REPORT OF INVESTIGATIONS NO. 104

Lignite Resources in Texas

by

W. R. KAISER, W. B. AYERS, JR., and L. W. LA BRIE

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W. L. Fisher, Director
The University of Texas at Austin
Austin, Texas 78712

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Texas Energy and Natural Resources Advisory Council
Milton L. Holloway, Executive Director

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CONTENTS

FIGURES

TABLES

ABSTRACT

Texas lignite occurs in three Eocene (lower Tertiary) geologic units—the Wilcox Group, Jackson Group, and Yegua Formation—and in three ancient depositional systems—fluvial, deltaic, and strandplain/lagoonal. Near-surface resources in Texas at depths between 20 and 200 ft (6.1 and 61 m) in seams 3 ft (0.9 m) or thicker are 23,377 million short tons (21,208 million metric tons) and are dominantly fluvial in origin. More than 90 percent of the resources occur in the Wilcox and Jackson Groups north of the Colorado River. The size of individual deposits ranges from 50 to 500 million tons (45 to 450 million metric tons). The average seam thickness is less than 5 ft (1.5 m); a 10-ft (3.0-m) seam is exceptional. Depending on mining depth, reserves are estimated to be 8,635 to 11,102 million tons (7,834 to 10,072 million metric tons). Deep-basin resources at depths between 200 and 2,000 ft (61 and 610 m) in seams 5 ft (1.5 m) or thicker are 34,819 million tons (31,588 million metric tons), 70 and 30 percent being in the Wilcox and Jackson Groups, respectively. Approximately 2.4 million acres (1.0 million ha) are leased for lignite; 84, 12, and 4 percent of the acreage is in the Wilcox, Jackson, and Yegua, respectively. Wilcox lignite is the best grade, Yegua is intermediate, and Jackson is the poorest grade lignite in Texas. Typical Wilcox lignite has a heating value of 6,500 Btu/lb (3,612 kcal/kg) and a 33-percent moisture, 1-percent sulfur, and 15-percent ash content.

Lignite reserves are adequate to meet the projected needs (6 to 7 billion short tons [5.4 to 6.3 billion metric tons]) of the electric utility and industrial sectors into the next century. Most of the lignite will continue to be used to generate electric power; however, lignite will be used in the future to produce synthetic fuels and chemicals.

INTRODUCTION

LIGNITE DEMAND

Texas has rediscovered lignite. Production in the 1970's increased from 2 to 26 million short tons (tons) (1.8 to 23.6 million metric tons [t]); today lignite is being used to generate approximately 20 percent of the State's electricity. Texas is now the Nation's tenth largest coal-producing state and is expected to move up in the rankings as production increases in the 1980's to an estimated 55 million tons (50 million t) in 1985 and 90 million tons (81 million t) in 1990.

The shift to lignite has been triggered by the higher prices of energy alternatives. For comparison, energy costs per million Btu are—Texas lignite, $1.00; Western coal, $1.75; new natural gas, $2.30; and oil at the world price, $5.45. The economic impacts of Federal legislation and regulation stimulate additional demand for lignite. The effects of the Railroad Revitalization and Regulatory Reform Act of 1976 (4R Act) and the Clean Air Act Amendments of 1977 are already apparent. Railroad rate increases granted by the Interstate Commerce Commission under the 4R Act have dramatically increased the cost of Western coal in Texas: about two-thirds of the cost of Western coal delivered to San Antonio is for rail transport cost. Universal scrubbing as required by the Clean Air Act Amendments means that scrubbers must be placed on all new coal-fired power plants irrespective of sulfur content. The amendments offset the advantage of low-sulfur Western coal. The Power Plant and Industrial Fuel Use Act of 1978 and the Natural Gas Policy Act of 1978 will ultimately force the conversion to coal in the industrial sector. At the moment, uncertainty over the Federal rules for implementing these acts and concerns about new environmental standards have effectively stopped coal conversion. Eventually, however, lignite will be used in the industrial sector.

In the context of expanding demand for lignite, rapidly changing economics, National energy policy calling for coal conversion, and the State's declining oil production, the Texas Energy Advisory Council, now the Texas Energy and Natural Resources Advisory Council, gave high priority to a new resource estimate. Long-range planning for fuel supply requires the best resource estimates possible. Decisions by planners to use Western subbituminous coal or Texas lignite ultimately depend on reserves (economically recoverable resources) and involve hundreds of millions of dollars for Texas consumers. Some projections based on present reserve estimates indicate that by 2000 lignite will be supply limited rather than demand limited. If indeed this is the case, then research and development priority should be given to technology for recovering lignite at increasingly greater depths. A major synthetic fuels industry will require routine mining to 200 ft (61 m) or deeper, something yet to be demonstrated in the Gulf Coast, and commercialization of underground coal gasification technology. Thus, resources play an important role in setting research priorities. Finally, the flow of Federal dollars into Texas for coal research is largely dependent on the size of the lignite resources.

PREVIOUS ESTIMATES

The degree of future dependence on lignite will ultimately be determined by resources and reserves. Public and private sector estimates of resources at strippable depths range from 3 to 20 billion tons (2.7 to 18 billion t). Perkins and Lonsdale (1955), presumably using the records of thousands of oil and gas wells (driller's logs), calculated resources of 3.3 billion tons (3 billion t) in seams greater than 5 ft (1.5 m) thick under less than 90 ft (27 m) of cover. The U. S. Bureau of Mines still carries this number as the reserve base for Texas, which unfortunately is too small. Fisher and Kaiser (1974) reported resources of 10 to 20 billion tons (9 to 18 billion t) in a minable thickness of 5 to 10 ft (1.5 to 3.0 m) under less than 200 ft (61 m) of cover.

Kaiser (1974a), in a comprehensive study of Texas lignite, calculated near-surface resources of 10.4 billion tons (9.4 billion t) under less than 200 ft (61 m) of cover in seams greater than 3 ft (0.9 m) thick. Basically, the method used was geologic projection and interpretation guided by geologic setting, mining activity, outcrop and well occurrences, and projection from deep-basin occurrences. In this way, prospective acreage, or that potentially underlain by lignite, was identified and termed "potential acreage." The most subjective element was the estimation of "productive acreage," or that actually underlain by lignite. This was done by multiplying potential acreage by a fraction reflecting the probability that lignite was within 200 ft (61 m) of the surface. These fractions were by necessity arbitrarily, but conservatively, chosen using geologic judgment and were assigned by region. Seam thicknesses were assigned on a county-by-county basis and assumed one continuous seam under each county's productive acreage. Deep-basin resources of approximately 100 billion tons (90 billion t) were calculated on the basis of a regional subsurface study (1,500 electric logs) in which the distribution of deep lignite was mapped throughout the Texas Coastal Plain for the first time. In the estimate, all seams to a depth of 5,000 ft (1,525 m) were assumed to be 2 ft (0.6 m) thick and laterally continuous.

On the basis of new geologic work, Kaiser (1978a) updated his estimate of near-surface resources and increased the total to 12.2 billion tons (11.1 billion t). Fisher (1978), using Kaiser's 1978 data and assuming surface mining to 150 ft (46 m), a recovery factor of 85 percent, and an illegal fraction, or that under highways, towns, rivers, and so forth, of 10 percent, calculated reserves of 6.7 billion tons (6.1 billion t).

Two other estimates have been published: 10 billion tons (9 billion t) or more by Phillips Coal Company (1977) and 11.5 billion tons (10.4 billion t) by Luppens (1978). The estimates are based on Phillips proprietary data, drilling to 300 ft (91 m) on a 2-mi (3.2-km) or smaller grid. No details are provided on the amount of data used nor the methodology employed to make the estimates. They are presented as reserves in seams greater than 3 ft (0.9 m) thick to a depth of 200 ft (61 m); however, calling them "reserves" is unwarranted since mining to 200 ft (61 m) is not current practice and probably not currently economic.

CURRENT ESTIMATE

The goal of this study was to document lignite resources in Texas to a depth of 2,000 ft (610 m) below the surface. Emphasis has been placed on identifying near-surface resources, or those under less than 200 ft (61 m) of cover in seams greater than 3 ft (0.9 m) thick. This is supplemented by a preliminary assessment of thin-seam resources in 2- to 3-ft (0.6- to 0.9-m) seams. The method of estimation rests on proprietary data (4,510 logs) collected from the private sector and on a thorough understanding of regional geology. Available on a proprietary basis were 51 county maps showing leased acreage. The proprietary logs and lease maps were complemented by a series of regional lithofacies, lignite-occurrence, and structure-contour maps (1:250,000 scale) prepared from approximately 4,000 oil and gas logs. The data base was more than adequate to make resource estimates that meet the public need.

In areas where data were numerous, critical parameters such as number of seams, thickness, and lateral extent were determined to calculate measured resources. Tons per acre, or a tonnage factor, was obtained and, using geologic evidence and projection, applied along trend in areas of similar geologic setting and less control to calculate indicated and inferred resources. Funding and personnel commitments did not permit calculation to satisfy the criteria of U. S. Geological Survey Bulletin 1450-B (1976). However, a multiyear Bureau of Economic Geology project, funded by the U. S. Geological Survey and the Energy Information Agency of the U. S. Department of Energy, is now underway to calculate resources according to the criteria of 1450-B.

Near-surface resources of 23.4 billion tons (21.2 billion t) and reserves of 8.6 to 11.1 billion tons (7.8 to 10.1 billion t) have been calculated in this study. Near-surface resources are reported by degree-of-certainty category, geologic unit, and region (for example, east-central Texas Wilcox or East Texas Jackson). Thin-seam resources have been estimated at 8 to 9 billion tons (7.2 to 8.1 billion t). Deep-basin resources have been evaluated in this study from 3,620 oil and gas logs using methodology modified from Kaiser (1974a). They are 34.8 billion tons (31.6 billion t) in seams greater than 5 ft (1.5 m) thick between depths of 200 and 2,000 ft (61 and 610 m) and are reported simply as resources by geologic unit and geographic region.

This report presents a review of the geologic setting, followed by a discussion of the near-surface resources by degree-of-certainty category and geologic unit and of the method of calculation. The section on near-surface resources ends with an assessment of thin-seam resources, a reserve estimate, and a review of grade. Deep-basin resources are discussed in a final section.

GEOLOGIC SETTING

Texas lignite occurs in three Eocene (lower Tertiary) geologic units—the Wilcox Group, Jackson Group, and Yegua Formation (table 1)—and in three ancient depositional systems—fluvial, deltaic, and strandplain/lagoonal. Cyclic deposition is the fundamental style of sedimentation in the Texas Eocene. The motif is an alternation of thick, regressive fluvial-deltaic units, such as the Wilcox, and thin, transgressive, fossiliferous marine units, such as the Weches (fig. 1). These units crop out as narrow, approximately coast-parallel belts stretching southwest-northeast across the State in the inner Texas Coastal Plain, and as a semicircular area in far East Texas (fig. 2). They extend deep into the subsurface and dip 1° to 2° gulfward until, for

Table 1. Stratigraphic occurrence of lignite in Texas.

Series	Group	North of Colorado River			South of Colorado River
OLIGOCENE				Catahoula Formation	
	Jackson Group	Whitsett Formation Manning Formation* Wellborn Formation Caddell Formation			lower Jackson*
EOCENE SERIES	Claiborne Group	Yegua Formation* Cook Mountain Formation Stone City Formation Sparta Sand Weches Formation Queen City Sand Reklaw Formation Carrizo Sand			Laredo Formation El Pico Clay Bigford Formation
	Wilcox Group	Calvert Bluff Formation* Simsboro Formation Hooper Formation	undivided Wilcox*		lower Wilcox*
				Midway Group	

*Principal lignite-bearing units.

example, the Wilcox is 10,000 ft (3,050 m) or more below the surface at Houston. The Wilcox and Jackson Groups are the most important lignite-bearing geologic units.

Depositional setting has been established from regional lithofacies maps (sand-percent, net-sand, maximum-sand) and lignite-occurrence maps. An exploration model built upon the relationship between sand-body geometry and lignite occurrence has been developed for Texas lignite. The model is facies dependent and permits resource estimation where data are meager, particularly in the deep basin. In fluvial facies tracts, sand-poor areas and abundant lignite overlap, whereas in deltaic and strandplain/lagoonal tracts, sand-rich areas and abundant lignite overlap (Kaiser and others, 1978).

WILCOX GROUP

EAST-CENTRAL TEXAS

The Wilcox Group between the Colorado and Trinity Rivers (fig. 2) ranges from 1,200 to 3,500 ft (366 to 1,068 m) thick and is bounded by the Midway Group below and Carrizo Sand above (fig. 1); it has been divided into three formations: Calvert Bluff, Simsboro, and Hooper (fig. 3). The Calvert Bluff, 500 to 2,000 ft (153 to 610 m) of sand and mud, is the major lignite-bearing unit; it conformably overlies the Simsboro, which contains some lignite. The Simsboro is a massive sand, as thick as 800 ft (244 m), that conformably and unconformably overlies the Hooper, which consists of 400 to 1,000 ft (122 to 305 m) of mud, sand, and minor lignite.

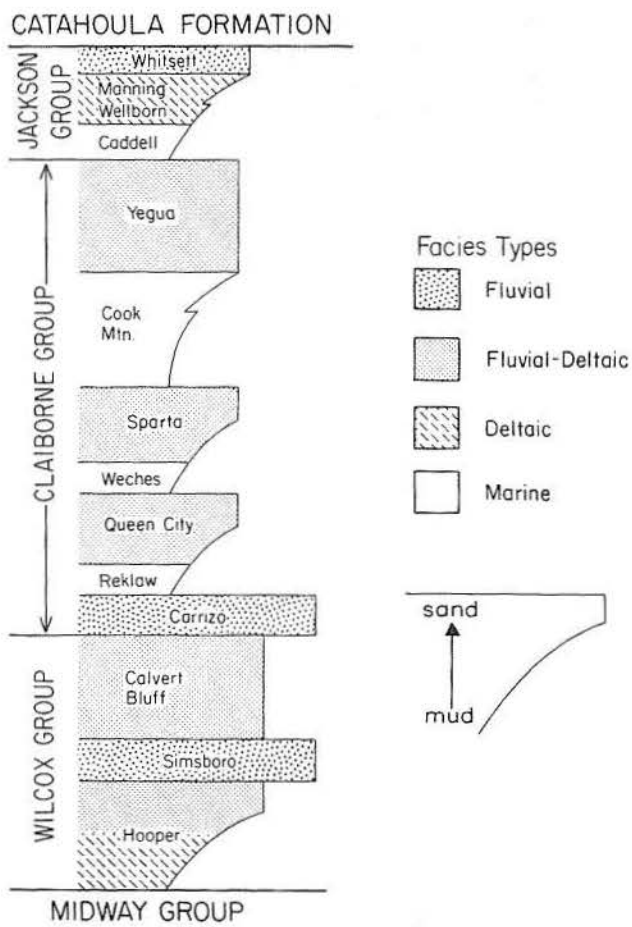


Figure 1. Cyclic deposition in the Texas Eocene (Kaiser and others, 1978).

Calvert Bluff and Simsboro sands form complex channel networks displaying straight, dendritic, and bifurcating geometries characteristic of fluvial and deltaic depositional systems (figs. 4 and 5). On modern deltas, channel sand belts with straight or slightly dendritic geometries characterize the transition zone between the lower alluvial and upper delta plains (Smith, 1966). This ancient zone is exposed at the Calvert Bluff outcrop and is present in the shallow subsurface, where major sand bodies are composed of multistory and multilateral fine- to coarse-grained meanderbelt deposits as thick as 200 ft (61 m) (Kaiser, 1978b). At its maximum development, the Simsboro is characterized by thick, multilateral channel sand belts displaying straight or slightly dendritic geometries. McGowen and Garner (1970) in an outcrop study interpreted the Simsboro to be coarse-grained meanderbelt deposits. Laterally extensive sand belts of high net thickness in the subsurface of Milam and Burleson Counties and meandering sand belts of low net thickness in Anderson County (fig. 5) indicate, in addition, the probable presence of braided-stream and fine-grained meanderbelt deposits. Sand-body geometries in the Hooper are similar to those of the Calvert Bluff.

Stratigraphically, lignite occurs regularly in a zone in the lower part of the Calvert Bluff Formation just above the Simsboro sand and irregularly in the upper part of the formation (fig. 3). Areally, lignite occurs between channel sand belts in elongate concentrations roughly parallel to the paleoslope or perpendicular to the outcrop (fig. 6). Sites of accumulation were hardwood swamps located in interchannel floodbasins formed by the bounding alluvial ridges of the ancient river courses. Modern analogs of Calvert Bluff interchannel basins are the Des Allemands-Barataria and Atchafalaya Basins of the Mississippi delta system (Kaiser, 1978b). Gulfward, these basins diminish in size and increase in number as trunk streams bifurcate into distributary networks that enclose

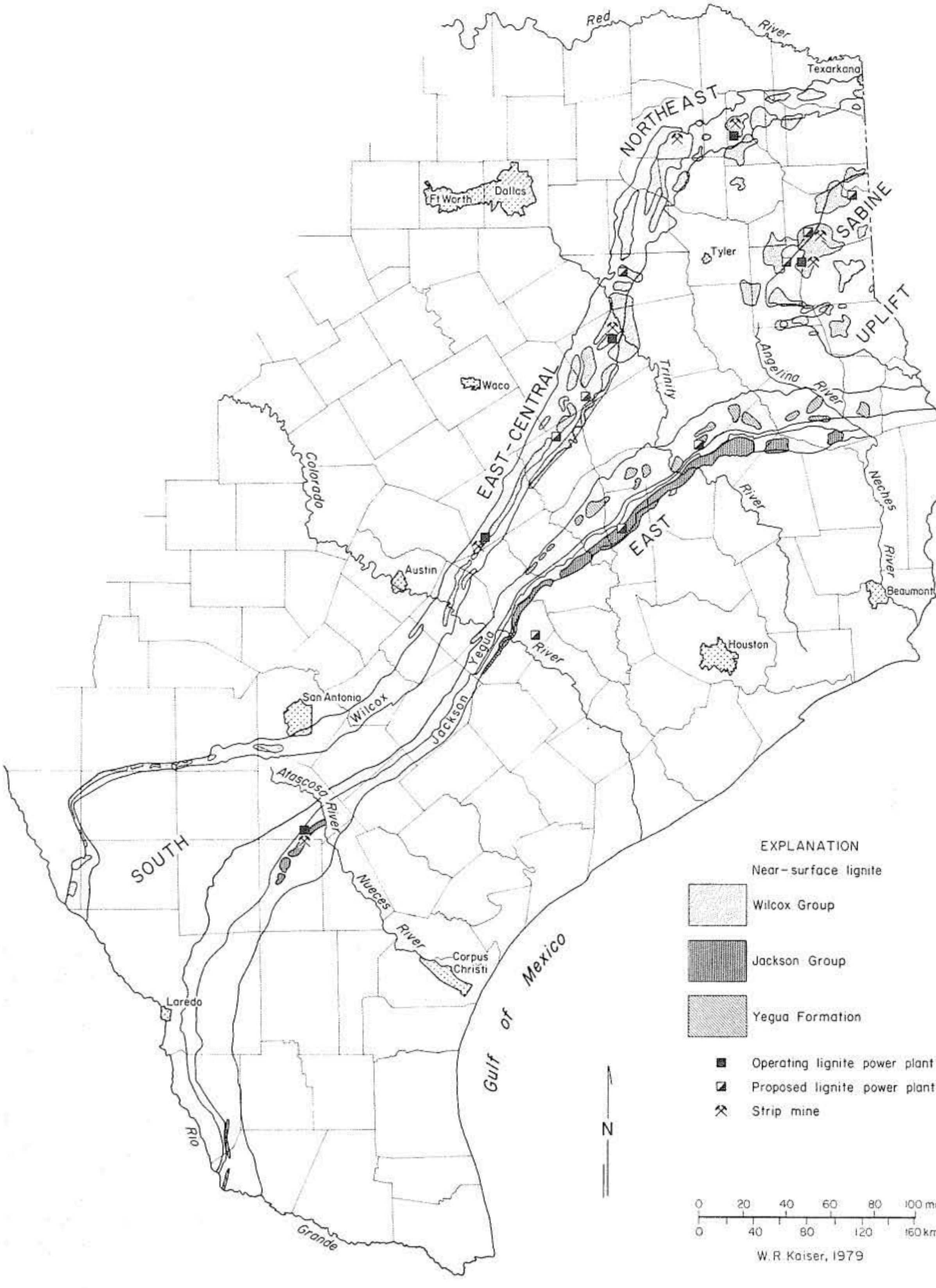


Figure 2. Distribution of near-surface lignite in Texas.

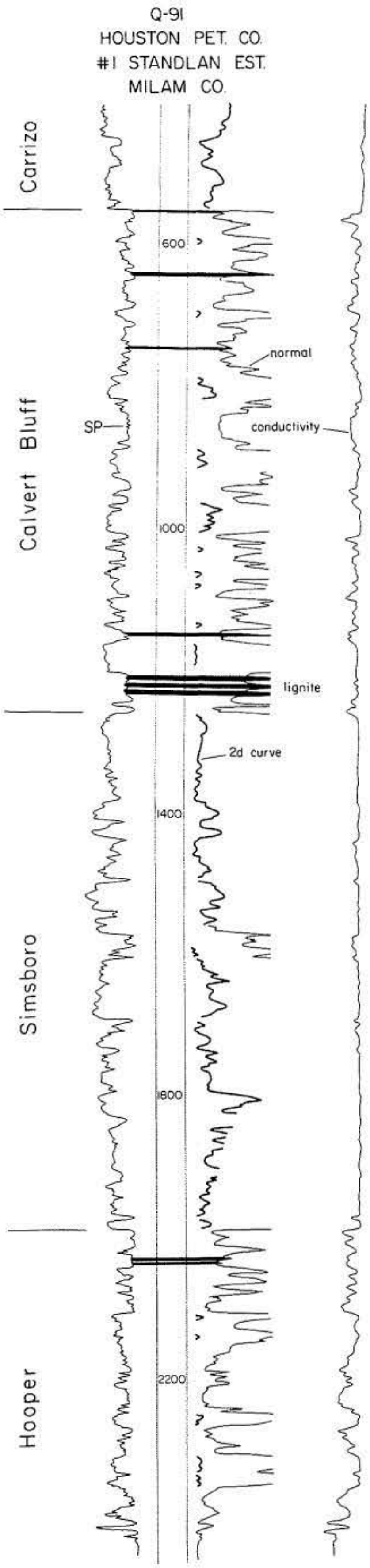


Figure 3. Wilcox stratigraphy in east-central Texas and the occurrence of lignite (Kaiser, 1978b). See figure 4 for location of log.

progressively smaller interdistributary basins. Peat is thickest and laterally most extensive at the junction of the alluvial and delta plains. Likewise in ancient strata, the best coals are found at this juncture. A single, thick inland-swamp peat may be time correlative with several coastal marsh peats genetically related to thin overlapped delta lobes (Frazier and others, 1978). Similarly, basinward in the Calvert Bluff the number of lignites increases and the median thickness decreases (Kaiser, 1978b).

The Simsboro Formation thins, breaks up, and changes facies northward toward the Trinity River and is actually a facies equivalent of the Calvert Bluff Formation in Leon, Freestone, and Anderson Counties. Simsboro and equivalent lignite occurs at this transition and is found primarly in sand-deficient interchannel areas (figs. 5 and 7).

Hooper lignites are most numerous and thickest in the upper part of the formation, just below the Simsboro (fig. 3). Fluvial lignite occurs in the shallow subsurface as small, widely spaced amoeboid-shaped areas, whereas deltaic lignite occurs in the deep basin and is areally extensive (fig. 8).

