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GEOLOGY AND COAL RESOURCES OF THE UPPER PART OF THE HORSESHOE CANYON FORMATION RED DEER AREA ALBERTA

By

J. R. Nurkowski

Alberta RESEARCH COUNCIL

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ABSTRACT

The upper Horseshoe Canyon Formation in the Red Deer area is studied to determine successive depositional environments and to relate these environments to the development of Carbon and Thompson coals. It is intended that these objectives contribute to sedimentological models which aid coal exploration and exploitation.

Four informal lithologic units were recognized. In stratigraphic order, these are the lower and upper fine units, consisting mainly of siltstones with minor shales and fine grained sandstones, and an overlying coal-bearing sequence, the Carbon and Thompson coal zones, consisting of coarser grained sandstones, coals, siltstones and shales. It is suggested that the name Whitemud Formation be abandoned, at least in the subsurface, and the rocks be included with the Horseshoe Canyon Formation. Evidence favours a lacustrine origin for the older fine grained dominated unit. The succeeding coal-bearing sequence accumulated in a meandering fluvial system, with the coarser clastics (sand size and greater) representing active channel fill, the finer clastics (very fine grained sands, silts and clays) representing inactive channel fill and overbank deposits and the coals representing back-levée, channel fill and flood basin swamps, developing parallel to the paleochannels. Within each coal-bearing zone, there are pronounced northwest-southeast alternating bands, typically 4 to 7 miles (6.4 to 11.3 km) wide, of preferred coal and sandstone development which relate to the spatial distribution of the abovementioned paleoenvironments. This result agrees with previous findings, notably work on the provenance of Upper Cretaceous sands, in indicating paleodrainage from the northwest.

Carbon and Thompson coals are low in percent sulfur (0.35 to 0.61 percent) and variable in ash content and non-coal partings. Coal resources are 6.640×10^9 tn (6.029×10^9 t) for the Carbon and 3.205×10^9 tn (2.910×10^9 t) for the Thompson for all coal seams at least 2 ft (0.6 m) thick, and 3.200×10^9 tn (2.906×10^9 t) for the Carbon and 1.100×10^9 tn (9.988×10^8 t) for the Thompson for all coal seams at least 2 ft (0.6 m) thick and with a cumulative thickness in excess of 6 ft (1.8 m).

Exploration for thick Carbon and Thompson coal seams should be concentrated within the northwest-southeast trends of thicker coal accumulation. As the regional dip is to the west, exploitation of seams in the western portion of the study area should be limited to underground mining and/or in situ gasification because of the large overburden thickness. Near-surface Carbon and Thompson coal seams, in the eastern portion of the study area, may be exploitable by strip mining methods.

INTRODUCTION

Recent sedimentologic studies have shown that recognizing paleoenvironments of coal-bearing sequences is an important tool to both coal exploration and development. For example, geometric aspects such as seam thickness and continuity, and quality characteristics such as susceptibility to splits and sulfur content, can be related to the paleoenvironments of the coal and associated strata.

The Coal Geology Group of the Geological Survey Department, Alberta Research Council, has been actively involved in coal resource studies of the plains area of Alberta. Between 1978 and 1980 the coals of the Upper Cretaceous Carbon and Thompson coal zones of the upper Horseshoe Canyon Formation were studied. This study goes beyond the scope of earlier studies, which were principally concerned with coal resource inventories, to include the details of stratigraphy and depositional environments of the coal seams and associated strata.

ACKNOWLEDGEMENTS

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STUDY AREA AND DATA USED

The study area extends from Tp 30 to 42, R 21 W4M to the fifth meridian (Fig. 1), and covers approximately 3132 square miles (8111 km^2). Data from 297 existing oil and gas wells were used, with 133 of these wells having the necessary suite of logs to determine coal thickness and percent sand. Twenty-two ARC 1978 testhole logs and six outcrop sections, measured by Gibson (1977), were also used for coal thicknesses. Cuttings and core from the ARC 1978 program provided very useful information toward the interpretation of paleoenvironments for the study area.

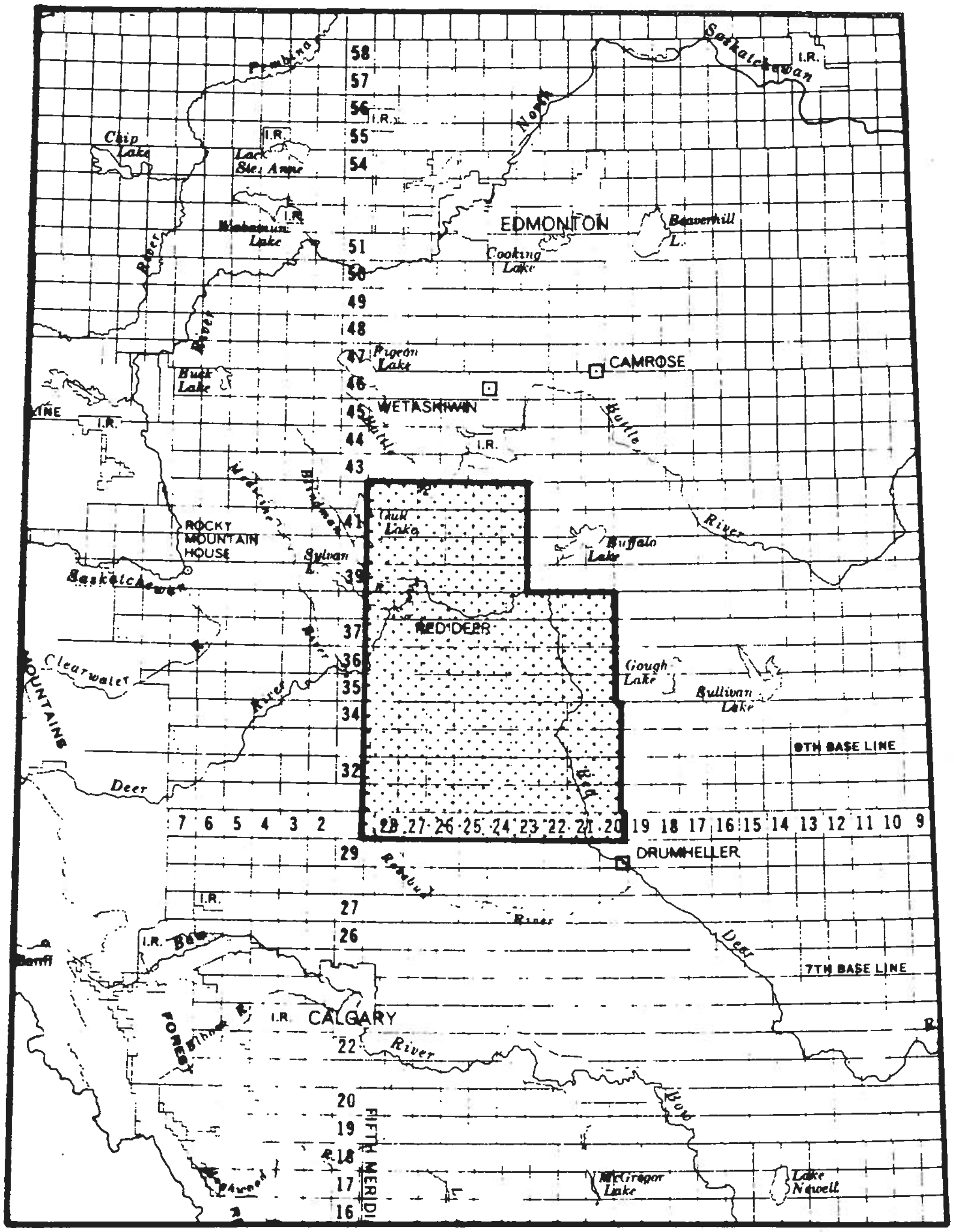

FIGURE 1. Study area

STRATIGRAPHIC NOMENCLATURE

The stratigraphic unit formerly designated as the Edmonton Formation, of Late Cretaceous age, was first described in detail by Allan and Sanderson (1945) and studied further by Ower (1960), Irish (1970) and Gibson (1977). Four alternative schemes of stratigraphic nomenclature for the study section are given in figure 2. The study section of this report extends from a level near the top of the Drumheller Marine Tongue (Allan and Sanderson, 1945) of the Horseshoe Canyon Formation to the top of the Battle Formation (Gibson, 1977). Within the study section, the sediments underlying the Battle Formation are considered a part of the Horseshoe Canyon Formation, thus discarding, at least in subsurface, the use of the term Whitemud Formation of Irish (1970) and Gibson (1977). Figure 3 relates to the surface and subsurface stratigraphy as defined by Allan and Sanderson (1945), Ower (1960) and this paper.

PREVIOUS WORK

Outcrop sections were studied by all the above-mentioned authors, with Ower (1960) and Irish (1970) increasing their area of investigation by including geophysical logs. A fluvial to fluvial-deltaic depositional setting for a major portion of the Horseshoe Canyon Formation is generally agreed upon by these authors. The sedimentology and palynology of the Battle Formation and immediate underlying sediments are described by Binda (1970) and Binda and Lerbekmo (1973). The depositional environment of the underlying sediments is interpreted as fluvial, grading upward to lacustrine for the Battle Formation. Srivastiva (1968) inferred the paleoclimatic conditions of "Edmonton" time from a palynologic study as varying from humid subtropical to warm temperate. Rahmani and Lerbekmo (1975) interpreted the paleodrainage direction for the Horseshoe Canyon Formation from a heavy mineral dispersal study as NW-SE.

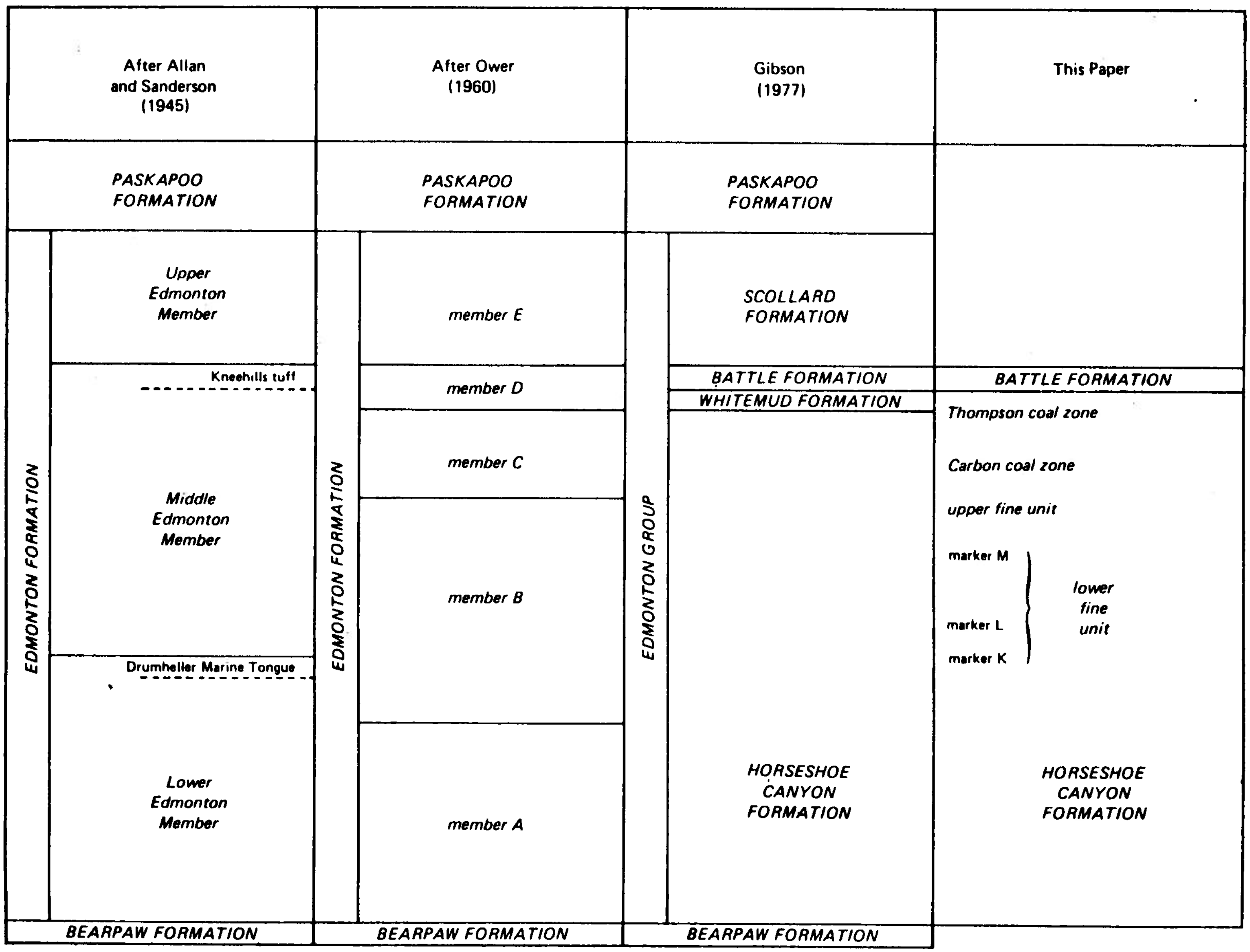

FIGURE 2. Stratigraphic nomenclature (modified after Gibson, 1977) showing present study's modification of the upper Horseshoe Canyon Formation

