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Geology of the Mary Lee Group of Coalbeds, Black Warrior Coal Basin, Alabama

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 8189

Geology of the Mary Lee Group of Coalbeds, Black Warrior Coal Basin, Alabama

By G. W. Murrie, W. P. Diamond, and S. W. Lambert
Pittsburgh Mining and Safety Research Center, Pittsburgh, Pa.

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GEOLOGY OF THE MARY LEE GROUP OF COALBEDS, BLACK WARRIOR COAL BASIN, ALABAMA

by

G. W. Murrie,[1] W. P. Diamond,[1] and S. W. Lambert[1]

ABSTRACT

A geologic study of the Mary Lee Group of coalbeds in the Black Warrior coal basin was undertaken to examine coal stratigraphy and determine regional trends and extent of the coalbeds. The area investigated encompasses 835 square miles in Jefferson, Walker, and Tuscaloosa Counties, Ala. More than 700 core logs were used to construct a structure map, coal, interval, and overburden isopachs, and cross sections.

There is evidence that structure affected sedimentation. Coalbed isopachs indicate the Mary Lee Group was deposited in fluvial-deltaic and low-lying coastal plain environments. The Mary Lee coalbed is the only coalbed which is continuous throughout the area, commonly with two benches which have a combined thickness of 2 to 12 feet. The Mary Lee coalbed changes rank in the basin from high- through medium- to low-volatile coal. The methane gas potential of the Mary Lee Group coals is estimated to be greater than 1 trillion cubic feet.

There is an excellent correlation between the orientation of surface cleats with those measured underground in the Mary Lee coalbed. The face cleats roughly parallel the axes of the area's folds and trend northeast-southwest.

INTRODUCTION

The investigation of the geology of the Mary Lee Group, Upper Pottsville age, was initiated with an evaluation of the methane content of the coalbeds of this group (6).[2] Over 700 core logs were used in the methane study and the maps, cross sections, and stratigraphic data provide a valuable geological framework heretofore unavailable for this part of the Warrior basin. All these data provide information with practical application for the coal mining industry as well as providing a basis for further geological investigations.

This report is part of a continuing effort of the Bureau of Mines to determine the factors that affect the safety of mining coal in U.S. coalbeds. In the course of these investigations it has been established that significant quantities of methane may be recovered from coalbeds before and during mining.

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[1] Geologist.

[2] Underlined numbers in parentheses refer to the list of references preceding the appendixes.

The study area (figs. 1 and 2) encompasses 835 square miles of the Warrior basin in Jefferson, eastern Tuscaloosa, and southern Walker Counties, Ala. Eighty-seven pct of the remaining coal reserves of Alabama are estimated

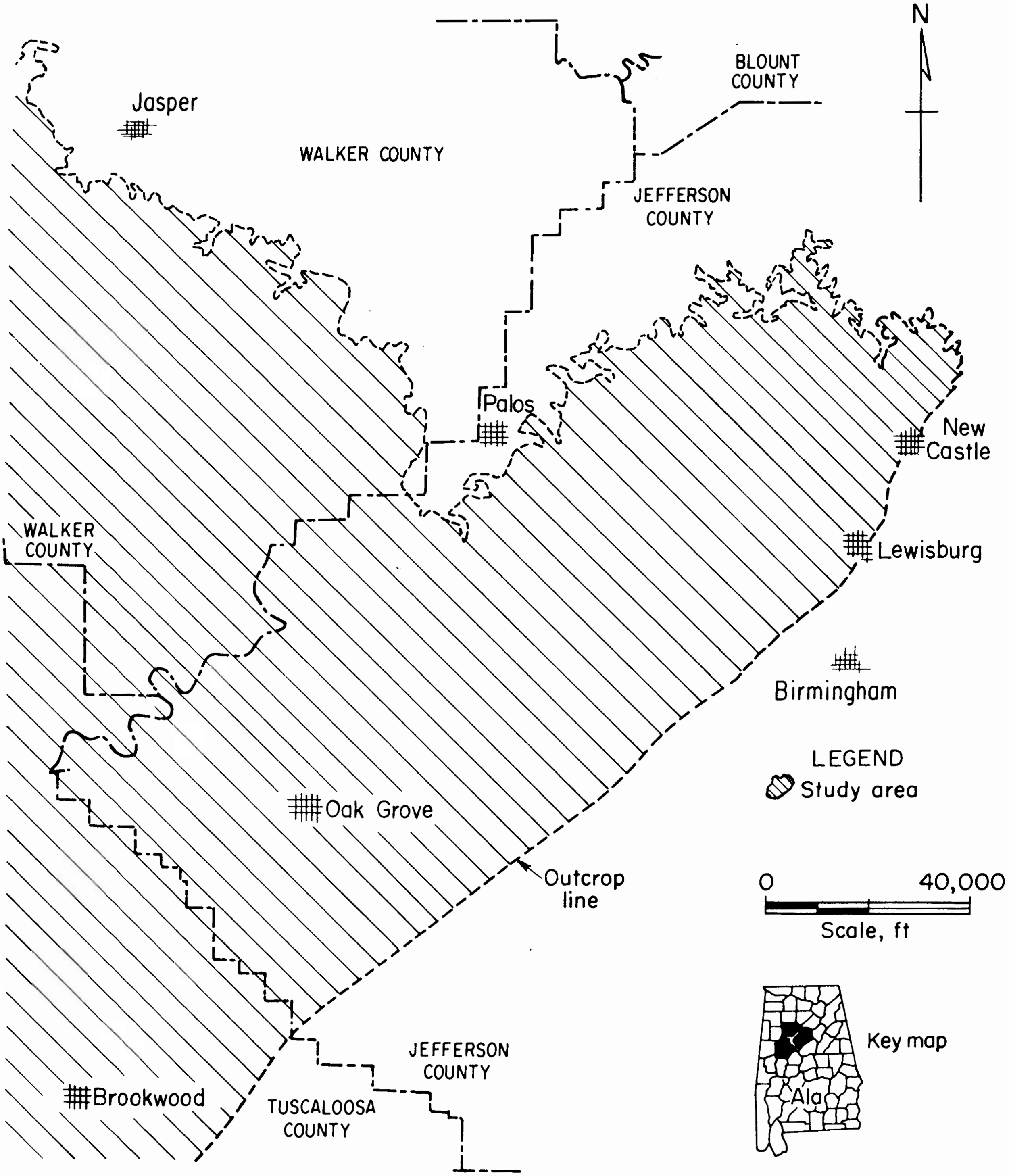


FIGURE 1. - Map of study area.

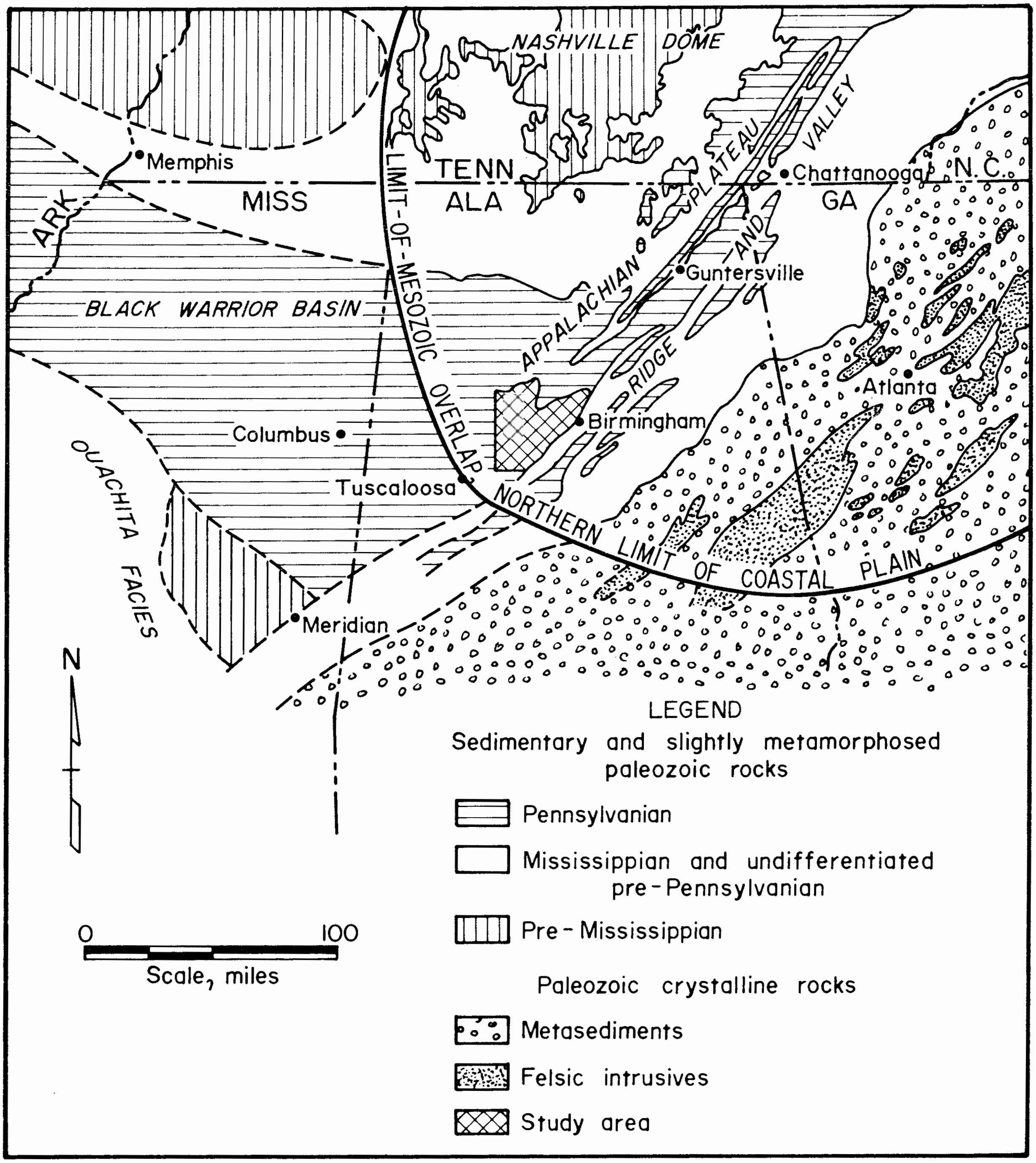


FIGURE 2. - Location of study area within the Black Warrior basin (10).

to be within the Warrior field (2). The Warrior coalfield now accounts for approximately 93 pct of Alabama's coal production. The Mary Lee Group is the most economically important of all the coal groups, containing three times more coal reserves than the combined estimate for the other three Alabama coalfields.

ACKNOWLEDGMENTS

The authors acknowledge the cooperation and assistance of several coal companies and their personnel without whose support this investigation could not have been completed. Core data and permission for mine surveys were supplied by the following: Charles Hager, vice president of mining; Jack Morris, chief geologist; Gary Myers and Norman Bowne, geologists, Jim Walter Resources; Douglas Cook, vice president of engineering-mines, Alabama By-Products Corp.; E. J. Files, general superintendent, and Henry Kerley, chief mining engineer, U.S. Steel Corp.'s Southern District; and W. H. Haynes, manager of fuels, and Harry Raykes, mining engineer, Southern Services Corp. Credit is also due to T. W. Daniel, J. A. Drahovzal, F. E. Evans, Jr., and W. E. Ward II, geologists, Geological Survey of Alabama, for joint surveys and general geological data collected under a grant from the Bureau of Mines.

PREVIOUS WORK

The first investigations of the Alabama coalfields were initiated in 1886 by McCalley (14) of the Geological Survey of Alabama. His report included an outcrop map of the coals in the Warrior basin and a general stratigraphic column. Culbertson (2), in 1964, described the geology of the coalbeds and estimated remaining reserves for all three major Alabama coalfields. More recent studies deal with petrology, stratigraphy, and paleogeography of the Black Warrior basin (3, 8-10, 21) and the methane gas content of Alabama coalbeds (6).

REGIONAL STRUCTURE

The Black Warrior coal basin lies within the Cumberland Plateau section of the Appalachian Highlands in north-central Alabama. The Mary Lee Group outcrops along the northern and eastern edge of the basin. The eastern margin of the study area is bounded by the Opossum Valley thrust fault (19) along most of its length. The coalbeds plunge into the basin dipping as much as 9° (fig. 3). The basin has a regional southwestern dip of 1° to 2° and is covered by the Cretaceous onlap to the west and south.

Black Warrior Coal Basin Structure

The major structural feature within the Black Warrior coal basin is the Sequatchie anticline trending northeast to southwest through the center of the study area. The Warrior syncline lies to the west of the Sequatchie anticline and the Coalburg syncline lies to the east. Faulting is widespread in the Warrior basin with high-angle faults predominating and fault grabens common.

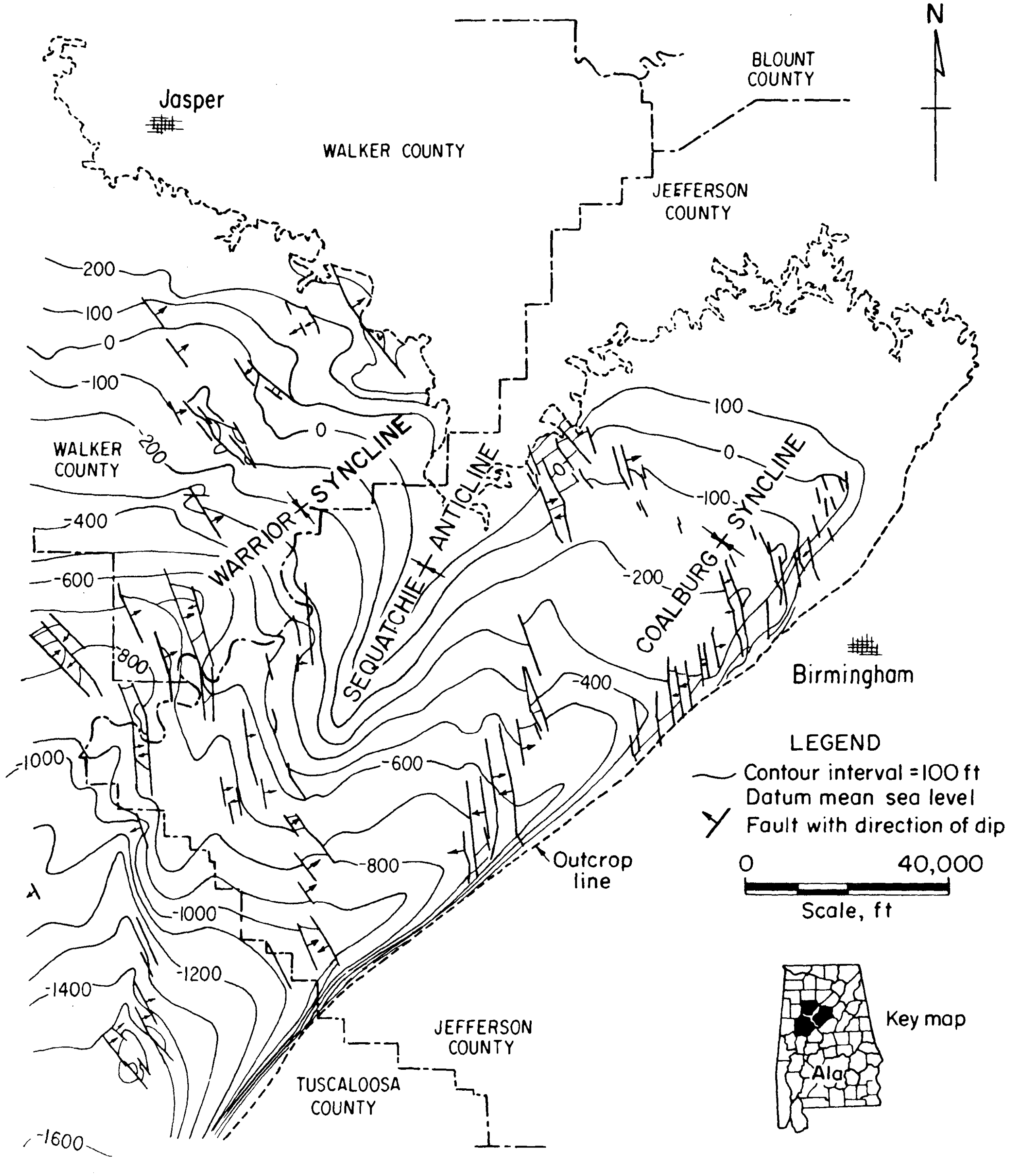


FIGURE 3. - Structure map drawn on the base of the Mary Lee coalbed.

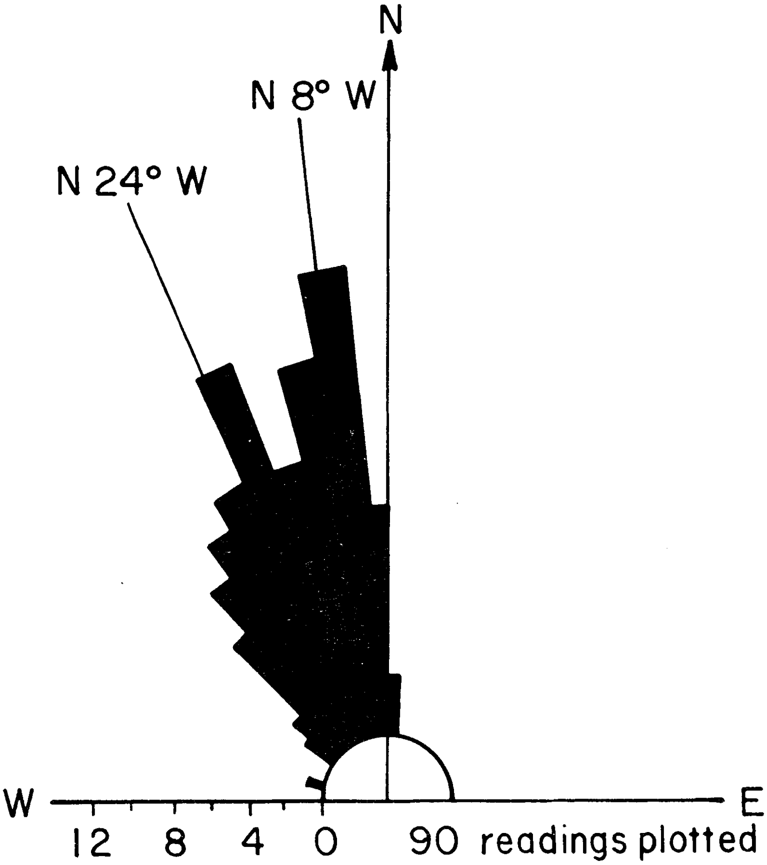


FIGURE 4. - Strike of normal faults in the Black Warrior coal basin.

The strike of the known normal faults and fault segments have been plotted on a rose diagram (fig. 4). The faults strike generally to the north-northwest, with two peaks on the rose diagram, N 08° W and N 24° W, indicating the dominant average strikes. Several lineaments detected with the use of remote sensing (LANDSAT-1) seem to coincide with certain known high-angle faults (7). The presence and length of these fault-paralleling lineaments indicate the existence of previously unrecorded faults and longer known faults than those previously mapped.