EAST TEXAS

Northeast of the Trinity River and on the Sabine Uplift (fig. 2), the Wilcox Group is composed of 400 to 1,400 ft (122 to 427 m) of undivided sand, mud, and lignite; vertical sequences and sand-body geometries are characteristic of fluvial systems (figs. 9 and 10). Two prominent north-south oriented channel sand belts, a western and an eastern belt, merge southward and lose their separate identities in Anderson and Cherokee Counties. An excellent dendritic- or tributary-channel geometry characteristic of the high alluvial plain is developed in the region.

Lignite is found throughout the Wilcox Group, but is most common in its upper two-thirds. Lignite is most abundant in the sand-poor interchannel areas between the two major channel sand belts and the tributaries feeding these belts (fig. 11); it accumulated in hardwood swamps established between bounding alluvial ridges. Possible modern analogs may occur in tropical and temperate regions. Currently, the tropical model is preferred because only in the tropics are major peat accumulations found between dendritic stream courses high on the alluvial plain (Kaiser and others, 1978).

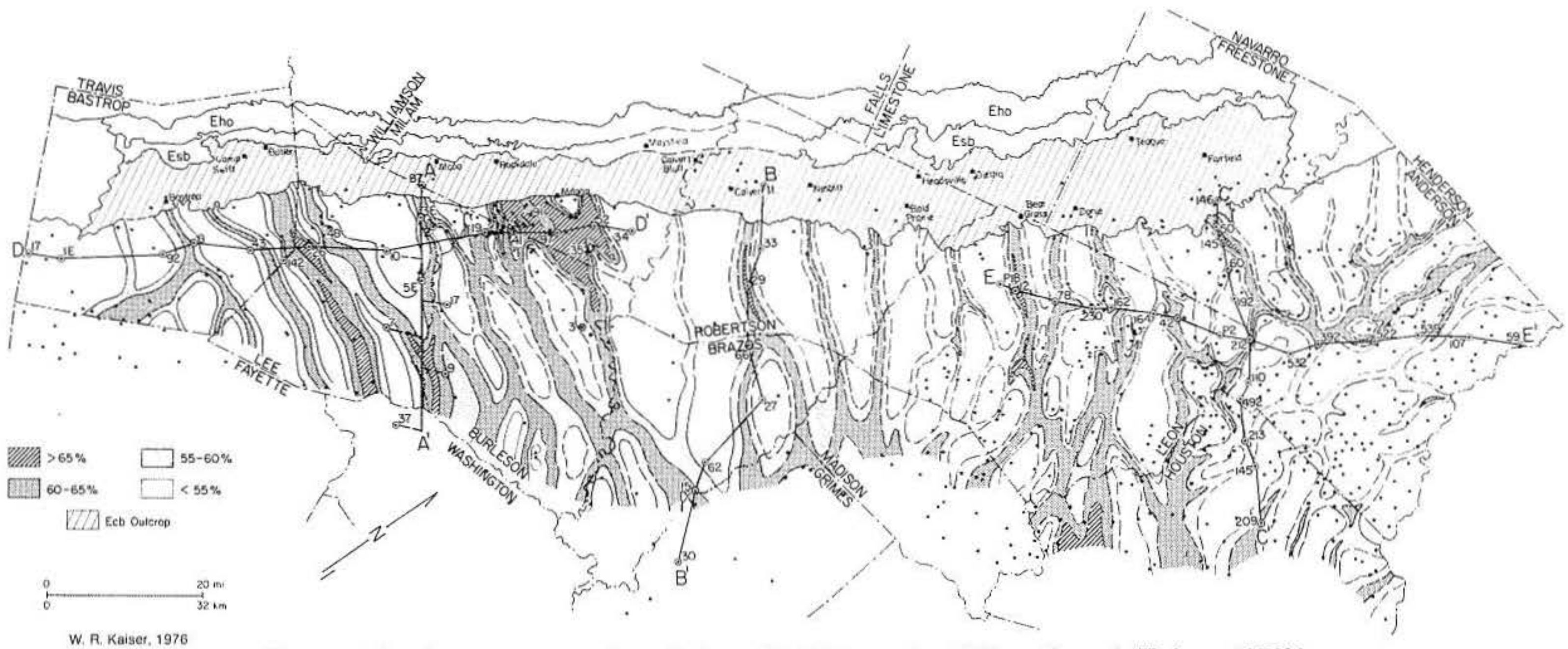


Figure 4. Sand-percent map of the Calvert Bluff Formation (Wilcox Group) (Kaiser, 1978b).

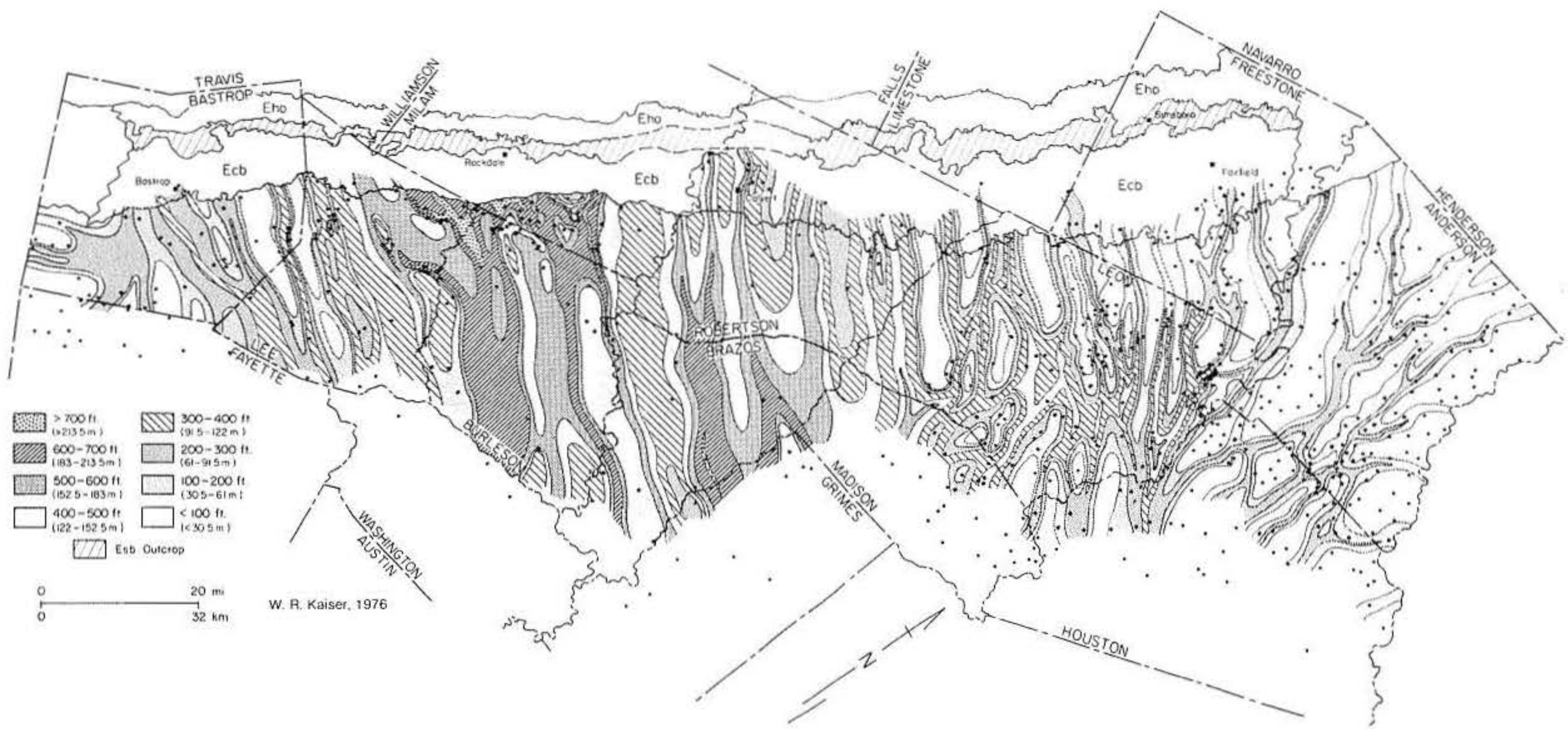


Figure 5. Net-sand map of the Simsboro Formation (Wilcox Group) (Kaiser, 1978b).

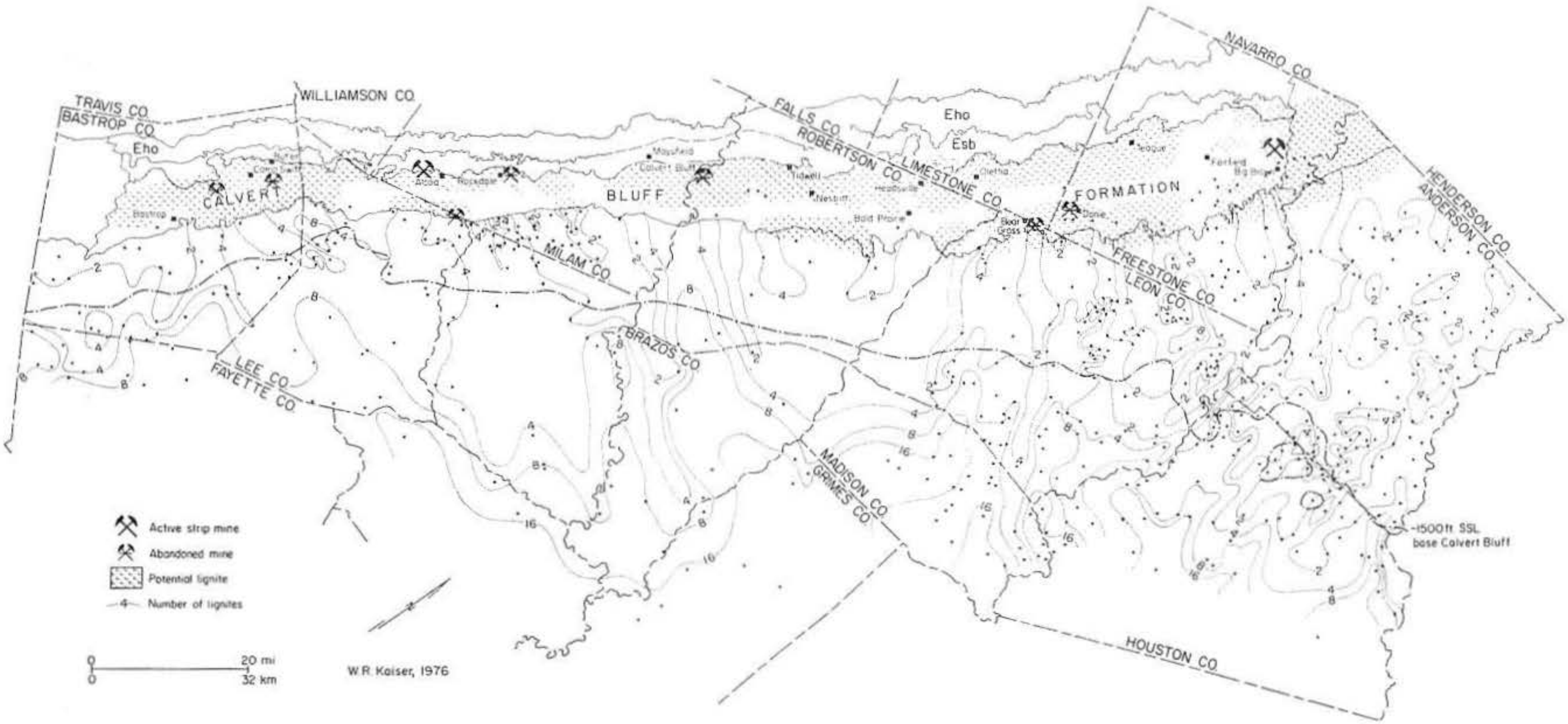


Figure 6. Occurrence of lignite in the Calvert Bluff Formation (Kaiser, 1978b). Deep-basin lignite, identified from electric logs using operational definition, shown by isopleths (number of lignite seams).

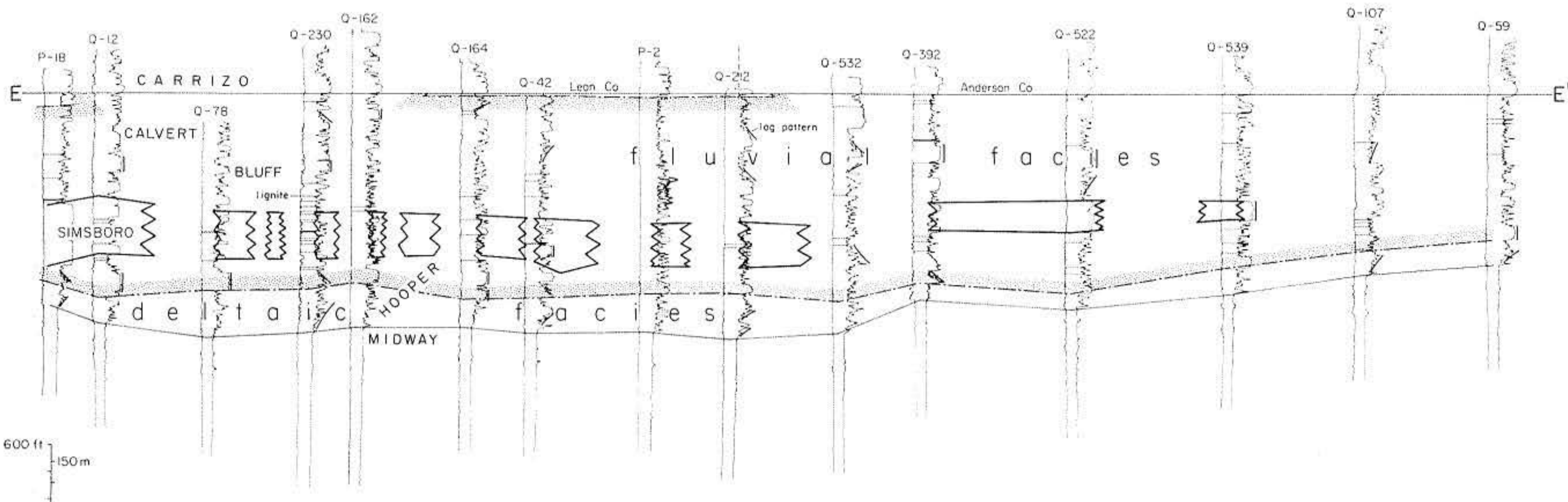


Figure 7. Cross section illustrating the transition from divided to undivided Wilcox (northward loss of Simsboro sand) and the occurrence of lignite. See figure 4 for location of section E-E′.

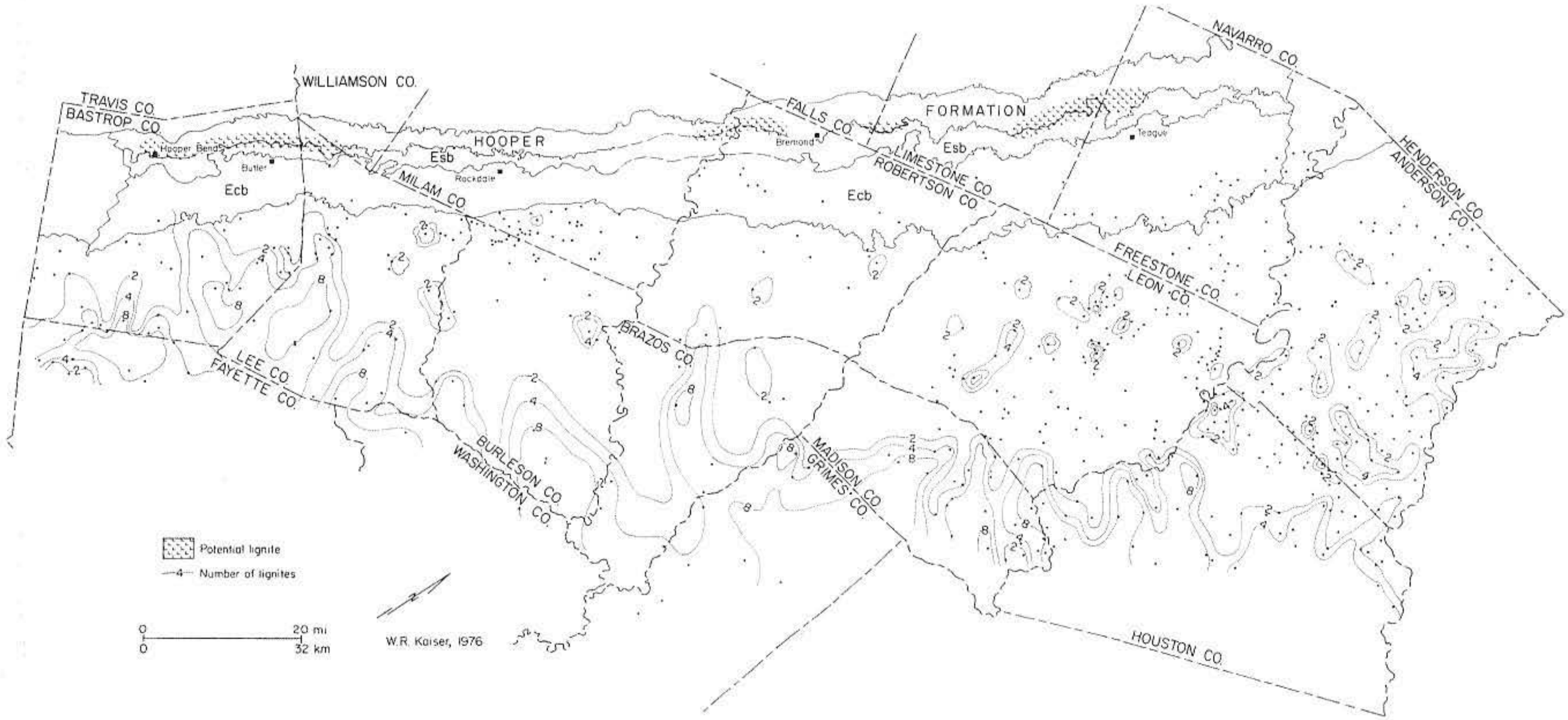


Figure 8. Occurrence of lignite in the Hooper Formation (Wilcox Group) (Kaiser, 1978b).

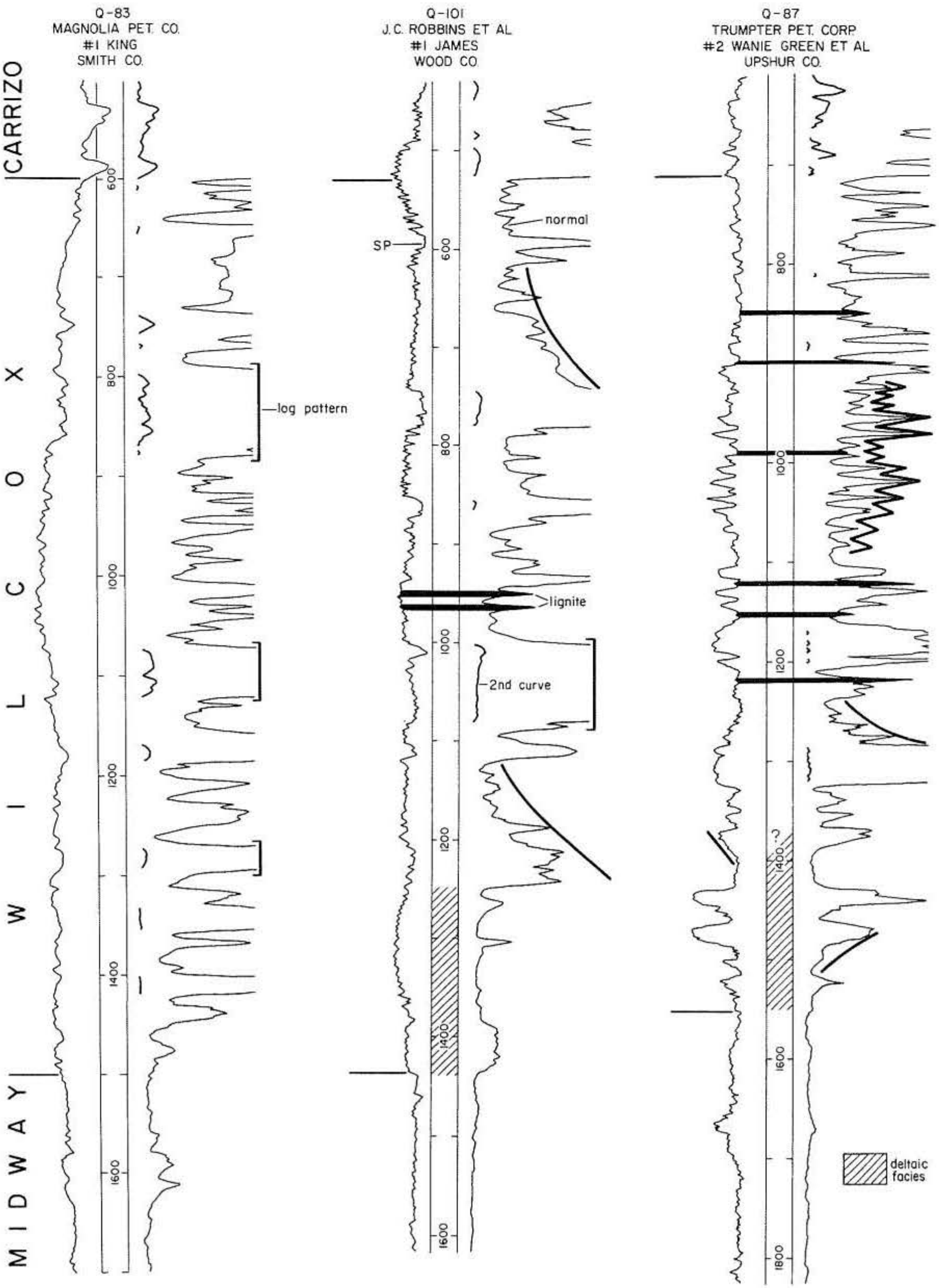


Figure 9. Wilcox stratigraphy in East Texas and the occurrence of lignite (Kaiser and others, 1978). See figure 10 for location of logs.

Figure 10. Sand-percent map of the undivided Wilcox Group (Kaiser and others, 1978).