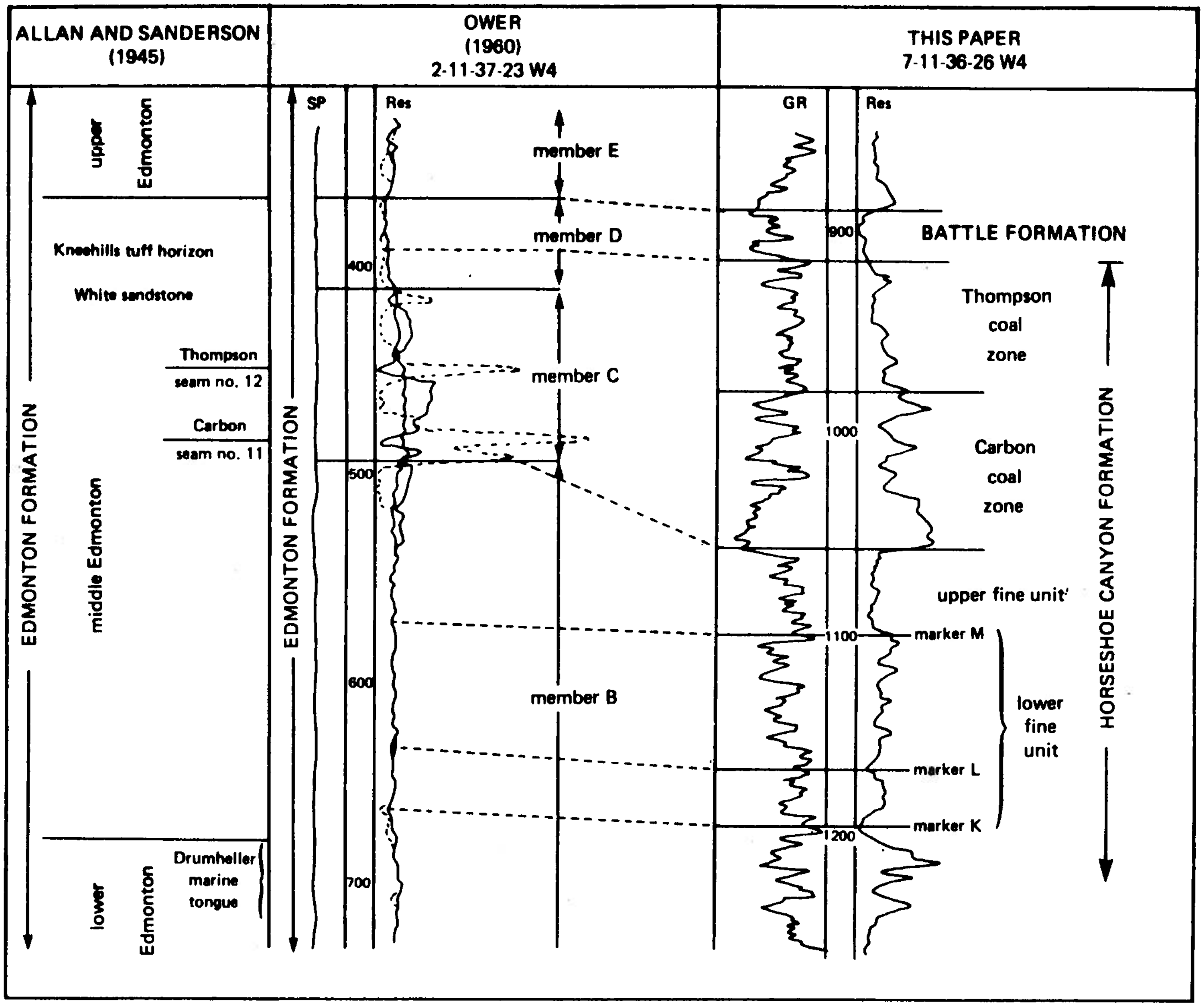

FIGURE 3. Surface/subsurface stratigraphic relationship between Allan and Sanderson (1945), Ower (1960) and this paper

METHODS OF STUDY

Coal thicknesses were determined by means of a resistivity log, gamma ray log, and one of a density log, sonic log or neutron log. As tool calibrations used on the porosity logs from oil and gas wells are different from those required for coal determinations, relative deflections, rather than fixed cutoffs, were used.

On logs obtained from ARC testholes, lithologies with densities less than 1.8 g/cc and with corresponding high resistivities and low gamma readings were taken as indicative of coal. Coal seams with thicknesses of two feet (0.6 m) and thicker were used to produce the cumulative coal thickness maps (Figs. 4 and 5). Determinations of sand were made from gamma ray logs using porosity and resistivity logs as aids. A shale base line, as determined by the average highest gamma readings, was first drawn and the sand cutoff was taken at approximately 15 API units less than the shale base line. Percent sand maps are presented on figures 6 and 7.

Due to the westerly dip of the Horseshoe Canyon Formation, more oil and gas wells are available as data points in the western portion of the study area where the study section is below the average surface casing depth. Data for the eastern portion of the study area is limited to ARC wells and outcrop information. Three marker beds were found within the upper Horseshoe Canyon Formation and these, along with the Battle Formation were used for stratigraphic correlation and map construction. The lower two marker beds, designated "K" and "L", appear to be bentonites or bentonitic shales, exhibiting lower resistivity and density readings and slightly higher gamma readings on logs. Both marker beds vary in thickness from 5 to 20 feet (1.5 to 6 m). From log response, marker bed M is also bentonitic and is often accompanied by a lithologic change (Fig. 3). Where a bentonitic shale is developed as marker bed M, it varies in thickness from 5 to 10 feet (1.5 to 3 m).

The study section of the upper Horseshoe Canyon Formation is divided informally into four units, with the units defined by marker beds and/or major changes in lithology. These units, in an ascending order, from the

K marker bed to the base of the Battle Formation (Figs. 2 ad 3), are termed as follows: lower fine unit, upper fine unit, Carbon coal zone and Thompson coal zone.

The lower and upper boundaries of the lower fine unit and the base of the upper fine unit are defined by marker beds K and M, as noted in figure 3. The boundary between the upper fine unit and the Carbon coal zone is marked by a lithologic change as discussed below. The Carbon and Thompson coal zones, extending from the top of the upper fine unit to the base of the Battle Formation, are lithologically similar in that both are coal bearing and coarser grained than the underlying units. The subdivision of this coal-bearing sequence was made for two reasons. The first is based on an increase in the number and coarseness of sandstone beds in the interval enclosing the Thompson coals; this will be described more fully in a later section. Secondly the subdivision maintains the traditional nomenclature. Ower (1960) describes four horizons of coal seam occurrence in his member C (Fig. 3); a horizon near the top, a second horizon 20 ft (6 m) below the top, a third horizon 60 ft (18 m) below the top and a fourth horizon 80 to 90 ft (24 to 27 m) below the top. He equates the upper two and lower two horizons to Allan and Sanderson's (1945) Thompson (no. 12) and Carbon (no. 11) seams, respectively. Gibson (1977), from sections measured in this study area, recognized the Carbon seam and Thompson seam 44 to 97 ft (13 to 30 m) and 16 to 54 ft (5 to 16 m), respectively, below the base of the Battle Formation. Gibson (1977) also notes the development of secondary seams associated with both his Carbon and Thompson seams.

In this report, all coals found from 60 ft (18 m) below the Battle Formation to the top of the upper fine unit are considered Carbon coals and along with their associated lithologies comprise the Carbon coal zone. The coals from the base of the Battle Formation to the top of the Carbon coal zone are considered Thompson coals and along with their associated lithologies comprise the Thompson coal zone. In wells where coal was not encountered within the uppermost 60 ft (18 m) of the Horseshoe Canyon Formation the division between the Carbon and Thompson coal zones was placed arbitrarily, usually at a lithology change about 60 ft (18 m) below the Battle Formation.

This study indicates coal seams can occur throughout the entire interval, from the top of the upper fine unit to the base of the Battle Formation. In order to document the vertical distribution of coal seams, the Carbon and Thompson coal zones were further subdivided into subzones, each subzone representing successive 20 ft (6 m) intervals below the Battle Formation. Thompson coal seams are therefore represented by subzones 1, 2 and 3, to a level 60 ft (18 m) below the Battle Formation. Carbon coal seams are represented by subzones 4 through 8, the latter (subzone 8) represents the lowermost development of coal in the study section, occurring 140 to 160 ft (43 to 49 m) below the Battle Formation. The number of coal seams 2 ft (0.6 m) and thicker encountered in boreholes in the study area are plotted, with respect to coal subzones, on figure 8.

The base of this study section occurs between 260 and 400 ft (80 to 122 m) below the top of the Battle Formation, corresponding to the K marker bed. The maximum true depth of the base of the study section is 1950 ft (504 m), encountered in the southwest portion of the study area.

LITHOSTRATIGRAPHY AND COAL DISTRIBUTION

LOWER FINE UNIT

The lower fine unit is defined by marker bed K at the base and by marker bed M at the top and contains marker bed L (Figs. 2 and 3). The interval between marker K and marker M is very consistent in thickness, varying from 95 to 105 ft (30 to 32 m) throughout most of the study area. Marker beds K, L and M can be correlated south of Tp 40 with a high degree of confidence, but north of Tp 40 they become more difficult to correlate although the enclosing lithology remains the same.

Cutting samples indicate that the lower fine unit consists mainly of pale green, calcareous, argillaceous siltstones, sandy siltstones and minor very fine and fine grained sandstones. The samples characteristically lack coals and carbonaceous material. A number of wells indicate an upward coarsening pattern on gamma ray logs, grading from high gamma, "shaly" readings at the base to lower gamma, "sandy" readings near the top (Fig. 9).