The faults tend to cluster in the two synclines, especially in the Coalburg syncline, with essentially no faults cutting the Sequatchie anticline. Semmes (19) attributes the faulting in the Coalburg syncline to a combination of lateral pressures from the Sequatchie folding, on the west, and the Opossum Valley thrust, on the east.

The presence of faults can severely affect underground coal mining operations as well as surface mining. The faults in the Warrior basin range up to 6 miles in length. The maximum vertical displacement reported by Semmes (19) is about 200 feet; however, displacement of more than 100 feet is rare. A first alternative is to encounter these faults underground which necessitates mining along the fault until the vertical displacement is so small as to permit conventional mining machinery to continue into coal on the other side of the fault. A second alternative is to tunnel through the faults and resume normal mining operations when the coalbed is located on the other side. Either alternative results in a loss in production and can cause disruptive changes in basic mine development projections. Geologic studies of proposed mining sites utilizing standard surface mapping and well-planned exploratory core hole drilling to provide structural, as well as coal thickness and coal quality data, can help locate faults and delineate their direction of strike, dip, and vertical displacement. More efficient mine development plans can be devised to deal with the faulting when these basic geological data are used before selecting shaft sites and beginning full-scale mine development.

Cleat and Inclined Fractures in the Mary Lee Coalbed

Cleat surveys were made in seven underground mines operating in the Mary Lee coalbed. Approximately 250 strike measurements were taken on cleats (vertical fractures) and a similar number of additional readings were taken where inclined fractures (fractures inclined at about 45° to bedding) were also present.

The five mines surveyed in the shallow, northern part of the study area have relatively well-defined, singular face cleat orientations (fig. 5), with few inclined fractures. Measurements taken in the Bessie mine indicate a bimodal face cleat. The face cleat orientations range from N 53° E to N 68° E in the north and are generally parallel to the axes of the folds. The butt cleat in the Mary Lee No. 1 mine is bimodal with the two peaks separated by 10°. The Segco No. 1 mine, in the same vicinity, has a wide, weakly trimodal butt cleat. The Chetopa and Bessie mines in the northeastern corner of the study area have well-defined, singular butt cleats. Butt cleat measurements in the Flat Top mine are quite variable, probably the result of difficulties in accurately measuring cleats where rib spalling has occurred. The butt cleats in the north of the study area varied in orientation from N 20° W to N 37° W, roughly parallel to the strike of the normal faults nearby, which have average strikes of N 08° W and N 24° W (fig. 5).

Fracturing is quite varied in the two mines located in the deeper, southern part of the basin and also nearer to the structural front than any of the other mines (figs. 6 and 7). Both cleat and inclined fractures are present. In the Oak Grove and Blue Creek mines, the inclined fractures, which dip at approximately 45° to the coalbed, are much more predominant than the vertical cleat systems. The Oak Grove mine has a well-defined face cleat peak at N 64° E which is within the range found in the northern part of the area (fig. 6A). Several peaks are present in the butt cleat direction with two (N 18° W and N 41° W) being the most dominant.

The cleat directions measured in the Blue Creek mine are complex (fig. 6B) with significant differences from the adjacent Oak Grove mine and the mines further to the north. Most cleats in the Blue Creek mine have strikes to the northwest, whereas in the other mines, the strikes are toward the northeast. Three peaks of similar dominance (N 48° W, N 13° W, and N 02° W) are present in the northwestern quadrant.

The rose diagram (fig. 6C) of the strike of inclined fractures in the Oak Grove mine has several well-defined peaks. The most dominant peak is N 26° W. No preferred orientation is present for the dip of these fractures, with approximately half dipping east to northeast and half dipping west to southwest.

Strikes of inclined fractures in the Blue Creek mine (fig. 6D) are more varied than those of the Oak Grove mine. The most dominant peak is N 07° W as compared with Oak Grove's N 26° W most dominant peak.

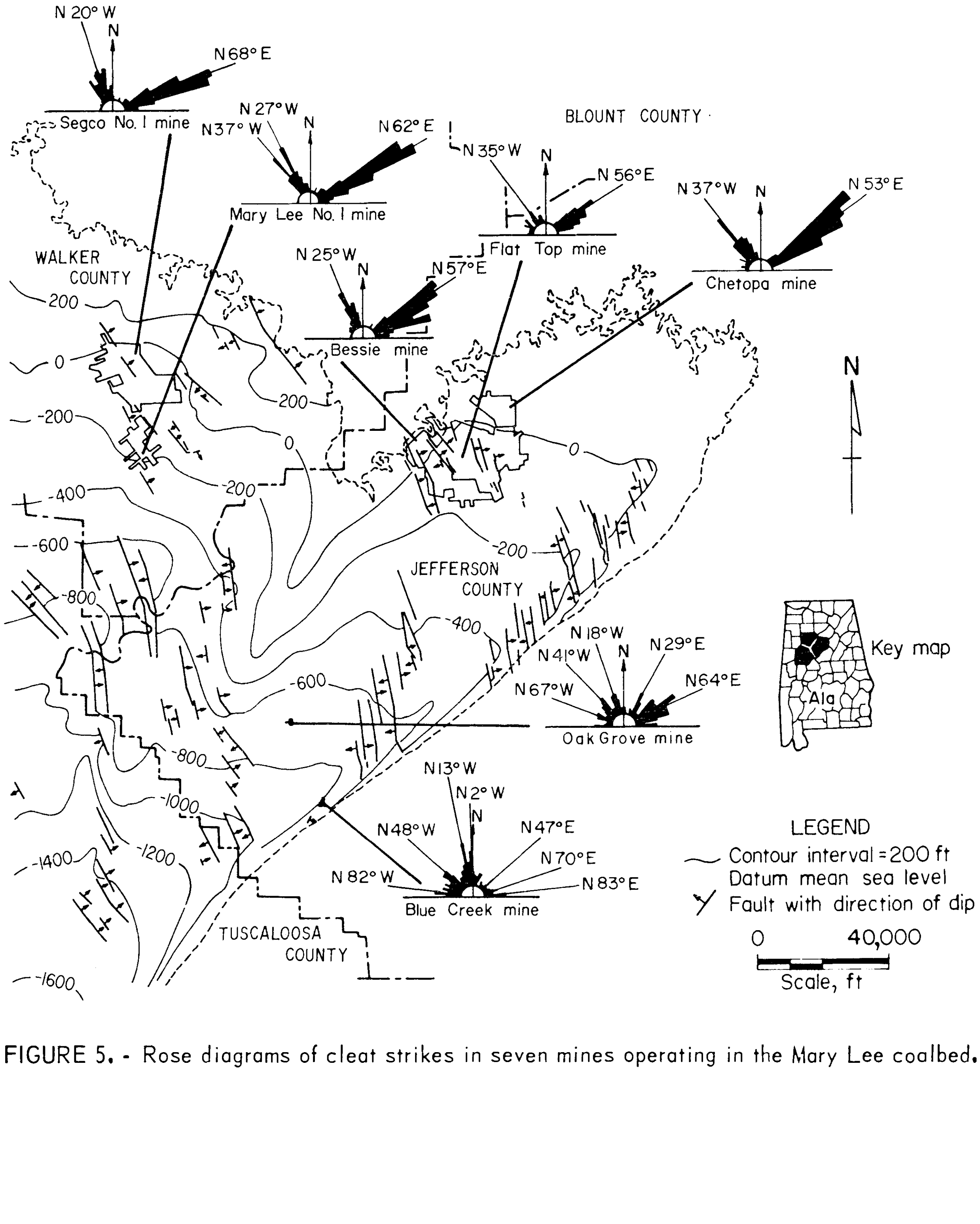


FIGURE 5. - Rose diagrams of cleat strikes in seven mines operating in the Mary Lee coalbed.

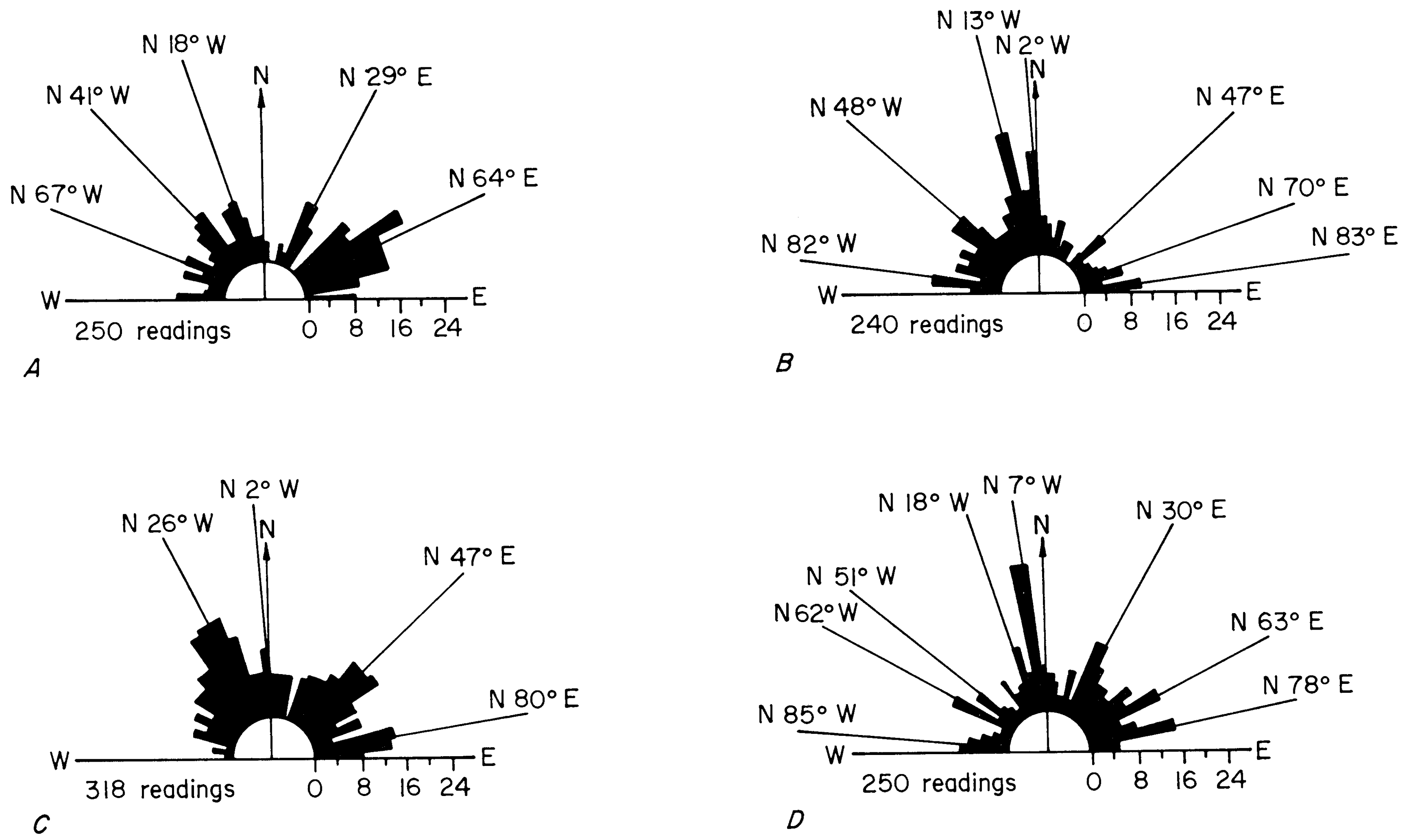
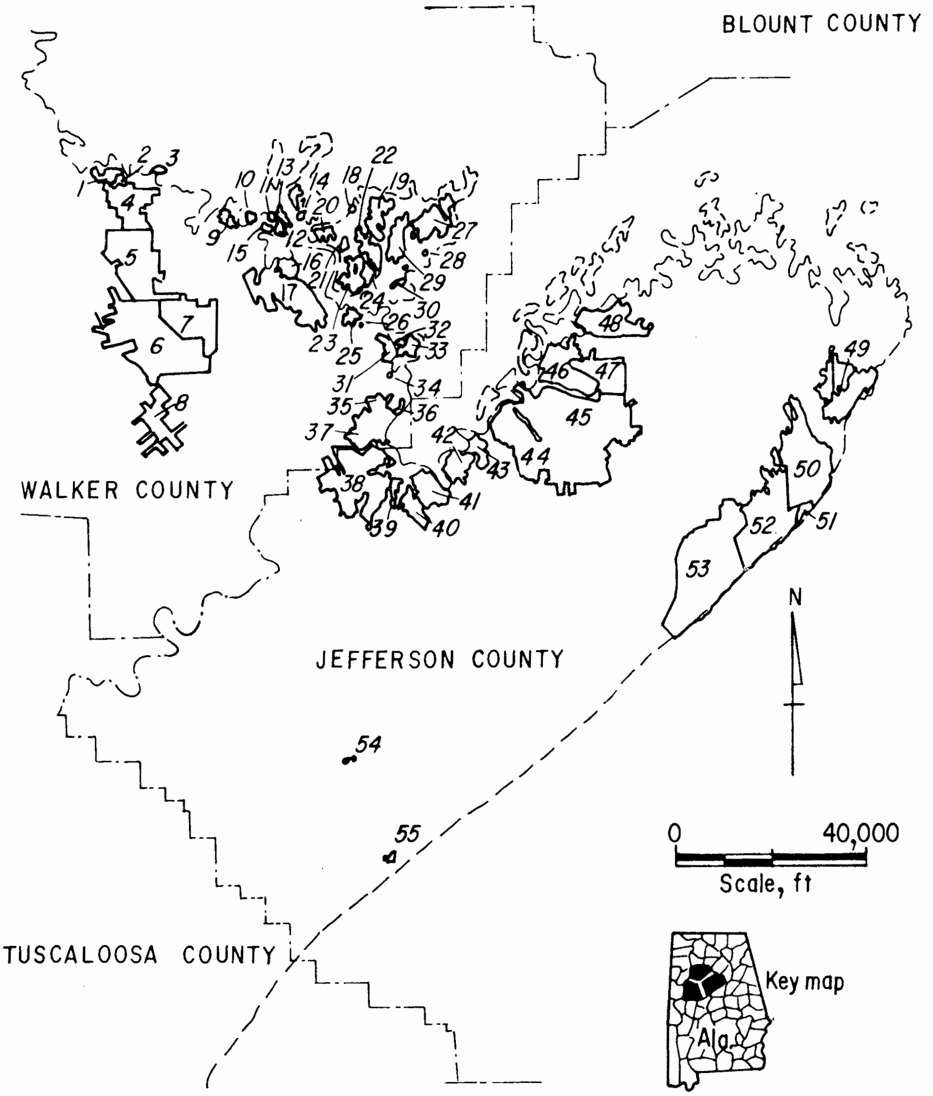


FIGURE 6. - Rose diagrams of strikes of cleat and inclined fractures in the Oak Grove and Blue Creek mines.



LEGEND

1 Calumet
2 Calumet
3 Howell
4 Bankhead
5 Railway Fuel
6 Segco No. 1
7 Stith
8 Mary Lee No. 1
9 NATCO
10 Acrowe Russell
11 Indian Head
12 Indian Head
13 Indian Head
14 Excelsior
15 Sulfur Springs
16 Ruby
17 Barney
18 Riverside
19 Pratt Fuel
20 Somerset
21 Benoit
22 No. 10
23 No. 11
24 No. 8
25 Red Star
26 T. N. Davis
27 Hall
28 Adair
29 Price
30 Piedmont
31 Burnwell
32 Burnwell
33 Yerkwood
34 Kershaw
35 Gamma
36 Colta
37 Wegra
38 Praco
39 Powahatan No. 2
40 Powahatan
41 Labuco
42 Porter
43 Palos
44 Bessie
45 Flat Top
46 Banner
47 Chelope
48 Sayre
49 New Castle Nos. 2, 5, 6
50 Mary Lee No. 1
51 Graves
52 Sayreton
53 Hamilton
54 Oak Grove
55 Blue Creek

FIGURE 7. - Mines in the Mary Lee coalbed.

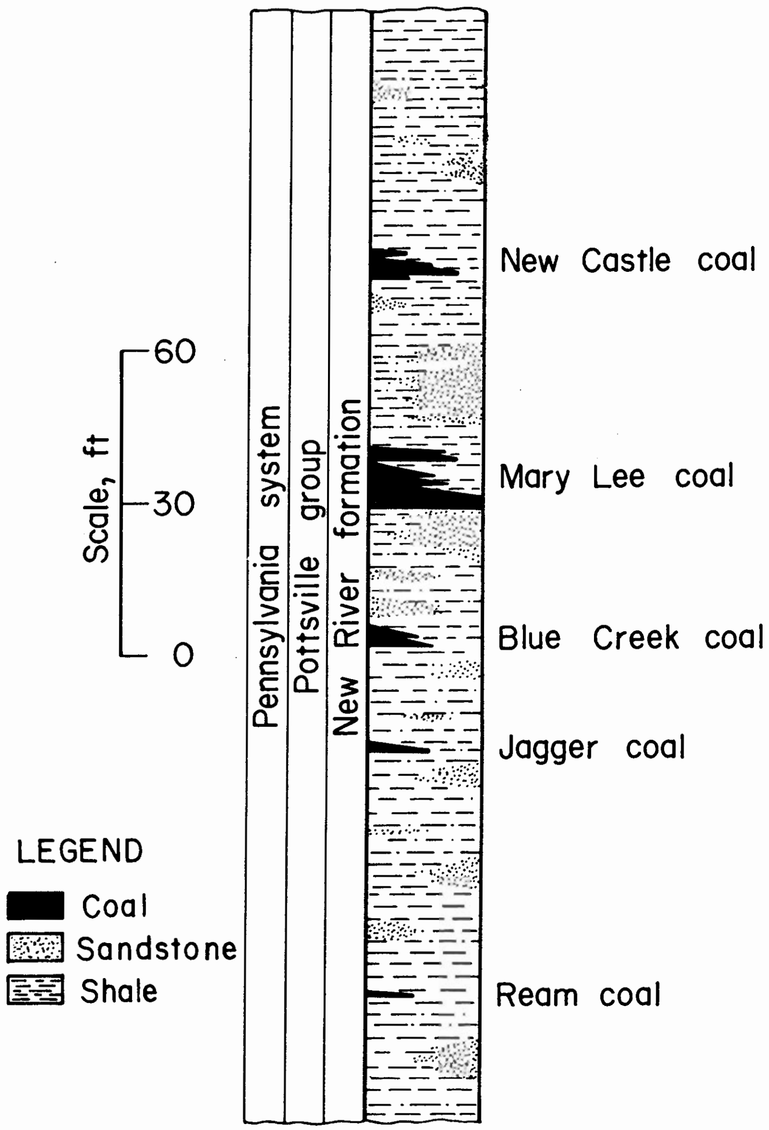


FIGURE 8. - Generalized stratigraphic column showing the Mary Lee Group coalbeds and adjacent strata.