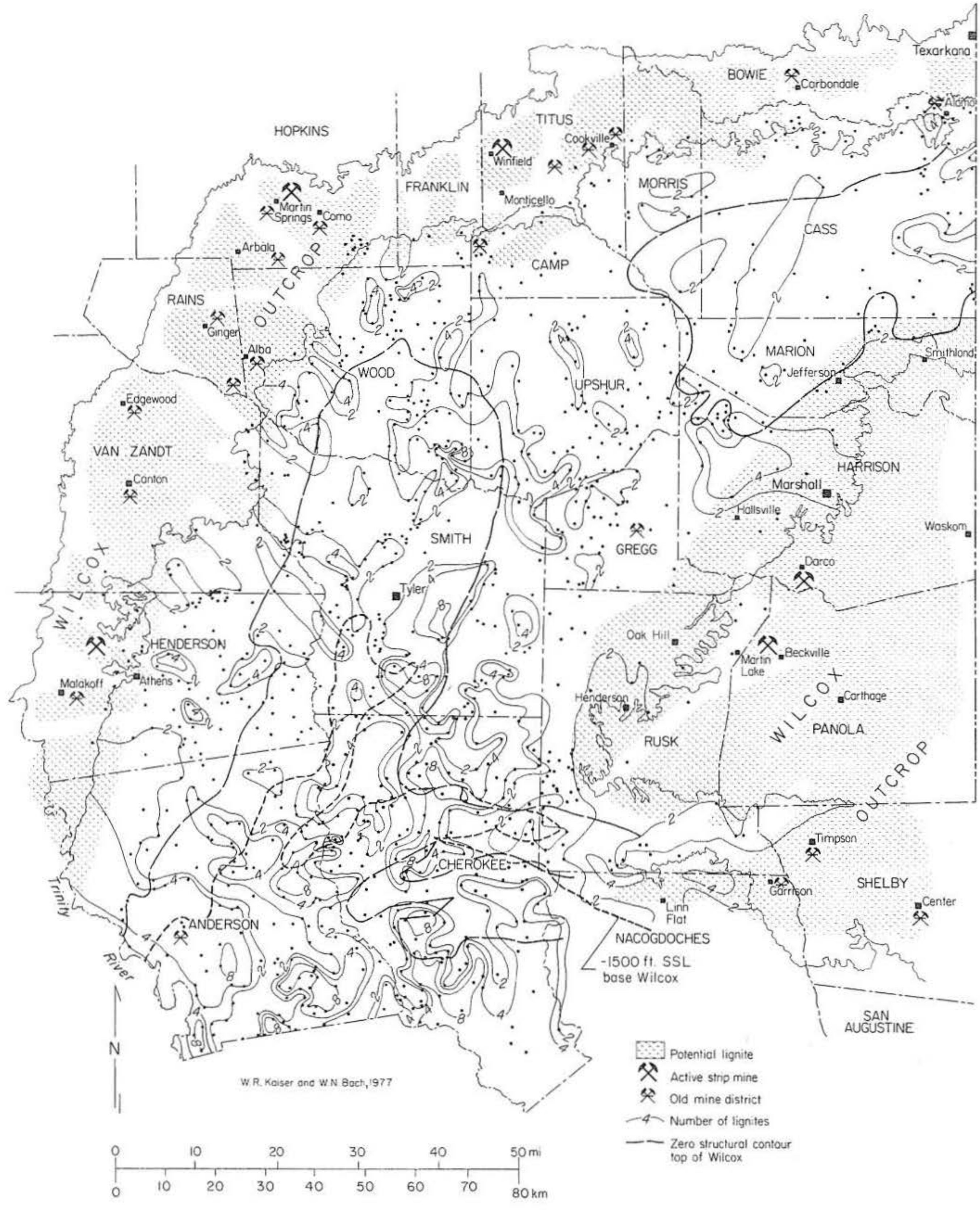


Figure 11. Occurrence of lignite in the undivided Wilcox Group (Kaiser and others, 1978).

SOUTH TEXAS

South of the Colorado River, the Wilcox Group is undivided but has been informally divided by several workers. West and southwest of San Antonio, the lower part of the Wilcox is composed of 400 to 1,400 ft (122 to 427 m) of sand, mud, and lignite (figs. 2 and 12). Fisher and McGowen (1967), in establishing the regional framework of lower Wilcox deposition, believed it was deposited as extensive barrier-bar and complementary lagoon-bay sediments. Their interpretation featured northeast-southwest oriented elongate sand bodies (barrier bars) parallel to depositional strike downdip and an extensive mud facies (lagoon) landward and updip to the northwest in the shallow subsurface. Johnston (1977) showed from sand-percent mapping well-developed, dip-oriented, elongate sand bodies in the shallow subsurface. He postulated that these represent bayhead delta systems, perhaps akin to the modern Colorado or Guadalupe River deltas, feeding a downdip barrier-bar system. Recent mapping of the lignite-bearing interval in the lowermost Wilcox Group (fig. 12), the first progradational sequence above the Midway Group, reveals elongate strike- and dip-oriented sand bodies (fig. 13). Tentative interpretation is that the dip-oriented sand bodies represent fluvial-deltaic feeders for downslope strike-oriented sand bodies common to linear clastic shorelines. Lignite occurrences have the same orientation as the sand bodies. Lignite overlaps dip-oriented sand bodies in Frio County and overlaps or is displaced updip of strike-oriented bodies in Zavala and Dimmit Counties (fig. 14).

JACKSON GROUP

EAST TEXAS

Between the Colorado and Angelina Rivers (fig. 2), the Jackson Group has been divided into four formations (table 1) and includes about 1,000 ft (305 m) (600 to 1,200 ft [183 to 366 m] in range) of mud, sand, and lignite extending from the top of the Yegua Formation to a correlative point at or near the base of the Catahoula Formation updip and the Vicksburg Formation downdip (fig. 15). Lithofacies mapping reveals lobate sand-body geometry that becomes digitate downdip to the south and southeast. Within individual lobes, a bifurcating or distributive geometry is either displayed or suggested (fig. 16). An ancient delta system is clearly indicated; it has been named the "Fayette delta system" by Fisher and others

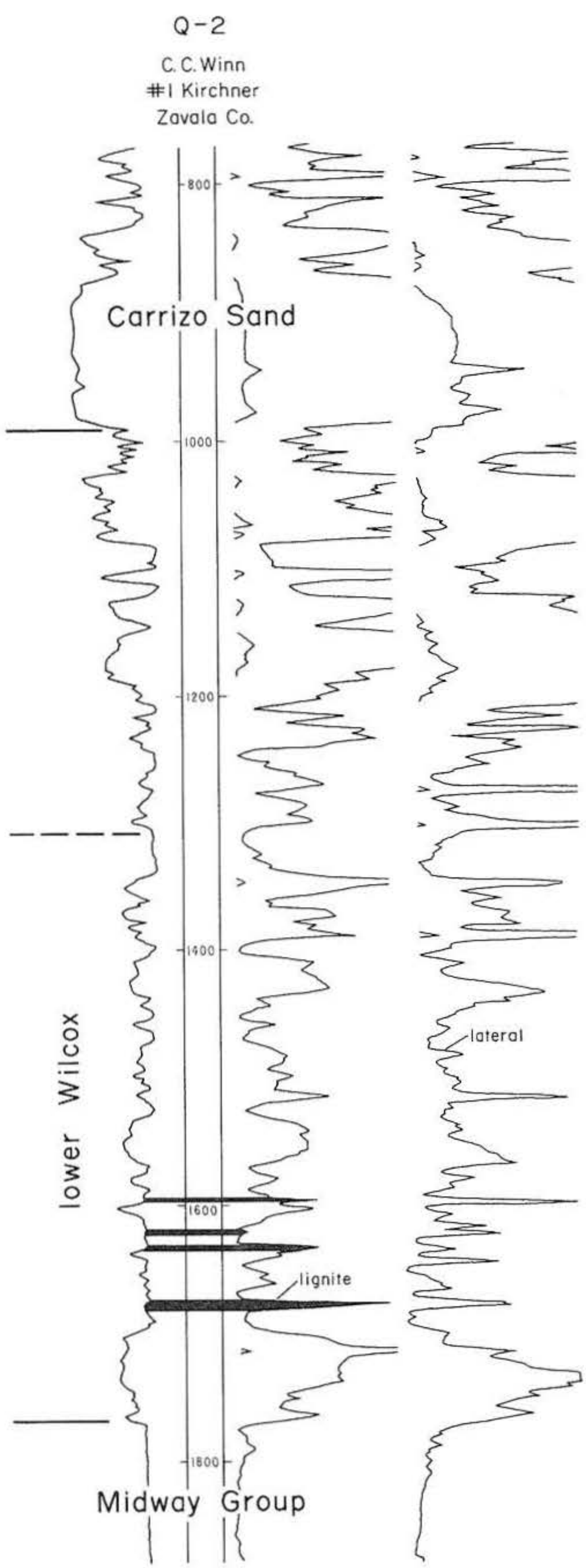


Figure 12. Wilcox stratigraphy in South Texas and the occurrence of lignite. See figure 13 for location of log.

(1970). Fluvially dominated delta lobes were supplied sediment by a fluvial system preserved in the Whitsett Formation, which marks the culmination of the Jackson progradational or regressive cycle (figs. 1 and 15).

Lignite occurs at the outcrop in the Manning and the upper part of the Wellborn Formations and in subsurface equivalents. Fisher and others (1970) showed the Manning to be the most important lignite-bearing Jackson unit. Lignite occurrences are lobate in outline and mirror the sand-percent map; in fact, lignite and relatively high sand percentages overlap almost exactly (figs. 16 and 17). Palynology (Elsik, 1978) and digitate and bifurcating sand-body geometries suggest that marshes on the lower delta plain were sites of organic accumulation (Kaiser and others, 1978). Thicker, laterally extensive lignites are postulated ancient blanket peats that accumulated on foundering delta lobes and spanned a variety of inactive environments that ranged from distributary-channel to lake and bay fills. The lateral extent of the peats was probably limited by the size of the underlying platform, which may have been as large as two coalesced delta lobes.

SOUTH TEXAS

South of the Atascosa River (fig. 2), the Jackson Group has been informally divided in such a way that the lower Jackson typically includes about 200 to 700 ft (61 to 213 m) of mud, sand, and lignite between the Yegua Formation and the muddy middle part of the group (fig. 18). Linear, strike-oriented sand bodies characterize the lower part of the Jackson and are interpreted to represent strandplain/barrier-bar sands (Fisher and others, 1970; Kaiser and others, 1978). They form a well-defined, north-northeast trending belt of mud-bounded sand 20 to 25 mi (32 to 40 km) wide, which is in part dip fed by small channel sands (fig. 19). These sands may represent the preserved remnants of small deltas that prograded across ancient lagoons and merged with seaward barrier islands, just as the modern Colorado and Brazos Rivers have done today. At the San Miguel Mine, channel sand facies have been identified above the lignite interval and assigned a fluvial origin by Snedden (1979). However, tidal sediments are to be expected in the lower Jackson strata, and a tidal origin is a possible alternative interpretation.

Lignite previously assigned to the Jackson-Yegua (Kaiser, 1974a) has been informally reassigned to the lower part of the Jackson (fig. 18), a genetic package of sediment including some strata previously placed in the underlying Yegua Formation. This package is easily recognized throughout South Texas; thus, all lignites are now referred to one stratigraphic unit of a single depositional genesis.

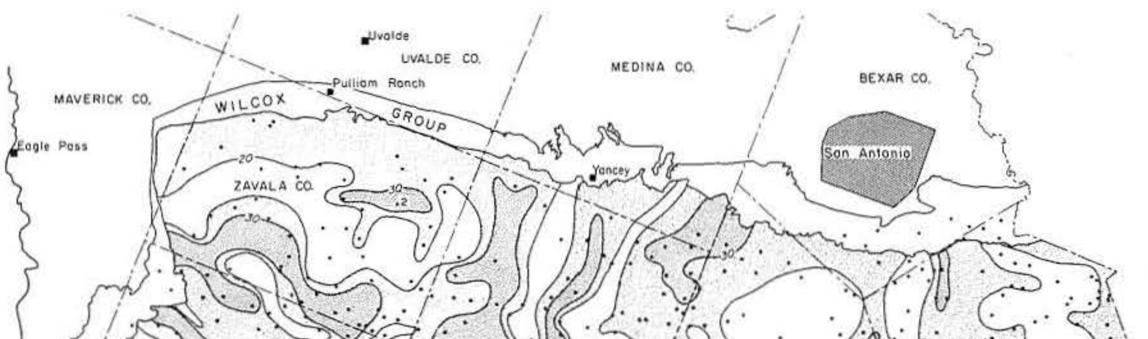


Figure 13. Maximum-sand map of the lower Wilcox Group lignite-bearing interval (youngest lignite down to top of Midway; see figure 12). Single thickest sand within interval irrespective of its stratigraphic position is isoplethed.

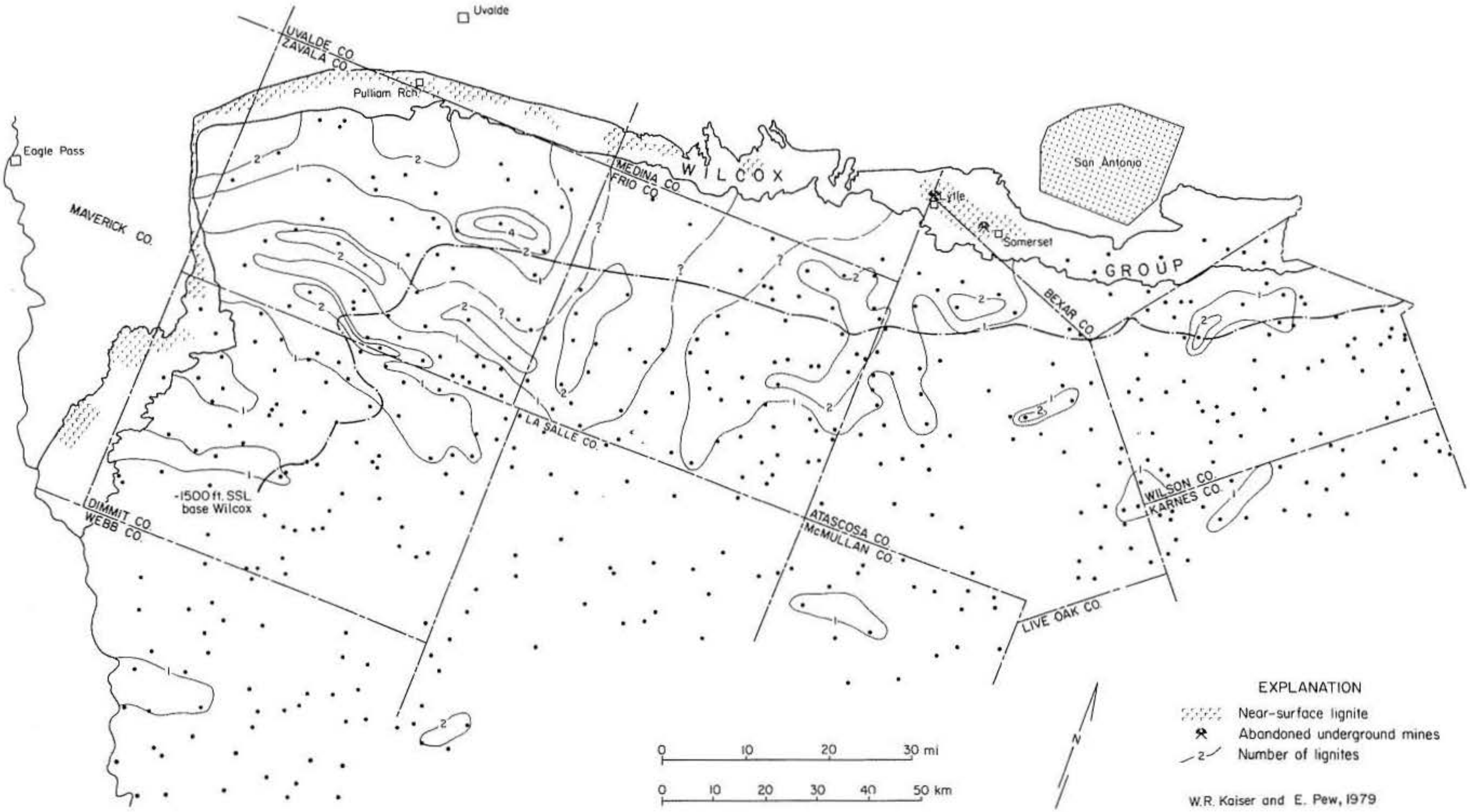


Figure 14. Occurrence of lignite in the lower Wilcox Group.

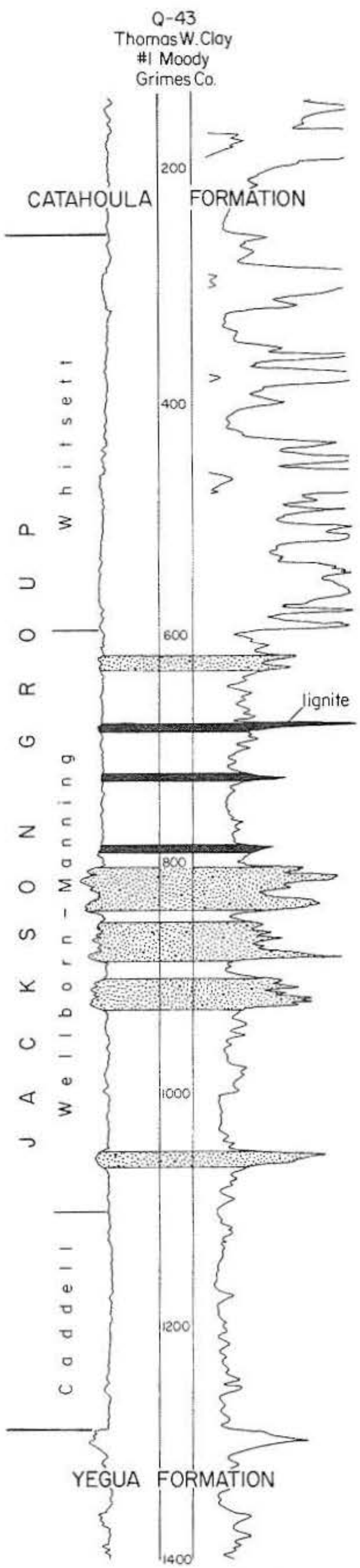


Figure 15. Jackson stratigraphy in East Texas and the occurrence of lignite (Kaiser and others, 1978). See figure 16 for location of log.

Lignite occurrences are elongate and coincide with maximum sand development. From south to north they extend unbroken through three counties until they break into discrete, irregular occurrences at the north in Live Oak County (fig. 20). Gaps between occurrences are believed to have been caused by the effects of syndepositional and/or post-depositional fluvial-deltaic or tidal channel deposition and erosion.

Lignite tops strandplain/barrier-bar beach sequences. Holocene analogs of Jackson linear, regressive shorelines and associated environments occur on the Nayarit coast of western Mexico, where marsh peats are accumulating in a strandplain/lagoonal system (Curray and others, 1969). Progradational coarsening-upward strandplain/barrier-bar sequences capped by peat-bearing marsh/strandplain or marsh/lagoonal sediments are closely analogous to sequences recognized in the lower Jackson strata—inferred strandplain/barrier-bar beach sequences, separated by strandplain/lagoonal mud and lignite (fig. 18).

YEGUA FORMATION

The Yegua in East Texas, between the Colorado and Angelina Rivers (fig. 2), includes 1,000 to 1,500 ft (305 to 457 m) of sand, mud, and lignite between the Cook Mountain Formation and the Jackson Group (fig. 21). Dip-oriented ribbons and dendroids of fluvial sand extend from the outcrop into the subsurface and merge downdip in the deep basin with lobate sand bodies connected by linear, strike-oriented sand sheets (fig. 22). The Yegua is here interpreted to be a wave-dominated delta system, whereas Fisher (1969) interpreted it to be a fluvial-dominated system. Lignite occurs in the middle two-thirds of the formation. In the shallow subsurface, at exploitable depths of less than 2,000 ft (610 m), lignite occupies an interchannel position and occurs as small oblong patches widely scattered along the trend (fig. 23). They probably reflect, relative to the Wilcox, accumulation in a fluvial system of limited size and stability. Lignite is most abundant in the deep basin and occurs at the junction of the alluvial and delta plains, where it overlaps deltoid-shaped sand accumulations (figs. 22 and 23).

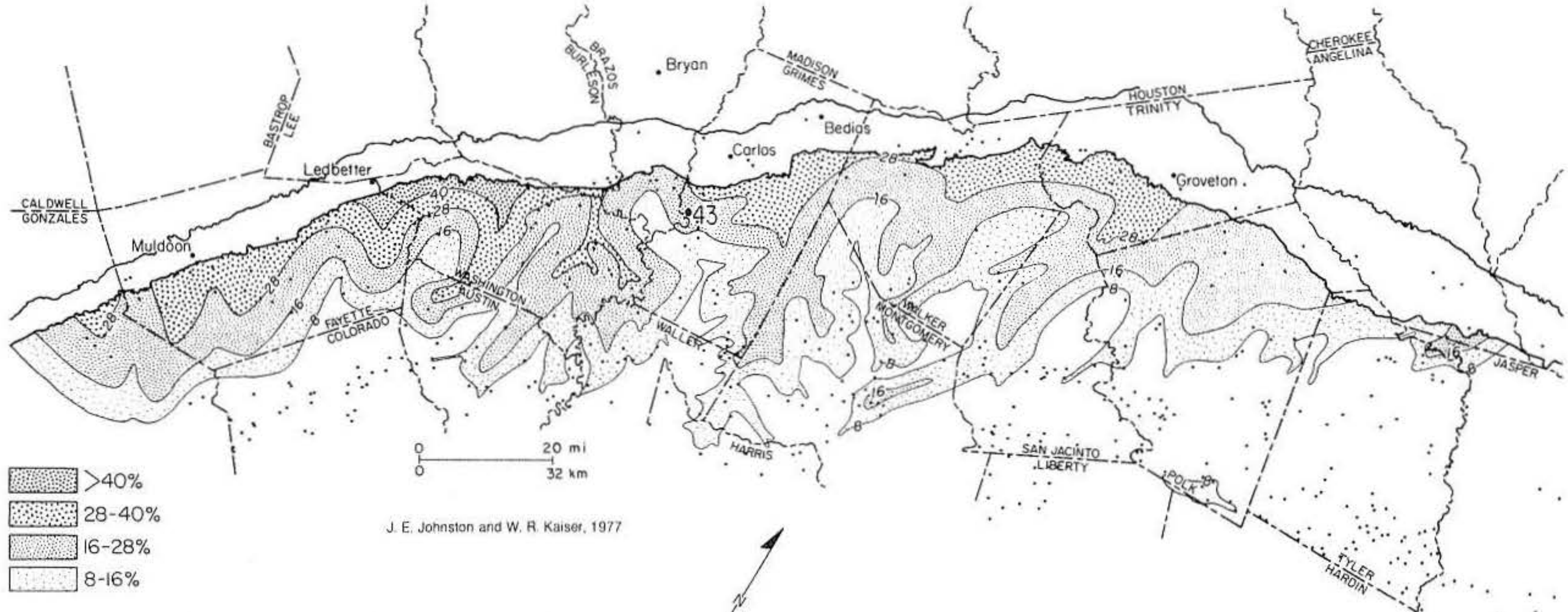


Figure 16. Sand-percent map of the Jackson Group, exclusive of the Whitsett Formation (Kaiser and others, 1978).

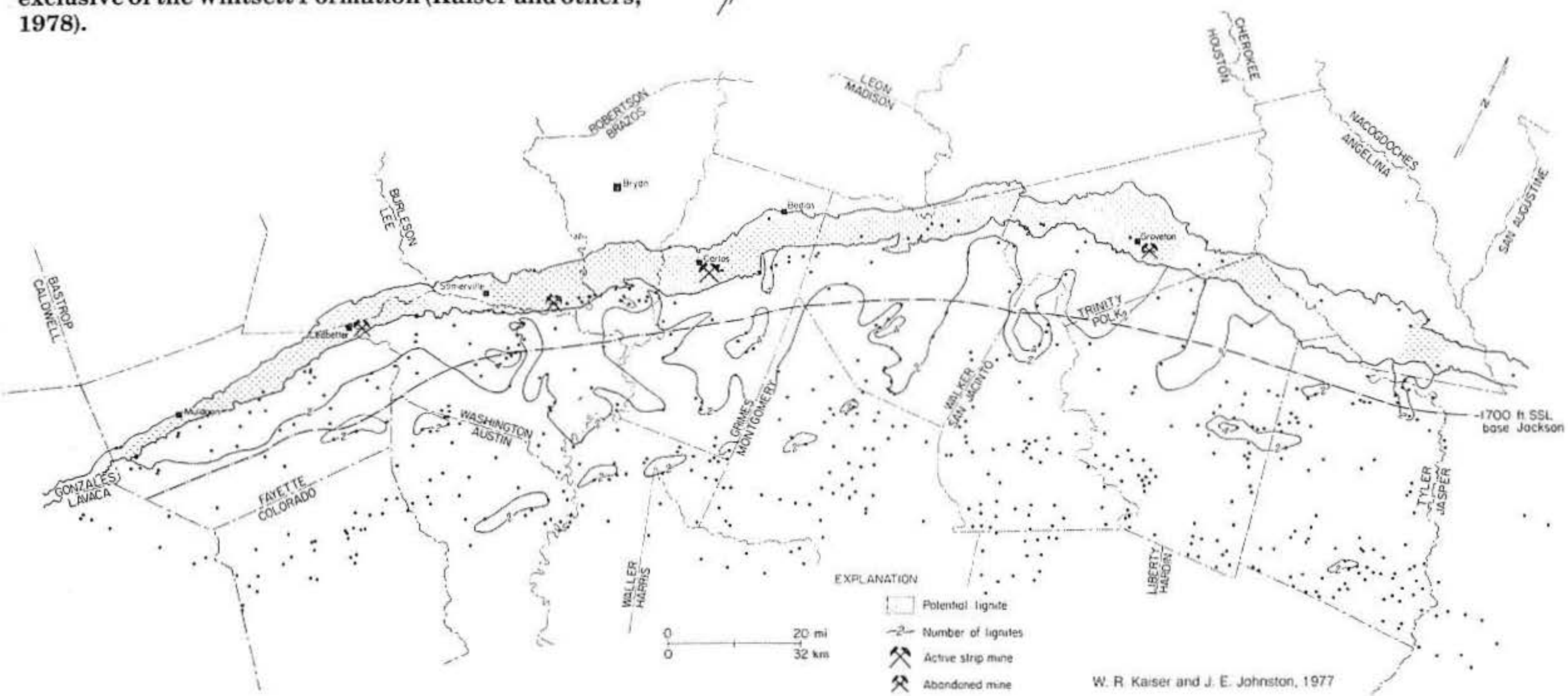


Figure 17. Occurrence of lignite in the Manning and Wellborn Formations (Jackson Group) (Kaiser and others, 1978).