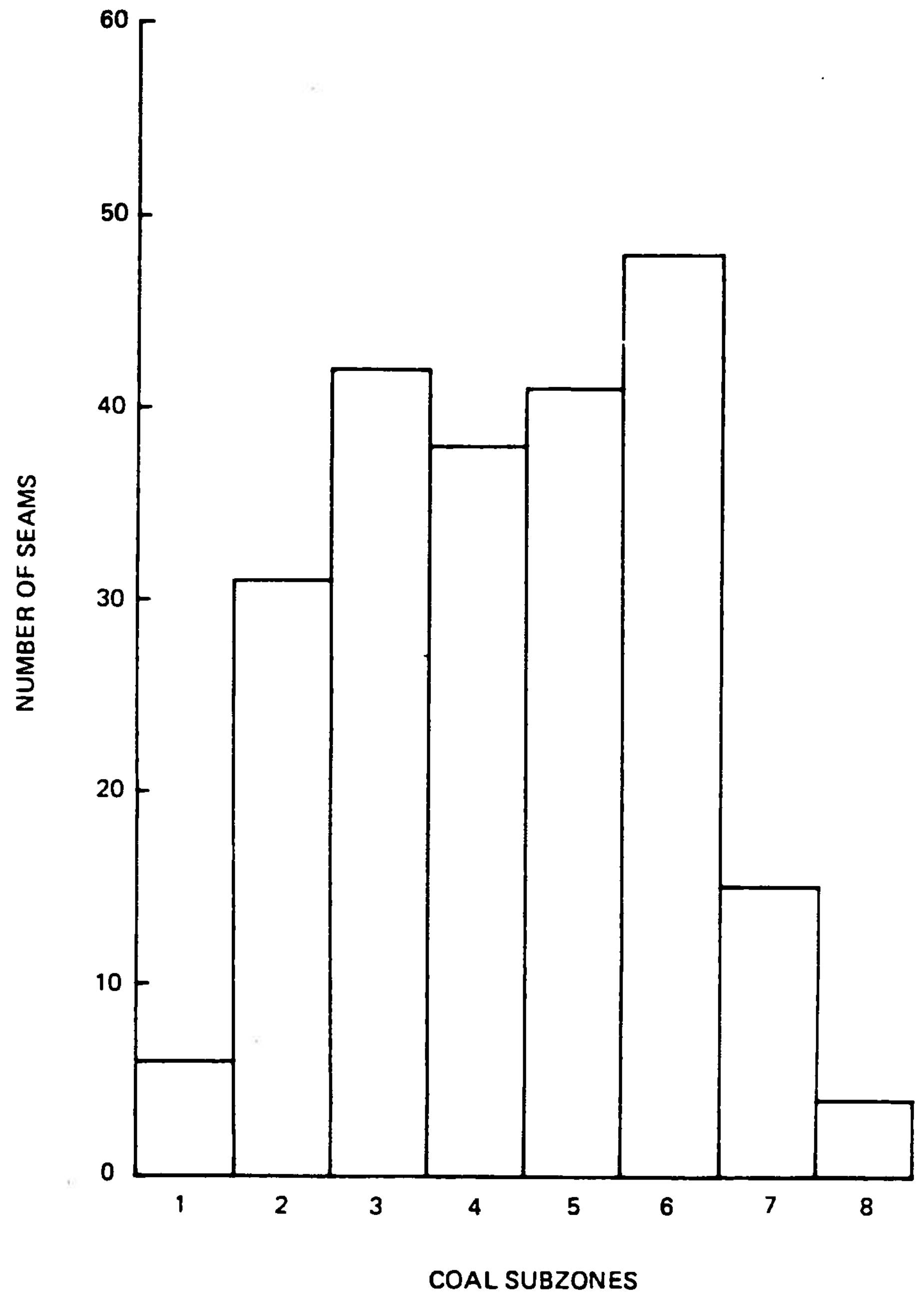

FIGURE 8. A histogram of coal subzone vs number of coal seams

The lithology described here for this unit is similar to the lithologic description given by both Ower (1960) and Gibson (1977) for their equivalent units.

Ower (1960) noted oyster shell fragments at an interval underlying the K marker bed in his figure 1, well 7-14-30-17W4M, east of this study area. These shell remains are considered to be part of the Drumheller Marine Tongue, a marine invasion that occurred during the deposition of the mid to upper Horseshoe Canyon Formation (Fig. 2).

Palynological results from outcrop samples collected 70 ft (21 m) above the Drumheller Marine Tongue at Horseshoe Canyon, 10 miles (16 km) west of Drumheller, indicated abundant *Azolla* megaspores. Sample cuttings from ARC Th 25-78, at a depth of 571 ft (174 m) (within the lower fine unit), were barren of organic remains.

UPPER FINE UNIT

Marker Bed M defines the base of the upper fine unit and the upper boundary is marked by the appearance of the first overlying coal or major sand development. This unit varies in thickness from 40 to 100 ft (12 to 30 m). Lithologically it is very similar to the lower fine unit, i.e. mostly silt size range sediment and with no coal. In wells where the basal sediments of the overlying Carbon coal zone are fine grained and non coal-bearing, a distinction cannot be made between the upper fine unit and the Carbon coal zone.

CARBON COAL ZONE

As previously defined, the Carbon coal zone occurs between the upper fine unit and the Thompson coal zone. The Carbon coal zone is differentiated from the underlying fine units by coarser grained (very fine to lower medium grained sand, Fig. 10) and thicker sandstone bodies and presence of coal seams. As well as sandstone and coal, siltstones and shales are also present. The sands are lithic with a "salt and pepper" appearance. Coal spars represent an estimated 5 to 10 percent of the grains in some sandstones.

Gamma ray log patterns through the Carbon coal zone indicate sandstone bodies varying from thin and isolated to interbedded, to thick and massive. Sandstones have an average maximum thickness of 30 ft (9 m) (ARC-25-78, 7-11-36-26W4M, Figs. 11 and 12). Sandstone bodies with abrupt basal contacts and an upward fining of grain size are found in the Carbon coal zone both in core and as indicated by gamma ray log patterns. Core description from ARC testhole 16-78 (Fig. 10) shows an upward fining tendency in a sandstone bed present in the interval 480 to 459 ft (146 to 140 m). This sandstone body has a sharp, possibly scoured, basal contact, with the sandstone varying in grain size from fine grained at the base, through very fine grained, to interbedded silt-shale-sandstone at the top. Another example is seen in figure 12 (well 7-11-36-26W4M, interval 1063 to 1020 ft [324 to 311 m]).

Percent sand for the Carbon coal zone was calculated from the interval between marker "M" and the base of the Thompson coal zone, thus including the upper fine unit in these calculations. Lack of a reliable marker at the base of the Carbon coal zone dictated the inclusion of the upper fine unit in calculating percent sand. The average percent sand in the Carbon coal zone throughout the study area is 18 percent. Areas underlain by higher than average abundance of sandstone (>20%) are emphasized on figure 6. In some cases the values indicate single bed of sandstone while in others they represent cumulative thickness of several sandstones. Although areal control is limited and sandstone occurrences are variable, pronounced NW-SE trends of sand accumulation are present.

Siltstones and shales represent a significant portion of the Carbon coal zone. Their color varies from pale green to light gray to dark gray and their structure from laminated to massive (Fig. 10). Well preserved plant fragments are common.

As previously discussed, Carbon coals are represented by coal subzones 4 through 8 (Fig. 8), with the best coal seam development occurring in subzones 5 and 6, 100 to 140 ft (30 to 43 m) below the base of the Battle Formation. A histogram showing the thickness of Carbon coal seams encountered in all oil and gas wells and ARC testholes is shown on figure 13. The maximum thickness attained for a Carbon coal seam is 13 ft (4 m), at location 7-13-36-27W4M (Fig. 12).

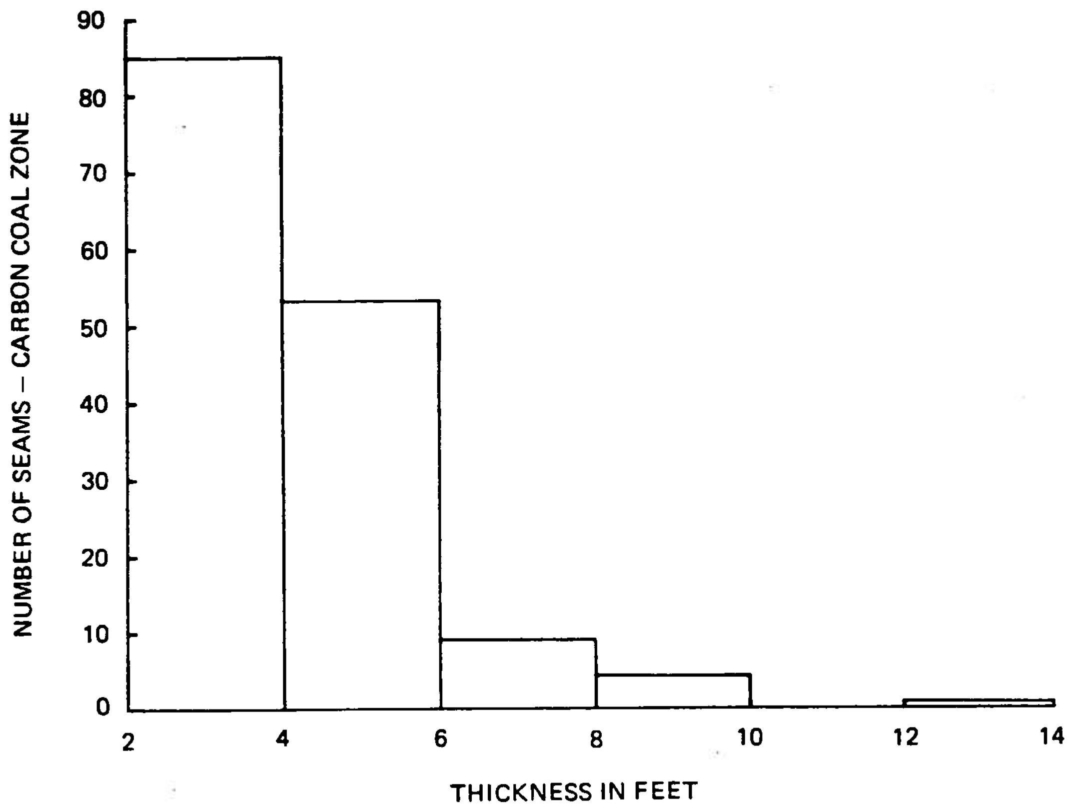

FIGURE 13. Frequency distribution of coal seam thicknesses in the Carbon coal zone

Contours of cumulative coal thickness values for the Carbon coal zone are shown in figure 4. Although the contouring becomes speculative in certain areas because of scarcity of control, pronounced NW-SE trends of thick coal accumulation are again visible. Subsurface correlation of Carbon coals is possible along the trends of maximum coal accumulation (Fig. 12), but becomes more difficult in a direction normal to the trends.

THOMPSON COAL ZONE

The Thompson coal zone represents the rocks occurring between the Carbon coal zone and the Battle Formation. This zone consists of sandstones, siltstones, shales and coals, with the sandstones being coarser grained and more massive than those in the Carbon coal zone. The grain size of the sandstones varies up to a maximum of lower coarse grained (Fig. 10), occasionally with clasts and pebbles up to 1 in (2.5 cm) in diameter (Fig. 10, at depth 436 ft [133 m]). Gamma ray log patterns and core description (Fig. 10, interval 444 to 421 ft [135 to 128 m]) indicate a weak upward fining of grain size. This tendency has also been noticed in outcrop by Binda and Lerbekmo (1973) and Gibson (1977) for equivalent sands.

The average percent sand for the Thompson coal zone throughout the study area is 36 percent. Areas underlain by higher than average abundance of sandstone are emphasized on figure 7. Well developed NW-SE trends are present.

The siltstones and shales in the Thompson coal zone are similar to those found in the Carbon coal zone, varying in color from pale green to dark gray and often containing plant fragments.

Coal subzones 1, 2 and 3 indicate the coal seam development in the Thompson coal zone (Fig. 8), with figure 14 showing a histogram of Thompson coal seam thickness. Coal development in the Thompson coal zone

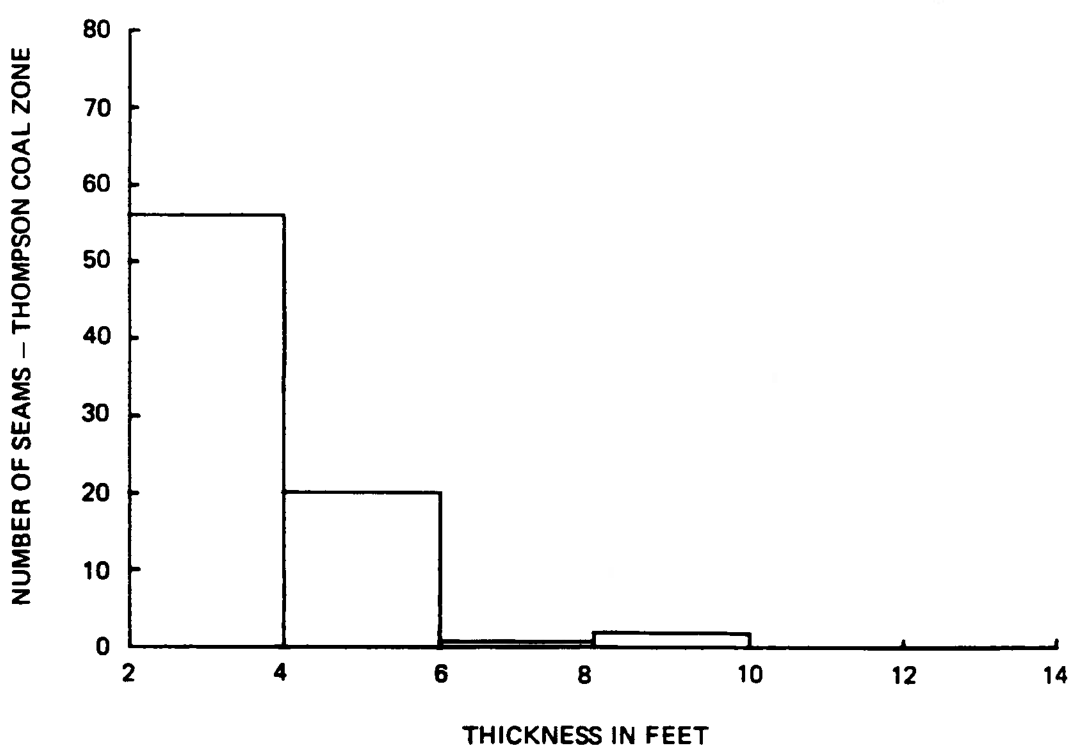

FIGURE 14. Frequency distribution of coal seam thicknesses in the Thompson coal zone

zone is similar to that of the Carbon coal zone, with areas of greatest coal accumulation forming sinuous bands trending NW-SE (Fig. 5).