The presence of both cleat, inclined fractures, and multiple strike directions in the southern part of the area is probably the result of the close proximity to the structural front of the eastern margin of the Warrior basin which is characterized by steep dips and thrust faults trending northeast-southwest and thrust to the northwest. The Blue Creek mine is closest to the structural front and has the most complex fracture patterns in the coal. Multiple periods of orogenic activity, whether from the Ouachitas to the south-southwest, or the Appalachian belt to the east, may have added to the complexity of the fracturing in the coalbed.

MARY LEE GROUP COAL STRATIGRAPHY

The Pottsville Formation is divided into two units based on the presence of productive coalbeds. The Upper Pottsville contains all of the thick, economically important coalbeds. These coalbeds have been divided into six groups which, in descending order, are the Brookwood, Gwin, Cobb, Pratt, Mary Lee, and Black Creek Groups (14). The Lower Pottsville contains no known thick, productive coalbeds and is predominantly a barren interval which begins at the base of the Black Creek Group.

The Mary Lee Group is comprised of five coalbeds which, in descending order, are the New Castle, Mary Lee, Blue Creek, Jagger, and Ream (fig. 8). The intervening strata are shales and sandstones with thin fireclays underlying the coalbeds in many areas. The stratigraphic section tends to thicken to the south and southwest.

New Castle Coal

The New Castle is a discontinuous coalbed that ranges from 0 to 4 feet in thickness. It attains maximum thickness in Tuscaloosa County, where, in places, it is comprised of three benches, spread through up to 35 feet of vertical section. Normally a single bench does not exceed 2 feet in thickness. In Walker and Jefferson Counties, the New Castle ranges from 0 to 1 foot, with the exception of a small area within the Coalburg syncline where it attains a maximum thickness of 3 feet (fig. 9). McCalley (14) indicated that west of Palos, the New Castle is seldom over 12 inches thick with the exception of a small area near Carbon Hill. The New Castle coal is absent in large areas of Jefferson and Walker Counties but is present throughout the area under investigation in Tuscaloosa County and attains a maximum thickness of 4 feet.

The New Castle coal, where present, occurs between 15 to 65 feet above the Mary Lee (fig. 10). The interval thicknesses within the hatchured areas, where the New Castle coal is absent, are approximate and based on trends in thickness and continuity of intervening lithologies. The sandstones in this interval range from 0 to 53 feet in thickness. There is a general correlation between interval thickness and sandstone thickness (fig. 11).

From analysis of core log and mine data it appears that in the vicinity of New Castle the Mary Lee coalbed may have been mistakenly called the New Castle. Data indicate that the New Castle coalbed is absent at New Castle and first appears to the south near Lewisburg, Ala. (figs. 1, 12, and 13).

Mine sections as described by Butts (1) were used for the construction of cross section E - E′ (figs. 12 and 14). Measured mine sections from the New Castle Nos. 2 and 6, Mary Lee No. 1, and Hamilton mines located north to south, respectively, appear to be correlative. The nomenclature problem has arisen since the coal in the New Castle No. 6 mine is named New Castle, whereas in the adjoining mines to the south the same coalbed is named Mary Lee.

Mary Lee Coal

The Mary Lee coalbed is comprised basically of two benches (figs. 12, 15, and 16) which coalesce in the northern part of the Warrior syncline. In certain localities, the Mary Lee is split into as many as five benches. On the basis of core log data, this coal is present throughout the entire study area, unlike the New Castle and Blue Creek coalbeds. The Mary Lee coalbed ranges in thickness from 2 to 12 feet and is normally 2 to 6 feet thick in the northwestern half of the basin and from 6 to 8 feet in the southwest. The combined thickness of all benches and intervening stringers of coal were included in the construction of the Mary Lee coal isopach (fig. 17). This map should not be construed as an interpretation of minable coal thickness, because in most areas of the Warrior field only one bench of the Mary Lee is mined.

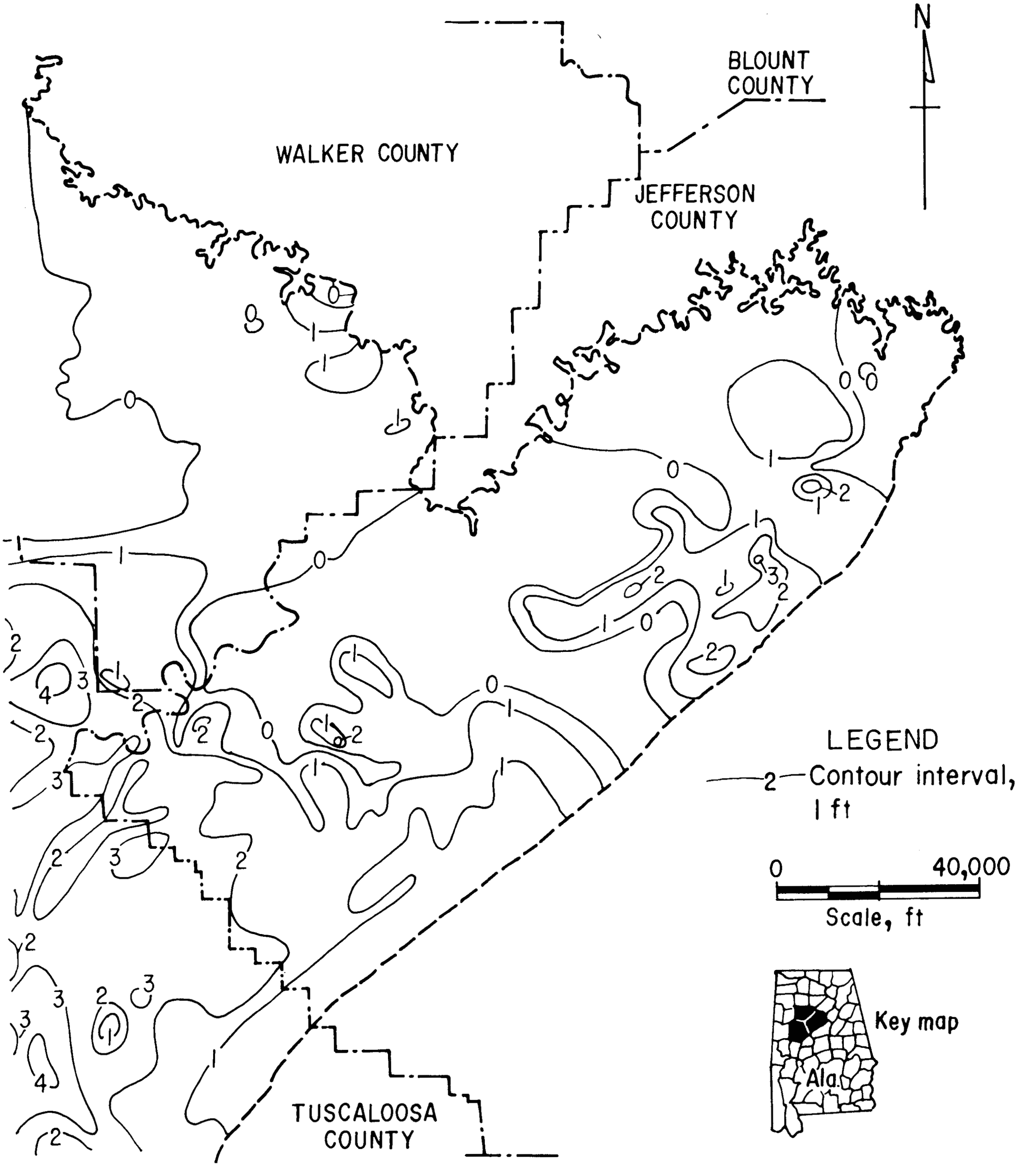


FIGURE 9. - New Castle coal isopach.

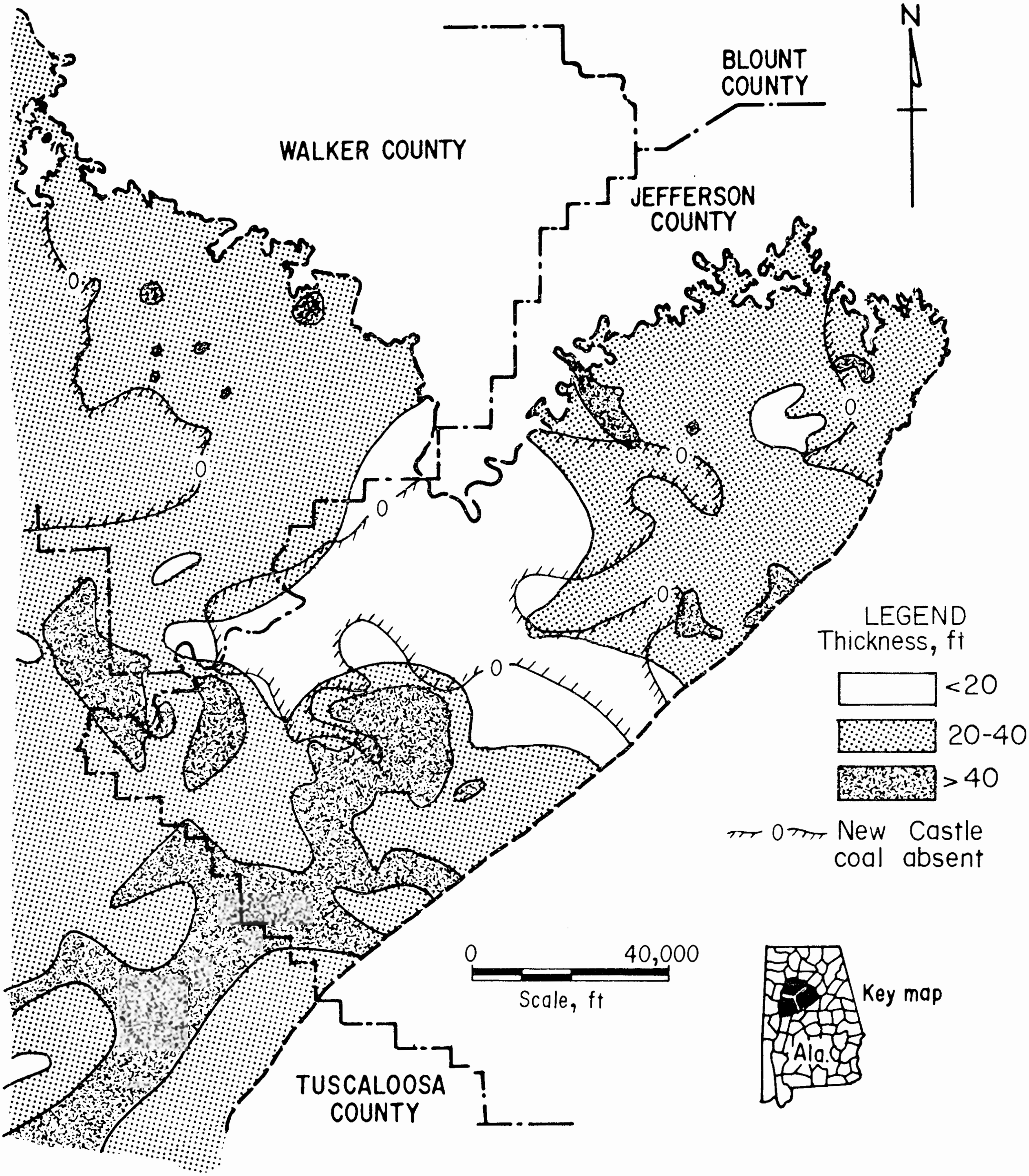


FIGURE 10. - New Castle-Mary Lee interval isopach.

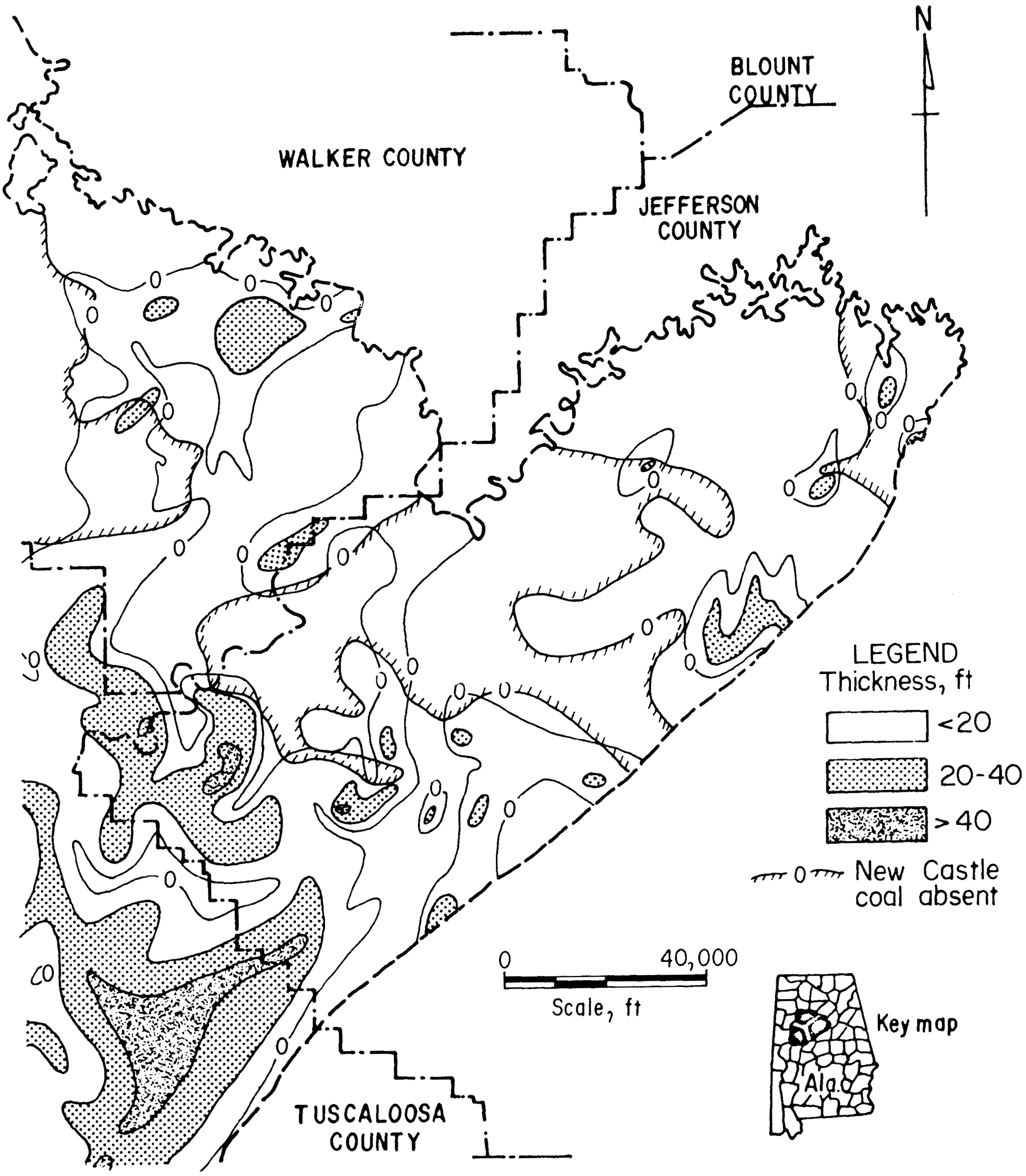


FIGURE 11. - Isopach of sandstone in the New Castle-Mary Lee interval.

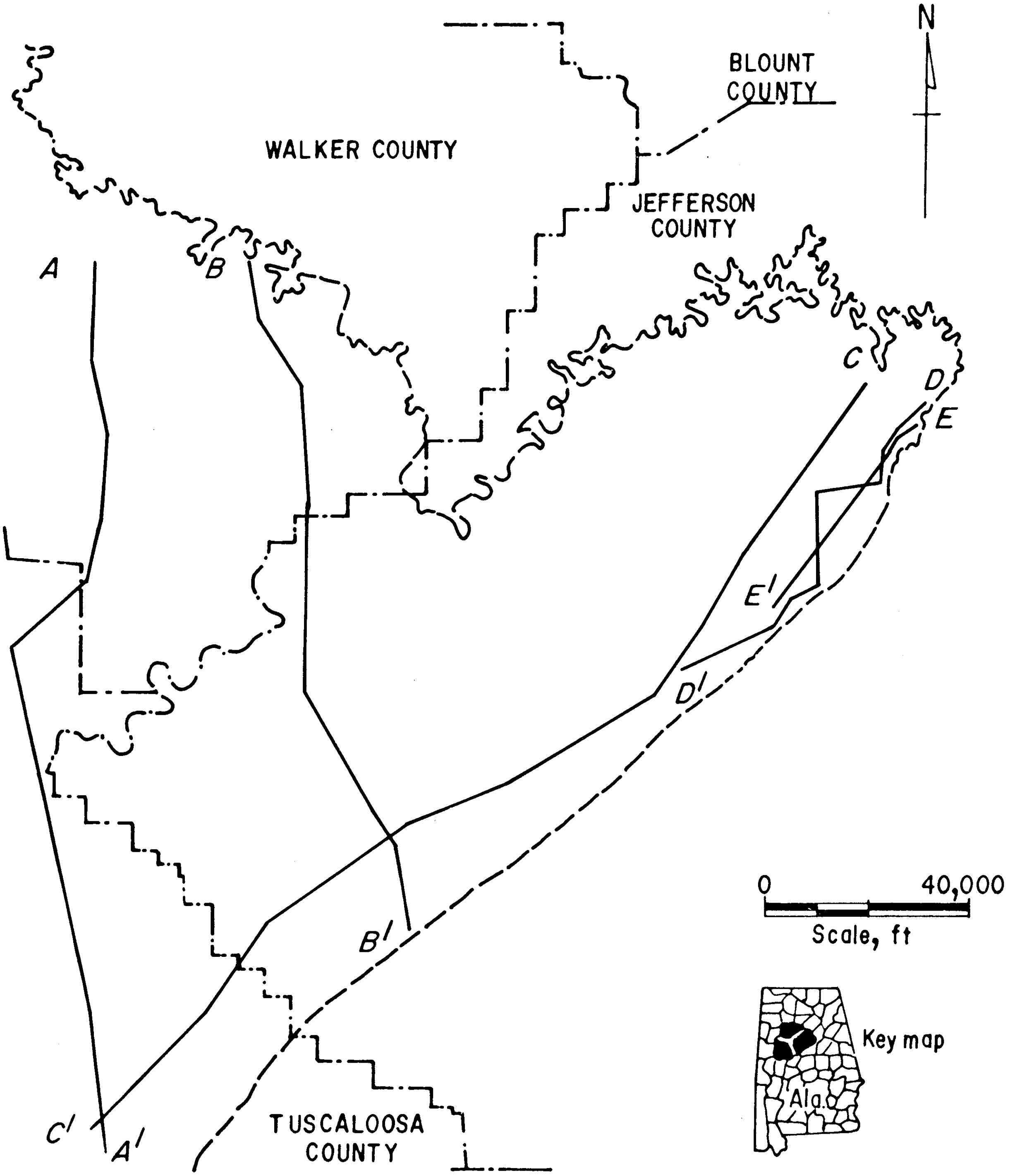


FIGURE 12. - Map showing location of regional cross section lines.