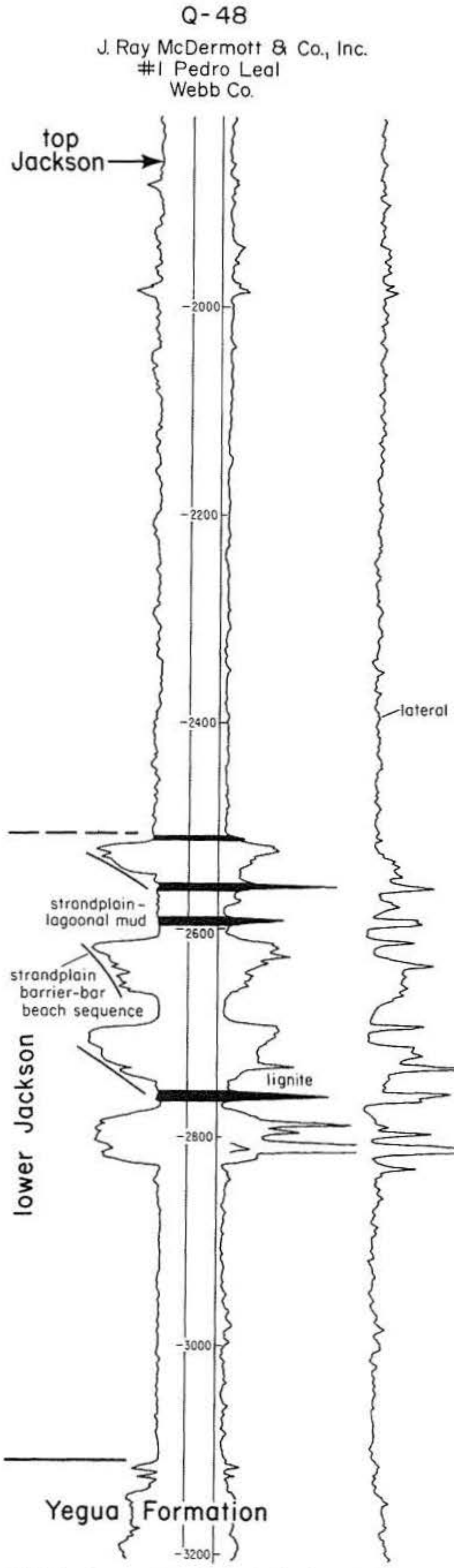


Figure 18. Jackson stratigraphy in South Texas and the occurrence of lignite. See figure 19 for location of log.

NEAR-SURFACE RESOURCES

Resource calculation depends on proprietary industry data (4,510 density and lithologic logs to depths of 120 to 300 ft [37 to 91 m]) collected from 34 companies and independent geologists (table 2) and encompasses 51 deposits or areas (38 Wilcox, 9 Jackson, and 4 Yegua). These data were supplemented by 6 regional lignite-occurrence maps and 16 lithofacies maps. Also available on a proprietary basis were 51 large-scale (1:33,000 scale) county maps showing acreage leased for lignite by company. Comparison of grade is based on 525 proximate analyses and a lesser number of ultimate, forms-of-sulfur, and ash composition and fusion temperature analyses. Analyses were not randomly collected and in some cases have come from but a few deposits within a region.

Resources are reported by geologic unit (three), geographic region (seven), and degree-of-certainty category (three). The seven 5- to 12-county regions were defined in the preceding section on the geologic setting; degree-of-certainty categories (measured, indicated, and inferred) are discussed below. In Texas, near-surface resources at depths between 20 and 200 ft (6.1 and 61 m) and in seams greater than 3 ft (0.9 m) thick are 23,377 million tons (21,208 million t), and almost all occur north of the Colorado River. Over 90 percent of the resources occur in the Wilcox and Jackson Groups.

RESOURCES BY DEGREE-OF-CERTAINTY

MEASURED RESOURCES

Measured resources are those computed from data points, usually boreholes with density logs, spaced in such a way that key geologic

Table 2. Data base (geophysical and lithologic logs).

	Region	Resource Class		Total
		Near-surface	Deep-basin	
Wilcox	east-central	1,244	626	1,870
Wilcox	northeast	618	506	1,124
Wilcox	Sabine Uplift	1,220	396	1,616
Wilcox	south	129	363	492
Wilcox	subtotal	3,211	1,891	5,102
Jackson	east	499	587	1,086
Jackson	south	238	547	785
Jackson	subtotal	737	1,134	1,871
Yegua	east	562	595	1,157
Total		4,510	3,620	8,130

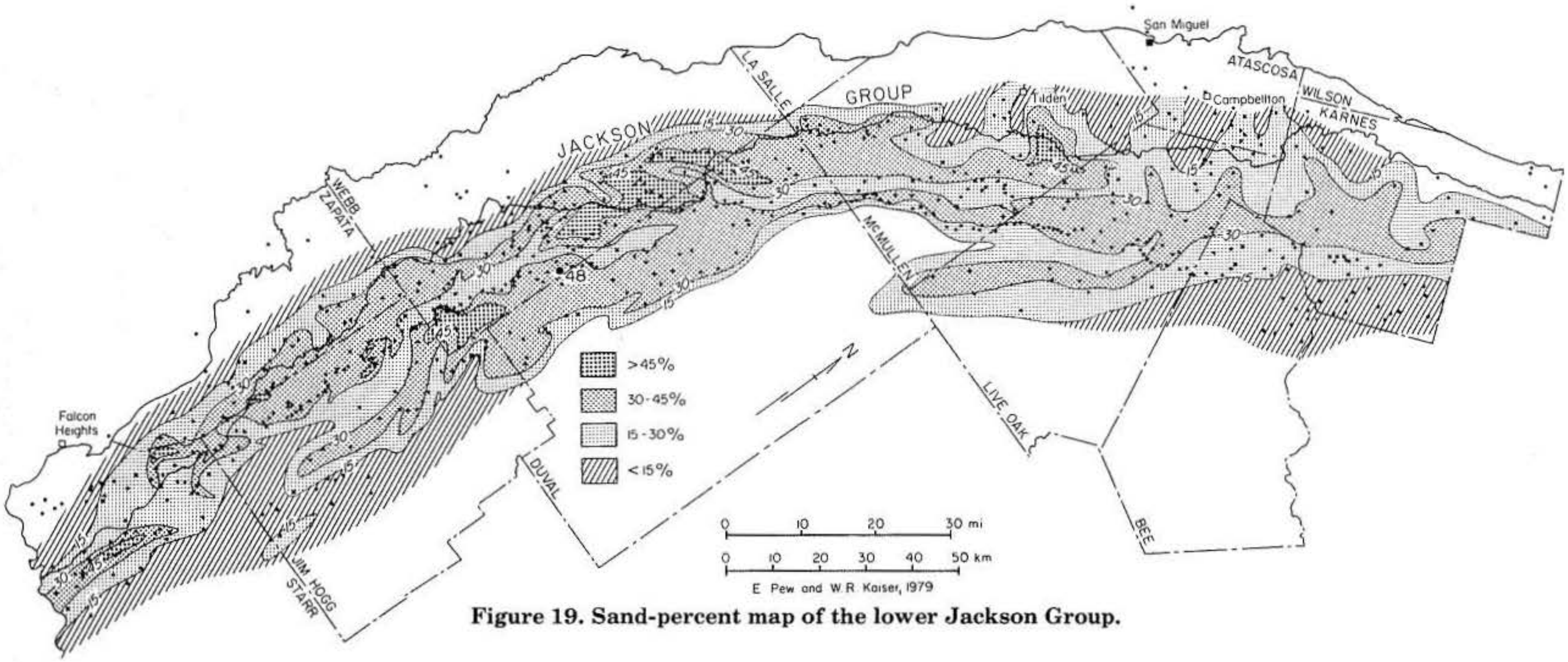


Figure 19. Sand-percent map of the lower Jackson Group.

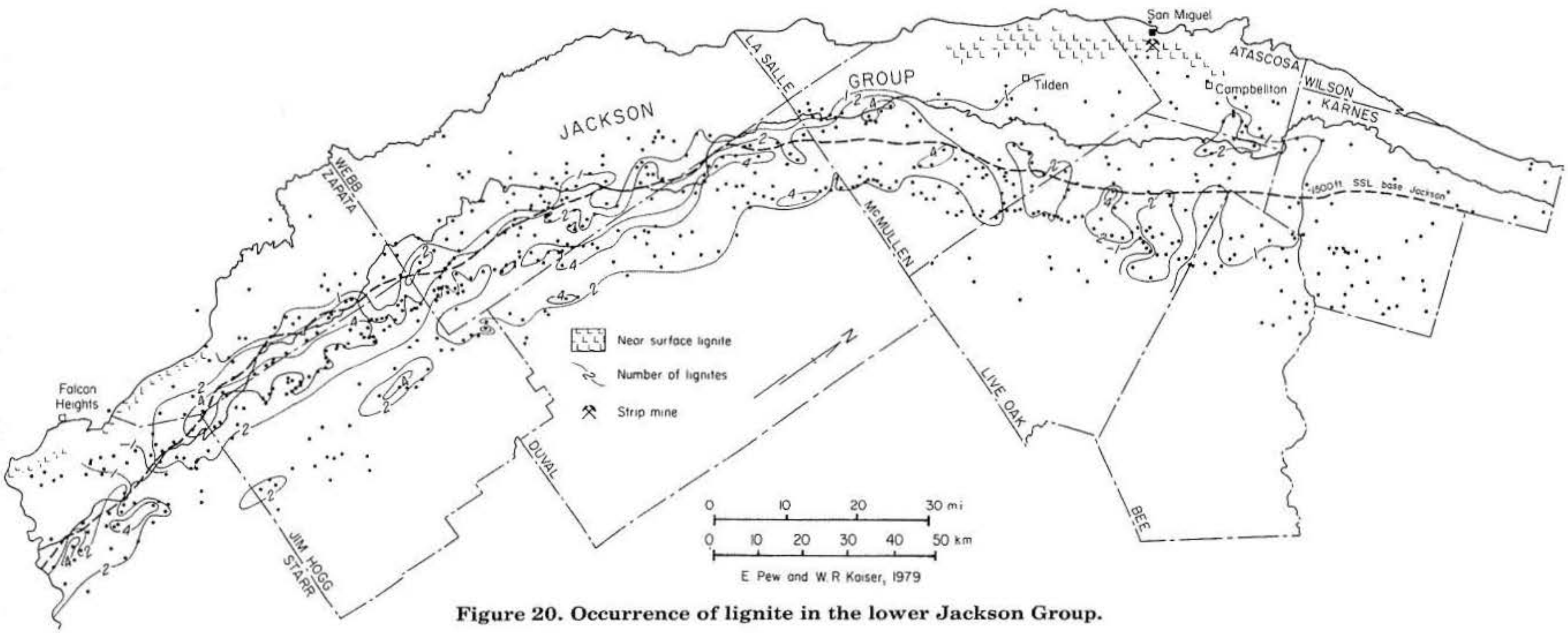


Figure 20. Occurrence of lignite in the lower Jackson Group.

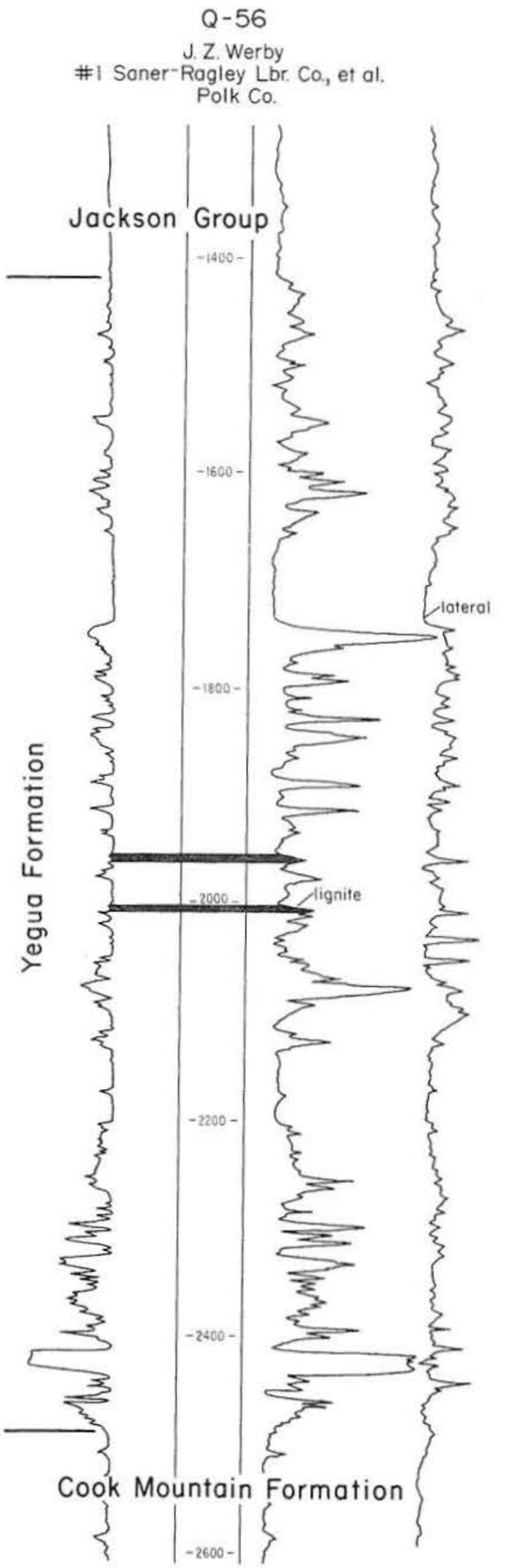


Figure 21. Yegua stratigraphy in East Texas and the occurrence of lignite. See figure 22 for location of log.

parameters, number of seams, thickness, and lateral extent can be established and deposits outlined. For each deposit, data usually consisted of 1 strike cross section and 2 or 3 dip sections prepared from 50 to 200 logs typically on quarter-mile centers. To outline the deposits, all seams were projected updip, using the local dip, to 20 ft (6.1 m) of cover and downdip to 200 ft (61 m) of cover. Total net lignite in seams greater than 3 ft (0.9 m) thick between 20 and 200 ft (6.1 and 61 m) was plotted for each borehole, isopached, and planimetered. Resources were calculated by multiplying acreage times total lignite thickness times 1,750 tons per ac-ft (12,869 t per ha-m). Tons per acre, the tonnage factor, was calculated by dividing resources by acreage. Factors range from 5,250 to 22,900 tons per acre (11,764 to 51,314 t per ha), equivalent to 3 ft (0.9 m) and 13 ft (4.0 m) of lignite, respectively. Resources were calculated by applying the appropriate tonnage factor to areas synthesized from deposit outline and leased acreage.

Statewide measured resources are 12,916 million tons (11,717 million t) (table 3) and constitute slightly more than half of the statewide total (table 4). Over half of the resources in the Wilcox and Jackson Groups are measured (table 5). Tonnages calculated for individual deposits using our method commonly range from 85 to 110 percent of private estimates.

Table 3. Near-surface resources in millions of short tons.

		Degree-of-Certainty Category			
	Region	Measured	Indicated	Inferred	Total
Wilcox	east-central	3,450	2,455	576	6,481
Wilcox	northeast	2,634	1,964	501	5,099
Wilcox	Sabine Uplift	3,200	598	114	3,912
Wilcox	south	150	359	569	1,078
Wilcox	subtotal	9,434	5,376	1,760	16,570
Jackson	east	2,410	1,760	329	4,499
Jackson	south	567	167	23	757
Jackson	subtotal	2,977	1,927	352	5,256
Yegua	east	505	164	882	1,551
Total		12,916	7,467	2,994	23,377

INDICATED RESOURCES

Indicated resources are those computed from widely spaced boreholes, approximately 1 to 6 mi (1.6 to 9.6 km) apart, and geologic evidence and projection. Productive acreage was determined by extension from measured deposits, geologic evidence (scattered density logs, old mine workings, stratigraphic occurrence), private industry comment, leased acreage, and geologic projection guided by tested exploration models.

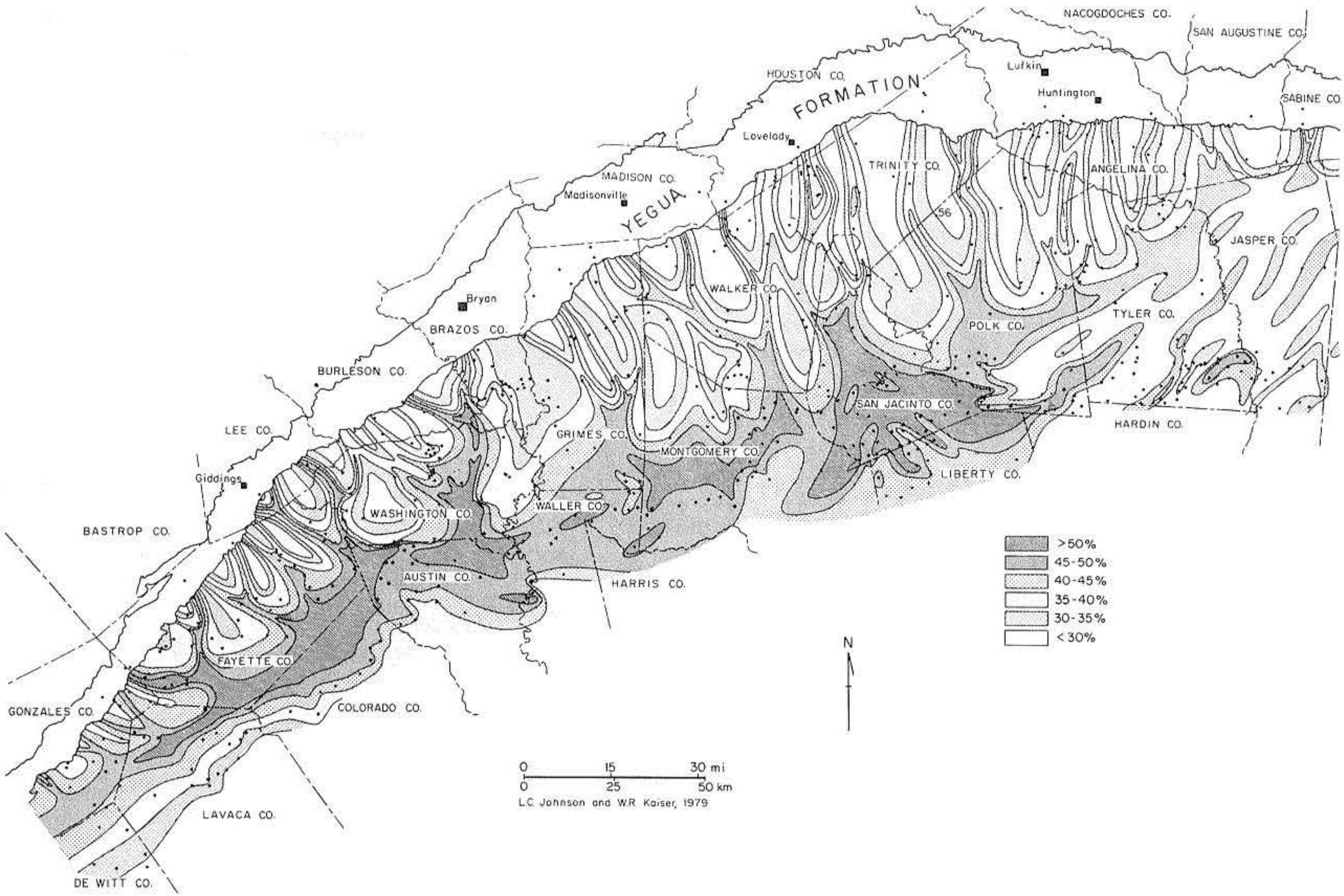


Figure 22. Sand-percent map of the Yegua Formation.

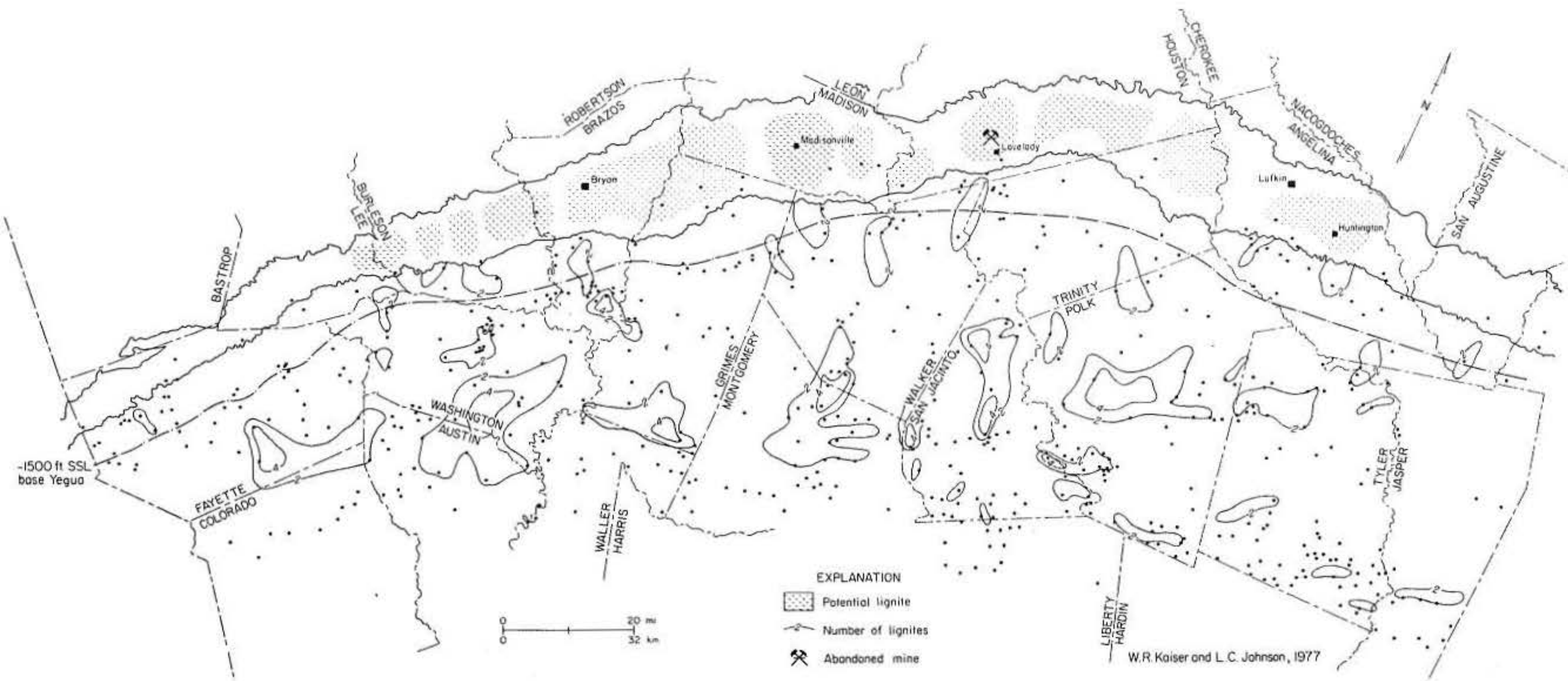


Figure 23. Occurrence of lignite in the Yegua Formation (Kaiser, 1978a).