As previously mentioned, the term Whitemud Formation (Irish, 1970; Gibson, 1977) that has been used to describe the white weathering lithology immediately underlying the Battle Formation has been discarded in this report. Rapid lateral and vertical facies changes of these sediments makes their correlation for any considerable distance rather difficult. Furthermore, the white coloration considered a distinctive feature of the Whitemud Formation is not as prominent in subsurface core and cuttings samples. In effect, it cannot be distinguished from the Horseshoe Canyon Formation.

Binda (1970) suggested that the Whitemud Formation, as recognized in the Cypress Hills area, should not be applied to the white sandstone underlying the Battle Formation in the central and southern plains area since a direct lithologic correlation is impossible. Binda (1970) also proposes that the sediments lying between the Drumheller Marine Tongue and the base of the Battle Formation of the plains area should be regarded as one unit.

BATTLE FORMATION

The Battle Formation provides a very characteristic subsurface marker useful in defining the upper boundary of the coal bearing interval of this study. The formation's low resistivity response on electric logs and accompanied slightly high gamma reading can be found in most wells (Figs. 3, 9, 11, and 12). Core cut in the Battle Formation from ARC Th 13-78 indicated the very characteristic mauve brown shale, with a siliceous, dense, hard, "siltstone like" bed 1 ft (30 cm) thick, probably representing the Kneehills tuff. A structural map on the top of the Battle Formation is provided on figure 15. The dip of the formation varies from 15 to 30 ft per mile (2.8 to 5.7 m per km), the greater dip found in the west to southwest portion of the study area. Occasional erosion or non-deposition of the Battle Formation does occur, indicated by dashed contouring on figure 15 (Tp 38, R27) and on figure 8, well 7-36-36-26W4M.

COAL QUALITY

Analysis of core samples from the 1978 program indicate the sulfur content to vary from 0.35 to 0.61 percent, the ash content from 7.25 to 17.00 percent and the heating value (total moisture basis) from 10974 to 11842 BTU/lb (6097 to 6579 cal/g).

Horne *et al.* (1978) relate the sulfur content of coal to the depositional setting of the coal seam. Iron disulfides, appearing as marcasite or pyrite, have been recognized in three forms: coarse grained masses (greater than 25μ) replacing original plant material, coarse grained platy masses occupying joints and framboidal pyrite, occurring as finely disseminated grains (0.25μ) throughout the coal. The framboidal pyrite was found to have been produced by sulfur-reducing microbial organisms of marine to brackish waters. Coals overlain by marine to brackish sediments were found to have high (greater than 2 percent) sulfur contents, of which 75 percent was attributed to the framboidal form of pyrite (Caruccio *et al.*, 1977, in Horne *et al.*, 1978). Coals formed and buried without a marine influence are found to have lower sulfur contents.

Ash content of coals can be attributed to clastic input during the development of the peat swamp. Splits and partings in coal seams are due to river flooding (Rehbein, 1977) or splaying (Horne *et al.*, 1979) and tend to be more numerous near the river channels (Rehbein, 1977).

COAL RESOURCES

Coal resources for the Carbon and Thompson coal zones were calculated from their cumulative coal thickness maps. A clean coal density of 1.35 g/cm^3 was chosen, indicating one section foot = 1.174 x 10^6 tn (1 km^2 m = 1.35 x 10^6 t).[1] A planimeter was used to determine the surface

[1] 1 tn = 2000 lbs (1 t = 1000 kg)

areas within each 2 ft (0.6 m) contour from the cumulative coal thickness maps. Fifteen percent of the calculated resources were subtracted to account for undetected splits or partings in the coal seams when coal seam thicknesses were determined from geophysical logs. Coal resources for the Carbon and Thompson coal zones are presented on table 1.

TABLE 1

Coal Resources of the Carbon and Thompson coal zones.

	Cumulative coal thickness of 2 ft (0.6 m) and thicker	Cumulative coal thickness of 6 ft (1.8 m) and thicker
Thompson coal zone	3.205×10^9 tn (2.910×10^9 t)	1.100×10^9 tn (9.988×10^8 t)
Carbon coal zone	6.640×10^9 tn (6.029×10^9 t)	3.200×10^9 tn (2.906×10^9 t)

AREAS OF POTENTIAL DEVELOPMENT

Wells encountering single Carbon or Thompson coal seams at least 6 ft (1.8 m) thick and their respective coal subzone are shown on figure 17. The best area for deep coal development, as indicated by existing well control, is within Tp 36 R 27 W4M. Thick (>6 ft [1.8 m]) Carbon or Thompson coal seams with thin overburden (less than 300 ft [91 m]) were not encountered. The 1000 ft (305 m) depth contour to the top of the Battle Formation (Fig. 17) represents a guideline to the approximate depth of thick coal seam development.

DEPOSITIONAL HISTORY

Rocks described above fall into three natural lithologic divisions; the lower and upper fine units forming the first, the Carbon and Thompson coal zones forming the second and the Battle Formation forming the third.

LOWER AND UPPER FINE UNITS

Comparing Gibson's (1977) outcrop descriptions of rocks overlying the Drumheller Marine Tongue to sample cuttings from the lower and upper fine units and correlating marker bed K east of this study area to Ower's (1960, his Fig. 1) study area indicates that the lower fine unit overlies the Drumheller Marine Tongue. The marine invasion represented by the Drumheller Marine Tongue is the last known incursion of the Bearpaw Sea (Ower, 1960). As no faunal break was found from the beds below to the beds above the Drumheller Marine Tongue, Sternberg (1947) suggests the marine invasion was of short duration.

Gibson (1977) suggested deposition by shallow braided streams for the interval overlying the Drumheller Marine Tongue to the base of the Carbon coal zone (as defined by this report). Walker and Cant (1978) mention that silt and clay size material tend to be transported through a braided stream system without accumulation. The lack of coarse grained material, the abundance of fine grained material and the lack of sharp erosional contacts on geophysical logs does not support Gibson's (1977) interpretation of braided stream deposition.

Two depositional models for the lower and upper fine units are proposed here; a lacustrine model and a fluvial model.

A number of the formations described by Collinson (1978) that are considered lacustrine in origin (e.g., Lockatong Formation of New Jersey and Escuminac Formation of southern Quebec) are remarkably similar to the lithology of the lower fine unit in parts of the study area. The lacustrine type formations are dominated by fine grained sediments, often calcareous, with minor sandstones. The upward coarsening sequences found on a number of gamma ray log patterns through the lower fine unit, suggesting sediment progradation, can also be found in modern lacustrine environments as deltas

(Collinson, 1978). Singh (pers. comm., 1980) indicates that the abundance of *Azolla* megaspores, recovered from sediment collected above the Drumheller Marine Tongue, supports lacustrine deposition for these sediments. Furthermore, the deposition and preservation of widespread marker beds is most likely to occur in subaqueous environment.

The lack of coals and carbonaceous material in the lower and upper fine units of this report is explained by Gibson (1977), for his equivalent section, as a function of aridity. This, however, is in disagreement with Srivastiva (1968), who interprets climatic conditions from microfloral content for this period as humid subtropical to humid continental. The lack of organics in the lower and upper fine units can be explained in light of the proposed lacustrine environment. Collinson (1978) associates low nutrient levels in modern lacustrine environments with low levels of organic productivity, which in turn allows the lake water to remain oxygenated (oligotrophic). The low levels of organic productivity as well as the oxygenated water conditions would cause the remaining sediment to be relatively depleted in organic remains.

A second proposal for the deposition of these sediments follows a model discussed by McCave (1969), where marine transgressions are correlated to a "laterally persistent thicker than normal section of fine grained overbank alluvium," on the landward or continental area of deposition. Figure 16 documents an example from the Middle and Upper Devonian of New York State. McCave's (1969) hypothesis suggests that a marine transgression raises the base level of in-coming rivers, thus decreasing the transporting power of these rivers. This results in deposition within the river channels and causes a greater frequency of flooding. The effect of raising the base level would be simultaneous throughout the lower floodplains of all in-coming rivers thus the overbank deposits are laterally persistent. McCave (1969) also mentions that these anomalously thick overbank alluvial deposits are likely to contain more evidence of swamp and lake deposition than normal overbank alluvial deposits.

Evidence of a marine transgression occurs in this study section with the presence of Drumheller Marine Tongue below marker bed K. The lower and upper fine units of this report (as traced by marker beds K, L and M) are

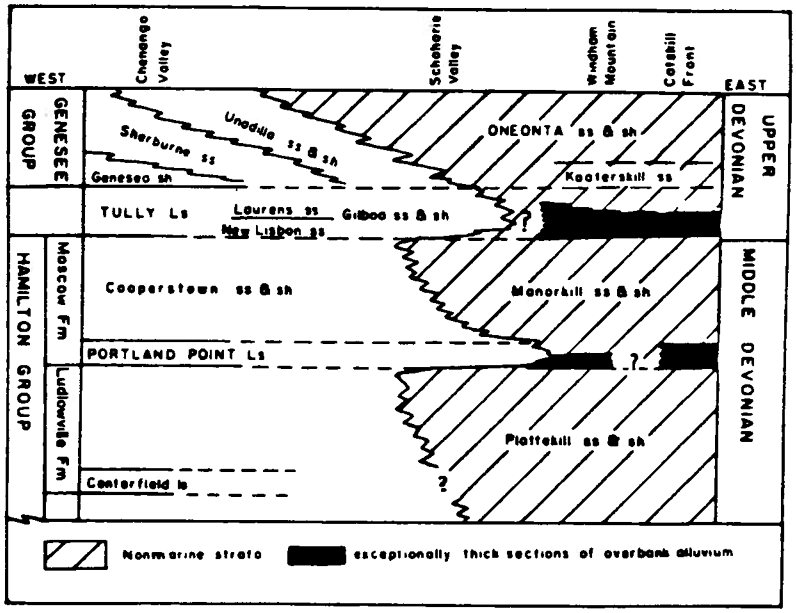

FIGURE 16. Correlation of non-marine strata with marine transgressions. Marine transgressions are indicated by Portland Point and Tully limestones (modified after McCave, 1969)

laterally persistent as they occur through a major portion of the study area. Sedimentologic characteristics of the rocks in these units fit Allen's (1964) description of vertically accreting overbank deposits; namely, the lack of coarse grained material, abundance of fine grained material and presence of small scale cross-bedding as noted by Gibson (1977).

Problems in following McCave's (1969) model for the deposition of the lower and upper fine units are the lack of "channel type" sands representing the source of the overbank alluvium and the lack of coals, which should have developed in the associated swamps.

The following lithologic and facies characteristics occur in the lower and upper fine units: 1) the sediments are dominantly fine grained; 2) marker beds persist throughout a major portion of the study area; 3) gamma ray logs indicate an upward coarsening of grain size in the lower fine unit; 4) carbonaceous material and coals are lacking; 5) abundant *Azolla* megaspores are present; and 6) the lower fine unit overlies a marine transgression.

From evidence cited above, deposition within a widespread lacustrine environment appears more likely. If McCave's (1969) model does apply, the lacustrine aspect of the model would have been the dominant feature.

