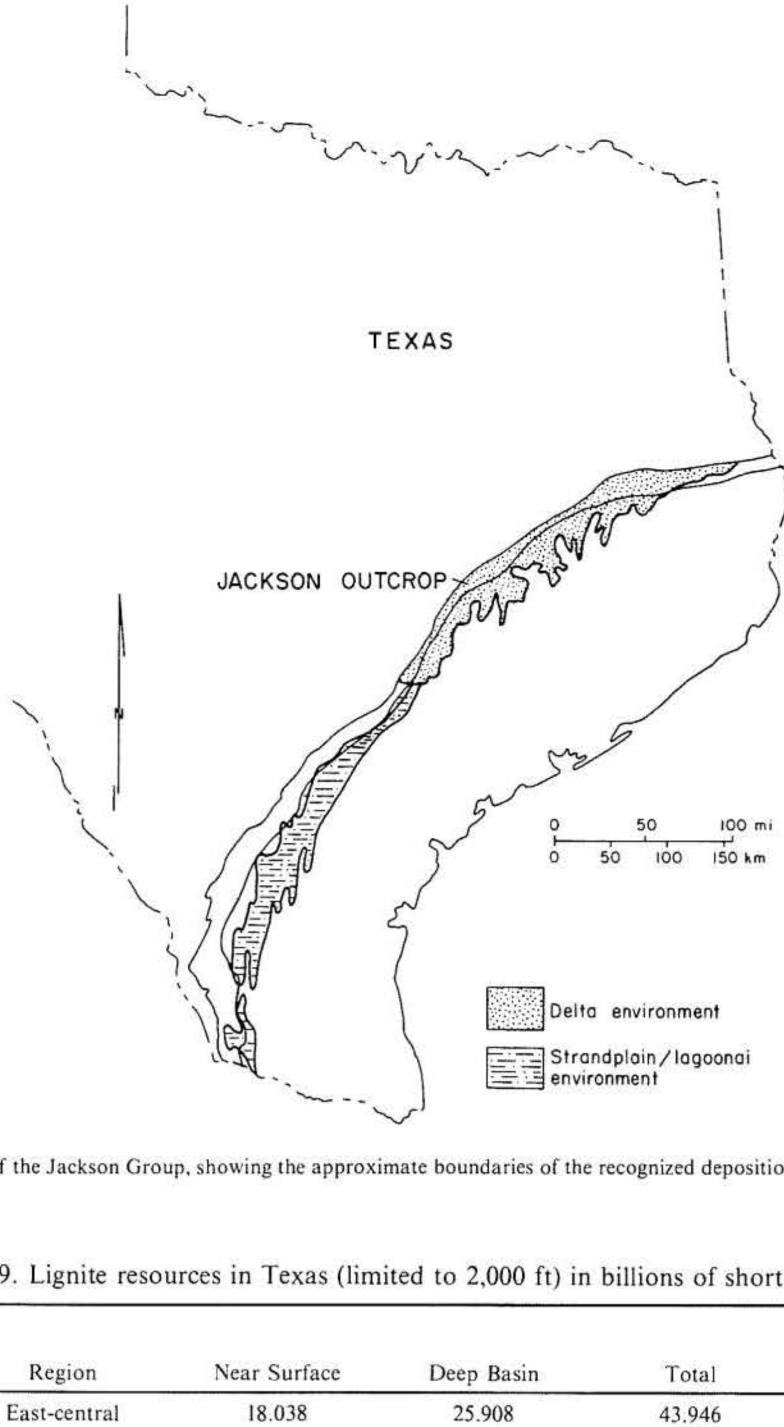


Figure 124. Interpretive map of the Jackson Group, showing the approximate boundaries of the recognized depositional systems. After Kaiser and others (1980).

Table 29. Lignite resources in Texas (limited to 2,000 ft) in billions of short tons.

	Region	Near Surface	Deep Basin	Total	Official Total Source: Kaiser and others, 1980
Wilcox	East-central	18.038	25.908	43.946	16.980
Wilcox	N.E. & Sabine Uplift	*	*	17.142	17.825
Wilcox	South	*	*	6.481	5.709
Wilcox	Subtotal			67.569	40.514
Jackson	East	*	*	19.376	10.099
Jackson	South	*	*	2.711	6.032
Jackson	Subtotal			22.087	16.131
Yegua	East	2.478	0	2.478	1.551
Total				92.134	58.196

*Not estimated separately.

CONCLUSIONS

An estimate of the uncertainty associated with a published resource figure is generally not given. Methods of resource estimation developed in this study were used to quantify this degree of uncertainty. Studies of lignite deposits in Texas demonstrate that the amount of uncertainty contributed to coal resource estimates by geologic features, such as seam thickness and continuity, varies with the depositional setting. Geologic features in an alluvial plain environment create the most uncertainty.

The variability of average seam thickness, which is a factor in resource estimation, was studied through geostatistics and other statistical methods. The minimum number of evenly spaced boreholes required to characterize the average seam thickness within ± 20 percent depends on the coefficient of variation of the seam. Depositional settings in which seams have a high coefficient of variation necessitate a larger minimum number of boreholes. Fewer boreholes are needed when a spatial dependency structure is established using a variogram. The variogram denotes the internal variability of seam thickness, but apparently does not describe the position or nature of seam boundaries. To apply geostatistics successfully, it is necessary to correlate seams and to fit a variogram, both of which require much data. Geostatistical estimation is more valuable to reserve, and not resource, evaluations. Nevertheless, geostatistics was useful to us in defining statistical sample populations that are likely to be independent.

At a regional scale, data availability and distribution often preclude accurate correlation of seams; therefore resources must be calculated for a summation of seams (total coal). Given this data, we were unable to use geostatistics to delineate dependency structures for total coal. Therefore, alternate statistical methods were devised that yielded resource figures and an estimate of their precision. These methods, which included equal weighting methods, grid methods, and homogeneous block methods, were used to calculate resources for a region, the Wilcox Group outcrop in east-central Texas. Using the grid method as a standard, we found that one of the factors which most affected the differences between the results of the various methods was the spatial distribution of the data. The more uneven the data distribution, the more the results of different methods varied from each other. Additional resource methodologies, the depositional-model method and the USGS method, were also used to calculate resources for the Wilcox Group. Results obtained by these methods indicate the wide variation in estimates obtained from different methods and different data constraints.

The regional methodology was successfully transferred to two other areas, the Tongue River Member of the Fort Union Formation in Wyoming, and the Allegheny Formation in eastern Ohio. Our resource estimations are larger than published official estimates, mainly because of the delineation of seams in the deeper parts of the basins using non-traditional data (oil and gas well logs). These deep-basin seams were not included in previous estimates.

Depositional models can be used alone to estimate resources for entire basins and were used to calculate resources for the Gulf Coast Basin. This method, however, does not provide a measure of the uncertainty associated with the estimate.

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