Resources were calculated by applying a tonnage factor consistent with measured deposits of a particular region. Statewide indicated resources are 7,467 million tons (6,774 million t) (table 3) and constitute about a third of the statewide total (table 4). In the Wilcox and Jackson about a third of the resources are indicated (table 5).

DEMONSTRATED RESOURCES

Demonstrated resources are the sum of measured and indicated resources and equal 20,383 million tons (18,491 million t): 14,810 (13,436) (73 percent) in the Wilcox, 4,904 (4,449) (24 percent) in the Jackson, and 669 (607) (3 percent) in the Yegua.

INFERRED RESOURCES

Inferred resources are those computed only from geologic evidence and projection; little proof of the presence of lignite exists, except for published reports of lignite outcrops. These resources lie in extensions beyond the boundaries of demonstrated resources and at the intersection with the outcrop of the updip projection of occurrences in the deep basin. Specific examples follow in separate discussions of the resources by geologic unit. Statewide inferred resources are 2,994 million tons (2,716 million t) (table 3) and constitute about an eighth of the statewide total (table 4). Only in the Yegua Formation are most of the resources inferred (table 5).

WILCOX RESOURCES

EAST-CENTRAL REGION

Resources occur in two narrow, almost continuous bands and as individual blocks of irregular shape (fig. 24). A band of lower Calvert Bluff lignite, adjacent to the Simsboro, begins south of the Colorado River and continues to the Twin Oak power plant. Its southern terminus (Walnut Creek, Bastrop County) is in the area of transition to undivided Wilcox, where the Simsboro is no longer recognizable; this limit coincides with the change from fluvial-deltaic to marine-influenced facies. A band of upper Calvert Bluff lignite, astride the Wilcox-Carrizo contact, begins in Robertson County and continues to Henderson County. Individual blocks occur in Limestone and Freestone Counties, where some lie in the mapped Simsboro and Hooper Formations. Those in the Simsboro and Hooper reflect the eventual northward loss of the Simsboro and the transition from divided to undivided Wilcox (figs. 7 and 24). These resources lie at the outcrop in updip extensions of sand-poor interchannel areas mapped in the Simsboro (fig. 5). In other words, where the Simsboro is no longer present as a massive fluvial sand, lignite is no longer stratigraphically confined to the Calvert Bluff Formation. Gaps between resource blocks and areas with relatively low tonnage factors coincide with the updip projections of channel sand belts identified in the Calvert Bluff and Simsboro (figs. 4, 5, and 24). Many channels are too narrow to map regionally. The Big Brown deposit, for example, is broken by a narrow channel sand belt 4,000 ft (1,220 m) wide (Henry and others, 1976).

Calvert Bluff near-surface resources are present downdip of and basinward of the mapped Wilcox-Carrizo contact. Presumably, this is due to a gentle dip and perhaps the influence of several salt domes in the area. Of course, it is possible that the Wilcox-Carrizo contact is incorrectly mapped (Barnes, 1967) and should be farther east; the contact is not easily mapped and is impossible to map in the Trinity River floodplain.

Resources in the region are 6,481 million short tons (5,880 million t) and constitute almost 40 percent of the Wilcox total (table 3). Tonnage factors in the Calvert Bluff normally range from 8,200 to 22,900 tons per acre (18,374 to 51,314 t per ha). Resource blocks range in size from 50 to 500 million tons (45 to 450 million t). Seams are commonly 2 to 10 ft (0.6 to 3.0 m) thick, but may be up to 16 ft (4.9 m) thick; some have been correlated

Table 4. Percentage of near-surface resources by region.

Region		Degree-of-Certainty Category: Measured	Indicated	Inferred	Total
Wilcox	east-central	15	10	3	28
Wilcox	northeast	11	8	2	21
Wilcox	Sabine Uplift	13	3	1	17
Wilcox	south	1	2	2	5
Wilcox	subtotal	40	23	8	71
Jackson	east	10	7	1	18
Jackson	south	2	1	0	3
Jackson	subtotal	12	8	2	22
Yegua	east	2	1	4	7
Total		54	32	14	100

Table 5. Percentage of near-surface resources within geologic units.

	Wilcox	Jackson	Yegua
Measured	57	56	32
Indicated	32	37	11
Inferred	11	7	57
Total	100	100	100

along strike for up to 17 mi (27 km), a distance consistent with the 14-mi (22-km) maximum width measured for Calvert Bluff interchannel areas as defined by the 55-percent isopleth (fig. 4). Seam continuity is ultimately limited by the width of sand-poor areas or the spacing between channel sands. For seams greater than 2 ft (0.6 m) thick, average thickness is 4.5 ft (1.4 m), and the average number of seams in the near-surface interval, or per borehole, is 2.4, 75 percent of them being 3 ft (0.9 m) or thicker (table 6).

NORTHEAST REGION

In this East Texas region, extending north of the Trinity River northeastward to Texarkana (fig. 2), resources occur as sub-rounded individual blocks and continuous bands (fig. 25). Their outcrop position reflects the occurrence of lignite in the upper two-thirds of the Wilcox Group; however, lower Wilcox lignite is found just above the Midway Group in Hopkins County in the vicinity of Thermo. Continuous resource bands in Van Zandt, Rains, Wood, and Hopkins Counties lie west of and parallel to the major western channel sand belts (fig. 10). These resource bands are broken by tributary channels, too small to map, that feed the major channel sand belts in the subsurface. The band in Van Zandt County is believed to be terminated at the north and south by channel sands. The broken deposits in the vicinity of the Forest Grove power plant lie at the updip extension of a major channel complex. The general absence of deposits in Franklin County is attributed to its outcrop position astride the northern extension of a major western channel sand belt (figs. 10 and 25). The effects of this sand belt are evident in the Winfield deposit; its seams become more lenticular and the host sediment sandier as the belt is approached from the east (Kaiser, 1974b).

Structural geology again causes near-surface deposits to occur basinward of the Wilcox outcrop. A deposit in Camp County lies across a broad structural arch extending from Monticello to Martin Lake (fig. 11). Deposits in east-central Van Zandt and west-central Wood Counties are probably influenced by the Van and Quitman salt domes, respectively (fig. 25). The domes are reflected in a convex eastward bulge of the Wilcox-Carrizo contact and by near horizontal or westward structural dip. An inferred deposit in Upshur County is also probably influenced by a salt dome, the Kelsey salt dome, located approximately 8 mi (13 km) northwest of Gilmer.

Resources in the region are 5,099 million tons (4,626 million t) and constitute just over 30 percent of the Wilcox total (table 3). Tonnage factors range from 5,500 to 9,600 tons per acre (12,324 to 21,512 t per ha). Resource blocks range in size from 50 to 500 million tons (45 to 450 million t). Seams are commonly 2 to 8 ft (0.6 to 2.4 m) thick, but occur up to 14 ft (4.3 m) thick; some are continuous for up to 10 mi (16 km), the maximum width of interchannel areas as defined by the 40-percent isopleth (fig. 10). In general, seams are less continuous than those in the east-central region and are the result of accumulation in smaller, temporally less persistent interchannel basins, characteristic of the region's physiographic position, high on the ancient alluvial plain. Average seam thickness is 3.7 ft (1.1 m), and the average number of seams is 2.8, 61 percent of them being 3 ft (0.9 m) or thicker (table 6). Among the Wilcox regions, the northeast has the thinnest and most numerous seams.

SABINE UPLIFT REGION

This East Texas region is a semicircular area of Wilcox outcrop adjacent to Louisiana (fig. 2). Resource blocks occur throughout the area, but primarily reflect occurrence of lignite in the upper part of the Wilcox Group; hence, they straddle the Wilcox-Carrizo boundary (fig. 25). They lie east of the major eastern channel sand belt (fig. 10) and occupy an extensive ancient interchannel back-swamp area. The best lignite, in terms of seam thickness and continuity, is found on the central Sabine Uplift in Panola and Rusk Counties. This area coincides with the transition zone between the ancient alluvial and delta plains, the same depositional environment as that assigned to the Calvert Bluff lignite of the east-central region. Similar seam geometries in the two areas are explained by the similarity of depositional setting.

Some near-surface deposits are completely or almost completely basinward of the Wilcox outcrop (Mill Creek, Pirkey, Karnack) owing to the gentle northwest dip (0.2°) on the flank of the uplift and a broad structural arch along an axis from Martin Lake to Monticello (fig. 11). Lignite in northeast Cherokee County is at strippable depths because it overlies a southwestwardly plunging structural nose shown by the zero and -1,500-ft (-457-m) structure contours (fig. 11).

Resources in the region are 3,912 million tons (3,549 million t) and constitute about a fourth of the Wilcox total (table 3). Tonnage factors range from 5,300 to 12,000 tons per acre (11,876 to 26,889 t per ha); resource blocks range in size from 50 to 500 million tons (45 to 450 million t). Seams are commonly 2 to 8 ft (0.6 to 2.4 m) thick, in places reach 12 ft (3.7 m) thick, and may extend for 15 mi

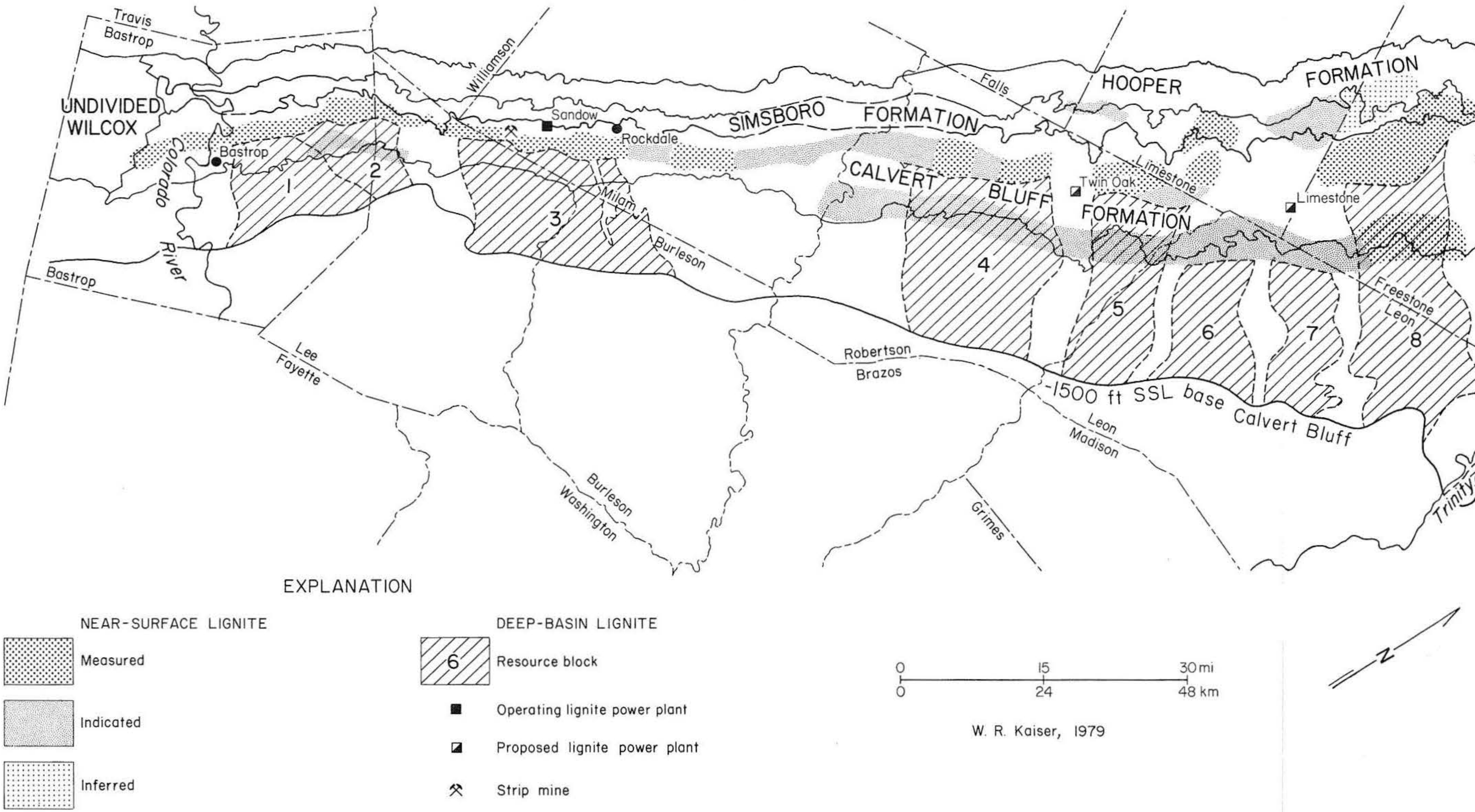
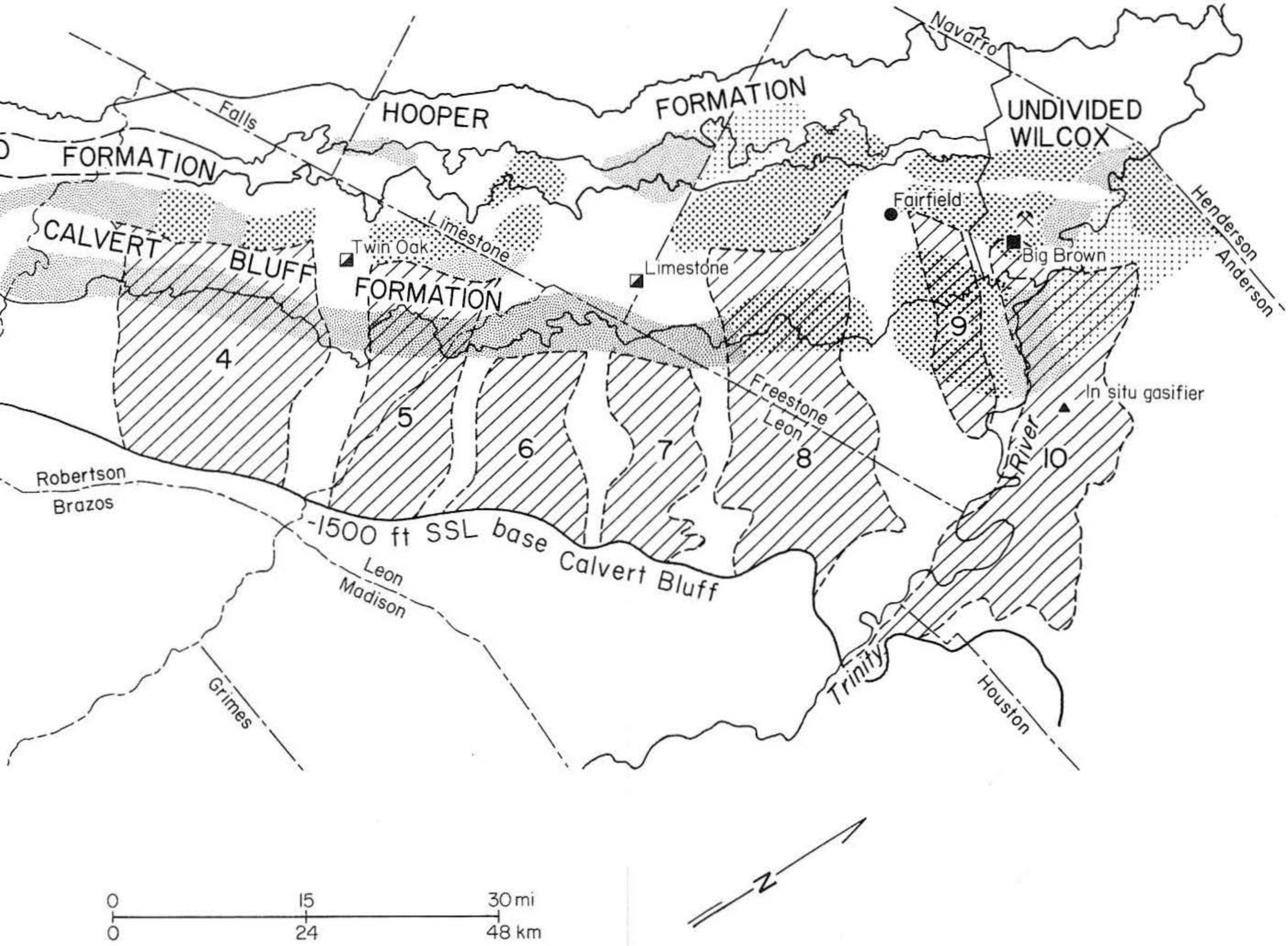


Figure 24. Distribution of lignite resources in the Wilcox of east-central Texas between the Colorado and Trinity Rivers.



W. R. Kaiser, 1979

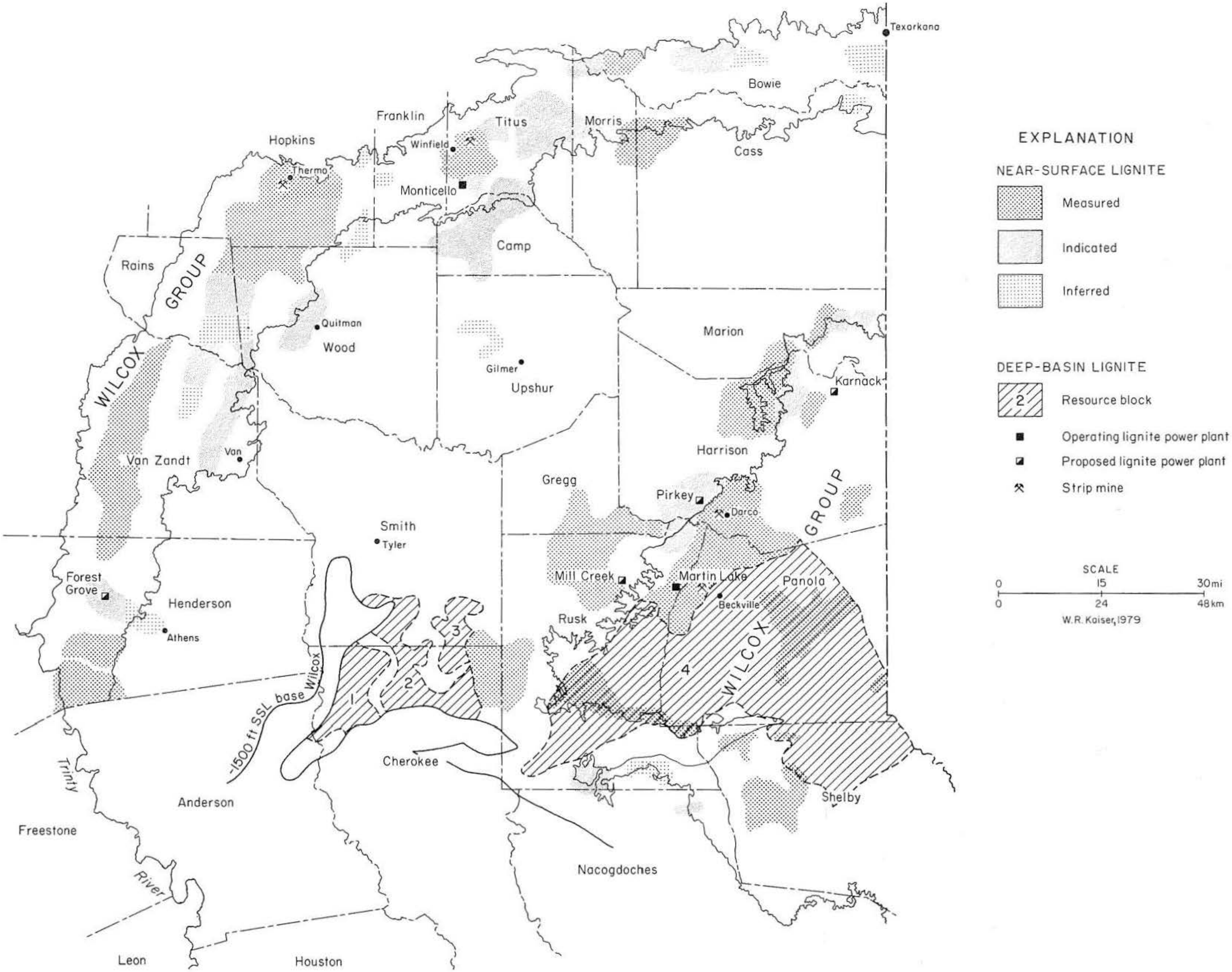


Figure 25. Distribution of lignite resources in the Wilcox of northeast Texas, north of the Trinity River northeastward to Texarkana, and on the Sabine Uplift adjacent to Louisiana.

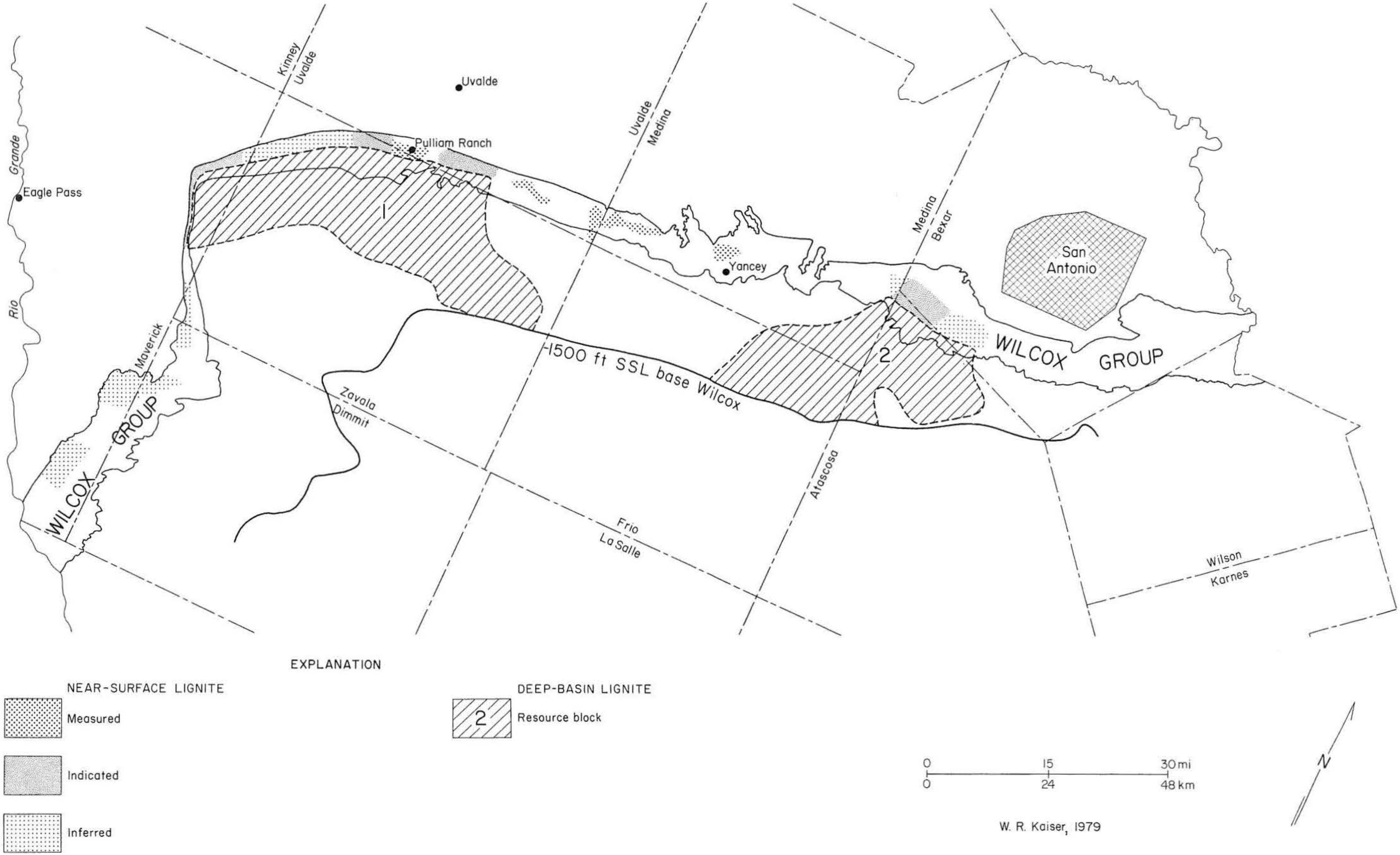


Figure 26. Distribution of lignite resources in the Wilcox of South Texas south of the Colorado River and southwest of San Antonio.