CARBON AND THOMPSON COAL ZONES

At the end of the deposition of the upper fine unit, energy conditions began to change, as evidenced by the appearance of coarser grained, thick sandstones, and coals. The first appearance of these sandstones occurs at a level 40 ft (12 m) above marker bed M.

Sandstone bodies, as noted in core and gamma ray logs, with sharp basal contacts and an upward fining of grain size have long been considered indicative of meandering river deposition (Allen, 1964, and others). Walker and Cant (1979) mention that sand body geometry of meandering rivers will be elongate or "shoestring" like, bounded on both sides by flood basin fines. As observed from subsurface logs, sandstone bodies in the Carbon and Thompson coal zones appear to be lenticular and isolated, in a section normal to their NW-SE trend, and are enclosed by finer grained sediments.

Coal occurrence in a fluvial environment is discussed by authors such as Weimer (1976), Kaiser *et al.* (1978), Beaumont (1979) and others. Weimer (1976) indicates coal development along-side levéed channels occurs as back-levée swamps and flood-basin swamps, with the back-levée swamps forming linear trends, parallel to the channels. The flood-basin swamps are larger and are located further from active channels. Beaumont (1979) studied the coals and enclosing sediments of the Fort Union Formation (Tertiary, northwest Colorado) and found thick coals paralleling major sand accumulations. The sand accumulations are interpreted as a result of meandering stream deposition and are parallel to the paleodrainage direction. Kaiser et al. (1978) report a similar situation for the Calvert Bluff Formation (Eocene, Texas) where a meandering fluvial depositional system was interpreted, and the coals were concentrated in elongate trends, parallel to each other and to the paleoslope. Furthermore, Kaiser *et al.* (1978) found areas of high sand concentration correlated with areas of low coal concentration.

Rahmani and Lerbekmo (1975) studied the heavy mineral dispersal patterns for the Upper Cretaceous and Tertiary rocks of central to southern Alberta and southwestern Saskatchewan and determined that the paleodrainage direction for the "Edmonton slice" (Horseshoe Canyon Formation) was from NW to SE. This direction is the same as the direction of major accumulation of sandstones and coals in the Carbon and Thompson coal zones.

The following lithologic and facies characteristics occur in the Carbon and Thompson coal zones: 1) sandstones are upward fining in grain-size; 2) sandstones are lenticular; 3) fine clastics are abundant; 4) sediments are of a continental affiliation (palynology); 5) major sandstone and thick coal accumulations are parallel and sinuous; and 6) sandstone and coal development is parallel to the regional paleodrainage direction. These facies geometries and relationships are similar to those found by other authors (discussed above) where deposition by meandering or high sinuous river conditions are interpreted.

From geophysical log and core observations, the number of sand bodies, along with their thickness and grain size, increases from near the base of the Carbon coal zone to near the top of the Thompson coal zone. The increase in sandstone is, in part, shown by the percent sand maps of the Carbon and Thompson coal zones. This, along with the occurrence of pebble size material (Gibson, 1977, and this report, Fig. 10) at the base of sandstones in the Thompson coal zone would indicate energy conditions gradually increased from the Carbon coal zone to the Thompson coal zone, wanning again prior to the deposition of the Battle Formation.

BATTLE FORMATION

As the Battle Formation is not of primary interest in this report, Binda's (1970) interpretation of deposition in a widespread swampy/lacustrine environment will be accepted at the present time.

EXPLORATION MODEL

The thick coal accumulation trends for the Carbon and Thompson coal zones (Figs. 4 and 5) are well established in the western portion of the study area and can be projected easterly (up dip) toward the outcrop section. Exploitation of coal in the western portion of the study area will be limited to underground mining and/or in situ gasification methods because of high overburden thicknesses. The eastern portion of the study area has potential for surface mining because the overburden becomes progressively thinner in an easterly direction. Exploration for thick Carbon and Thompson coal seams should be limited to the areas within the trends of potential thick coal development. Marker beds K, L and M can be used for drilling control to mark the lower limit and the Battle Formation can be used to mark the upper limit of Carbon and Thompson coal development.

Coal seams within the Carbon and Thompson coal zones are lenticular, with their direction of greatest continuity parallel to the paleoslope (NW-SE). The sulfur content of these seams is low and the number of splits and partings within the seams is variable, increasing in areas proximal to channels.

SUMMARY AND CONCLUSIONS

Two litho-types were recognized in the upper Horseshoe Canyon Formation, the lower and upper fine units forming the first and the overlying Carbon and Thompson coal zones forming the second.

Lithologically the lower and upper fine units consist mainly of argillaceous siltstones, with minor fine grained sandstones. Three wide-spread bentonitic marker beds were found and, along with the Battle Formation, were used for stratigraphic correlation. An upward coarsening of grain size through the lower fine unit was found on a number of gamma ray logs. The deposition of the lower and upper fine units is interpreted as being within a lacustrine environment.

The Carbon and Thompson coal zones consist of sandstones, siltstones, shales and coal seams, with the sandstones being considerably more abundant, thicker and coarser grained than the sandstones in the lower and

and upper fine units. Sandstone bodies in the Carbon and Thompson coal zones show an upward fining of grain size. Areas of greatest accumulation of sandstones and coals form sinuous trends, parallel to each other and to the NW-SE paleodrainage direction. Sediment deposition and coal seam formation is interpreted to have occurred within a fluvial, meandering river system. The coarser clastics (sand size and greater) represent mainly active channel fill and the finer clastics (very fine sands, silts and clays) represent mainly inactive channel fill and overbank type deposits. The coals represent back-levée, flood-basin and channel fill swamps.

Carbon and Thompson coals are low in present sulfur and have variable amounts of ash and non-coal partings. Coal resources are calculated to be 6.640×10^9 tn (6.029×10^9 t) for the Carbon and 3.205×10^9 tn (2.910×10^9 t) for the Thompson for all coal seams at least 2 ft (0.6 m) thick, and 3.200×10^9 tn (2.906×10^9 t) for the Carbon and 1.100×10^9 tn (9.988×10^8 t) for the Thompson for all coal seams at least 2 ft (0.6 m) thick, but with a cumulative thickness in excess of 6 ft (1.8 m).

In exploiting Carbon and Thompson coal deposits, especially by underground mining and in situ gasification methods, their facies geometries should be seriously considered. Areas of potential development are restricted to within the individual NW-SE trends of major coal accumulation. Determination of the depositional environments of these coals also helps in predicting coal quality parameters, such as sulfur content and susceptibility to splits.

REFERENCES CITED

Allan, J.A. and Sanderson, J.O.G. (1945): Geology of Red Deer and Rosebud sheets, Alberta; Research Council of Alberta, Report No. 13, 110 p.

Allen, J.R.L. (1964): Studies in fluviatile sedimentation: Six cyclothems from the Lower Old Red Sandstone, Anglo-Welsh Basin; Sedimentology, v. 3, p. 163-198.

Beaumont, E.A. (1979): Depositional environments of Fort Union sediments (Tertiary, Northwest Colorado) and their relation to coal; The American Association of Petroleum Geologists Bulletin, v. 63, No. 2, p. 194-217.

Binda, P.L. (1970): Sedimentology and vegetal micropaleontology of the rocks associated with the Cretaceous Kneehills Tuff of Alberta; unpublished Ph.D. thesis, University of Alberta, 273 p.

Binda, P.L. and Lerbekmo, J.F. (1973): Grain-size distribution and depositional environment of Whitemud sandstones, Edmonton Formation (Upper Cretaceous), Alberta; Bulletin Canadian Petroleum Geology, v. 21, No. 1, p. 52-80.

Collinson, J.D. (1978): Alluvial sediments; in H.G. Reading (editor), Sedimentary Environments and Facies; Blackwell Scientific Publications, England, p. 15-60.

Collinson, J.D. (1978): Lakes; in H.G. Reading (editor), Sedimentary Environments and Facies; Blackwell Scientific Publications, England, p. 61-79.

Gibson, D.W. (1977): Upper Cretaceous and Tertiary coal-bearing strata in the Drumheller-Ardley region, Red Deer River Valley, Alberta; Geological Survey of Canada, Paper 76-35, 41 p.

Horne, J.C., Ferm, J.C., Caruccio, F.T., and Baganz, B.P. (1978): Depositional models in coal exploration and mine planning in Appalachian Region; The American Association of Petroleum Geologists Bulletin, v. 62, No. 12, p. 2379-2411.

Irish, E.J.W. (1970): The Edmonton Group of south-central Alberta; Bulletin Canadian Petroleum Geology, v. 18, No. 2, p. 125-155.

Kaiser, W.R., Johnston, J.E., and Bach, W.H. (1978): Sand body geometry and the occurrence of lignite in the Eocene of Texas; Proceedings of the Second Symposium on the Geology of Rocky Mountain Coal, 1977, Colorado Geological Survey, Resource Series 4, p. 67-87.

McCave, I.N. (1969): Correlation of marine and non-marine strata with example from Devonian of New York State; The American Association of Petroleum Geologists Bulletin, v. 53, No. 1, p. 155-162.

Ower, J.R. (1960): The Edmonton Formation; Journal of the Alberta Society of Petroleum Geologists, v. 8, No. 11, p. 309-323.

Rahmani, R.A. and Lerbekmo, J.F. (1975): Heavy-mineral analysis of Upper Cretaceous and Paleocene sandstones in Alberta and adjacent areas of Saskatchewan; in W.G.E. Caldwell (editor), The Cretaceous System in the Western Interior of North America, Geological Association of Canada, Special Paper 13, p. 607-632.

Rehbein, E.A. (1977): Preliminary report on stratigraphy and depositional environments of the lignites in the Fort Union Formation, West-Central North Dakota; United States Geological Survey, open file report 77-69, 23 p.

Srivastiva, S.K. (1968): Angiosperm microflora of the Edmonton Formation, Alberta, Canada; unpublished Ph.D. thesis, University of Alberta.

Sternberg, C.M. (1949): The Edmonton fauna and description of a new *Triceratops* from the Upper Edmonton Member: Phylogeny of the Ceratopsidae; Annual Rept. 1947-1948, National Museum Bulletin No. 113, p. 33-46.

Walker, R.G. and Cant, D.J. (1979): Sandy fluvial systems; in R.G. Walker, (editor), Facies Models, Geoscience Canada Reprint Series 1, Geological Association of Canada, p. 23-33.

Weimer, R.J. (1976): Stratigraphy and tectonics of western coals; in D.K. Murry, (editor), Geology of Rocky Mountain Coal, a symposium, Colorado Geological Survey, Resource Series 1, p. 9-27.

ERRATUM

Drafting processes used in producing the enclosed maps (Figs. 4, 5, 6, 7, 15, 17) involved photographing overlaps, and in this process, a slight offset occurred between the indicated location (i.e. oil, gas or abandoned well indicated by a ■) and the actual location of the data wells. This offset is noticeable in the southern portion of the maps.

The indicated locations (i.e. ■'s) should be moved north, up to 1 mm, to cover the oil, gas or abandoned well they represent.