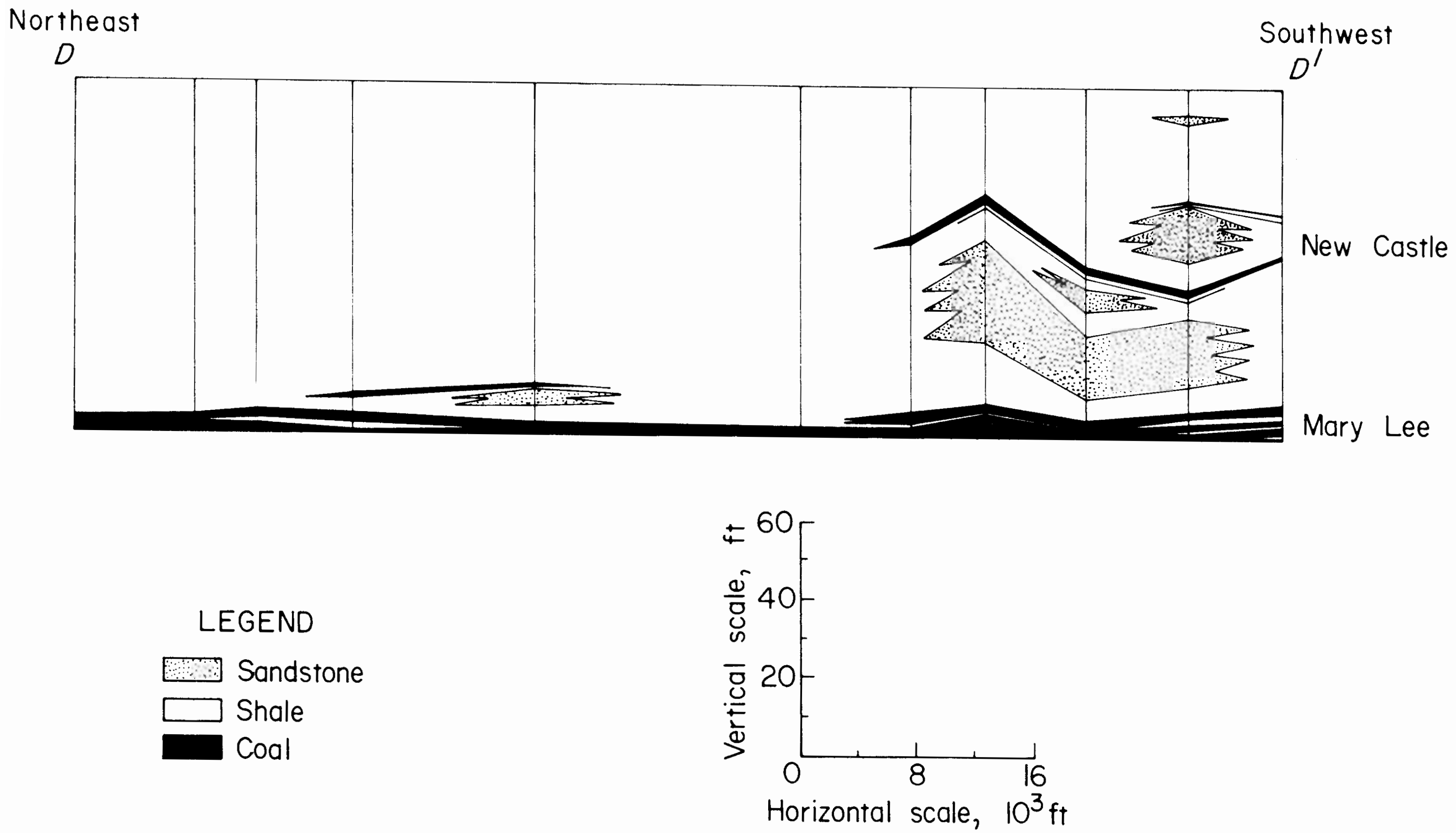


FIGURE 13. - Cross section D - D.

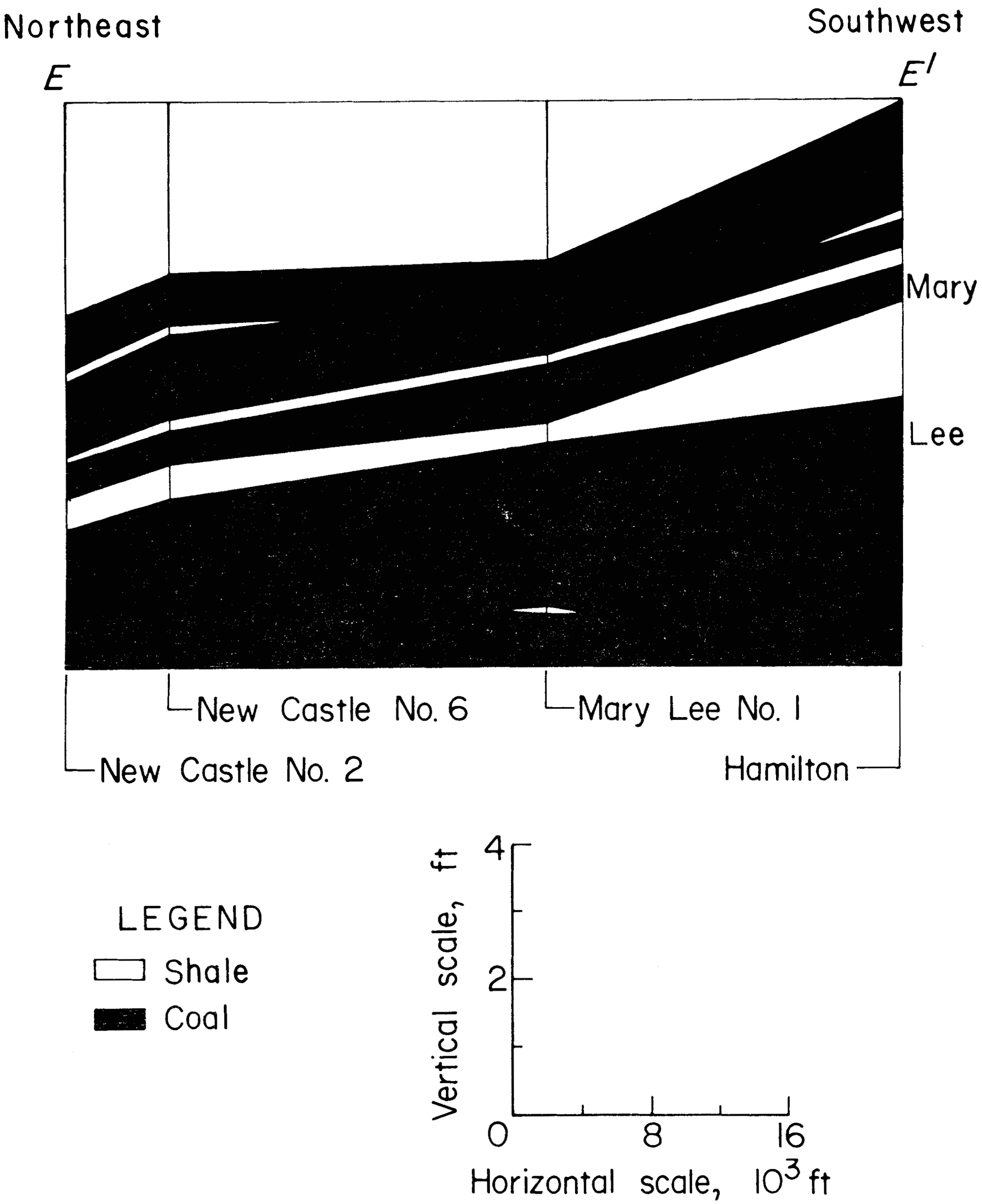


FIGURE 14. - Cross section E - E .

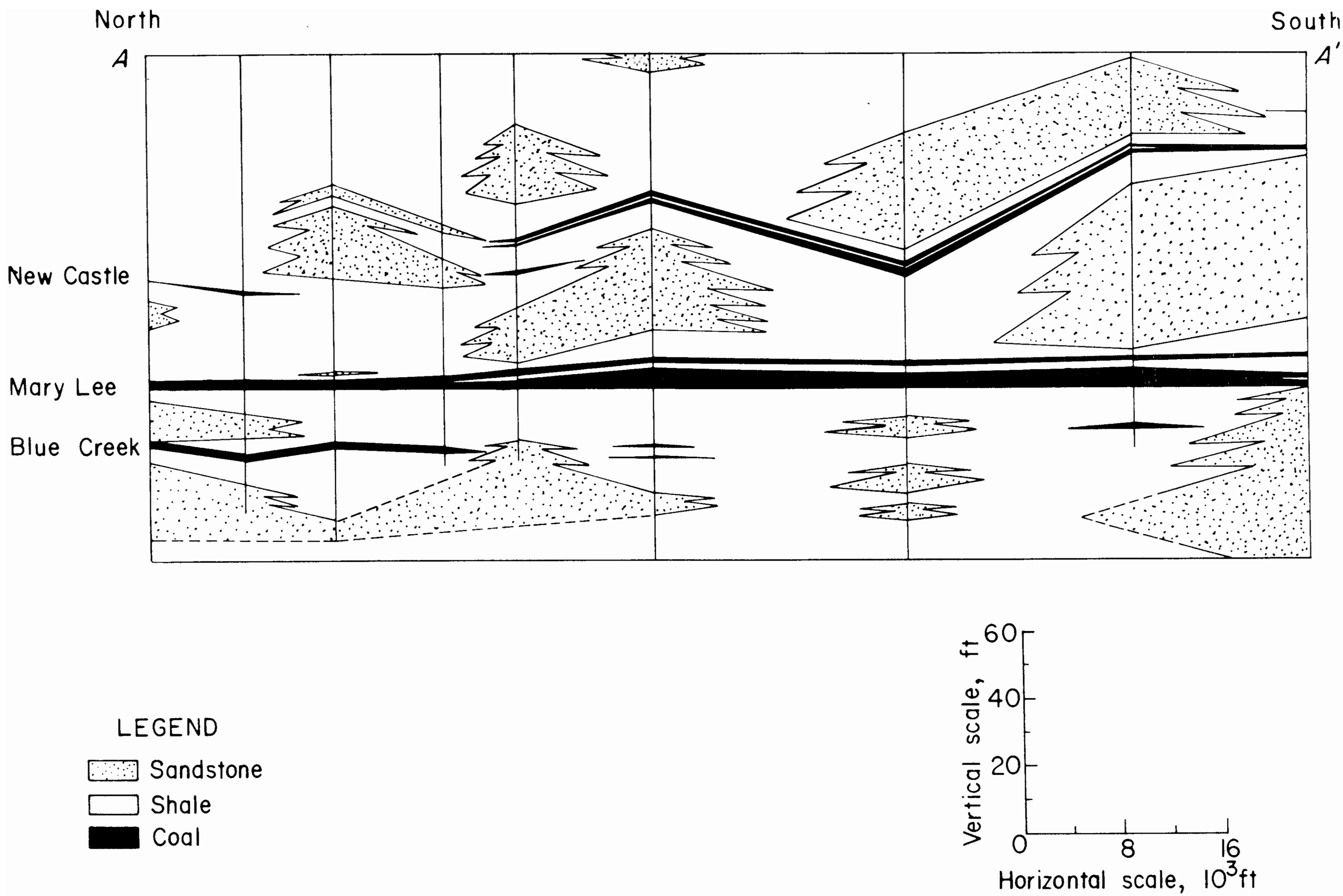


FIGURE 15. - Crcss section A - A .

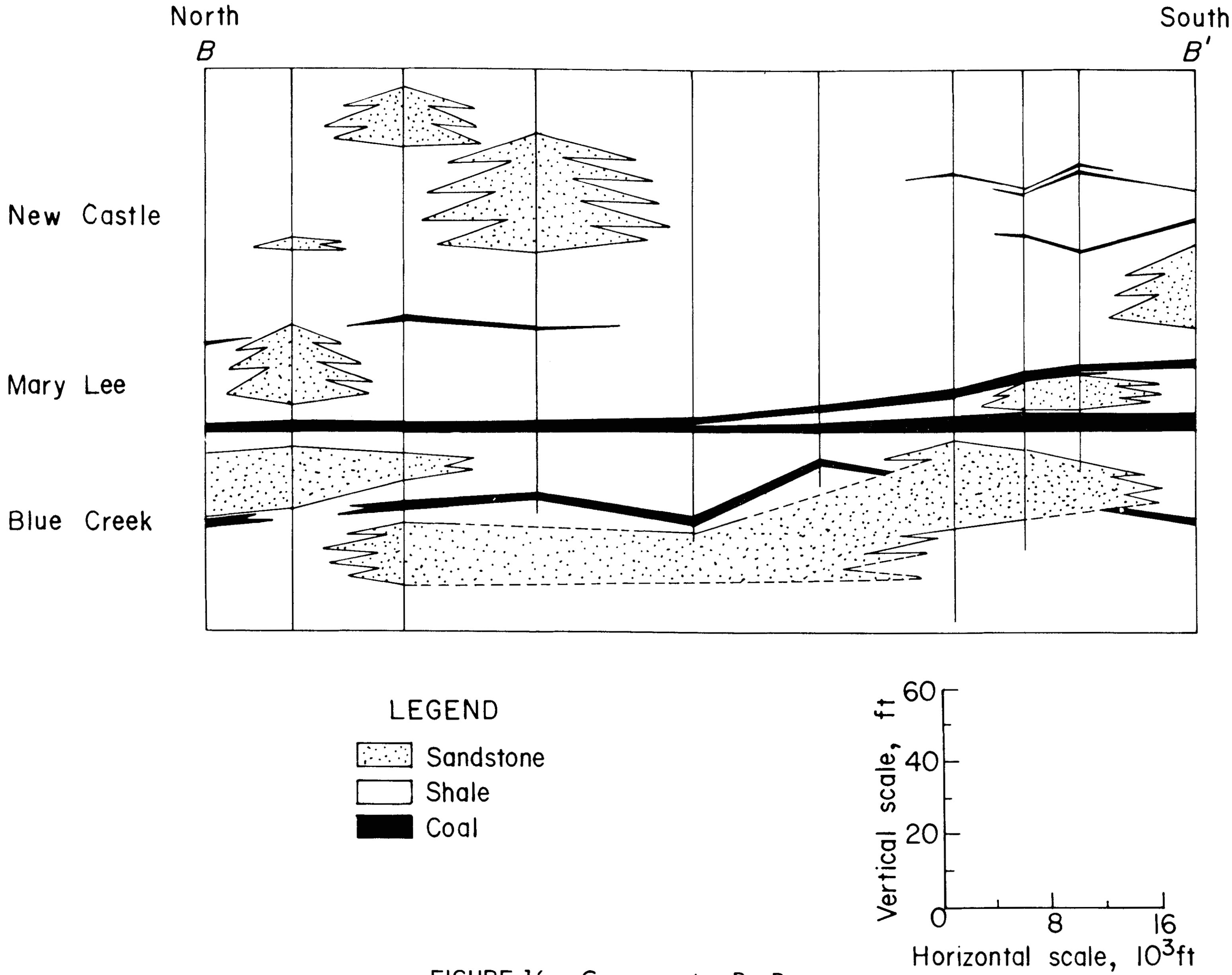


FIGURE 16. - Cross section B - B .

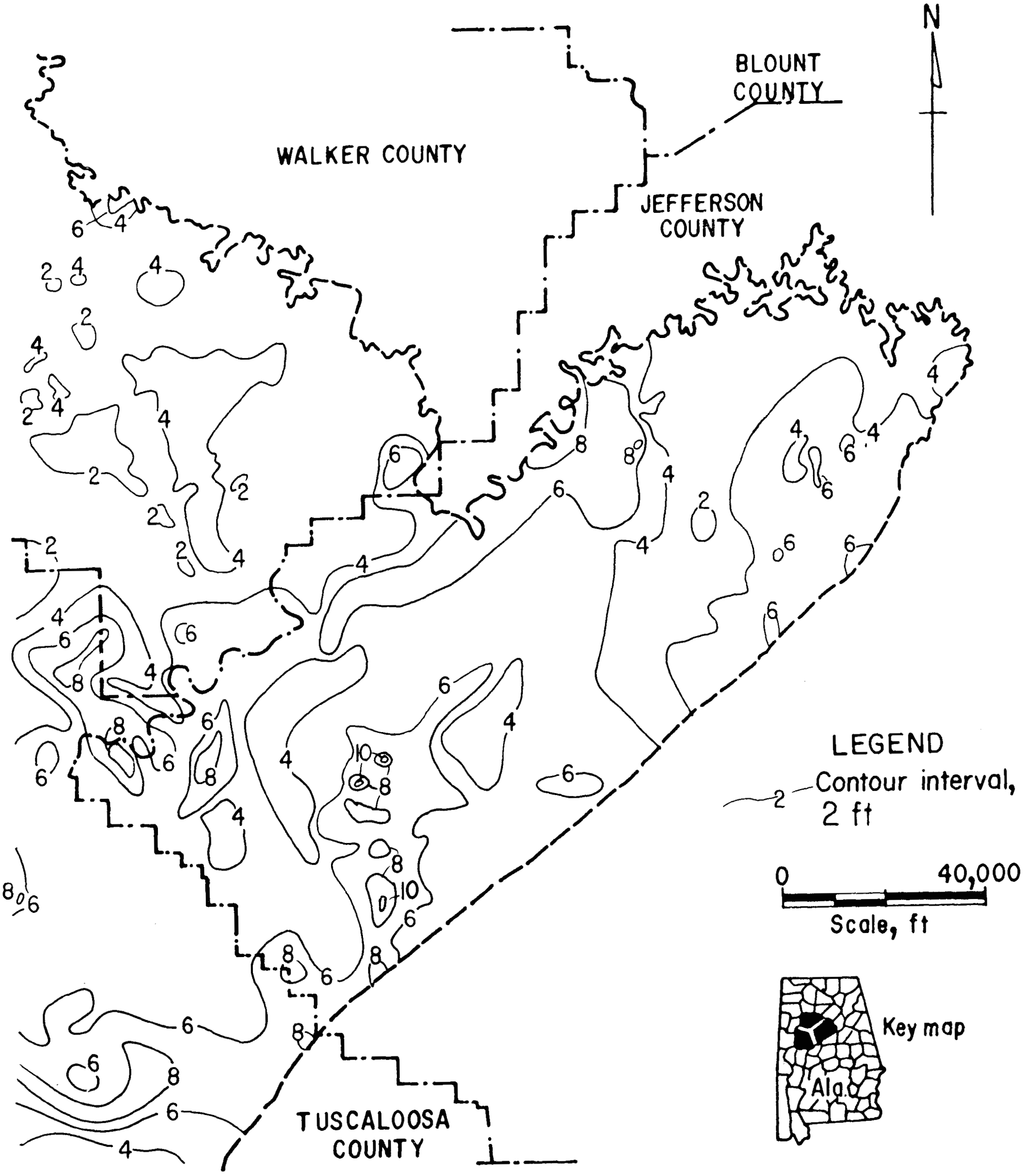


FIGURE 17. - Mary Lee coal isopach.