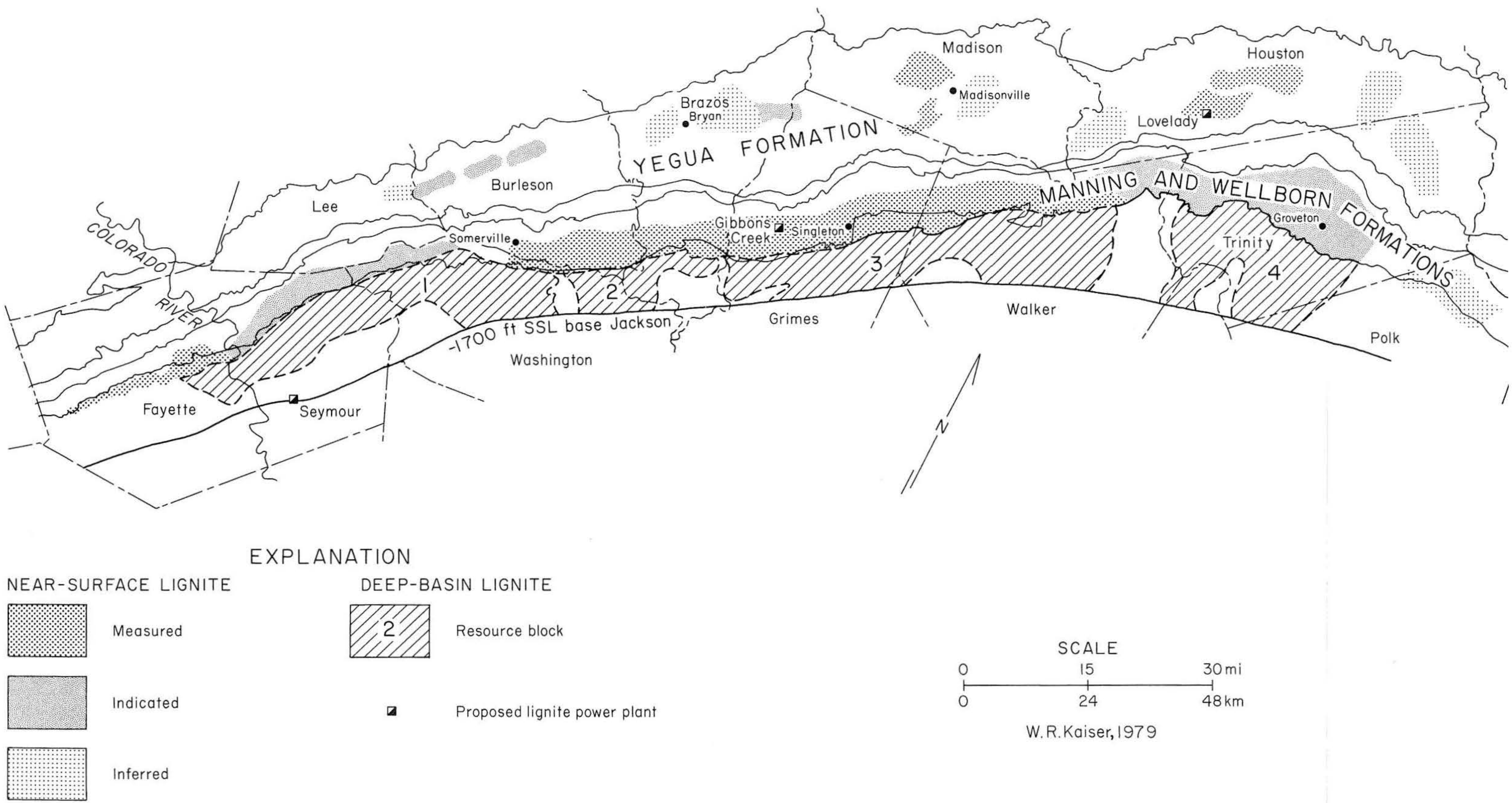
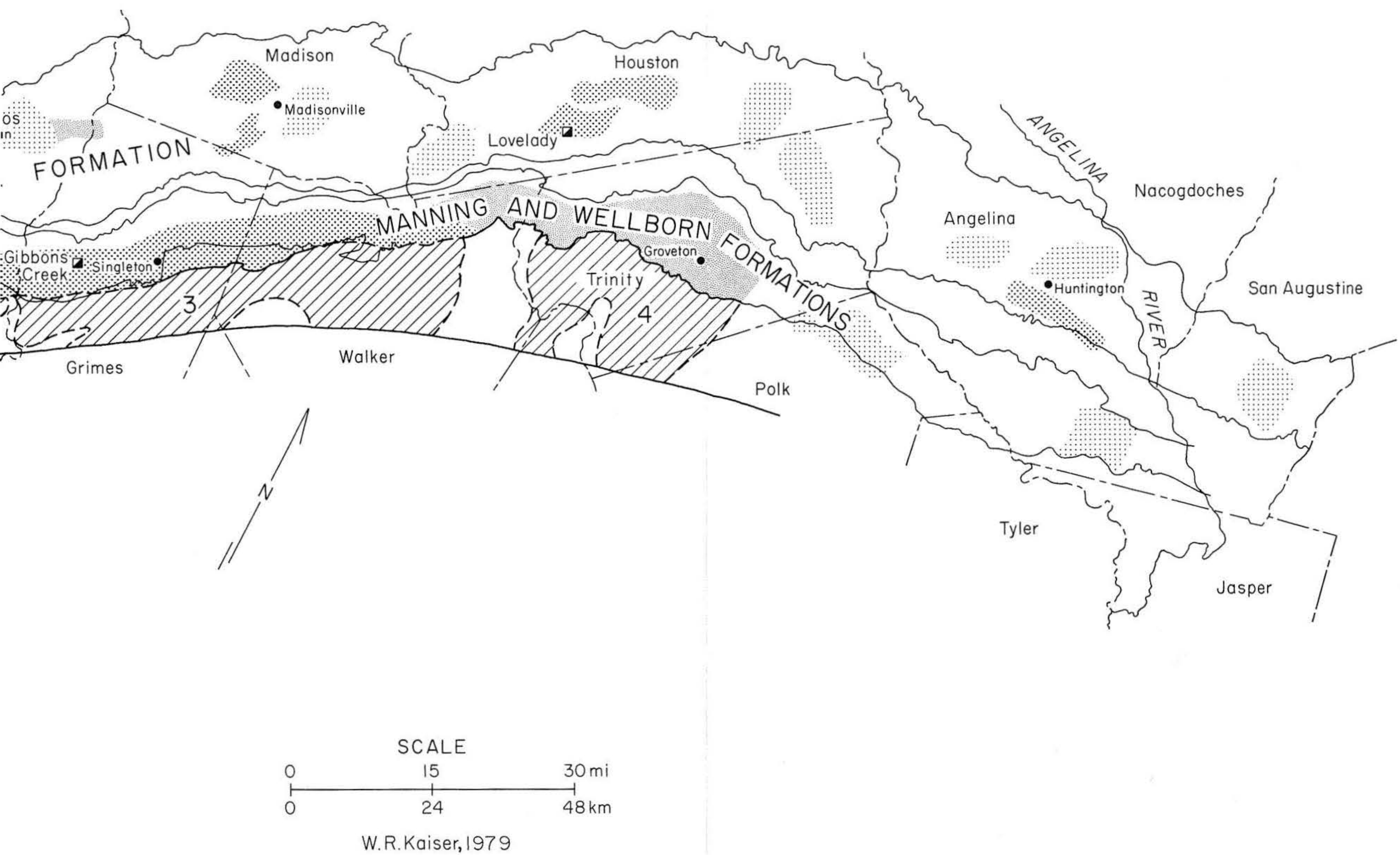


Figure 27. Distribution of lignite resources in the Jackson and Yegua of East Texas between the Colorado and Angelina Rivers. Deep-basin resources in the Jackson only.



FORMATION
MANNING AND WELLBORN FORMATIONS
Madison
Madisonville
Houston
Lovelady
Gibbons Creek
Singleton
Groveton
Trinity
3
4
Grimes
Walker
Polk
ANGELINA RIVER
Nacogdoches
Angelina
Huntington
San Augustine
Tyler
Jasper
N
SCALE
0
15
30 mi
0
24
48 km
W.R.Kaiser, 1979

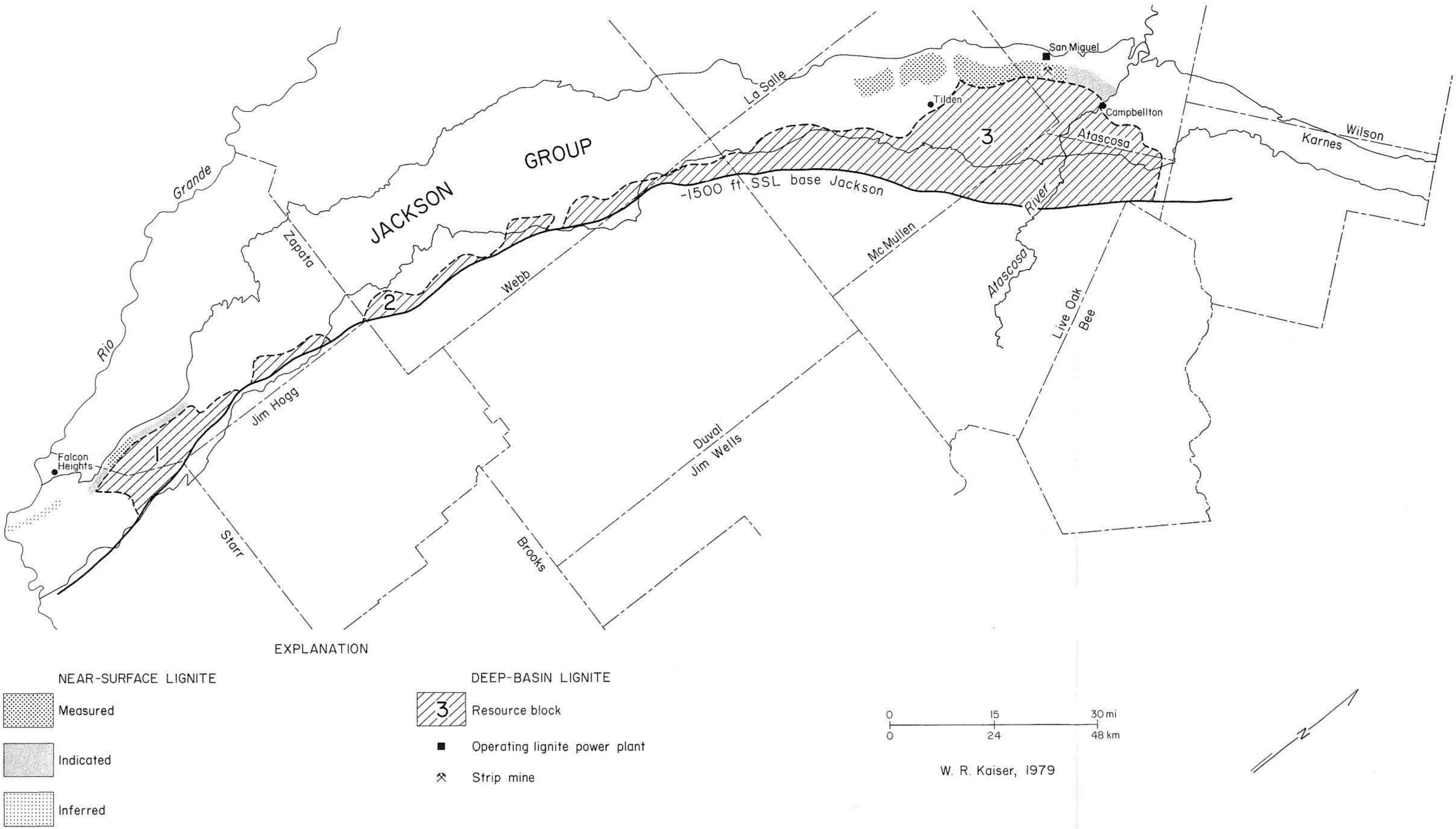


Figure 28. Distribution of lignite resources in the Jackson of South Texas south of the Atascosa River.

(24 km) or more. Average seam thickness is 4.1 ft (1.25 m), and the average number of seams is 2.0, 72 percent of them being more than 3 ft (0.9 m) thick (table 6).

SOUTH REGION

Resource blocks of commercial importance are found west of San Antonio (fig. 2). Because of sparse data, few details are known about these resources (table 2). Regional work has shown that the only significant lignite occurs in the lowermost part of the Wilcox (fig. 12). This is reflected in narrow measured deposits adjacent to the Midway contact or at a more northerly position within the outcrop (fig. 26). Stratigraphic occurrence has been used to outline indicated and inferred resources. The inferred resources were located mainly by projection of deep-basin occurrences to the outcrop. For example, those of Maverick County were defined by projecting east-

Table 6. Number of seams, thickness, and thin-seam resources.[a]

		Wilcox east-central	Wilcox northeast	Wilcox Sabine Uplift	Jackson east	Jackson south[b]	Yegua east[c]
Number of seams	X	2.46	2.76	2.01	1.73	1.64	1.32
	S	0.67	0.65	0.46	0.11	0.50	0.29
	C	0.27	0.23	0.23	0.06	0.31	0.22
Number ≥ 5 ft thick	X	0.75	0.59	0.44	0.67	0.60	0.46
	S	0.44	0.37	0.29	0.22	0.42	0.31
	C	0.58	0.63	0.66	0.36	0.69	0.66
	pct.	31	21	21	39	37	35
	S	18	15	17	9	36	32
Number 3-5 ft thick	X	0.58	0.60	0.63	0.52	0.17	0.31
	S	0.22	0.22	0.38	0.10	0.41	0.21
	C	0.37	0.37	0.61	0.19	2.4	0.67
	pct.	24	22	31	30	10	24
	S	8	7	13	6	17	12
Number 2-3 ft thick	X	1.12	1.57	0.94	0.55	0.87	0.55
	S	0.45	0.53	0.35	0.08	0.77	0.41
	C	0.40	0.33	0.37	0.14	0.88	0.75
	pct.	46	57	47	32	53	42
	S	18	13	11	4	32	24
Seam thickness in ft per seam ≥ 2 ft	X	4.49	3.69	4.14	4.65	6.90	4.32
	S	1.75	0.58	1.38	0.24	3.53	1.07
	C	0.39	0.16	0.33	0.05	0.51	0.25
Ave. total lignite per hole in ft		11.05	10.18	8.32	8.04	11.32	5.70
Pct. in ≥ 5 ft seams		54	37	42	57	75	54
Pct. in 3-5 ft seams		21	24	30	26	6	22
Pct. in 2-3 ft seams		25	39	28	17	19	24
Pct. in seams ≥ 3 ft thick		75	61	72	83	81	76
Lignite per hole in ≥ 3 ft seams		8.3	6.2	6.0	6.7	9.2	4.3
Resources in 2-3 ft seams (millions of short tons)		2,160	3,260	1,521	921	178	490
Percentage increase over resources in ≥ 3 ft seams		33	64	39	20	23	32

[a]Insufficient data for Wilcox south.
[b]Based on one measured deposit.
[c]Based on three measured deposits.
X = arithmetic mean.
S = standard deviation.
C = S/X = coefficient of variation.

west trending lignite occurrences lying immediately downdip in Dimmit County westward (updip) to the lower Wilcox outcrop (figs. 14 and 26).

Resources in the region are 1,078 million tons (978 million t) and constitute less than 10 percent of the Wilcox total; over half of the resources are inferred (table 3). Tonnage factors range from 6,500 to 17,500 tons per acre (14,565 to 39,214 metric tons per ha). Resource blocks range in size from 50 to 200 million tons (45 to 180 million t) and are considerably smaller than those in the other Wilcox regions but large enough to support mine-mouth power plants. The largest blocks are found near Pulliam Ranch southwestward to where the outcrop doglegs sharply to the southeast (fig. 26). Meager data did not allow an analysis of seam geometry. Subsurface analysis indicates the presence of seams 3 to 10 ft (0.9 to 3.0 m) thick, but of limited lateral continuity. One or two seams are common; however, on some electric logs three or four lignites have been counted in a 200-ft (61-m) interval, an indication of the possible presence of 12 to 16 ft (3.7 to 4.9 m) of near-surface lignite.

JACKSON RESOURCES

EAST REGION

Resources occur between the Colorado and Angelina Rivers (fig. 2) as a continuous band from southern Fayette County to eastern Trinity County and as two individual blocks farther east (fig. 27). They lie in the outcrop of the Manning and upper part of the Wellborn Formations. The only exception is resources lying in the mapped Whitsett Formation south of the Colorado River. Jackson facies become more marine in character southward; thus, in southern Fayette County it is suggested that only in the uppermost Jackson did deltas advance and platforms develop to the extent that would have allowed peat (lignite) to accumulate. Inferred blocks east of Trinity County that lie on the flank of the main Jackson delta system were outlined by projecting overlapping lobate sand bodies and lignite occurrences in the subsurface (figs. 16 and 17) updip to the Manning-Wellborn outcrop (fig. 27). Essentially, the exploration model, developed for deltaic facies tracts, was used to identify inferred resources.

Resources in the region are 4,499 million tons (4,081 million t) and constitute 86 percent of the Jackson total (table 3). Tonnage factors normally range from 9,800 to 12,700 tons per acre (21,960 to 28,458 t per ha). Resource blocks are large, up to 1,000 million tons (900 million t),and cover many thousands of acres. Seams are commonly 3 to 8 ft (0.9 to 2.4 m) thick, can be as thick as 12 ft (3.7 m), and are laterally continuous for up to 30 mi (48 km) or more. Because continuity is controlled by the size of the underlying platform (foundered delta), it is suggested that maximum continuity may approach 40 mi (64 km), or the width of two coalesced Jackson lobate sand bodies or delta lobes (fig. 16). Lateral extents of 20 mi (32 km) may be common. Average seam thickness is 4.7 ft (1.4 m), and the average number of seams is 1.7, 83 percent of them being greater than 3 ft (0.9 m) thick. These seams are the most tabular and least lenticular of any in Texas, as indicated by their low standard deviation and coefficient of variation (table 6), and reflect their deltaic origin.

SOUTH REGION

Resources occur south of the Atascosa River (fig. 2) in two widely separated areas: the Campbellton-Tilden area and the Rio Grande Valley (fig. 28). The absence of lignite between them is attributed to the dominance of ancient lagoonal sediments, suggesting the absence of suitable platforms for peat (lignite) accumulation. Resource blocks are narrower at the south than the north because of a steeper regional dip, 190 ft per mi compared with 80 ft per mi (36 m per km versus 15 m per km), respectively.

Resources in the region are 757 million tons (687 million t), concentrated mainly in the north, and constitute 14 percent of the Jackson total (table 3). Tonnage factors range from 7,000 to 12,200 tons per acre (15,685 to 27,338 t per ha). Resource blocks range in size from 50 to 300 million tons (45 to 270 million t); seams are commonly 5 to 10 ft (1.5 to 3.0 m) thick. Average seam thickness is 6.9 ft (2.1 m), and the average number of seams is 1.6, 81 percent of them being more than 3 ft (0.9 m) thick (table 6).

The San Miguel lignite extends for 20 to 25 mi (32 to 40 km) along strike and occurs in an interval 10 to 15 ft (3.0 to 4.6 m) thick. The interval contains 4 to 6 splits that are 6 to 12 inches (15 to 30 cm) thick, which thicken to the north and south and cause the lignite-bearing interval to expand to 30 to 40 ft (9.1 to 12.2 m) thick (McNulty, 1978; Snedden, 1979); it is bounded by dip-oriented sands and muds of postulated tidal and fluvial-deltaic origin mapped near Campbellton and Tilden (fig. 19). Seam dimensions are ultimately controlled by the width and length of the platform of accumulation—filled lagoons and abandoned strandplains.

YEGUA RESOURCES

Yegua resources are found only in East Texas north of the Colorado River (fig. 2). They occur along the trend as small, widely spaced, elliptical resource blocks occupying the middle two-thirds of the outcrop belt (fig. 27). Lignite at exploitable depths is fluvial and occurs in sand-deficient interchannel areas. The best deposits are found east of Madisonville, where they are correlated with the larger Yegua interchannel basins mapped in the immediate subsurface (fig. 22). Inferred blocks were outlined by projecting sand-poor areas and oblong lignite occurrences in the subsurface updip to the outcrop, where lignite has been reported in the older literature (figs. 22 and 23). In contrast with the Jackson, the exploration model developed for fluvial facies tracts was used to identify inferred resources.

Resources in the region are 1,551 million tons (1,407 million t), of which over half are inferred (table 3). Tonnage factors range from 5,250 to 10,600 tons per acre (11,764 to 23,752 t per ha). Resource blocks range in size from 40 to 150 million tons (36 to 135 million t) and are the smallest in Texas. The best deposits typically have one 5- to 6-ft (1.5- to 1.8-m) seam. Seams are commonly 2 to 6 ft (0.6 to 1.8 m) thick and may extend for up to 11 mi (18 km). Average seam thickness is 4.3 ft (1.3 m), and the average number of seams is 1.3, 76 percent of them being more than 3 ft (0.9 m) thick (table 6).

THIN-SEAM RESOURCES

From the analysis-of-thickness data, a preliminary assessment of resources in 2- to 3-ft (0.6- to 0.9-m) seams was made. The estimate was derived from the percentage of lignite in seams thicker than 3 ft (0.9 m) in each region. For example, in the Wilcox east-central region, the total lignite per borehole in seams more than 2 ft (0.6 m) thick is 11.05 ft (3.4 m) (2.46 x 4.49 ft = 11.05 ft) (table 6). Multiplying the number of 3- to 5-ft (0.9- to 1.5-m) and 2- to 3-ft (0.6- to 0.9-m) seams by a mean thickness, 4 ft (1.2 m) and 2.5 ft (0.8 m), respectively, yielded a thickness per borehole for the thickness interval, which was converted to a percent (0.58 x 4 ft/11.05 ft = 0.21). Subtracting the sum of the percentage in 3- to 5-ft (0.9- to 1.5-m) and 2- to 3-ft (0.6- to 0.9-m) seams from 100 gave the percentage in seams greater than 5 ft (1.5 m) thick: 54 percent (table 6). If, for the east-central region, resources of 6,481 million tons (5,880 million t) were generated by 75 percent of the total lignite present, or that in seams greater than 3 ft (0.9 m) thick (table 6), then by simple proportion 8,641 million tons (7,839 million t) would be generated by all the lignite. The difference, 2,160 million tons (1,960 million t), is judged to be a crude estimate of the resources in 2- to 3-ft (0.6- to 0.9-m) seams (table 6). Statewide resources would be increased 35 to 40 percent, or approximately 8 to 9 billion tons (7.2 to 8.1 billion t), if thin seams were included.