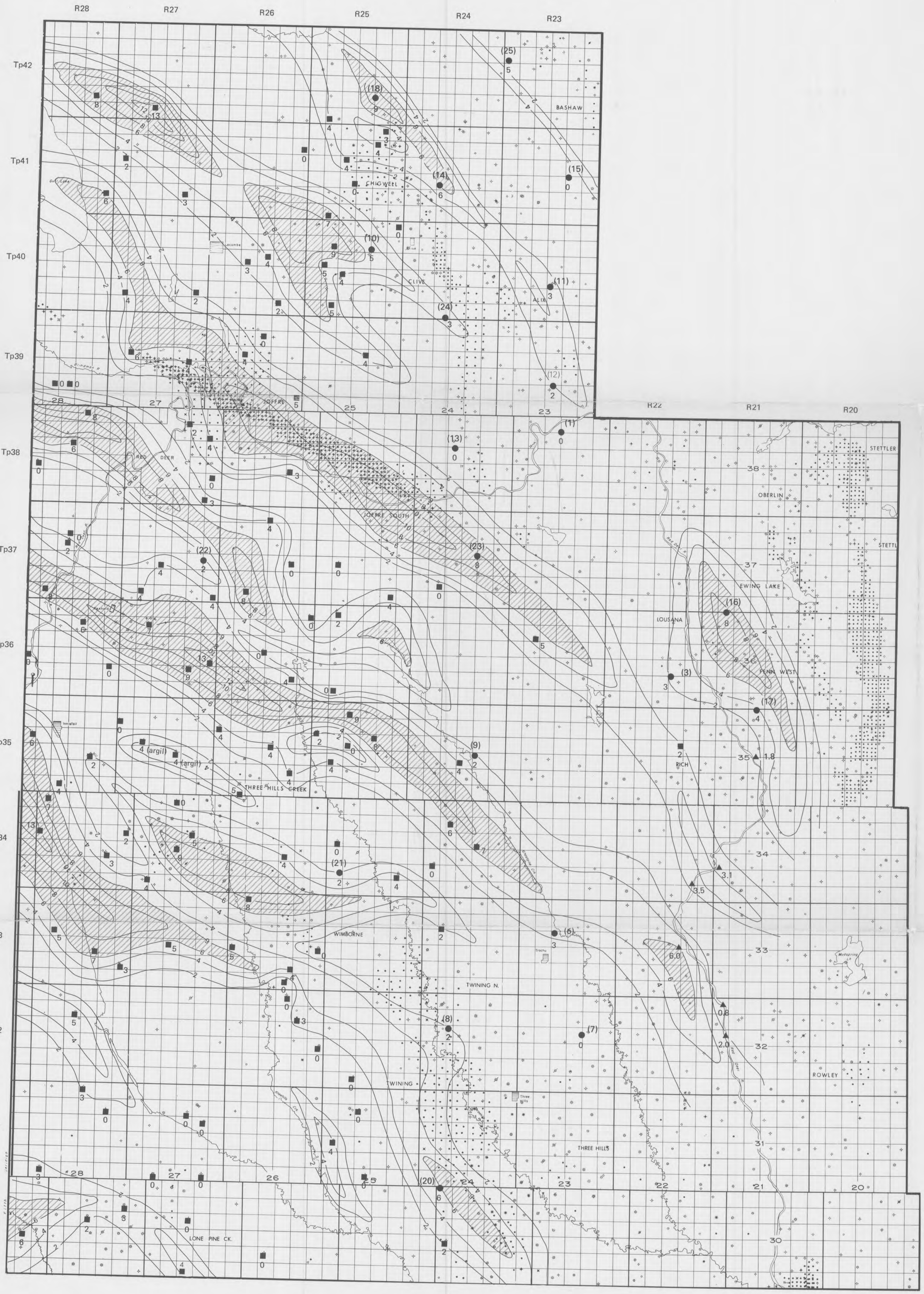

FIGURE 4. CARBON COAL ZONE CUMULATIVE COAL THICKNESS

1978 ARC testhole number .... (16)
Coal thickness 8

Oil, gas, or abandoned well ....
Coal thickness 4

Outcrop location (after Gibson, 1977) ....
Coal thickness 1.8

Coal thickness greater than 6 feet ....

C.I. = 2 feet

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MILES
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0 4 8 12 16
Km

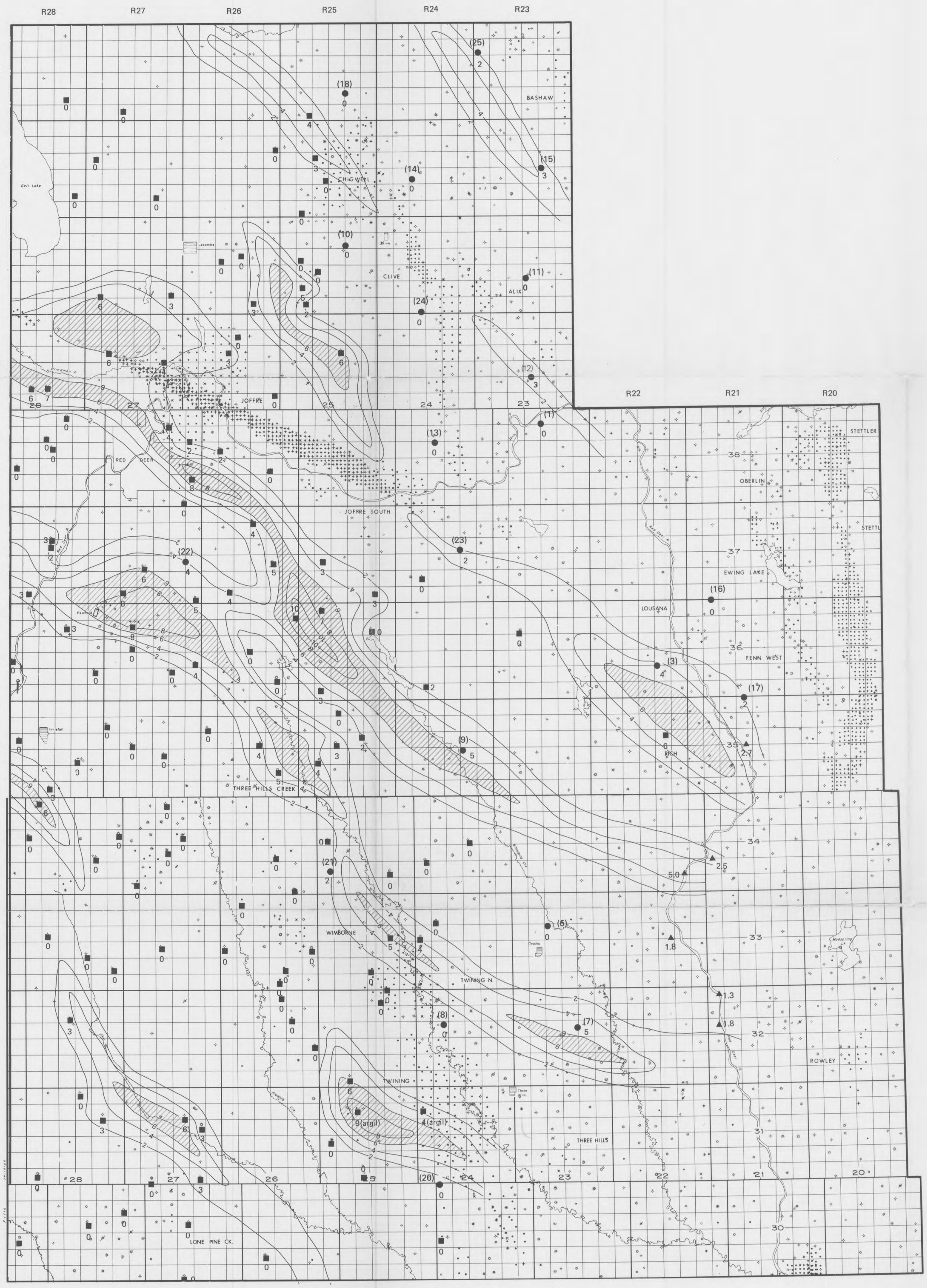

FIGURE 5. THOMPSON COAL ZONE CUMULATIVE COAL THICKNESS

1978 ARC testhole number .... (7) ●
Coal thickness 5

Oil, gas, or abandoned well .... ■
Coal thickness 0

Outcrop location (after Gibson, 1977) .... ▲
Coal thickness 1.3

Coal thickness greater than 6 feet ....

C.I. = 2 feet

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MILES
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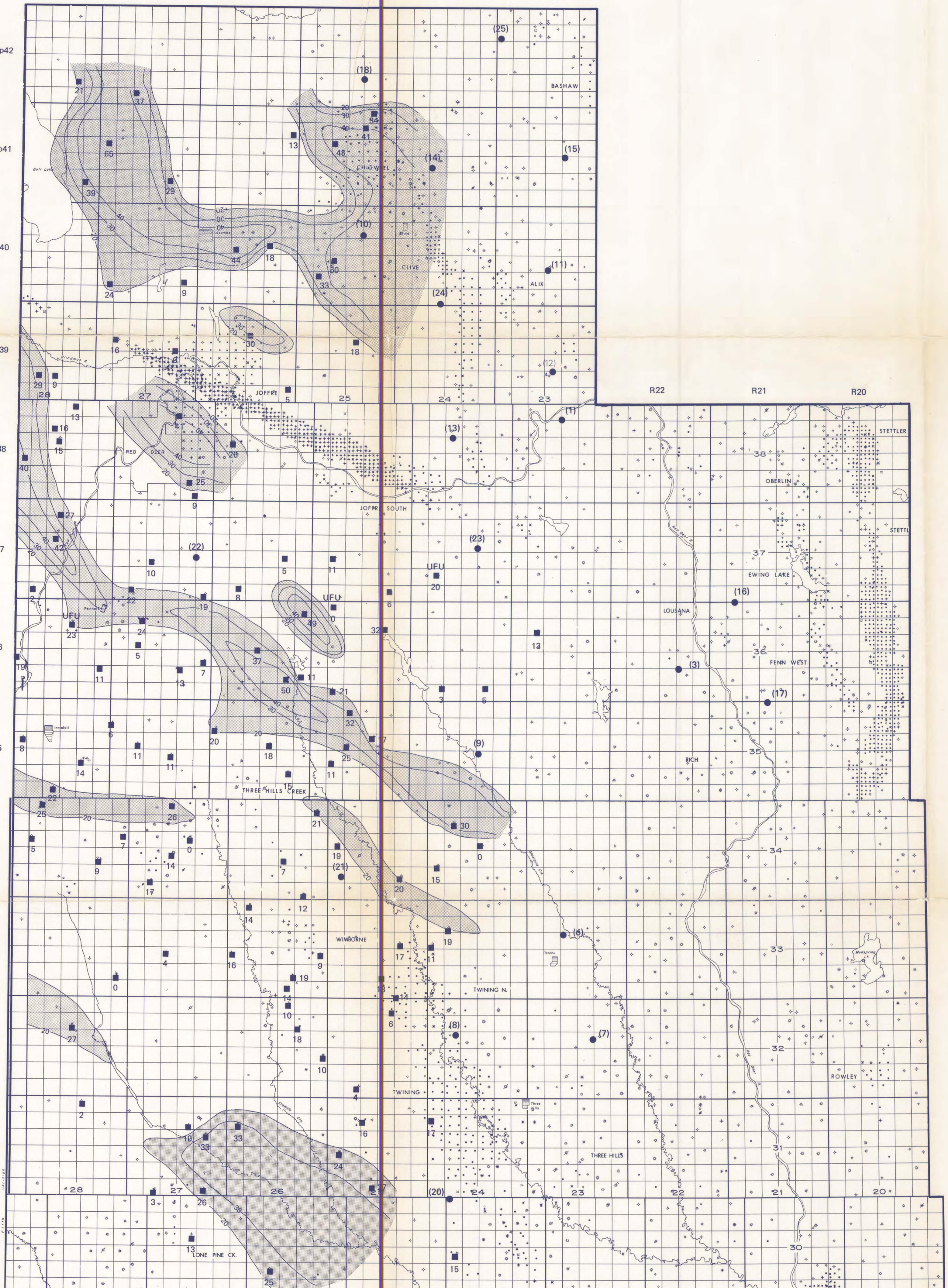

FIGURE 6. CARBON COAL ZONE PERCENT SAND

1978 ARC testhole number .... (3) ●

Oil, gas, or abandoned well .... ■
Percent sand 7

Greater than 20 percent sand ....