Two benches of the Mary Lee are present over much of the basin and are separated by a parting which ranges to a maximum of 10 feet in Jefferson County near Oak Grove, Ala. The top bench of coal is usually 0 to 24 inches in thickness, whereas the bottom bench is normally between 30 and 90 inches thick.

There is a general correlation between the Mary Lee coalbed thickness and the thickness of sandstone in the New Castle-Mary Lee interval (fig. 11). There is an excellent correlation between the thickness of the Mary Lee coalbed and the thickness of the New Castle-Mary Lee interval (figs. 10 and 17).

In the study area, the Mary Lee coal ranges from high-volatile in parts of Walker County, through medium-volatile to low-volatile coal in northeastern Tuscaloosa and southwestern Jefferson Counties (fig. 18). The Pratt coalbed also exhibits a similar increase in rank to the southeast, across the Warrior coalfield (2). This rank variation can be attributed to the degree of tectonism combined with depth of burial of the coalbeds.

Blue Creek Coal

The Blue Creek coal, where present, occurs from 7 to 40 feet below the Mary Lee and typically lies 10 to 25 feet beneath it. This coalbed reaches a maximum thickness of 5 feet, but is normally between 1 and 2 feet thick (fig. 19). The Blue Creek coal, absent over much of Tuscaloosa County, is oriented in a wide belt trending northwest-southeast and exhibits minor increases in thickness in the synclines.

Most regional maps in this report were constructed by using data from more than 700 core logs. The isopach of the Blue Creek coalbed was based on approximately 200 core logs because of the general practice of terminating coring a short distance below the lower bench of the Mary Lee coalbed, which is the bed of primary importance in mining.

Correlations of the Mary Lee and Blue Creek coalbeds have generally been based upon limited data. The limited access to all pertinent data, the geologic complexities due to the close stratigraphic proximity of the two coalbeds, and the splitting of the Mary Lee into two or more benches has made correlation difficult. The investigators in this study have had the distinct advantage of access to data obtained in exploratory core hole drilling by most of the coal mining companies in the Warrior field. Correlations presented here were derived from the construction of several cross sections and panel diagrams of individual mine properties, which were subsequently linked together for regional studies. Representative general cross sections (figs. 12, 13, 15, 16, and 20) are presented to illustrate regional stratigraphic trends.

The lower bench of the Mary Lee coalbed is now being mined in the newer deep mines in the southern part of the basin. This bench, commonly called the "Blue Creek" in the south can be traced northward through core logs to where it coalesces with the top bench of the Mary Lee. The correlations can further be traced to outcrops in Walker and northwestern Jefferson Counties

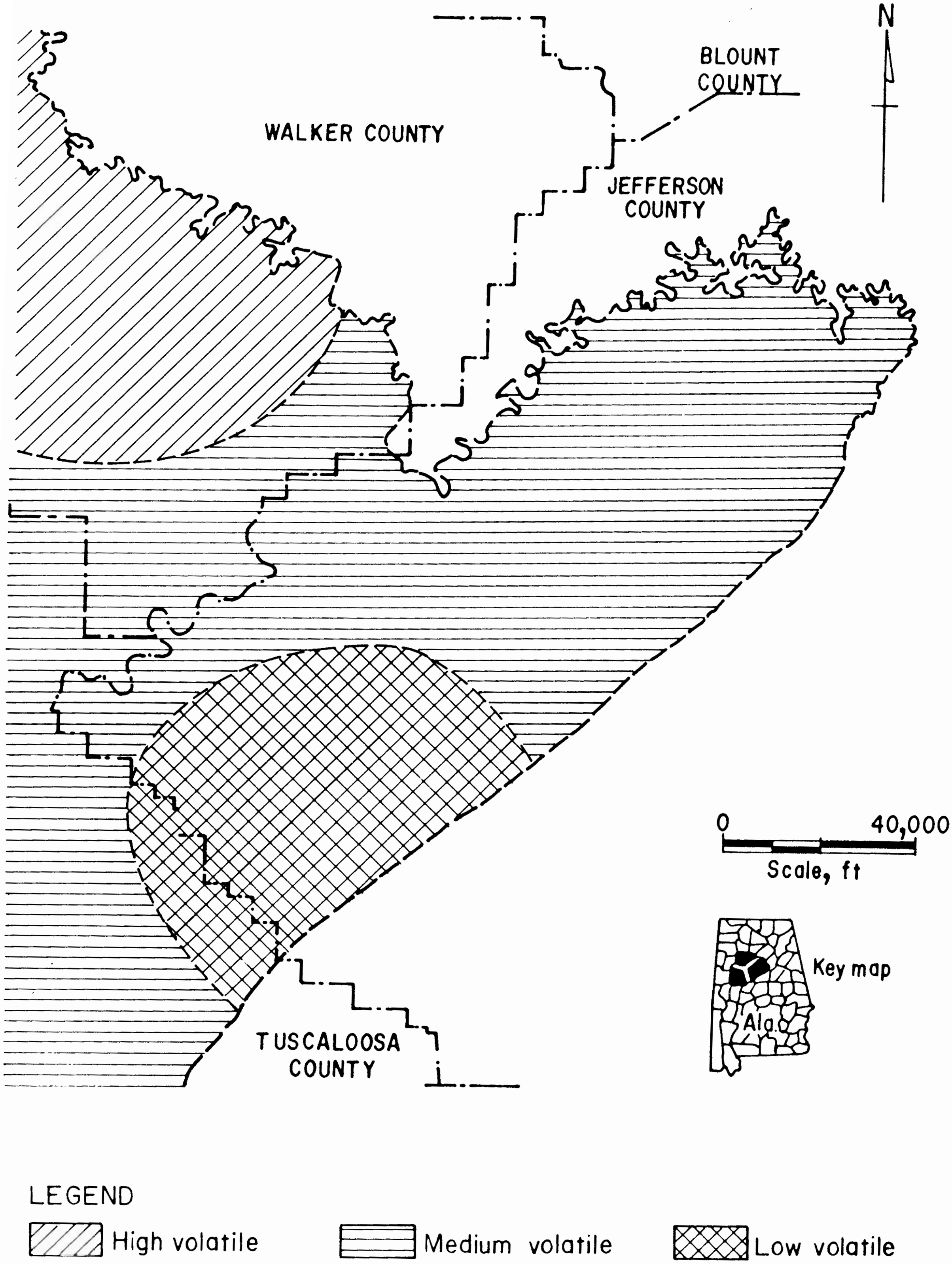


FIGURE 18. - Map of volatile content of the Mary Lee coalbed.

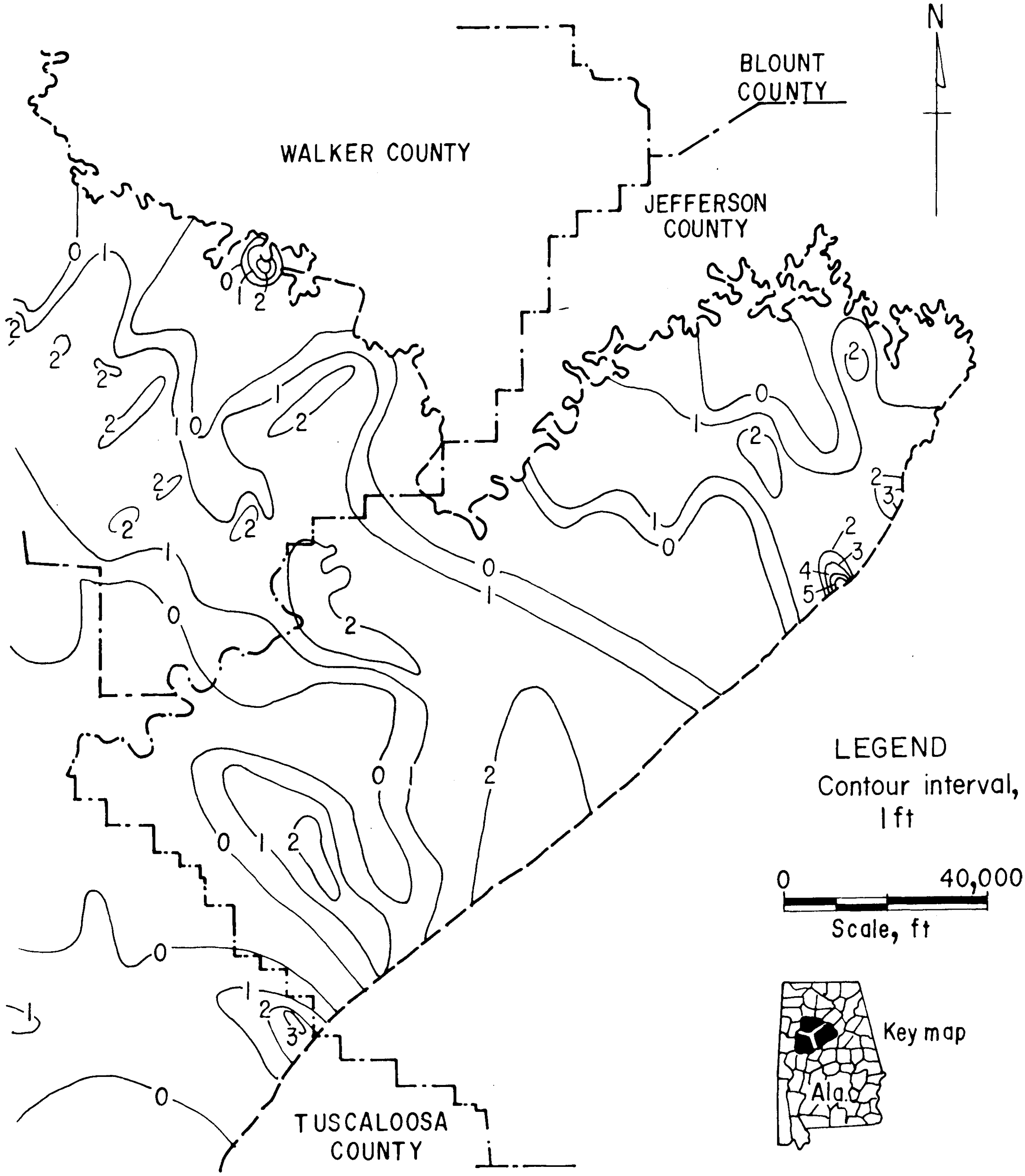


FIGURE 19. - Blue Creek coal isopach.

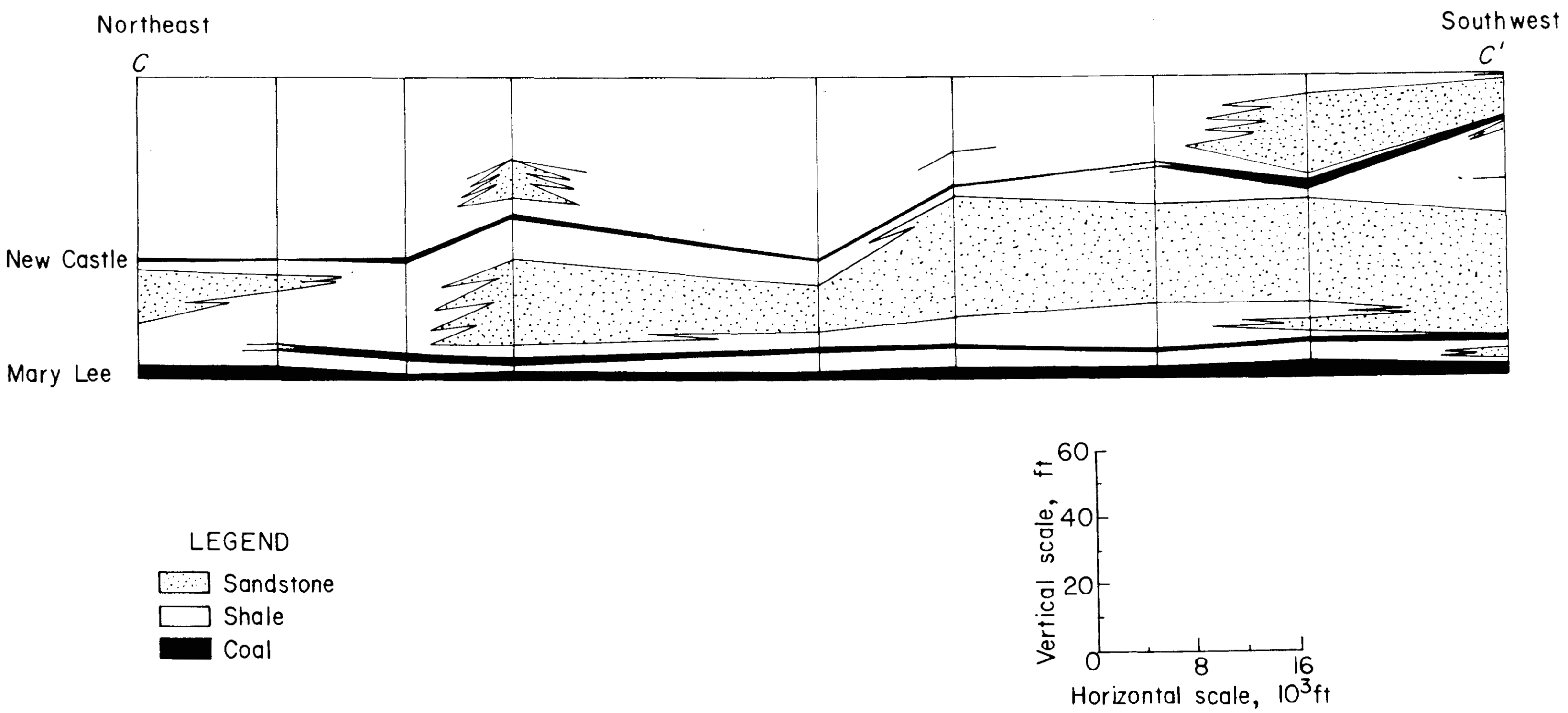


FIGURE 20. - Cross section C - C .

where the coalbeds were originally distinguished by McCalley (14). Two cross sections (figs. 15 and 16) show the sporadic occurrence of the actual Blue Creek coalbed beneath the Mary Lee.

Nomenclature and correlation problems are in part due to the fact that the Mary Lee coal changes rank in the basin. In the northern part of the field, where most of the mining has occurred, the Mary Lee is known as a high- to medium-volatile coal. To the south, where newer mines have been opened, the Mary Lee is a higher rank, low-volatile coal (fig. 18). In Tuscaloosa and southern Jefferson Counties this coal is called the "Blue Creek," although stratigraphically it is the lower bench of the Mary Lee.

Jagger and Ream Coals

Data on the Jagger and Ream coals are insufficient to construct regional coal isopach maps. Only a very small number of core holes have been drilled deep enough below the Blue Creek to intercept either coal. The few data show the Jagger and Ream coalbeds to be often absent, thin, and erratic in occurrence, and to vary greatly in depth beneath the Blue Creek.

Depositional Setting of the Mary Lee Group

The American coalbed is the lowermost productive member of the Pratt Group of coalbeds and overlies the Mary Lee Group by 350 to 750 feet in the study area. An isopach (fig. 21) of the interval between the Mary Lee and American coalbeds shows a southward thickening wedge of sediments which suggests a primary source of detrital material generally to the south. A map of sandstone distribution between the Mary Lee and the overlying New Castle coalbed (fig. 11) shows the largest concentration of sandstone in the south and southwest portion of the area. This again indicates a south or southwest source area. Previous investigations of sediment source directions into the southern portions of the Black Warrior basin have shown results similar to those indicated on figures 20 and 21. Ehrlich (8) found that the quartz content of low rank graywackes in the basin diminishes to the south indicating proximity to the original sediment source. Ferm (9) observed that all Pennsylvanian intervals, including the coal groups, expand southward. Davis and Ehrlich (3) found that mineral compositional trends in late Carboniferous sediments of the Black Warrior basin show variation along roughly north to south trends and that no compositional trends have been detected at high angles to present Appalachian trends. This was interpreted by Davis and Ehrlich to have been a manifestation of tectonic activity along the Ouachita structural belt to the south. The Ouachita structural belt defines the southern boundary of the Warrior basin (11, 21) and was probably the ultimate source of Pennsylvanian clastic sediments which were brought into the basin. Within the study area, the local source area was to the southwest and sands were transported primarily to the north and northeast.

An isopach map of the New Castle-Mary Lee interval (fig. 10) shows the relatively thick sedimentary section to the northeast separated to the west and south by low interval thicknesses (less than 20 feet); the sediment present in the northeast may have been derived from a second source area to

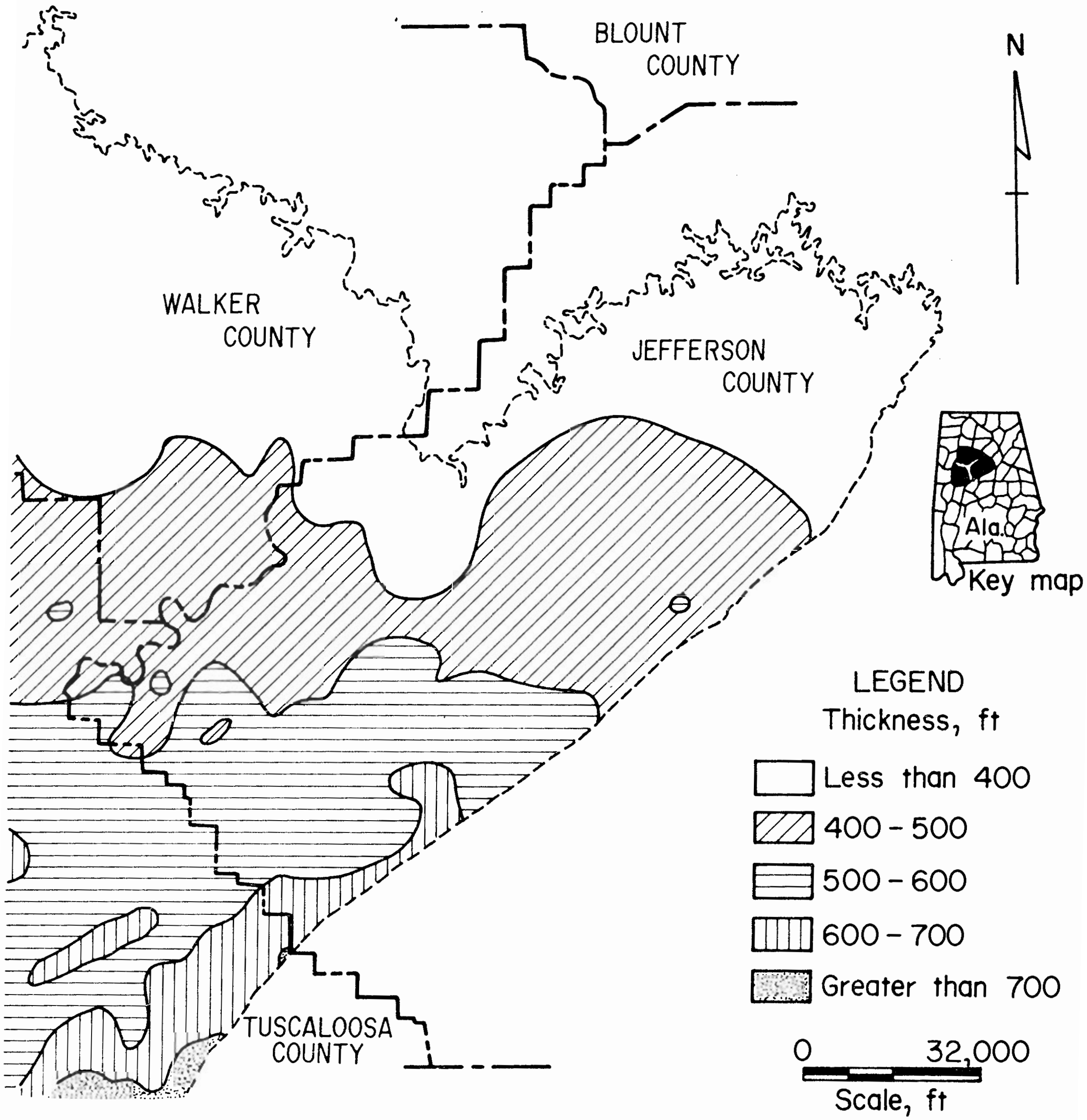


FIGURE 21. - American-Mary Lee interval isopach.

to the north or northeast. Mary Lee Group coal thickness (combined isopachs of the New Castle, Mary Lee, and Blue Creek coalbeds) distribution (fig. 22) indicates that thick areas of coal in the northeast are more or less separate from the coals farther to the south and west. This suggests contemporaneous peat deposition within two separate locations as in two distinct deltaic complexes--one developing to the northeast and the other to the southwest. Thomas (20) found evidence for these two different source directions in late Mississippian and Pennsylvanian sandstones northeast of the study area. Hobday (10) studying Pennsylvanian-Pottsville sandstone cross-bed directions found evidence of two sedimentary systems which merged near Cullman County, just north of the study area.