RESERVES

Reserves are that part of the demonstrated resources that can be economically and legally extracted at the time of determination. Reserves are dynamic and change with the times, being affected by mining depth, stripping ratio, minimum seam thickness, mining method, recovery factor, multiseam versus single-seam deposit, illegal fraction, air quality regulations, price and availability of competing fuels, and ultimate use. Only the mining factors and the illegal fraction were evaluated in this study.

MINING FACTORS

Area stripping is the mining method used in Texas. Mining is by dragline sidecasting or scrapers at less than 120 ft (37 m); average stripping ratios are approximately 10 to 1 (yd^3 overburden per ton of lignite mined). Recovery factors of 80 to 90 percent are achieved. The average maximum stripping ratio is currently about 15 to 1 and is expected to increase to 20 to 1. Dragline sidecasting when mining single- or double-seam deposits at less than 120 ft (37 m) is the least expensive method. However, the dragline is inefficient in multiseam mining. No more than two overlying seams can be efficiently mined on the way down to the main seam. Scrapers are suitable for multiseam, thin-seam mining where output is small, 1 to 2 million tons (0.9 to 1.8 million t) per year. Fleet size is the limiting factor. Scrapers are being used at Texas Utilities' Thermo Mine, Hopkins County (fig. 25); all other mines in Texas use draglines (Kaiser, 1978a).

Mining will become more complex as thinner, more lenticular seams with attendant higher stripping ratios (>15 to 1) are mined. Depending on the deposit, minimum seam thickness will decrease from 3 ft (0.9 m) to 2 ft (0.6 m), particularly in a multiseam deposit where shallow thin seams overlie the main seam or seams. Lenticular seams present a problem in maintaining pit length. Lengths greater than 1 mi (1.6 km) are optimum; lengths down to 0.5 mi (0.8 km) can be sustained.

Most mining will continue to be done by dragline sidecasting. Draglines at their maximum size (360 ft [110 m] boom, 95 yd^3 [73 m^3] bucket) are limited to 125 ft (38 m) without rehandling of the overburden. Deeper mining will require benching and draglines in tandem, bucket-wheel excavator (BWE) and dragline combinations, or BWE's alone. Without dewatering and isolation of recharge areas, mining is not likely to exceed 150 ft (46 m). Dewatering is necessary to avoid slope failure and pit-floor heave. Boom length and spoil height are other limitations. Deep mining of any kind will be more difficult in important aquifers such as the Wilcox-Carrizo, whereas it should be easier in less transmissive, mud-rich geologic units like the Jackson.

Mining to the depths contemplated by some companies, 200 to 250 ft (61 to 76 m) or more, is technically feasible; however, it has yet to be demonstrated in the Gulf Coast. Deep mining of multiseam, thin-seam deposits will probably require BWE's because draglines are inefficient mining machines for these deposits. BWE's frequently have lower initial capital and ownership costs than draglines used in deep, multiseam mining (Russell, 1980). Seams and splits as thin as 20 inches (51 cm) and 12 inches (30 cm), respectively, can be selectively mined by BWE's. They are efficient where splits are numerous, but less so where seams are of variable thickness.

BWE's merit serious consideration in high-volume applications where material must be mined rapidly and continuously and transported beyond the pit. They will probably be used first in large-scale mines producing more than 4 million tons (3.6 million t) per year and where multiseam mining will occur well below 120 ft (37 m). Sandy, unconsolidated overburden free of nodules and boulders is the ideal mining material for the BWE. The wheel can cut a gentle slope near the angle of repose and thereby overcome problems of slope stability.

ILLEGAL FRACTION

The illegal fraction is that fraction of productive acreage under populated areas, highways, pipelines, railroads, rivers, and reservoirs that cannot be mined. The width of the area affected by these features is shown in table 7. Widths were then multiplied by their lengths within the lignite belt to obtain the areas. Reservoirs and populated areas were evaluated on a case-by-case basis. County roads, small streams, and oil fields were not considered because roads and streams will be moved or restored after mining, and in the few areas where oil fields are present, lignite leasing suggests that the area will ultimately be mined. Data were collected from 11 representative counties. The mean illegal fraction was 11.1 percent, standard deviation 6.8 percent, range 19 percent, coefficient of variation 0.61, and modal class 5 to 10 percent.

Approximation of the illegal fraction can be obtained from a plot of illegal fraction versus population density (fig. 29), where density was determined by dividing rural population of a county by its area. Because the lignite belt is rural in character, towns of 5,000 population or more were subtracted from the county total (1970 U. S. census) to yield the rural population as used here. Figure 29 implies, all other considerations remaining equal, shrinking reserves with increasing population.

Table 7. Parameters for calculating illegal fraction.

Type of feature	Right-of-way	Mining clearance	Width in ft
Farm-to-market road	95	2 x 150	395
State highway	132	2 x 150	432
Interstate highway	338	2 x 150	638
Railroad	100	2 x 150	400
Pipeline		2 x 100	200
River	300[a]	2 x 150	600
Reservoir and Populated area		Specific area plus 150 ft mining clearance	

[a]Average river width.

MARKET FACTORS

Currently, growth in electricity demand is the most important factor affecting demand for lignite. Of major importance to potential industrial users is the price and availability of alternate fuels. As long as natural gas is available under long-term contract for less than the estimated cost of lignite from future mines, there will be little incentive to convert to lignite. Furthermore, capital and operating costs required to use lignite compared with those of alternative fuels affect all decisions on conversion.

Ultimate use, for example in electric power generation, industrial boilers, or synthetic fuel plants, affects the definition of reserves. A deposit of 15 million tons (14 million t) or less is large enough to supply industrial boilers, but is an order of magnitude too small for large-scale power generation, whereas a deposit for a synthetic fuel plant must be four or five times the size required for a power plant.

Grade, irrespective of the effect on capital and operating costs, is not expected to affect significantly electric utility demand for lignite because lignite of all grades is currently planned for use in electric power generation. Grade will probably affect industrial conversion more because of the difficulty in meeting air quality regulations and the specialized process needs. For example, at this time low-combustion temperature makes lignite unsuitable for firing cement kilns. Conversion of lignite to synthetic fuels will also be subject to many process-specific requirements.

ASSUMPTIONS AND CURRENT ESTIMATE

Reducing demonstrated resources (20,383 million tons [18,491 million t]) by the illegal fraction (11 percent) yields 18,141 million tons (16,458 million t), or the legally available resources. These are further reduced by a mining depth factor to establish the reserve base. Currently, mining to 120 ft (37 m) is common in Texas. Draglines now in use and on order for future mines can mine to that depth without rehandling the overburden. If mining depth is 120 ft (37 m), a mining factor of 0.56 can be calculated from the ratio 120-20/200-20, or 100/180. Applying this factor to the available resources yields a reserve base of 10,159 million tons (9,216 million t). Recovery factors depend on seam thickness and are estimated by dividing thickness minus 0.5 ft (15 cm) by thickness. This translates to factors of 75, 83, and 90 percent for 2-, 3-, and 5-ft (0.6-, 0.9-, and 1.5-m) seams, respectively. Because seams less than 5 ft (1.5 m) thick are common, 85 percent is realistic and is used here. Multiplying the reserve base by 0.85 gives reserves of 8,635 million tons (7,834 million t).

In the future when mining deeper than 120 ft (37 m) is commonplace, reserves will increase; for example, reserves would be 11,102 million tons (10,072 million t) if mining depth were 150 ft (46 m). Deeper mining is certain. In the opinion of some mining experts, mining to 200 ft (61 m) will be economical and will make the available resources (18,141 million tons [16,458 million t]) calculated here, in effect, the reserve base for lignite in Texas. When multiseam mining becomes common, recovery of thin seams (2 to 3 ft [0.6 to 0.9 m] thick) will be routine. At that time, some fraction of the extensive resources in thin seams will be added to the reserve base.

GRADE

Lignite of the highest grade (6,500 Btu/lb [3,612 kcal/kg] as received) occurs in the Wilcox Group north of the Colorado River. The State's poorest grade lignite (4,500 Btu/lb [2,501 kcal/kg]) occurs in the Jackson Group. Yegua lignite (5,800 Btu/lb [3,223 kcal/kg]) is intermediate in grade between Wilcox and Jackson lignite (table 8).

WILCOX LIGNITE

North of the Colorado River, the average lignite on an as-received basis has 33 percent moisture, 15 percent ash, 0.9 percent sulfur, and a heating value of 6,504 Btu/lb (3,614 kcal/kg). Meager data were available for South Texas, but it

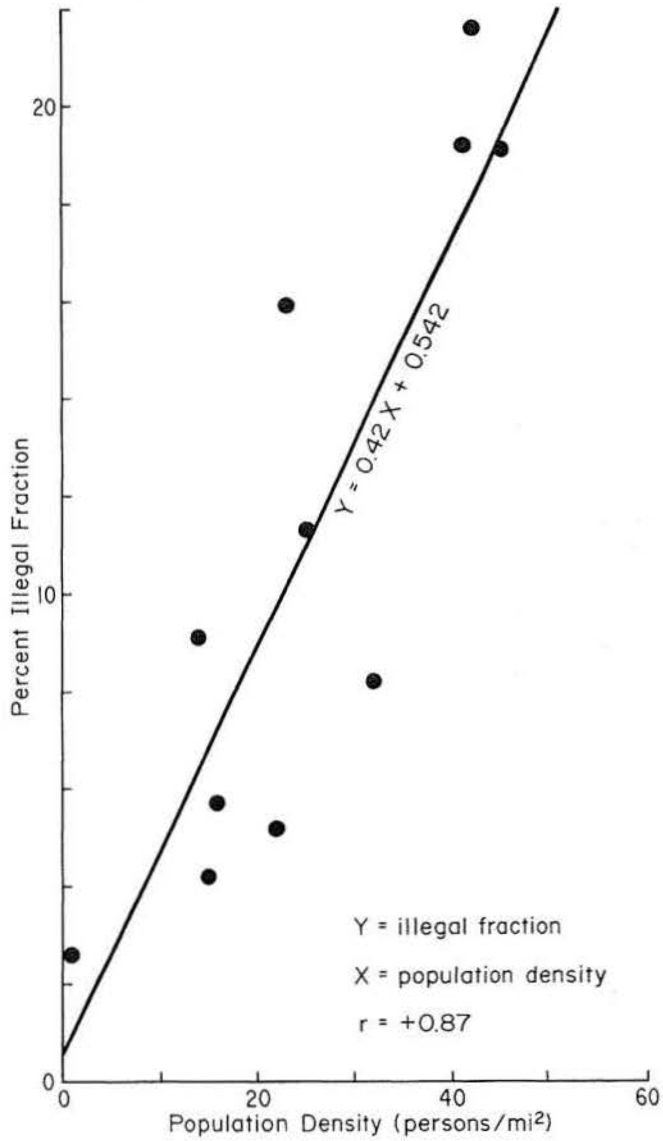


Figure 29. Linear regression of illegal fraction on population density.

Table 8. Proximate analyses (as-received and dry basis).

		Wilcox east-central	Wilcox northeast	Wilcox Sabine Uplift	Wilcox mean	Jackson east	Jackson south	Jackson mean	Yegua east	Weighted mean north of Colorado River[a]
					As-received basis					
Moisture	X	32	33	33	33	41	23	37	37	35
	S	4	4	4	4	6	6	10	4	
	R	26	28	29	29	29	27	45	15	
	C	0.12	0.12	0.11	0.12	0.14	0.25	0.27	0.12	
	N	83	79	113	275	169	55	224	29	
Volatile matter	X	29	27	27	28	23	22	23	26	27
	S	3	4	4	4	4	6	4	4	
	R	15	25	24	27	23	37	43	17	
	C	0.10	0.13	0.14	0.13	0.16	0.26	0.19	0.14	
	N	83	79	113	275	169	55	224	29	
Fixed carbon	X	24	25	25	24	15	13	14	19	22
	S	4	4	4	4	4	6	4	4	
	R	23	25	26	31	21	20	24	17	
	C	0.17	0.14	0.18	0.17	0.25	0.42	0.29	0.18	
	N	83	79	113	275	169	55	224	29	
Ash	X	15	15	15	15	21	42	26	18	17
	S	7	8	10	9	10	12	14	8	
	R	31	45	53	53	43	52	60	31	
	C	0.46	0.53	0.67	0.57	0.48	0.29	0.52	0.45	
	N	83	79	113	275	169	55	224	29	
Sulfur	X	1.0	0.8	0.9	0.9	1.3	1.9	1.4	1.0	1.0
	S	0.5	0.4	0.5	0.5	0.7	1.3	0.9	0.4	
	R	2.9	1.7	2.8	3.2	6.4	8.2	8.4	1.6	
	C	0.49	0.46	0.56	0.51	0.50	0.65	0.62	0.43	
	N	76	78	113	267	174	55	229	29	
Btu/lb	X	6,593	6,499	6,441	6,504	4,729	3,972	4,547	5,761	6,095
	S	822	873	1,087	952	942	1,647	1,192	796	
	R	4,673	5,407	6,231	7,293	4,581	8,721	8,721	3,701	
	C	0.12	0.13	0.17	0.15	0.20	0.41	0.26	0.14	
	N	83	79	113	275	174	55	229	29	
					Dry basis					
Volatile matter	X	43	41	41	41	40	28	37	41	41
	S	4	6	6	6	8	8	9	7	
	R	24	32	36	39	45	51	55	27	
	C	0.10	0.13	0.16	0.14	0.19	0.28	0.25	0.16	
	N	65	78	116	259	153	48	201	29	
Fixed carbon	X	35	37	37	37	25	17	24	31	34
	S	7	6	8	7	7	8	8	7	
	R	31	36	42	43	32	27	37	30	
	C	0.19	0.15	0.21	0.19	0.28	0.46	0.34	0.21	
	N	65	78	116	259	153	48	201	29	
Ash	X	22	22	22	22	34	54	39	28	25
	S	9	10	13	11	14	13	16	11	
	R	42	58	71	71	60	59	67	42	
	C	0.43	0.46	0.61	0.52	0.40	0.24	0.41	0.40	
	N	65	78	116	259	153	48	201	29	
Sulfur	X	1.4	1.2	1.4	1.3	2.3	2.2	2.2	1.6	1.5
	S	0.7	0.5	0.8	0.7	0.9	1.0	0.9	0.7	
	R	4.1	2.5	4.3	4.3	5.2	3.6	5.2	2.7	
	C	0.49	0.44	0.55	0.52	0.41	0.44	0.42	0.44	
	N	65	78	113	256	261	48	309	29	
Btu/lb	X	9,715	9,760	9,764	9,750	8,222	5,077	7,733	9,166	9,403
	S	1,468	1,414	1,801	1,605	1,622	2,019	2,036	1,521	
	R	6,036	7,561	10,152	10,152	8,918	7,029	10,926	6,042	
	C	0.15	0.14	0.18	0.16	0.20	0.40	0.26	0.17	
	N	65	78	116	259	261	48	309	29	

[a]Based on percentage of resources.
X = arithmetic mean.
S = standard deviation.
R = range.
X, S, R in weight percent.
C = S/X = coefficient of variation.
N = number of analyses.
Note: Analyses do not represent a random sample.

Table 9. Forms of sulfur.

Form	Basis	Stat	Wilcox east-central	Wilcox northeast	Wilcox Sabine Uplift	Wilcox mean	Jackson east	Yegua east	Weighted mean north of Colorado River
Total sulfur	As received	X	0.96	0.79	0.94	0.90	1.29	0.99	0.99
		S	0.47	0.36	0.51	0.46	0.67	0.43	
		R	2.91	1.66	2.83	3.15	6.44	1.59	
		C	0.49	0.46	0.53	0.51	0.52	0.43	
		N	76	78	113	267	174	29	
	Dry	X	1.41	1.18	1.42	1.35	2.25	1.57	1.56
		S	0.70	0.52	0.79	0.70	0.93	0.69	
		R	4.05	2.53	4.34	4.34	5.21	2.71	
		C	0.49	0.44	0.55	0.52	0.41	0.44	
		N	65	78	113	256	261	29	
Pyritic sulfur	As received	X	0.22	0.29	0.26	0.26	0.40	0.50	0.31
		S	0.15	0.37	0.18	0.25	0.26	0.41	
		R	0.51	1.50	0.78	1.50	1.12	1.21	
		C	0.67	1.27	0.72	0.98	0.66	0.82	
		N	25	27	30	82	38	14	
	Dry	X	0.34	0.44	0.39	0.40	0.54	0.81	0.46
		S	0.23	0.52	0.28	0.38	0.42	0.66	
		R	0.68	2.28	1.14	2.28	3.07	1.97	
		C	0.67	1.18	0.71	0.96	0.78	0.81	
		N	14	29	30	73	141	14	
Sulfate sulfur	As received	X	0.02	0.01	0.03	0.02	0.02	0.02	0.02
		S	0.03	0.004	0.04	0.03	0.03	0.01	
		R	0.17	0.01	0.19	0.19	0.14	0.04	
		C	1.42	0.36	1.23	1.35	1.33	0.60	
		N	25	27	30	82	38	14	
	Dry	X	0.01	0.01	0.05	0.03	0.03	0.03	0.03
		S	0.01	0.01	0.07	0.05	0.06	0.01	
		R	0.03	0.04	0.37	0.37	0.34	0.05	
		C	0.78	0.62	1.45	1.75	1.90	0.50	
		N	14	29	30	73	141	14	
Organic sulfur[a]	As received	X	0.72	0.49	0.65	0.62	0.87	0.47	0.66
		S	0.13	0.13	0.32	0.28	0.40	0.10	
		R	0.54	0.62	1.11	1.32	1.64	0.43	
		C	0.19	0.31	0.38	0.43	0.32	0.16	
		N	25	27	30	82	38	14	
	Dry	X	1.06	0.73	0.98	0.92	1.68	0.73	1.07
		S	0.24	0.25	0.50	0.46	0.67	0.20	
		R	0.85	1.15	1.80	2.17	3.40	0.75	
		C	0.24	0.37	0.39	0.47	0.34	0.18	
		N	14	29	30	73	141	14	

[a]X determined by difference; S, R, and C calculated from available analyses, N.

is known that lignite of comparable grade is present. Generally, it has lower moisture, higher ash (up to 20 percent), higher sulfur (1.5 to 2.0 percent), and similar or higher heating value. Most of the sulfur (about 70 percent) in Wilcox lignite is present as organic sulfur (table 9), which is reflected in the direct correlation of higher sulfur with lower ash content.

North of the Colorado River, no obvious differences exist between regions; this supports the conclusion drawn from the geology that no major differences exist in depositional environment—all were fluvial. However, absolute differences occur that may not be statistically significant, but may nevertheless be geologically significant. Sulfur content is lowest in the northeast region, which is thought to be due to its location high on the ancient alluvial plain (table 9). Lignites in the other two Wilcox regions accumulated somewhat lower on the ancient coastal plain and may have been subject to slightly more marine influence, higher temperatures because of deeper burial, and/or slower rates of accumulation. No difference exists between the means for ash; however, variation is less (lower standard deviation and coefficient of variation) for the east-central region (table 8). This is attributed to accumulation lower on the alluvial plain, where interchannel basins were larger, structurally more stable, and less vulnerable to overbank flooding and crevassing. Striking differences between individual deposits from the three

Table 10. Ash composition and fusion temperatures.

	Wilcox east-central	Wilcox northeast	Wilcox Sabine Uplift	Jackson east	Jackson south[a]	Yegua east
SiO_2	48.53	44.53	40.51	57.58	62.88	53.64
Al_2O_3	17.12	11.39	16.28	20.26	17.49	14.96
TiO_2	1.09	1.14	0.89	0.81	0.82	0.79
CaO	13.20	13.74	12.51	7.49	4.82	9.89
MgO	2.30	2.55	3.03	1.13	0.72	1.81
Fe_2O_3	6.23	7.39	11.46	3.20	2.83	6.61
Na_2O	0.38	0.56	0.80	0.86	3.10	1.23
K_2O	0.84	0.63	0.70	0.84	1.96	1.24
SO_3	9.35	10.87	11.81	7.10	4.62	8.87
P_2O_5	0.11	0.06	0.10	0.05	0.06	0.06
Number of analyses (oxides)	26	21	35	116	design	16
Base/acid[b]	0.34	0.44	0.49	0.17	0.17	0.30
SiO_2/Al_2O_3	2.8	3.9	2.5	2.8	3.6	3.6
Initial deformation	2,226	2,186	2,108	2,240	2,660	2,149
Softening (H=W)	2,261	2,280	2,168	2,351	>2,700	2,200
Hemispherical ($H=\frac{1}{2}W$)	2,315	2,284	2,215	2,378	>2,700	2,256
Fluid	2,357	2,388	2,393	2,466	>2,700	2,475
Number of analyses (temperature)	27	27	26	32	design	14

Oxides in weight percent.
Fusion temperatures in reducing atmosphere, °F.
[a]San Miguel lignite.
[b]$\frac{\text{base}}{\text{acid}} = \frac{CaO+MgO+Fe_2O_3+Na_2O+K_2O}{SiO_2+Al_2O_3+TiO_2}$

regions (Kaiser, 1978a) parallel those suggested here between regions.

Fouling and slagging of boilers burning Wilcox lignite has not been an operating problem because Wilcox ash content is moderate and it contains little Na_2O (table 10) (Kaiser, 1978a). In the future, the possible adverse effect of high iron content (Fe_2O_3) should not be overlooked when evaluating the slagging and fouling potential of an ash (Selle, 1978). Some lignite ash from the Sabine Uplift region contains 15 to 25 percent Fe_2O_3. Nitrogen and chlorine contents are expected to present no major obstacles to utilization (table 11).

JACKSON LIGNITE

The best Jackson lignite is in East Texas (table 8); it has higher moisture, ash, and sulfur content and lower heating value than Wilcox lignite. The San Miguel lignite (30 percent moisture, 28.4 percent ash, 1.67 percent sulfur, and 5,000 Btu/lb [2,779 kcal/kg] as received) is the best lignite in South Texas. Moderately high sulfur and high ash Jackson lignites reflect accumulation in marshes on the delta plain or the strandplain/lagoonal complex. Higher sulfur content is a direct result of accumulation at a more seaward location, subject to eventual invasion or permeation by sulfate-rich waters. High ash content is a function of contamination by clastic sediment, such as that washed onto a foundering delta or strandplain or over and through barrier beaches into associated marshes, and possibly of airborne volcanic ash.

South Texas Jackson lignite poses a serious fouling potential. The Na_2O content is higher than that in any other Texas lignite ash (table 10), but is less than 5 percent and is not considered excessive. The potential problem is posed by the combination of high ash content with high Na_2O and silica contents (Kaiser, 1978a). Jackson base-to-acid ratios are lower and fusion temperatures somewhat higher than values for ash from Wilcox and Yegua lignite (table 10). Predictably, slags from these high-acid ashes will have high viscosities; therefore, Texas lignite in general may be best suited to non-slagging conversion processes.

Table 11. Ultimate analyses (as-received and dry basis).