Sand contribution mainly from upper fine unit .... UFU

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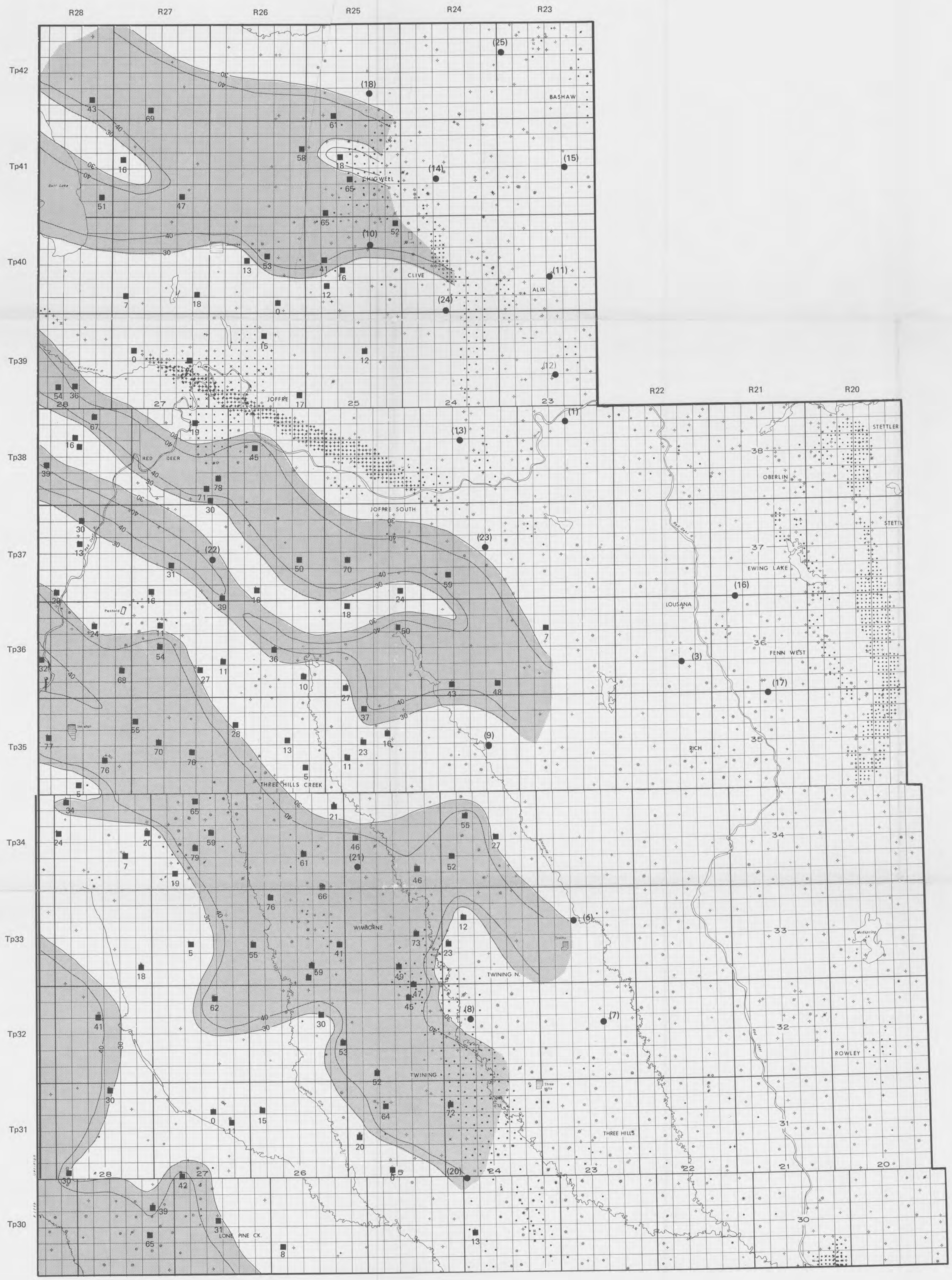

FIGURE 7. THOMPSON COAL ZONE PERCENT SAND

1978 ARC testhole number . . . . (16)

Oil, gas, or abandoned hole . . . . ■
Percent sand 7

Greater than 30 percent sand . . . .

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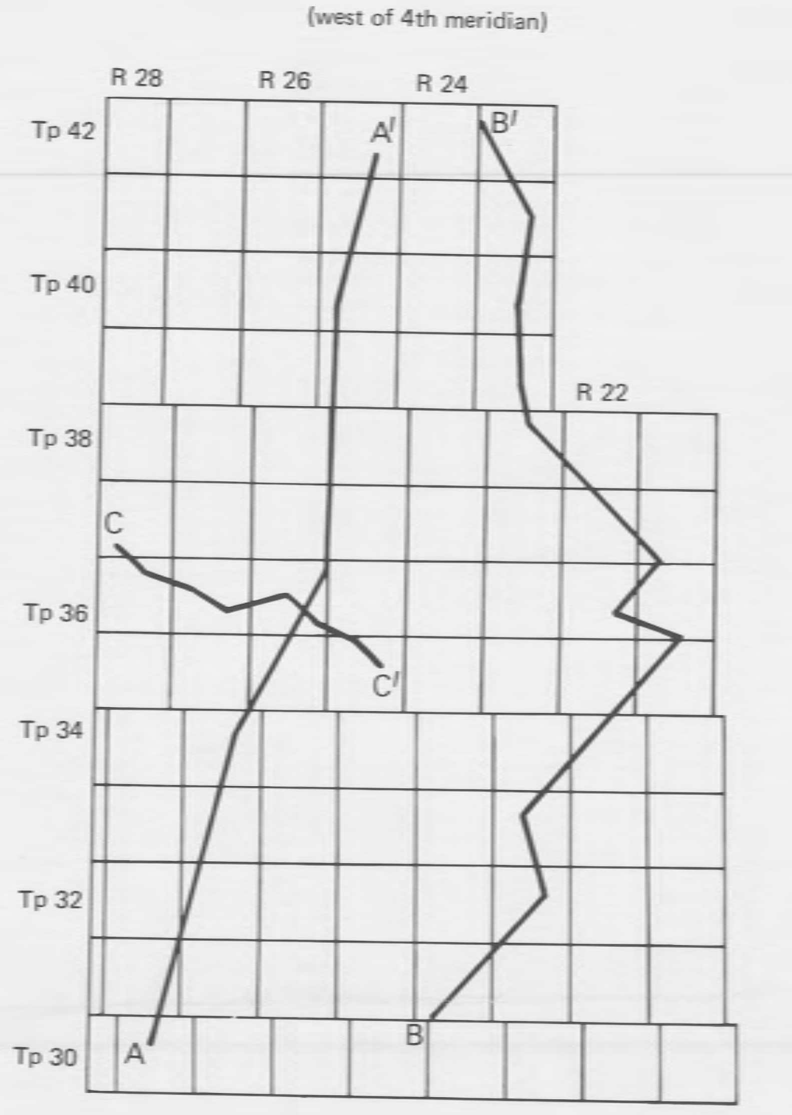


Cross section location map

LEGEND

Erosion ....

Upward fining grain size ....

Upward coarsening grain size ....

NOTES

Dashed lines indicate inferred correlation.
Bracketed numbers beside coal seams indicate thickness of seam (feet).

FIGURE 9. Cross section A-A′

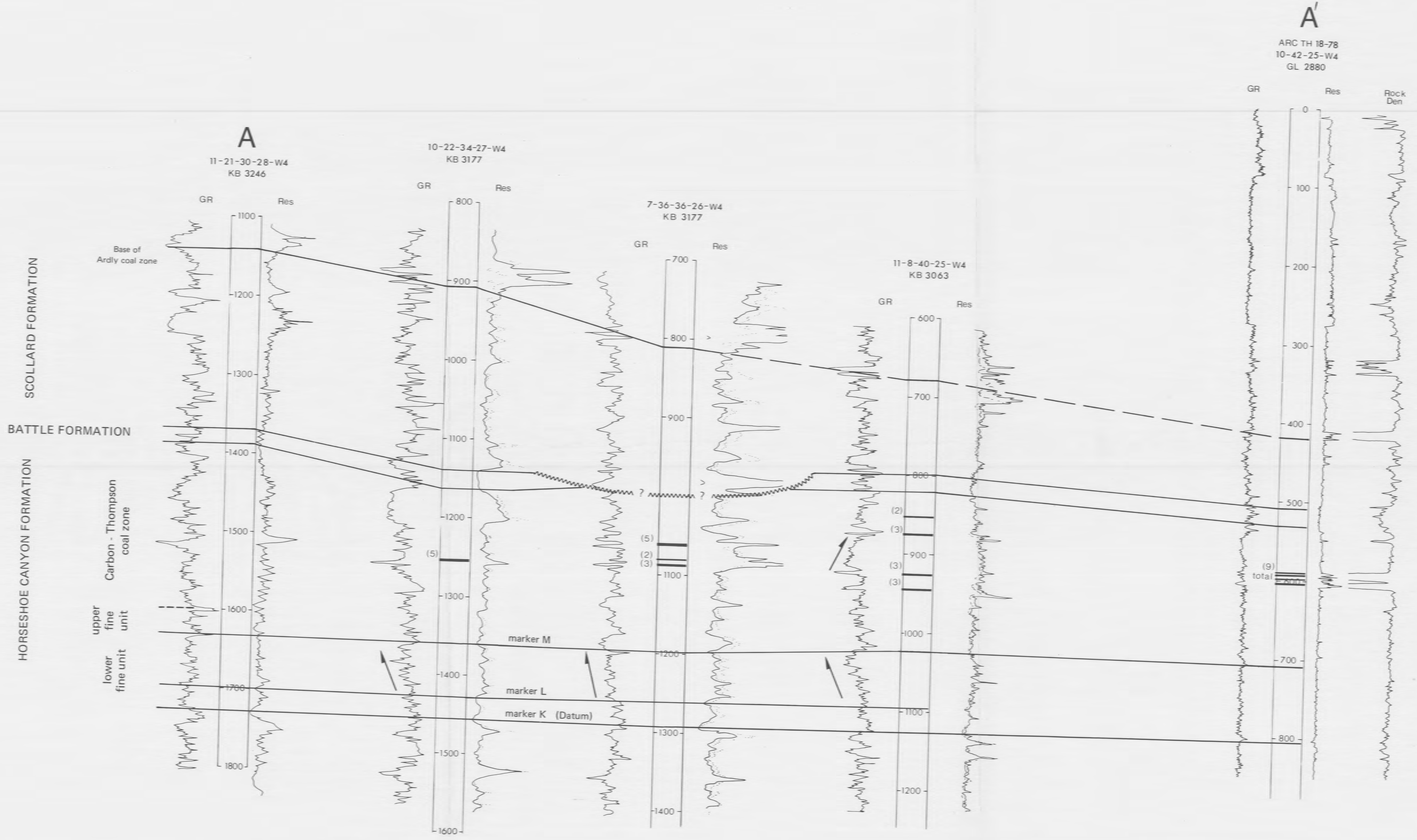
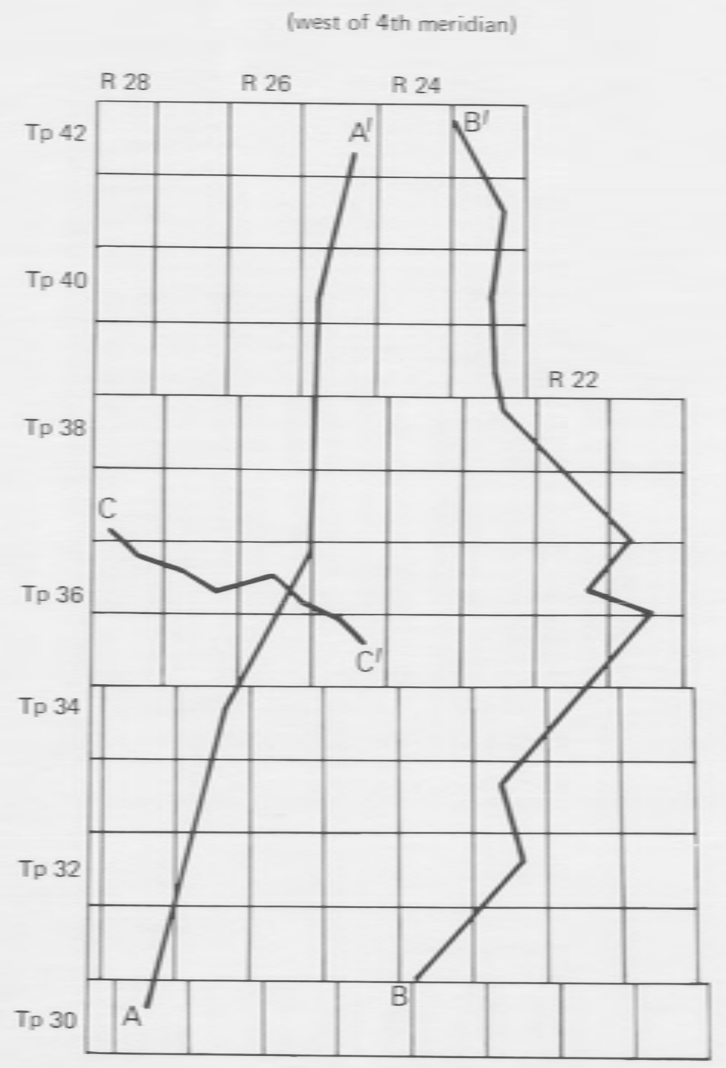


FIGURE 10. CORE AND SAMPLE LITHOLOG DESCRIPTION (ARC 16-78)



Cross section location map

LEGEND

Erosion . . . .