Individual coalbeds within the Mary Lee Group show thickness distributions that suggest original peat accumulation in fluvial-deltaic and low-lying coastal plain environments. The New Castle coalbed (fig. 9) represents peat deposition associated with an ancient deltaic complex. The northward thinning wedge of sediment on which the New Castle coal lies (fig. 10) indicates that delta progradation was primarily from the southwest, although small sediment contributions are thought to have been brought in from the northeast. Areas of thicker coals (over 2 feet) were probably locations of peat swamps between major distributary channels that flowed to the north and northeast filling the basin. Once the delta had been cut off from its source of detrital matter, peat could accumulate over most of the delta platform forming extensive, relatively thin coal deposits.

The Mary Lee coalbed (fig. 17) is representative of peat deposition within an ancient low-lying fluvial system. Thicker Mary Lee coal bodies (over 6 feet) form sinuous patterns trending generally northeast-southwest. These thick coal bodies probably represent locations of ancient low-lying inland valleys that were associated with the major stream courses in the upper delta plain.

The Blue Creek coalbed is distributed as wide belt-shaped bodies (fig. 19). Trends of thicker coal (over 2 feet) parallel these wide belts in the eastern and southeastern portions of the area. To the northwest, however, thick Blue Creek coal bodies are elongated at right angles to the wider coal belts. The Blue Creek coal appears to represent peat accumulation along coastal plains and perhaps, within shallow lagoonal lows behind ancient beach barriers. The beltlike distribution of the Blue Creek coal suggests a general parallelism to such an ancient coastline. The change in trend directions of thick coals indicate at least two different environments associated with peat accumulation: (1) Peat accumulation parallel to the larger belts probably represents abandoned deltaic distributary channel environments associated with delta progradation from the south and southeast and (2) coastal processes become more pronounced farther to the north and northwest and resulted in channel development perpendicular to the strand line. Small tidal channels which drain lagoonal areas are good examples of such features. With a drop in sea level these channels were abandoned and became locations of thick peat accumulations.

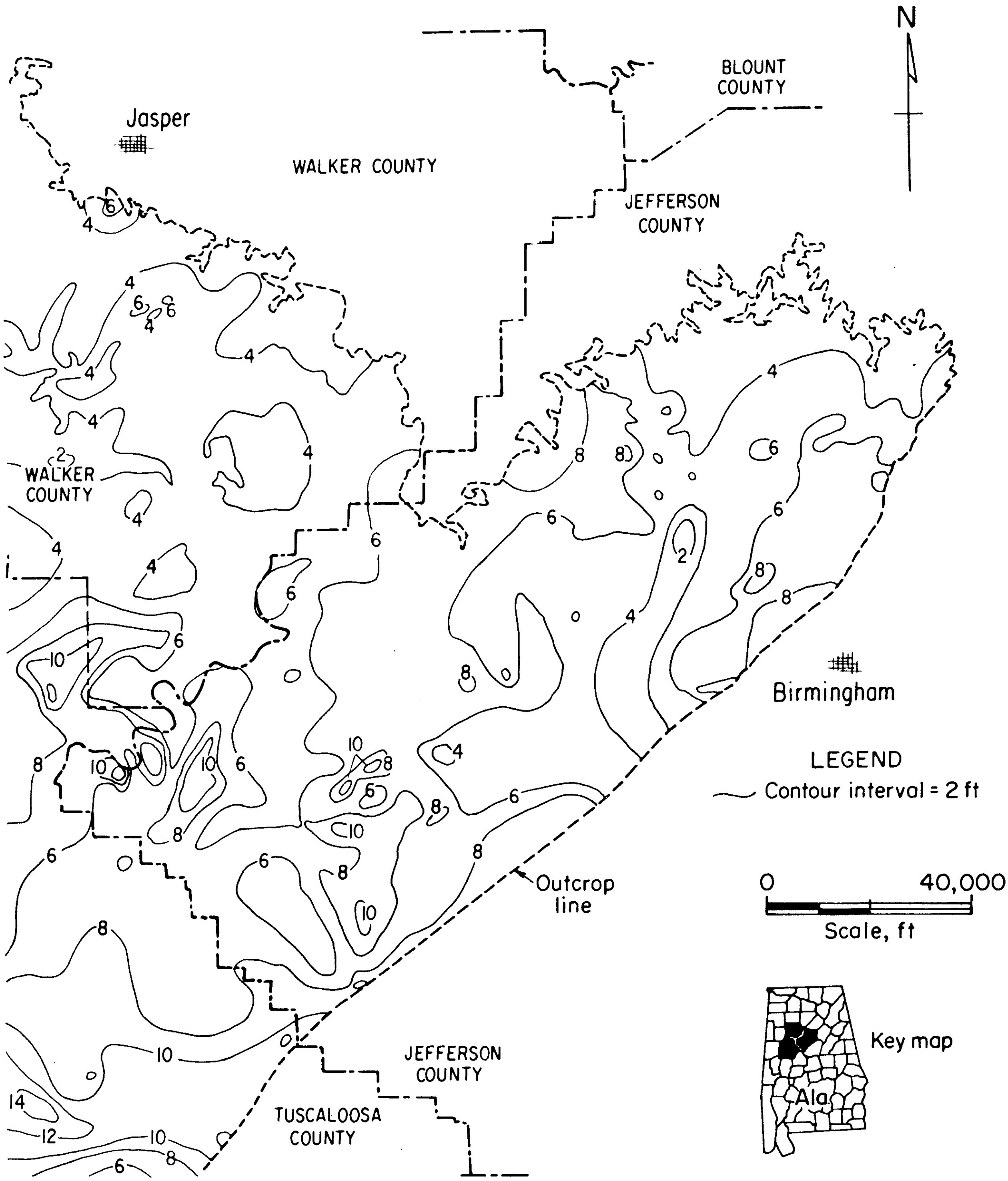


FIGURE 22. - Combined isopach of the Mary Lee Group of coalbeds.

STRUCTURAL CONTROL OF MARY LEE GROUP SEDIMENTATION

There is a good correlation between interval thicknesses, Mary Lee Group coal thickness distribution, and structure. Comparison of the New Castle-Mary Lee interval isopach (fig. 10) with thickness distribution of the Mary Lee Group of coalbeds (fig. 22) shows an excellent correlation between thick sediments (greater than 40 feet) and thick coal (greater than 6 feet). In addition, the structure map (fig. 3) shows that these areas of thick sediments and thick coal tend to correspond with either structurally low or highly faulted portions of the basin. Examination of isopachs of individual coalbeds within the Mary Lee Group of coals indicates varying degrees of structural control over coalbed distribution.

New Castle Coal

An isopach of the uppermost coalbed, the New Castle, is shown on figure 9. This coalbed is altogether absent in the vicinity of the Sequatchie anticline but is present within the Coalburg and Warrior synclines. Thicker New Castle coal also predominates in the structurally deep southwestern part of the area. A concentration of thick New Castle coal in the northeast is associated with an excessively faulted region west of Birmingham. The close association of structure with New Castle coal thickness suggests that ancient physiographic low-lying areas of peat accumulation correspond to synclinal features present at the time of original deposition. Some of the faulted zones on the structure map (fig. 3) may have been subsiding areas at the time of coal deposition and thus were loci for thicker than "normal" peat accumulation. Because these normal faults are nearly perpendicular to major sediment source directions (northeast and southwest), they may be growth or slump features similar to those in the Cretaceous sediments of the Gulf Coast. Apparently deposition was structurally controlled before time of New Castle deposition because similar relationships are seen in the New Castle-Mary Lee interval isopach (fig. 10).

Mary Lee Coal

An isopach of the Mary Lee coalbed (fig. 17) shows that most of the coal more than 4 feet thick occurs within the general area of the Coalburg syncline and also within structurally deep areas to the southwest. As with the New Castle, thick Mary Lee coal is associated with the faulted region in the northeast. The most notable difference between the New Castle and Mary Lee coal isopachs is that a significant thickness of Mary Lee coal is present along the Sequatchie anticline whereas the New Castle coal is absent.

Like the New Castle, the Mary Lee coalbed isopach indicates peat accumulation was affected by the structural configuration of the area at the time of deposition. Thick and extensive coal within the general confines of the present Coalburg syncline suggests that this structural feature was the location of extensive physiographic lows where peat could accumulate. The present day Sequatchie anticline apparently was a minor feature during the time of Mary Lee coal deposition and, therefore, did not influence peat accumulation. Consistent and abrupt changes in coal thickness just north and west of the present Sequatchie anticlinal axis indicate the position of an ancient "hingle line" oriented northeast-southwest that separated the deep southeastern basin from shallower northwestern areas. The area of Mary Lee coal over 4 feet thick northwest of the hingle line cannot be correlated with the present day Warrior syncline, but there is a good correlation of thick coal with a faulted region immediately to the north of the syncline.

Cross sections taken north to south across the basin show that the Mary Lee coal is thicker within areas of (greater) structural deepening. These sections, shown in figures 12, 15, and 16, indicate that thicker Mary Lee coal in the southern portions of the area is a result of a gradual southerly increase in the number and thickness of individual coal benches. Although up to five separate benches have been recognized on some core log descriptions, two major benches can be readily traced throughout the southern portion of the field. To the north these two benches coalesce to form a single minable unit. Intermittent and relatively rapid subsidence of the southern area, accompanied by influx of detrital material, is recorded by the numerous splits in the Mary Lee. An increasing number of coal benches to the south indicates more frequent periods of subsidence in this direction. The stability of the northern areas accounts for relatively thin coal and few or no shale partings.

Blue Creek Coal

Data used to construct the isopach of the Blue Creek coalbed (fig. 19) were limited and there is little correlation of coal thickness with present structural configuration (fig. 3). The distribution of the Blue Creek coal suggests only a subtle influence of structure on original peat deposition. Differences in trend directions of thick Blue Creek coals suggest at least two different modes of original peat accumulation which were ultimately controlled by differential structural movements between the more actively subsiding Coalburg syncline and the more stable area to the northwest.

GEOLOGIC FACTORS INFLUENCING MINING OPERATIONS

Roof instability and methane emissions are two major problems which affect underground coal mining operations in the Warrior basin. Comprehensive geological investigations can be used by mine operations to anticipate areas of possible roof problems. Desorption tests of coal samples from vertical boreholes can be used to estimate the methane content of virgin bituminous coalbeds. This information can then be applied to design mine ventilation systems and to determine whether degasification of the coalbed in advance of mining will be necessary.

Strata Overlying the Mary Lee Coalbed

The rock directly overlying the Mary Lee coalbed throughout most of the Warrior field is shale (figs. 13, 15, 16, and 20). There is an overall increase in the frequency and size of sand bodies in the southern parts of the basin (fig. 11). In Tuscaloosa County, where sandstone directly overlies the Mary Lee, there has been very little erosion of the top bench of coal. There are no known cases where the Mary Lee coal has been reported to be absent due to erosion and subsequent filling by channel sands.

Roof problems may be encountered during mining of the lower bench of the Mary Lee where only a thin parting may separate it from the upper bench, which is often left in place. Roof bolts should be long enough to penetrate the parting, upper bench and to firmly anchor into competent overlying strata. Roof problems may also be encountered in areas where the interval to the New Castle coalbed is smallest. The interval with the next higher coalbed (fig. 10) is critical because the uppermost plane along which the roof tends to separate is the bottom of the coalbed immediately above (15). Other areas of unstable roof may be related to sandstone channel deposits where differential compaction has occurred along the margins of sandstone channels.

Methane Gas Content and Degasification

Coal production in the Warrior basin has in the past (fig. 7) been from relatively shallow (less than 1,000 feet) depths in older mines where methane emissions were not a serious problem. New mines are now operating at depths exceeding 1,000 feet and there are mines planned for depths approaching 2,000 feet. The newer deep mines are already encountering problems with methane emissions. Desorption tests of coal cores indicate that at these greater depths, the problem of methane gas affecting mining operations will be acute. One sample obtained at a depth of 2,200 feet yielded 17 cm^3/g or 544 ft^3/ton of coal in place (13, 16). The methane emission from a mine in cubic feet per ton of coal mined would be much greater than the calculated cubic feet of methane per ton of coal in place because gas is also emitted from the coal in the face, ribs, roof, floor, pillars, old workings, and gob areas (12).

Coal samples were obtained from seven core holes ranging in depths from 600 to 2,200 feet. A graph (fig. 23) for estimation of gas content was constructed by plotting the measured gas content versus depth for each sample. The methane gas content of the Mary Lee Group, within the study area, has been estimated to be more than 1 trillion ft^3 (6). Nearly 70 pct of this gas is contained within the Mary Lee coalbed alone and could be encountered by mining operations.

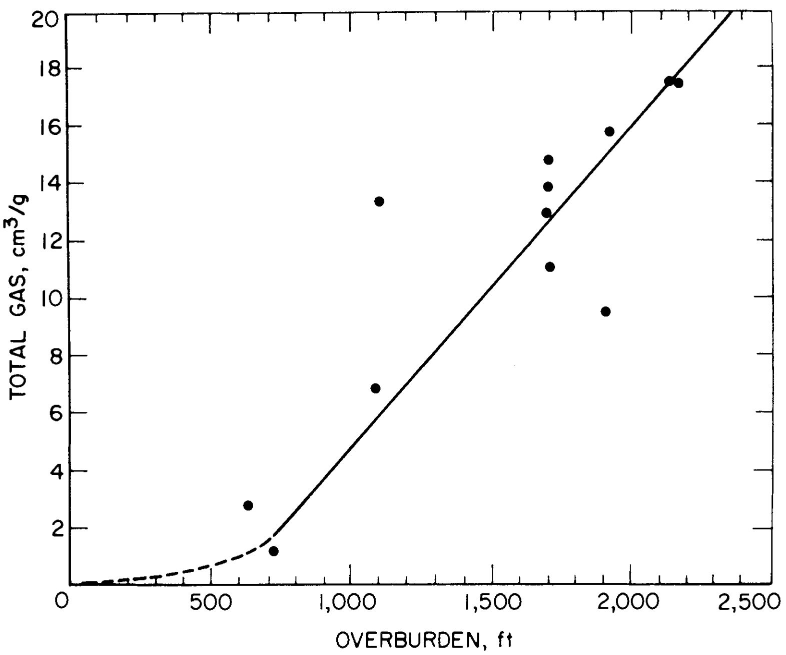


FIGURE 23. - Depth of coalbed versus gas content.

The relationship of gas content to depth, as shown on the graph (fig. 23), can be used to delineate geographic areas of high gas concentrations. The Mary Lee coals are more than 1,500 feet deep in only 12 pct of the study area (fig. 24),

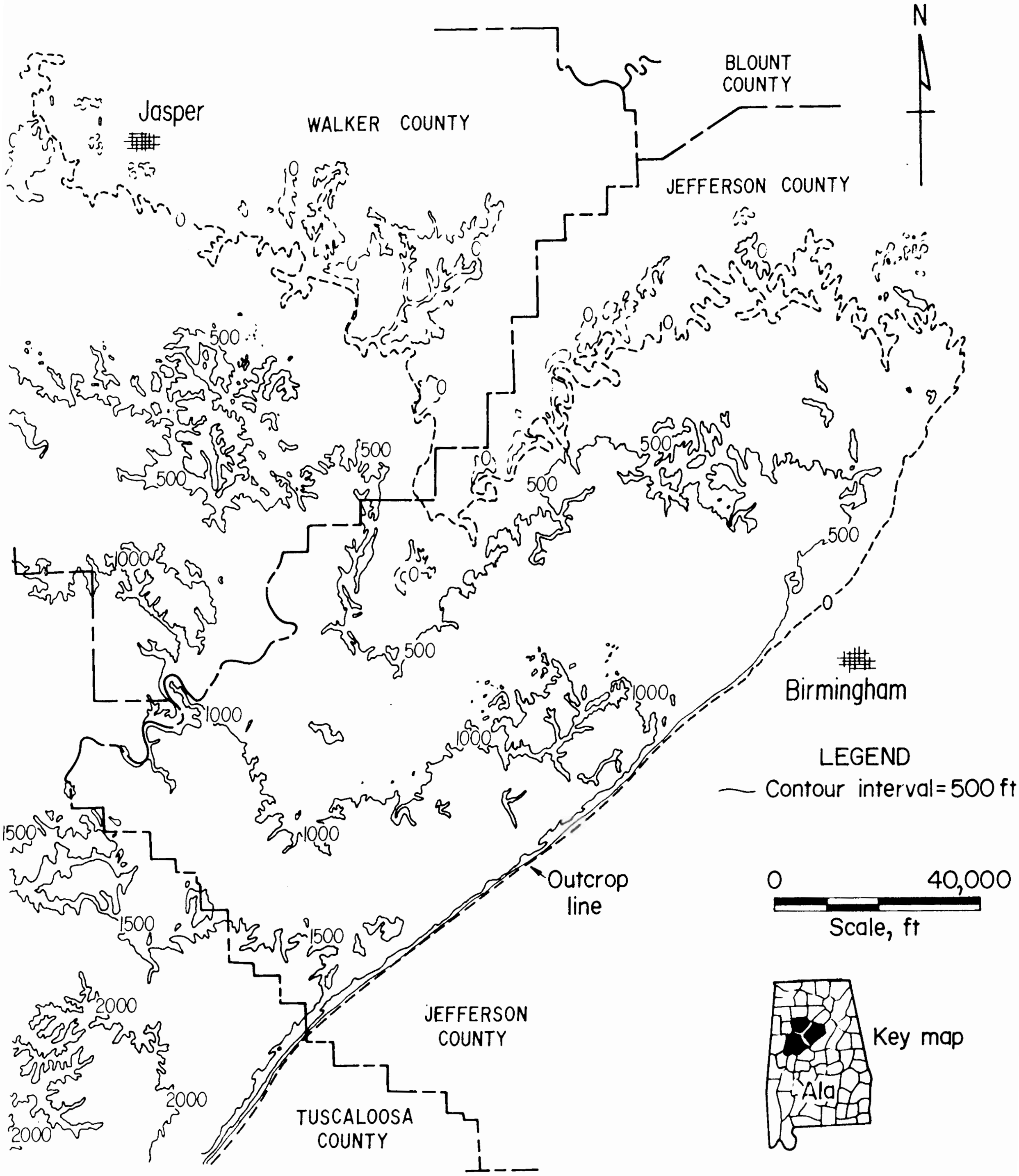


FIGURE 24. - Overburden isopach of strata overlying the Mary Lee coalbed.

yet more than half of the methane is estimated to be in these deep coals. The average methane content and the calculated methane resources of each overburden interval is given in table 1.

TABLE 1. - Methane resources

Overburden (ft)	Av methane content		Methane resources (ft^3), Mary Lee Group
	Cm^3/g	Ft^3/ton	
0-500............	0.25	7.5	0.13×10^{11}
500-1,000.........	2.00	64.0	1.15×10^{11}
1,000-1,500.......	7.50	240.0	3.76×10^{11}
1,500-2,000.......	13.10	419.0	3.54×10^{11}
2,000-2,500.......	18.60	595.2	1.96×10^{11}
Total..........	-	-	10.54×10^{11}

Due to the lack of data, the gas content of the Mary Lee Group in the deeper part of the Warrior basin, outside of the study area (fig. 2), could not be calculated, but it should be noted that in the deeper part of the Warrior basin it is enormous. Every additional square mile of coal 6 feet thick, at a depth of 2,000 feet, could contribute 3.3 billion ft^3 of gas to the 1 trillion cubic foot total.

Methods to remove methane in advance of mining are being tested in the Mary Lee coalbed. The Bureau of Mines is currently involved in a cooperative venture in the Warrior basin to test the feasibility of degasification of the Mary Lee coalbed from vertical boreholes in advance of mining.

SURFACE JOINT AND CLEAT MEASUREMENTS

As part of the structural interpretation of the study area, joint and cleat strikes were measured in outcrops. The primary purpose was to obtain data for evaluation of a cleat-prediction technique which was successfully applied in the northern Appalachian coalfields (4-5). Cleat directions are important because they influence the flow of methane in coalbeds. It has been demonstrated in degasification experiments in coalbeds with high permeability, conducted underground by the Bureau of Mines, that horizontal holes drilled perpendicular to and, therefore, intersecting the largest number of face cleats will yield 2.5 to 10 times the amount of gas as holes drilled perpendicular to the butt cleat.

The directional permeability is, in turn, important in the placement of vertical and slant degasification holes drilled from the surface into a coalbed. A vertical hole in a coalbed with a well developed cleat system will collect gas at a higher rate from the face cleat direction than from the butt cleat direction. An elliptical drainage pattern will be developed with the long axis parallel to the face cleat. When drilling slant holes from the surface to intersect coalbeds horizontally, it is important that the hole penetrates the face cleats as nearly perpendicular as possible for maximum gas flow. To determine the most efficient pattern for vertical degasification holes and orientation for slant holes in virgin coal, it is requisite that the cleat orientation be determined.

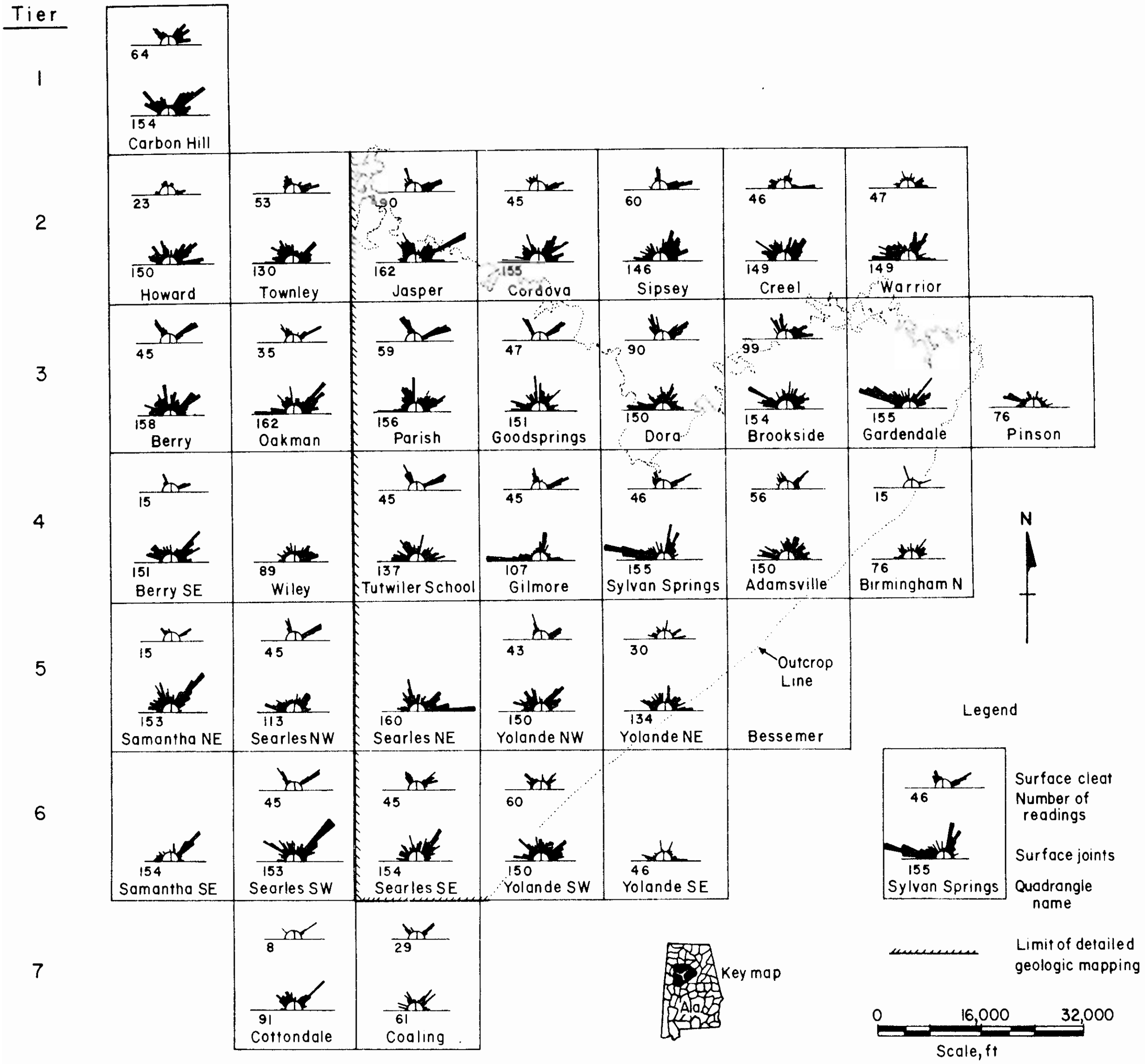


FIGURE 25. - Rose diagrams of surface joints for 35 quadrangles.

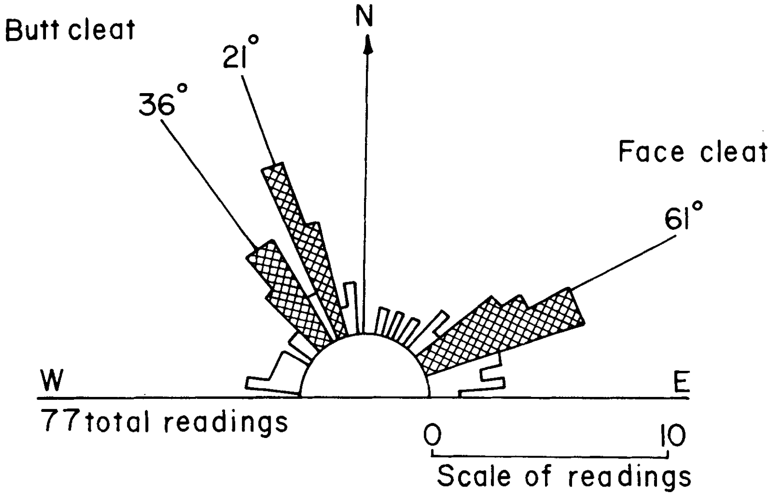


FIGURE 26. - Composite rose diagram of principal surface cleat trends.

Field Methods and Data Compilation

Surface joints were measured in 35 quadrangles in and around the primary study area (fig. 25). Whenever possible, 15 readings were taken at 10 separate locations within the quadrangles. Locations were spaced as evenly as the outcrops would permit. Fewer readings were obtained along the eastern margin of the area, mainly because of the increasing structural complexity of the outcrops and because portions of the quadrangles are outside of the Warrior basin study area. Individual readings were taken on joints of varying prominence and in various lithologies and bed thicknesses to obtain an unbiased representation of the principal joint strikes.

When coal outcrops or strip mines were present, data were also obtained on surface cleat strikes (fig. 26). Fifteen readings from three locations were about the average number of surface cleat measurements taken per quadrangle. The uniformity of the generally orthogonal cleat system found in coalbeds permits the measurement of fewer readings to establish directional trends.

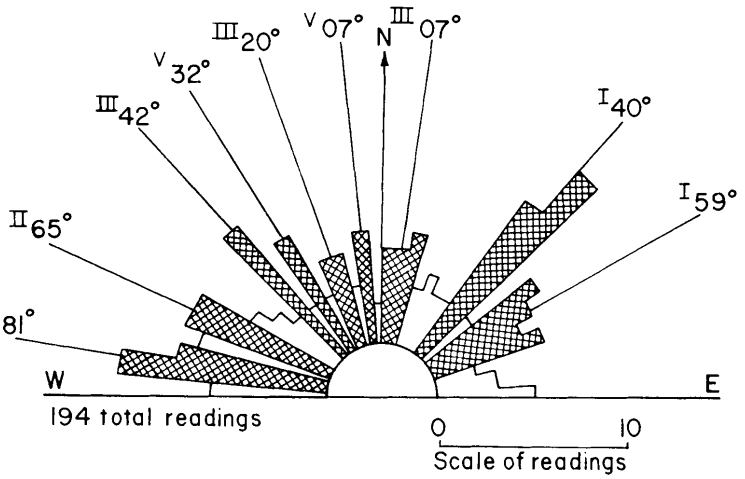


FIGURE 27. - Composite rose diagram of principal surface joint trends.

The principal surface joint trends of each quadrangle in figure 25 were determined as described by Diamond (4-5) and are tabulated in appendix A. The principal surface cleat trends were also determined and are tabulated in appendix B. The principal surface joint and surface cleat trends from each quadrangle were plotted on composite rose diagrams for regional evaluation (figs. 26 and 27).

Prediction of Subsurface Cleat Orientations

The composite rose diagram of principal surface

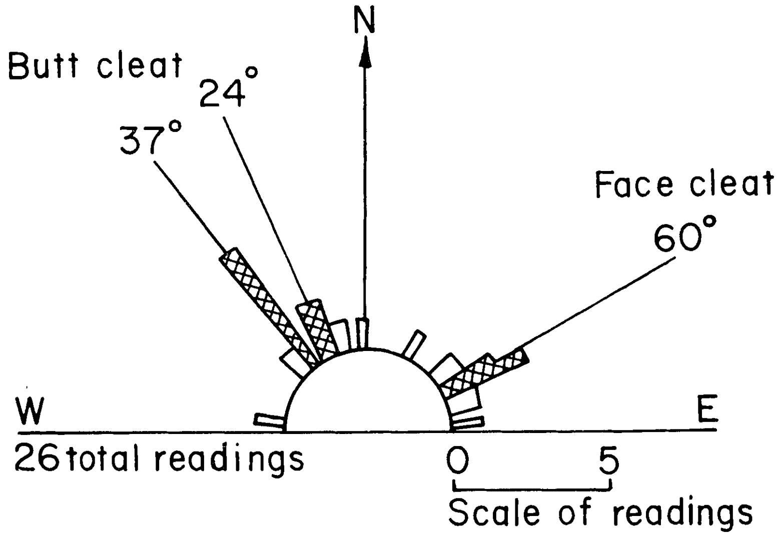


FIGURE 28. - Composite rose diagram of principal underground cleat trends.

joint strikes (fig. 27) indicates numerous trends, especially in the west. For cleat prediction, individual peaks are assigned orders of dominance based on the number of readings comprising the peak. The most dominant peak is assigned the first order of dominance; the next most dominant is the second order, etc. The peaks in the west are then paired with those in the east (table 2) to determine the possible fundamental joint systems (joint sets oriented perpendicular to each other).

TABLE 2. - Fundamental regional systems from directional data

Data source	System	Degrees separation
Surface joints......	(1) N 65° W^{II} -*N 40° E^{I}	105
	(2) *N 81° W^{I} -N 07° E^{III}	88
	(3) N 20° W^{III} -*N 59° E^{I}	79
	(4) N 32° W^{V} -*N 59° E^{I}	91
	(5) N 42° W^{III} -*N 59° E^{I}	101
Underground cleat...	(1) N 24° W-*N 60° E	84
	(2) N 37° W-*N 60° E	97
Surface cleat.......	(1) N 21° W-*N 61° E	82
	(2) N 36° W-*N 61° E	97

NOTE.--Superscripts indicate the order of dominance within the directional group (east or west) for surface joints and an asterisk denotes the dominant trend of each system.

It was found in an investigation of the Pittsburgh coalbed in southwestern Pennsylvania and northern West Virginia (4-5) that a joint system composed of the most dominant set when combined with a perpendicular set of the first or second order of dominance will usually give the best estimation of cleat orientation. The most dominant set of the selected system is ordinarily the face cleat direction. These estimation criteria were formulated by comparing the surface joint data to cleat data obtained in underground mines in the same area.

A composite rose diagram (fig. 28) of the principal underground cleat strikes measured in the Mary Lee coalbed was constructed to serve as a standard against which the surface joint data could be evaluated. This diagram indicates two possible fundamental systems as follows: N 24° W- N 60° E = 84° separation, and N 37° W-N 60° E = 97° separation (table 2). Both systems contain the N 60° E face cleat trend and neither system seems to be dominant over the other. The two separate butt cleat trends present do not appear to be segregated within any particular geographic or structurally defined area. In fact, the Chetopa mine (fig. 5) has a bimodal butt cleat with trends of N 27° W and N 37° W, which are nearly identical to the average butt cleat orientations on the regional composite (fig. 26). The presence of a bimodal butt cleat, both in the Chetopa mine and on the composite diagram is probably the result of an "overlapping" of dominant trends as described by Nickelsen and Hough (18).

Of the five fundamental joint systems in table 2, only one (N 65° W'' - N 40° E' = 105° separation) satisfies the established estimation criteria. The dominant set of this system (N 40° E'), while not being the closest surface joint set to the underground face cleat is only 20° from the N 60° E actual face cleat orientation (fig. 28, table 2). The N 65° W'' set diverges 30° to 40° from the bimodal butt cleat trends. The 20° divergence of the estimated value of the face cleat from the actual value is not considered to be of such a magnitude to severely affect planning of well-density patterns or orienting slant hole drilling paths.

The N 59° E' surface joint peak is essentially the same as the N 60° E face cleat orientation observed in the underground mines (fig. 28). However, the three western joint sets that this peak could be paired with to form potential fundamental systems (Nos. 3, 4, and 5, table 2) are of very low dominance. Hence no system containing the N 59° E' joint set would meet the established criteria and be selected as an estimator of the underground cleat orientation. Although the analysis of surface joints has provided an adequate estimate of underground cleat orientations on a regional basis in the Black Warrior coal basin, it is not always reliable for an individual mine property or single quadrangle size area. Similar studies on the Pittsburgh coalbed (4-5) determined that the small number of joint readings usually obtainable for a limited area does not provide sufficient data to clearly delineate individual trends.

The geologic section above the Mary Lee Group contains numerous coalbeds. Many of these coalbeds outcrop in the study area and measurements on cleat strikes were obtained (fig. 5). The principal cleat directions from all the quadrangles were plotted on a single regional composite rose diagram (fig. 26). The composite diagram has a very pronounced face cleat peak at N 61° E, and a bimodal butt cleat peak at N 21° W and N 36° W. These peaks are essentially identical to the underground cleat orientation represented on figure 28 and in table 2. It is apparent that in areas where coalbeds outcrop at the surface, measurements and evaluation of their cleat orientations should provide the best estimate of the subsurface cleat orientation. Recent investigations in other coalbeds (17) have confirmed that cleat orientations remain parallel throughout a vertical section.

Origin of Joints and Cleats

The two fundamental surface joint systems (table 2) composed of the two dominant western sets (N 65° W^{II}-N 40° E^{I} and N 81° W^{I}-N 07° E^{I}) are quite similar to the two dominant surface joint systems (N 57° W^{I}-N 27° E^{II} and N 76° W^{I}-N 15° E^{I}) measured in the Appalachian Plateau of Pennsylvania and West Virginia (4-5, 18). Nickelsen and Hough (18) relate the origin of the western component of the two fundamental joint systems in the north-central Appalachians to extensional forces related to the principal compressive stress which was ultimately responsible for the northeast-southwest folding in the area. It seems likely that a similar origin for the N 65° W^{II} and N 81° W^{I} joint sets in Alabama is possible. The eastern component of the joint systems would probably result from late, release-type fractures resulting from a combination of residual tectonic stress differences during erosion and unloading.

Several complications to the compressive stress origin theory are recognized. The most serious problem is that in the Warrior basin the N 65° W^{II} and N 81° W^{I} surface joint sets are about 20° to 36° off, respectively, from a perpendicular orientation with the structural axis. In the north-central Appalachians, however, the dominant surface joint sets to the northwest were more nearly perpendicular to the structural axis and parallel to their associated maximum compressive stress. Nickelsen and Hough believe that in their study area the principal joints formed early, before the folding and faulting, and along slightly varying stress axes. One possible explanation is that the compressive stress from the southeast that eventually led to the formation of the folds and faults in the Alabama area was shifted to a more east-southeast orientation during the formation of the joints.

A second possible explanation for the orientation of the joints with respect to the maximum compressive stress axis of the folds is that they are associated shear fractures. The N 65° W^{II} and N 81° W^{I} joint sets are within the theoretical interval for shears associated with a compressive stress oriented at approximately N 45° W (perpendicular to the fold axes). The N 20° W^{IV} and N 7° W^{IV} surface joint trends (fig. 27) could then be the conjugates of the N 65° W^{II} and N 81° W^{I} sets, respectively. A minor complication to both compressive stress-related joint origins is that there is no obvious tangential movement observed on the joint surfaces as would be expected. However, the joint surfaces in the north-central Appalachians, as described by Nickelsen and Hough as being of compressive origin, also were similarly lacking in evidence of tangential movement.