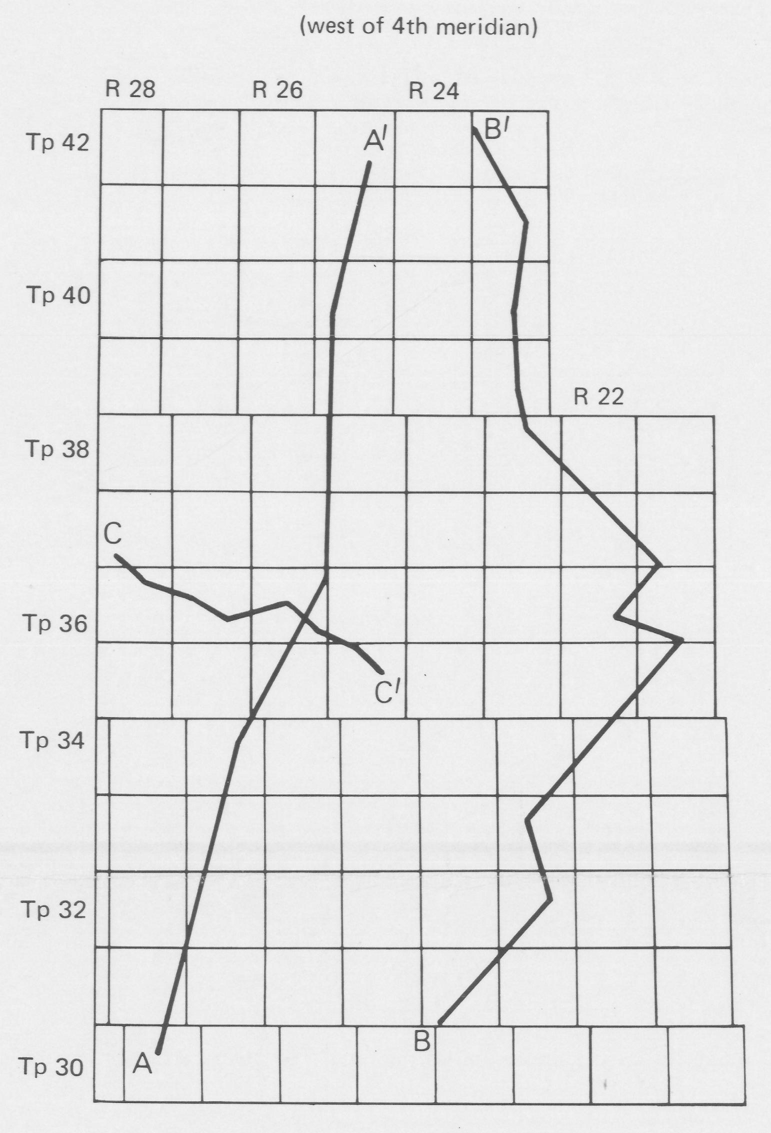
Upward fining grain size . . . .

Upward coarsening grain size . . . .

NOTES

Dashed lines indicate inferred correlation.
Bracketed numbers beside coal seams indicate thickness of seam (feet).

FIGURE 11. Cross section B-B'



Cross section location map

LEGEND

Erosion . . . .

Upward fining grain size . . . .

Upward coarsening grain size . . . .

NOTES

Dashed lines indicate inferred correlation.
Bracketed numbers beside coal seams indicate thickness of seam (feet).

FIGURE 12. Cross section C-C′

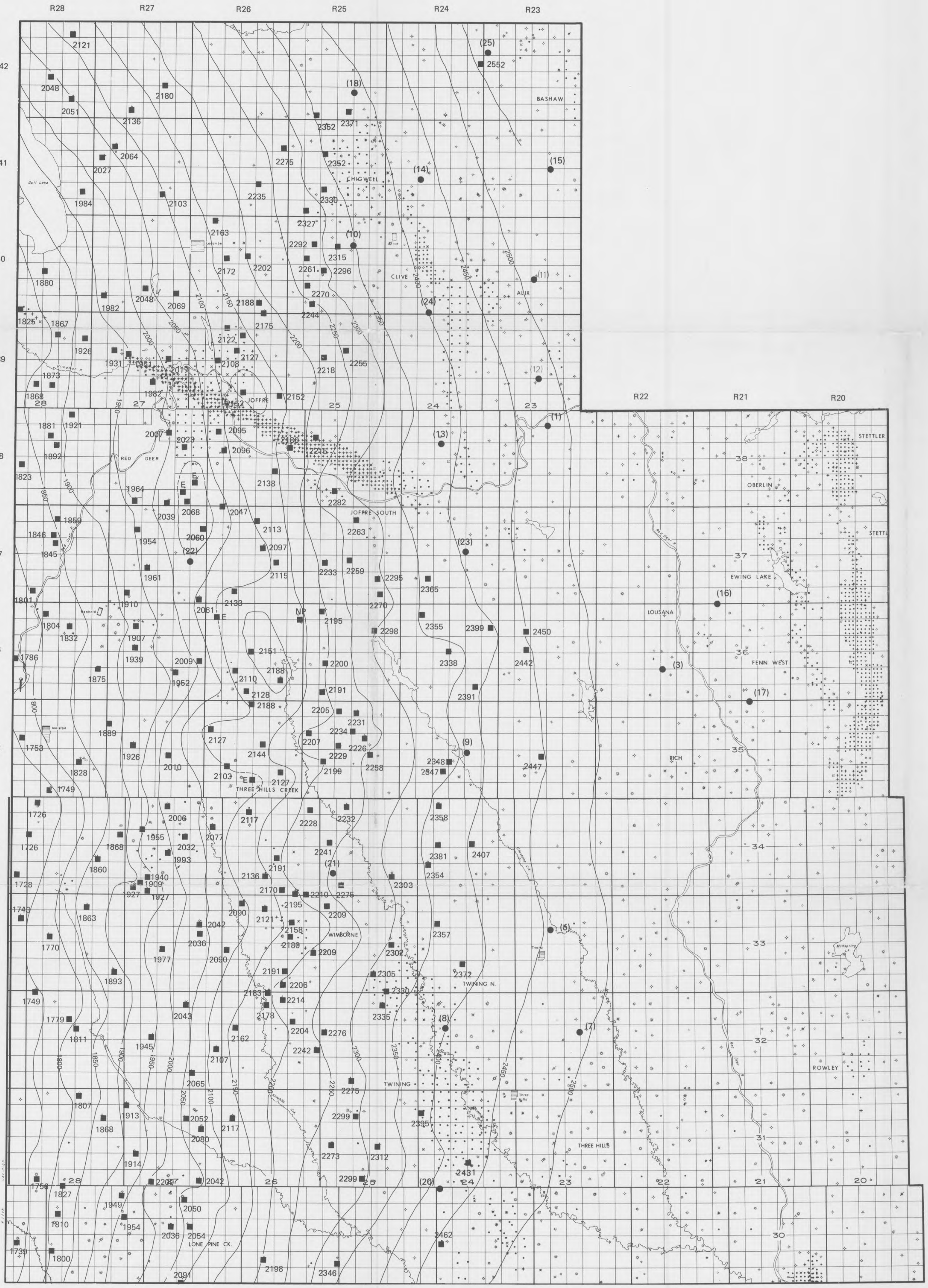


FIGURE 15. BATTLE FORMATION STRUCTURE

1978 ARC Testhole number .... ● (3)

Oil, gas, or abandoned well
Evaluation of Battle Formation .... ■ 2151

Erosion or non-deposition of Battle Formation .... E

C.I. = 50 feet

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MILES
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0 4 8 12 16
Km

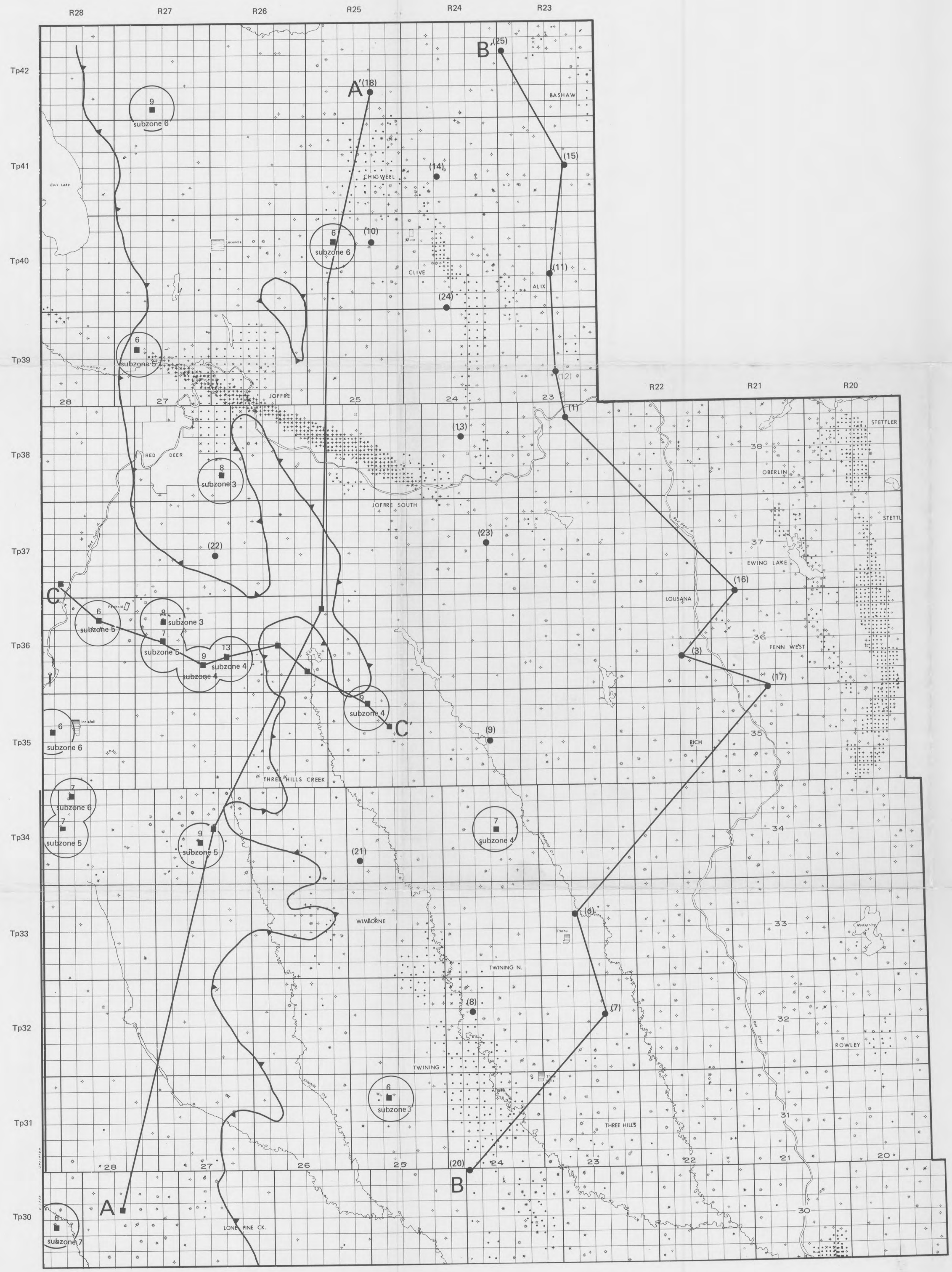

FIGURE 17. AREAS OF POTENTIAL DEVELOPMENT AND CROSS-SECTION LOCATION MAP (showing coal seams 6 feet and thicker)

1978 ARC testhole number .... (14)

Seam thickness 7
Oil, gas, or abandoned well ....
Stratigraphic level .... subzone 5

Line of 1000 feet depth to top of Battle Formation. Apices point to areas shallower than 1000 feet ....

Areas of potential development ....

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MILES 0 2 4 6 8 10
0 4 8 12 16 Km