A third possible explanation for the orientation of the dominant westerly surface joint sets is that they have a tensional origin as a result of either the warping of a sedimentary basin or the vertical growth of basement structures (18). No readily apparent, properly oriented downwarping or vertical growth is associated with the study area to produce the observed N 65° W^{II} and N 81° W^{I} joint sets by tensional forces.

The last major surface joint set to consider on figure 27 is the N 59° E^{I} trend. This set and the N 40° E^{I} set are the most dominant joints to the east.

The N 59° E' surface joint set is essentially parallel to the N 61° E composite surface face cleat (fig. 26) and the N 60° E composite underground face cleat (fig. 28). The origin of all three fractures is probably related. An origin related to the Appalachian structural front is not readily apparent. A more likely source for the stresses which produced the N 59° E' surface joint is the Ouachita orogeny in the southwest. Depending on the actual orientation of the Ouachita structural front, the N 59° E' surface joint and the face cleats could either be extensional fractures oriented parallel to the maximum compressive stress or they could be shear fractures. A tensional origin has been discounted. The maximum tensional stress related to the Warrior basin would be oriented perpendicular to the northeast-southwest axis of the depositonal basin. This tensional stress would probably not produce a fracture in the vicinity of N 60° E.

SUMMARY

The Mary Lee coalbed is the only coal of the Mary Lee Group that is persistent throughout the entire study area. It is split into as many as five benches and is comprised basically of two benches which have a combined thickness of 2 to 12 feet. The Mary Lee coalbed changes rank from a high-volatile coal, in parts of Walker County, through medium-volatile to low-volatile coal in northeastern Tuscaloosa and southwestern Jefferson Counties.

Faults in the Warrior coalfield strike north-northwest. Face cleats measured in mines operating in the Mary Lee coalbed are oriented generally parallel to the axes of folds. The butt cleats trend parallel to the strike of the faults.

Sedimentation was subject to structural control. Areas of thick coal and sediment correspond to structurally low or highly faulted portions of the basin. Individual coalbeds within the Mary Lee Group show thickness distributions which indicate original peat accumulation in fluvial-deltaic and low-lying coastal plain environments.

The methane gas resources of the Mary Lee Group coalbeds exceeds 1 trillion cubic feet in the area under investigation. Seventy percent of this gas is contained within the Mary Lee coalbed alone and, at depths exceeding 1,000 feet, methane emissions will adversely affect mining operations.

Subsurface cleat orientations can be accurately predicted on the basis of cleat directions measured at the surface. As structural complexity increases the variation in surface and subsurface cleat orientations also increases in complexity. On a local basis, proximity to structural fronts may mask regional cleat trends, but throughout a vertical section the cleat orientations remain parallel. Surface joint trends can only be used on a regional basis in the Warrior basin to determine the general orientation of cleats.

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APPENDIX A.--SURFACE JOINT READINGS OF INDIVIDUAL QUADRANGLES

NOTE: Numbered trends are arranged by increasing divergence from north and not by their order of dominance. Trends within the same vertical column of a directional group (east or west) are assumed correlative.

Quadrangle	West									
	1	2	3	4	5	6	7	8	9	10
Tier 1:										
Carbon Hill.......	-	N 16° W	-	-	N 48° W	-	N 61° W	-	-	-
Degrees deviation.	-	-	-	-	-	-	-	-	-	-
Directional mean..	-	N 16° W	-	-	N 48° W	-	N 61° W	-	-	-
Tier 2:										
Howard...........	-	N 14° W	-	N 40° W	-	-	-	N 66° W	-	-
Townley..........	-	-	N 30° W	-	N 49° W	-	-	N 73° W	-	N 87° W
Jasper...........	-	N 21° W	-	N 41° W	-	-	-	-	-	-
Cordova..........	-	N 22° W	-	N 43° W	-	-	-	-	N 77° W	N 88° W
Sipsey...........	-	-	N 30° W	-	-	-	N 62° W	-	N 84° W	-
Creel............	-	-	N 29° W	N 44° W	-	-	N 57° W	N 69° W	-	-
Warrior..........		-	-	-	-	-	N 63° W	-	N 77° W	N 88° W
Degrees deviation.	-	1	1	4	-	-	6	7	7	1
Directional mean..	-	N 19° W	N 30° W	N 42° W	N 49° W	-	N 61° W	N 69° W	N 79° W	N 88° W
Tier 3:										
Berry............	N 10° W	-	N 33° W	-	N 51° W	-	-	N 70° W	-	-
Oakman...........	N 6° W	-	-	-	-	-	-	-	-	N 89° W
Parish...........	-	N 24° W	-	-	-	-	-	-	-	N 89° W
Goodsprings.......	N 7° W	-	-	-	-	-	-	N 73° W	-	N 87° W
Dora.............	-	-	-	N 42° W	-	-	-	-	N 84° W	-
Brookside.........	N 9° W	-	N 32° W	-	-	-	N 62° W	-	N 76° W	-
Gardendale........	-	-	-	-	-	-	-	N 67° W	-	-
Pinson...........	-	N 18° W	-	-	-	-	-	N 68° W	N 84° W	-
Degrees deviation.	4	6	1	-	-	-	-	6	8	2
Directional mean..	N 8° W	N 21° W	N 33° W	N 42° W	N 51° W	-	N 62° W	N 70° W	N 81° W	N 88° W

Quadrangle	West									
	1	2	3	4	5	6	7	8	9	10
Tier 4:										
Berry SE..........	-	-	-	-	N 52° W	-	-	N 69° W	-	-
Wiley.............	N 7° W	N 20° W	-	N 39° W	-	-	N 63° W	-	N 81° W	-
Tutwiler School...	-	-	N 32° W	-	-	-	-	N 67° W	N 84° W	-
Gilmore...........	-	-	-	-	-	-	-	-	N 84° W	-
Sylvan Springs....	-	-	-	-	-	-	-	-	N 77° W	-
Adamsville........	N 2° W	-	-	-	-	-	N 61° W	-	N 77° W	-
Birmingham North..	-	-	N 33° W	-	N 54° W	-	-	-	N 84° W	-
Degrees deviation.	5	-	1	-	2	-	2	2	7	-
Directional mean..	N 5° W	N 20° W	N 33° W	N 39° W	N 53° W	-	N 62° W	N 68° W	N 81° W	-
Tier 5:										
Samantha NE.......	N 9° W	N 22° W	N 34° W	-	-	-	N 58° W	N 71° W	N 82° W	-
Searles NW........	-	-	-	-	-	-	N 57° W	-	N 75° W	-
Searles NE........	-	N 19° W	-	N 37° W	-	-	-	N 74° W	-	-
Yolande NW........	-	N 19° W	-	N 41° E	-	-	N 62° W	-	-	-
Yolande NE........	-	-	-	-	-	-	N 62° W	-	-	-
Bessemer..........	-	-	-	-	-	-	-	-	-	-
Degrees deviation.	-	3	-	4	-	-	5	3	7	-
Directional mean..	N 9° W	N 20° W	N 34° W	N 39° W	-	-	N 60° W	N 72° W	N 79° W	-
Tier 6:										
Samantha SE.......	-	-	-	-	-	N 54° W	-	N 66° W	N 79° W	-
Searles SW........	N 1° W	-	N 35° W	-	-	N 55° W	-	-	-	-
Searles SE........	-	N 18° W	-	N 45° W	-	-	-	N 68° W	N 82° W	-
Yolande SW........	-	N 13° W	-	N 43° W	-	-	-	-	N 82° W	-
Yolande SE........	N 7° W	-	-	-	-	-	-	-	N 79° W	-
Degrees deviation.	6	5	-	2	-	1	-	2	3	-
Directional mean..	N 4° W	N 16° W	N 35° W	N 44° W	-	N 55° W	-	N 67° W	N 81° W	-
Tier 7:										
Cottondale........	N 8° W	-	N 25° W	N 42° W	-	N 56° W	-	-	-	-
Coaling...........	-	-	N 27° W	N 42° W	-	-	-	N 71° W	N 82° W	-
Degrees deviation.	-	-	2	0	-	-	-	-	-	-
Directional mean..	N 8° W	-	N 26° W	N 42° W	-	N 56° W	-	N 71° W	N 82° W	-

Quadrangle	East							
	1	2	3	4	5	6	7	8
Tier 1:								
Carbon Hill.......	-	-	-	N 43° E	-	N 69° E	-	-
Degrees deviation.	-	-	-	-	-	-	-	-
Directional mean..	-	-	-	N 43° E	-	N 69° E	-	-
Tier 2:								
Howard...........	-	-	-	N 37° E	N 51° E	-	-	N 84° E
Townley..........	-	-	-	-	N 49° E	-	-	-
Jasper...........	-	-	-	N 35° E	-	N 60° E	-	N 89° E
Cordova..........	-	-	-	N 36° E	N 55° E	-	N 72° E	-
Sipsey...........	N 7° E	N 24° E	-	N 41° E	-	N 67° E	-	-
Creel............	-	N 18° E	-	-	N 47° E	-	-	-
Warrior..........	-	N 19° E	-	N 39° E	-	-	-	-
Degrees deviation.	-	6	-	7	8	7	-	5
Directional mean..	N 7° E	N 20° E	-	N 38° E	N 51° E	N 64° E	N 72° E	N 87° E
Tier 3:								
Berry............	N 11° E	-	-	-	N 51° E	-	-	-
Oakman...........	-	-	-	N 44° E	N 55° E	-	-	-
Parish...........	0	-	N 31° E	-	-	N 61° E	-	-
Goodsprings.......	N 8° E	-	-	N 41° E	-	-	-	-
Dora.............	N 2° E	N 23° E	-	N 39° E	-	-	-	-
Brookside.........	N 6° E	N 16° E	N 29° E	-	N 54° E	N 66° E	-	-
Gardendale.......	-	-	-	N 35° E	-	N 59° E	-	-
Pinson...........	N 12° E	-	-	-	-	N 67° E	-	N 87° E
Degrees deviation.	12	7	2	9	4	8	-	-
Directional mean..	N 7° E	N 20° E	N 30° E	N 40° E	N 53° E	N 63° E	-	N 87° E
Tier 4:								
Berry SE.........	-	-	-	N 44° E	-	N 60° E	-	-
Wiley............	N 1° E	-	N 33° E	N 44° E	-	N 64° E	-	-
Tutwiler School...	N 12° E	-	-	-	-	N 64° E	N 77° E	-
Gilmore..........	N 11° E	-	-	-	-	-	-	N 84° E
Sylvan Springs....	N 12° E	N 26° E	-	-	-	-	-	-
Adamsville........	-	N 22° E	-	N 41° E	N 54° E	-	N 73° E	N 87° E
Birmingham North..	N 1° E	-	-	N 37° E	N 54° E	-	-	-
Degrees deviation.	11	4	-	7	0	4	4	3
Directional mean..	N 7° E	N 24° E	N 33° E	N 42° E	N 54° E	N 63° E	N 75° E	N 86° E

Quadrangle	East							
	1	2	3	4	5	6	7	8
Tier 5:								
Samantha NE.......	-	-	-	N 41° E	-	-	-	-
Searles NW........	-	-	-	N 39° E	-	-	-	-
Searles NE........	-	-	-	-	N 52° E	-	N 78° E	N 88° E
Yolande NW........	-	-	-	N 40° E	N 59° E	-	-	-
Yolande NE........	N 11° E	-	-	N 44° E	-	N 66° E	N 79° E	-
Bessemer..........	-	-	-	-	-	-	-	-
Degrees deviation.	-	-	-	5	7	-	1	-
Directional mean..	N 11° E	-	-	N 41° E	N 56° E	N 66° E	N 79° E	N 88° E
Tier 6:								
Samantha SE.......	N 8° E	-	-	N 42° E	-	-	-	-
Searles SW........	-	-	-	N 44° E	-	-	-	-
Searles SE........	N 8° E	N 22° E	-	N 38° E	N 56° E	-	-	-
Yolande SW........	N 2° E	-	N 30° E	-	N 57° E	-	-	N 83° E
Yolande SE........	-	-	N 27° E	-	-	-	-	N 87° E
Degrees deviation.	6	-	3	6	1	-	-	4
Directional mean..	N 6° E	N 22° E	N 29° E	N 41° E	N 57° E	-	-	N 85° E
Tier 7:								
Cottondale........	-	-	-	-	N 48° E	-	-	-
Coaling...........	-	-	-	N 37° E	N 51° E	-	-	-
Degrees deviation.	-	-	-	-	3	-	-	-
Directional mean..	-	-	-	N 37° E	N 50° E	-	-	-

APPENDIX B.--SURFACE CLEAT READINGS OF INDIVIDUAL QUADRANGLES

NOTE: Numbered trends are arranged by increasing divergence from north and not by their order of dominance. Trends within the same vertical column of a directional group (east or west) are assumed correlative.

Quadrangle	West				
	1	2	3	4	5
Tier 1:					
Carbon Hill.......	-	N 24° W	N 45° W	-	-
Degrees deviation.	-	-	-	-	-
Directional mean..	-	N 24° W	N 45° W	-	-
Tier 2:					
Howard...........	-	-	-	-	-
Townley..........	-	N 19° W	-	-	-
Jasper...........	-	N 22° W	-	-	-
Cordova..........	N 6° W	N 25° W	N 37° W	-	-
Sipsey...........	N 5° W	-	-	-	-
Creel............	-	-	-	N 63° W	N 84° W
Warrior..........	-	N 16° W	-	N 70° W	-
Degrees deviation.	1	9	-	7	-
Directional mean..	N 6° W	N 21° W	N 37° W	N 67° W	N 84° W
Tier 3:					
Berry............	-	-	N 33° W	-	-
Oakman...........	-	N 24° W	N 35° W	-	-
Parish...........	-	N 24° W	-	-	-
Goodsprings.......	-	-	N 35° W	-	-
Dora.............	-	N 27° W	-	-	-
Brookside.........	N 11° W	-	N 33° W	-	-
Gardendale........	-	-	-	-	-
Pinson...........	-	-	-	-	-
Degrees deviation.	-	3	2	-	-
Directional mean..	N 11° W	N 25° W	N 34° W	-	-
Tier 4:					
Berry SE..........	-	N 22° W	-	-	-
Wiley.............	-	-	-	-	-
Tutwiler School...	-	-	N 30° W	-	-
Gilmore...........	-	N 21° W	-	-	-
Sylvan Springs....	-	N 24° W	-	-	-
Adamsville........	-	N 18° W	N 40° W	-	-
Birmingham North..	-	N 17° W	-	-	-
Degrees deviation.	-	7	10	-	-
Directional mean..	-	N 20° W	N 35° W	-	-
Tier 5:					
Samantha NE.......	-	-	N 37° W	-	-
Searles NW........	-	N 23° W	-	-	-
Searles NE........	-	-	-	-	-
Yolande NW........	-	N 19° W	-	-	-
Yolande NE........	-	-	N 32° W	N 65° W	N 76° W
Bessemer..........	-	-	-	-	-
Degrees deviation.	-	4	5	-	-
Directional mean..	-	N 21° W	N 35° W	N 65° W	N 76° W

Quadrangle	West				
	1	2	3	4	5
Tier 6:					
Samantha SE.......	-	-	-	-	-
Searles SW........	-	-	N 35° W	-	-
Searles SE........	-	-	N 34° W	-	-
Yolande SW........	-	-	N 44° W	-	-
Yolande SE........	-	-	-	-	-
Degrees deviation.	-	-	10	-	-
Directional mean..	-	-	N 38° W	-	-
Tier 7:					
Cottondale........	-	-	N 51° W	-	-
Coaling...........	-	-	N 41° W	-	-
Degrees deviation.	-	-	10	-	-
Directional mean..	-	-	N 46° W	-	-

	East						
	1	2	3	4	5	6	7
Tier 1:							
Carbon Hill.......	-	N 32° E	N 43° E	N 57° E	-	N 75° E	-
Degrees deviation.	-	-	-	-	-	-	-
Directional mean..	-	N 32° E	N 43° E	N 57° E	-	N 75° E	-
Tier 2:							
Howard............	-	-	-	-	-	-	-
Townley...........	-	-	-	-	N 67° E	-	-
Jasper............	-	-	-	-	N 68° E	-	-
Cordova...........	-	-	-	-	-	N 72° E	-
Sipsey............	-	-	-	-	-	N 75° E	-
Creel.............	N 22° E	-	-	-	-	-	N 86° E
Warrior...........	-	-	-	-	-	N 72° E	-
Degrees deviation.	-	-	-	-	1	3	-
Directional mean..	N 22° E	-	-	-	N 68° E	N 73° E	N 86° E
Tier 3:							
Berry.............	-	-	-	N 54° E	-	-	-
Oakman............	-	-	-	N 63° E	-	-	-
Parish............	-	-	-	-	N 67° E	-	-
Goodsprings.......	-	-	-	N 56° E	-	-	-
Dora..............	-	-	-	N 60° E	-	-	-
Brookside.........	-	-	-	N 59° E	-	-	N 82° E
Gardendale........	-	-	-	-	-	-	-
Pinson............	-	-	-	-	-	-	-
Degrees deviation.	-	-	-	9	-	-	-
Directional mean..	-	-	-	N 58° E	N 67° E	-	N 82° E

Quadrangle	East						
	1	2	3	4	5	6	7
Tier 4:							
Berry SE..........	-	-	-	-	N 70° E	-	-
Wiley.............	-	-	-	-	-	-	-
Tutwiler School...	-	-	-	N 63° E	-	-	-
Gilmore...........	-	-	-	-	N 67° E	-	-
Sylvan Springs....	-	-	-	-	N 65° E	-	-
Adamsville........	-	-	-	N 54° E	-	-	-
Birmingham North..	-	-	-	-	N 67° E	-	-
Degrees deviation.	-	-	-	9	5	-	-
Directional mean..	-	-	-	N 59° E	N 67° E	-	-
Tier 5:							
Samantha NE.......	-	-	-	N 64° E	-	-	-
Searles NW........	-	-	-	N 64° E	-	-	-
Searles NE........	-	-	-	-	-	-	-
Yolande NW........	-	-	-	N 63° E	-	-	-
Yolande NE........	N 12° E	-	-	N 63° E	-	-	N 81° E
Bessemer..........	-	-	-	-	-	-	-
Degrees deviation.	-	-	-	1	-	-	-
Directional mean..	N 12° E	-	-	N 64° E	-	-	N 81° E
Tier 6:							
Samantha SE.......	-	-	-	-	-	-	-
Searles SW........	-	-	-	N 54° E	-	-	-
Searles SE........	-	-	N 47° E	N 57° E	N 68° E	-	-
Yolande SW........	-	-	N 43° E	-	-	-	-
Yolande SE........	-	-	-	-	-	-	-
Degrees deviation.	-	-	4	3	-	-	-
Directional mean..	-	-	N 45° E	N 56° E	N 68° E	-	-
Tier 7:							
Cottondale........	-	-	-	N 56° E	-	-	-
Coaling...........	-	-	-	N 53° E	-	-	-
Degrees deviation.	-	-	-	3	-	-	-
Directional mean..	-	-	-	N 53° E	-	-	-

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