		Wilcox east-central	Wilcox northeast	Wilcox Sabine Uplift	Wilcox mean	Jackson east	Yegua east	Weighted mean north of Colorado River
				As-received basis				
Carbon	X	37	37	39	38	26	32	35
	S	5	6	4	5	6	3	
	R	16	25	15	27	23	10	
	C	0.13	0.15	0.10	0.13	0.21	0.10	
	N	32	37	43	112	41	14	
Hydrogen	X	3.8	5.1	3.1	3.9	5.1	2.6	4.0
	S	1.6	1.8	0.3	1.6	2.4	0.2	
	R	4.6	4.6	1.3	4.8	6.1	0.7	
	C	0.42	0.35	0.09	0.40	0.48	0.09	
	N	32	37	43	112	41	14	
Nitrogen	X	0.8	0.7	0.7	0.7	0.5	0.7	0.7
	S	0.1	0.1	0.1	0.1	0.4	0.1	
	R	0.5	0.6	0.5	0.7	2.7	0.2	
	C	0.16	0.18	0.18	0.18	0.83	0.10	
	N	32	37	43	112	41	14	
Chlorine	X	0.03	0.05	0.05	0.04	0.04	0.06	0.04
	S	0.03	0.05	0.04	0.04	0.02	0.03	
	R	0.10	0.11	0.12	0.12	0.07	0.11	
	C	0.97	1.00	0.84	0.88	0.62	0.55	
	N	21	9	39	69	16	14	
Sulfur	X	1.0	0.7	1.1	1.0	1.7	1.2	1.2
	S	0.3	0.4	0.4	0.4	0.5	0.4	
	R	1.1	1.6	1.6	1.6	2.4	1.3	
	C	0.27	0.54	0.38	0.43	0.29	0.36	
	N	32	37	43	112	41	14	
Oxygen[a]	X	10	8	8	8	5	9	7
	S	12	15	2	13	20	1	
	R	35	35	13	36	48	3	
	C	0.71	0.51	0.21	0.69	0.65	0.10	
	N	32	37	43	112	41	14	
				Dry basis				
Carbon	X	54	56	59	57	48	53	55
	S	9	9	6	8	8	7	
	R	26	44	22	44	48	22	
	C	0.17	0.17	0.10	0.14	0.17	0.13	
	N	14	38	46	98	144	14	
Hydrogen	X	4.6	4.3	4.6	4.5	3.9	4.2	4.4
	S	0.5	0.7	0.4	0.5	0.5	0.5	
	R	1.7	3.5	1.5	3.7	2.7	1.7	
	C	0.10	0.15	0.09	0.12	0.13	0.11	
	N	14	38	46	98	144	14	
Nitrogen	X	1.0	1.0	1.0	1.0	0.8	1.0	1.0
	S	0.2	0.2	0.2	0.2	0.5	0.2	
	R	0.7	0.9	0.7	1.0	5.5	0.5	
	C	0.23	0.19	0.18	0.19	0.56	0.15	
	N	14	38	46	98	144	14	
Chlorine	X	0.08	0.07	0.07	0.07	0.03	0.10	0.07
	S	0.04	0.07	0.06	0.06	0.07	0.06	
	R	0.11	0.17	0.19	0.19	0.77	0.17	
	C	0.45	0.96	0.88	0.80	2.39	0.54	
	N	10	11	39	60	119	14	
Sulfur	X	1.3	1.2	1.7	1.4	2.5	1.9	1.7
	S	0.3	0.6	0.7	0.6	0.9	0.6	
	R	0.9	2.5	2.5	2.5	4.9	2.0	
	C	0.22	0.52	0.41	0.46	0.34	0.34	
	N	14	38	46	98	144	14	
Oxygen[a]	X	17	15	12	14	11	11	13
	S	7	3	4	4	2	2	
	R	18	20	20	25	12	7	
	C	0.35	0.18	0.23	0.25	0.15	0.14	
	N	14	38	46	98	144	14	

[a]X determined by difference; S, R, and C calculated from available analyses, N.

Note: Analyses do not represent a random sample.

DEEP-BASIN RESOURCES

Deep-basin lignite resources between 200 and 5,000 ft (61 and 1,525 m) were estimated in 1974 by Kaiser (1974a) to be approximately 100 billion tons (90 billion t). All seams were assumed to be 2 ft (0.6 m) thick and laterally continuous. Today, resources defined in terms of seams greater than 5 ft (1.5 m) thick and between 200 and 2,000 ft (61 and 610 m) are more realistic for in situ gasification, deep surface mining, or even possibly for underground mining in the distant future. Resources have been calculated here in those terms and in the context of a thorough understanding of the regional geology based on 16 lithofacies, 7 lignite-occurrence, and 6 structure-contour maps. The 35-billion-ton (32-billion-t) estimate rests on a data base of 3,620 electric and induction logs run in oil and gas wells (table 2).

METHODOLOGY

RESOURCE IDENTIFICATION

In the absence of porosity logs such as density or neutron logs, lignite is operationally defined as a bed with a sharp resistivity spike and a baseline or shale spontaneous potential (SP) (Kaiser, 1974a). The operational definition becomes increasingly more difficult to apply as formation waters become fresher and the SP less well defined. Therefore, lignites become increasingly more difficult to identify moving updip from the deep basin into the shallow subsurface, where they cannot be easily distinguished from thin, fresh-water sands. In this case, the exploration model is used to project lignite updip from the deep basin into the shallow subsurface.

Lignites are most easily identified on electric logs. Opposite a lignite seam, the lateral curve has an extremely peaked resistivity kick; this curve can identify lignites as thin as 1 ft (30 cm). The long normal curve (64-inch [163-cm] spacing) displays a reversal toward the baseline in beds thinner than 64 inches (163 cm) (fig. 30, well Q-30) and thus provides a way to identify seams greater than 5 ft (1.5 m) thick. The induction log is not well suited to the identification of lignites less than 4 ft (1.2 m) thick; however, thicker beds can be identified reasonably well on curve peakedness (fig. 30, well Q-48).

The occurrence of lignite in the deep basin is shown on a series of isopleth maps on which the total number of lignites, as defined operationally, in the stratigraphic interval of interest was mapped (figs. 6, 11, 14, 17, 20, and 23). Also recorded was the number of seams greater than 5 ft (1.5 m) thick. A structure-contour map on the base of each interval was made and allows estimation of the drilling depth necessary to test all the lignite-bearing interval at any point in the basin. Only the -1,500-ft (-457-m) sub-sea-level (SSL) structure contour is shown on the occurrence maps.

Resource blocks were outlined by projecting mapped occurrences as defined by the two- or one-lignite isopleth line updip to the downdip limit of near-surface deposits or the 200-ft (61-m) depth line. The one-lignite line was used in South Texas, where a more restricted stratigraphic interval was evaluated. In fluvial facies tracts, lignite occurrences were projected parallel to and between channel sand belts, whereas for deltaic facies tracts, projection is confidently made on individual delta lobes into areas of sparse control. Strandplain/lagoonal occurrences are elongate and coincide with maximum sand development where the elongate trend guides projection.

The -1,500-ft (-457-m) SSL structure contour (approximately the 2,000-ft [610-m] depth line) on the base of the stratigraphic unit in question marked the downdip limit of the resource block. Other blocks are limited by the absence of lignite and are contained within the 200-ft (61-m) and 2,000-ft (610-m) depth lines. Examples are blocks 3 and 4 on the Sabine Uplift (fig. 31). North of the Colorado River, gaps between blocks generally coincide with major channel sand belts or interdeltaic embayments. The updip limit of South Texas lower Jackson lignite is defined along most of its extent by muddy lagoonal sediments.

TONNAGE FACTORS

Tonnage factors were determined from seam thickness data in the adjacent near-surface resource block and from the distribution of seams greater than 5 ft (1.5 m) thick in the deep basin. The average number of near-surface lignites more than 5 ft (1.5 m) thick ranged from 0.44 to 0.75 in the Wilcox Group and 0.60 to 0.67 in the Jackson Group. The number of deep-basin seams greater than 5 ft (1.5 m) thick rarely exceeds one.

Tonnage factors assigned were 8,750, 13,125, and 17,500 tons per acre (19,607, 29,410, and 39,214 t per ha), equivalent to a 5-ft (1.5-m), 7.5-ft (2.3-m), and 10-ft (3.0-m) seam, respectively. Factors were applied uniformly to each outlined resource block and imply, for instance, at least one 5-ft (1.5-m)

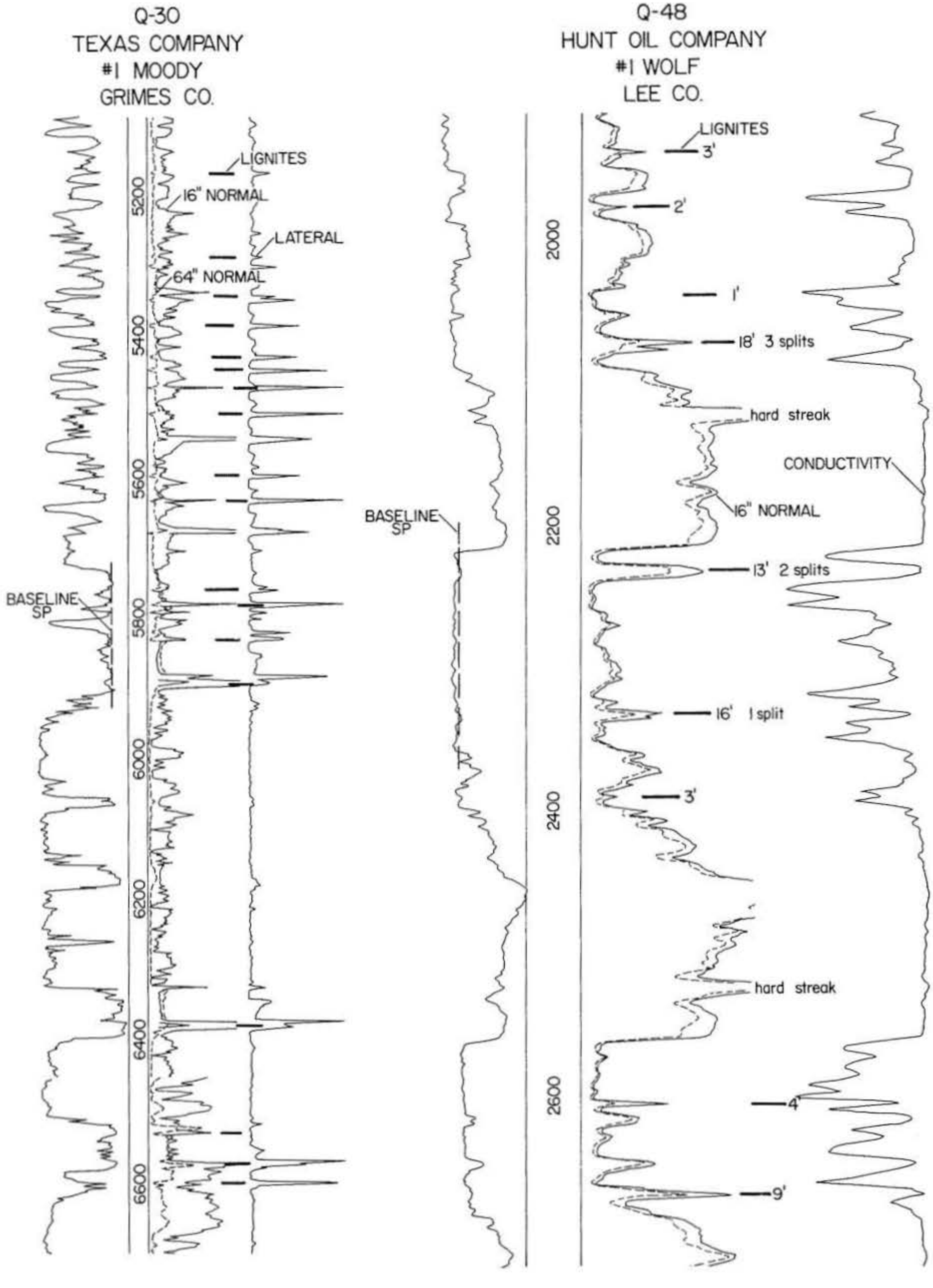


Figure 30. Lignite response on an electric log (Q-30) and an induction log (Q-48) (Kaiser, 1978b). Lignites on Q-48 identified from a companion neutron log. See figure 4 for location of logs.

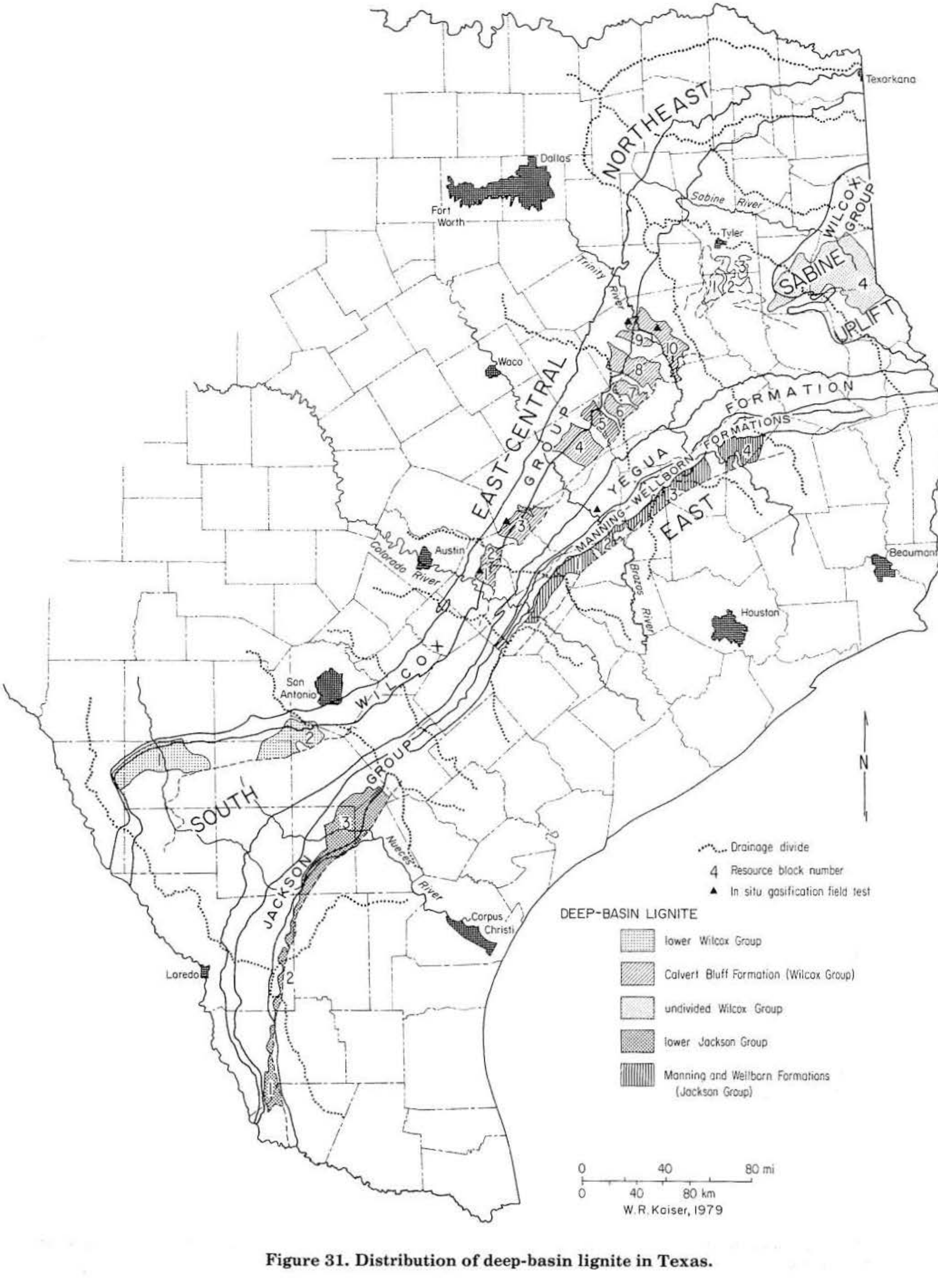


Figure 31. Distribution of deep-basin lignite in Texas.

seam throughout, a 5-ft (1.5-m) seam in one half and a 10-ft (3.0-m) seam in the other half, and one 10-ft (3.0-m) seam or two 5-ft (1.5-m) seams throughout.

RESOURCES

Mapping shows that deep-basin resources occur primarily in the Wilcox Group and secondarily in the Jackson Group; deep lignite in the Yegua Formation is relatively unimportant at exploitable depths. Yegua lignite occurrences are small and widely spaced (fig. 23), and on this basis the Yegua was eliminated as an important host for deep lignite.

Statewide resources are 34,819 million tons (31,588 million t) and divided 70 to 30 percent between the Wilcox and Jackson Groups and similarly divided geographically between north and south of the Colorado River (tables 12 and 13). These estimates were made with no consideration of any site-specific factors, such as hydrology, roof condition, relative seam thickness, depth of occurrence, and rank of coal. Clearly, reserves will be substantially less than the resource number.

From a resource standpoint, the Wilcox is superior to the Jackson (23,944 versus 10,875 million tons [21,722 versus 9,866 million t]). However, the Wilcox is a much sandier geologic unit than the Jackson and is a major aquifer in Texas; only locally is the Jackson an aquifer. Overall sand percentage is much higher in the Wilcox than for any area mapped in the Jackson at comparable depths. Essentially, the Jackson is less transmissive and therefore hydrologically superior to the Wilcox for the deep recovery of lignite.

WILCOX RESOURCES

Major occurrences are in the Calvert Bluff Formation of east-central Texas and the undivided Wilcox on the central Sabine Uplift (figs. 24, 25, and 31). Thick seams in these areas have been traced for several miles in the deep basin. Resources in South Texas are of secondary importance because of smaller resources, lesser seam continuity, and relative geographic isolation (figs. 26 and 31). The northeast region is characterized by thin seams (table 6). Thick seams, where present, are commonly about 5 ft (1.5 m) thick or slightiy thicker. On this basis, the region was eliminated from consideration as an important host for deep lignite. The Hooper Formation (east-central region) was eliminated because it contains few thick seams, and they occur immediately below the massive Simsboro aquifer (fig. 3). Resources in the east-central, Sabine Uplift, and south regions are 10,499, 8,814, and 4,631 million tons (9,525, 7,996, and 4,201 million t) and constitute respectively 44, 37, and 19 percent of the Wilcox total (table 12). Resources by block are shown in table 14.

JACKSON RESOURCES

Deep lignite in East Texas occurs in the middle Jackson Group Manning and Wellborn Formations and their equivalents (figs. 27 and 31). Important occurrences are found in Grimes and Walker Counties. In South Texas the major occurrence is in the San Miguel area, where the San Miguel lignite has been traced for approximately 15 mi downdip (figs. 28 and 31). Resources in the east and south regions are 5,600 and 5,275 million tons (5,080 and 4,785 million t) and constitute respectively 51.5 and 48.5 percent of the Jackson total (table 12).

Table 12. Lignite resources in Texas in millions of short tons.

		Resource Class		
	Region	Near-surface	Deep-basin	Total
Wilcox	east-central	6,481	10,499	16,980
Wilcox	northeast	5,099	0	5,099
Wilcox	Sabine Uplift	3,912	8,814	12,726
Wilcox	south	1,078	4,631	5,709
Wilcox	subtotal	16,570	23,944	40,514
Jackson	east	4,499	5,600	10,099
Jackson	south	757	5,275	6,032
Jackson	subtotal	5,256	10,875	16,131
Yegua	east	1,551	0	1,551
Total		23,377	34,819	58,196

Table 13. Percentage of lignite resources by resource class.

		Resource Class		
	Region	Near-surface	Deep-basin	Combined
Wilcox	east-central	28	30	29
Wilcox	northeast	21	0	9
Wilcox	Sabine Uplift	17	25	22
Wilcox	south	5	14	10
Wilcox	subtotal	71	69	69
Jackson	east	19	16	17
Jackson	south	3	15	10
Jackson	subtotal	22	31	28
Yegua	east	7	0	3
Total		100	100	100

CONCLUSIONS

1. Wilcox lignite north of the Colorado River occurs in the upper part of the group, whereas south of the river lignite occurs in the lower part. Lignite in the lower Wilcox of South Texas has commercial significance. Some lignite occurs in the Simsboro and Hooper Formations and their equivalents in east-central Texas. Jackson lignite north of the river occurs in the middle part of the group, whereas south of the river lignite occurs in the lower part. Yegua lignite occurs only north of the Colorado River.

2. North of the Colorado River, Wilcox and Yegua lignite at exploitable depths of 20 to 2,000 ft (6.1 to 610 m) occurs as a component facies of ancient fluvial depositional systems, whereas Jackson lignite is deltaic. In South Texas, Wilcox and Jackson lignites top strandplain/barrier-bar beach sequences. Approximately three-fourths of the near-surface resources are fluvial, one-fifth deltaic, and one-tenth strandplain/lagoonal.

3. Lignite resources in Texas between depths of 20 and 2,000 ft (6.1 and 610 m) are 58,196 million tons (52,795 million t); 23,377 million tons (21,208 million t) (40 percent) are near surface, of which 20,383 million tons (18,491 million t) are demonstrated; 34,819 million tons (31,588 million t) (60 percent) occur in the deep basin.

Table 14. Deep-basin resources by resource block in millions of short tons.

Wilcox east-central		Wilcox Sabine Uplift	
* 1.	823	1.	414
* 2.	672	2.	610
* 3.	2,206	3.	247
4.	1,406	* 4.	7,543
5.	862		8,814
* 6.	857		
7.	521	Wilcox south	
8.	1,394	* 1.	2,783
9.	325	2.	1,848
*10.	1,433		4,631
	10,499		
*subtotal	5,591		

Jackson east		Jackson south	
1.	1,462	1.	829
2.	426	2.	314
* 3.	2,570	* 3.	4,132
4.	1,142		5,275
	5,600		

*Blocks of high potential based on resources, seam geometry, and geohydrology; total starred resources—22,619.

About 80 percent of the resources are found north of the Colorado River. Approximately 70 percent of the resources occur in the Wilcox Group, 16,570 and 23,944 million tons (15,032 and 21,722 million t) being in the near surface and deep basin. Thin-seam near-surface resources are approximately 8 to 9 billion tons (7.2 to 8.1 billion t). Deep-basin resource blocks of highest potential for early exploitation are 1, 2, and 3 (Wilcox east-central); 4 (Sabine Uplift); and 3 (Jackson east) (fig. 31). The Yegua is not an important host for deep lignite.

4. Individual lignite deposits in Texas range in size from 50 to 500 million tons (45 to 450 million t). Seams are thin; the average seam is less than 5 ft (1.5 m) thick; a 10-ft (3.0-m) seam is exceptional. The thickest seams are in the Wilcox east-central, Wilcox central Sabine Uplift, and Jackson east regions; the thinnest seams are in the Wilcox northeast region. Seam continuity is as predicted from the depositional model—less in fluvial and greater in deltaic facies tracts. Jackson lignites are the most laterally continuous and have been traced for more than 30 mi (48 km).

5. Reserves are calculated from demonstrated resources and estimated to be 8,635 million tons (7,834 million t), if mining depth is 120 ft (37 m), minimum seam thickness 3 ft (0.9 m), recovery factor 85 percent, and illegal fraction 11 percent. Reserves are expected to increase substantially in the future as deep multiseam mining by dragline and bucket-wheel excavator combination becomes commonplace. Reserves would be 11,102 million tons (10,072 million t), if mining depth is 150 ft (46 m). Underground mining has no near- or mid-term promise in Texas.

6. Lignite north of the Colorado River is superior in grade to that south of the river. Wilcox lignite (6,500 Btu/lb [3,612 kcal/kg] as received) is the best grade; Yegua is intermediate (5,800 [3,223]); and Jackson (4,700 [2,612]) is the poorest grade lignite. On an as-received basis, Texas lignite ranges from 4,000 to 7,400 Btu/lb (2,223 to 4,112 kcal/kg), 20- to 45-percent moisture, 10- to 40-percent ash, and 0.5- to 3.0-percent sulfur. The weighted average lignite north of the Colorado River has a heating value of 6,100 Btu/lb (3,390 kcal/kg) and a 35-percent moisture, 17-percent ash, and 1-percent sulfur content.

7. Near-surface resource estimates have increased through time; they have approximately

Table 15. Estimates of near-surface resources, past and present, in millions of short tons.

Region		1955[a]	1974[b]	1978[c]	1980[d]
Wilcox	east-central	1,178	2,846	2,954	6,481
Wilcox	northeast	1,310	3,347	2,548	5,099
Wilcox	Sabine Uplift	850	1,738	2,487	3,912
Wilcox	south	309	675	550	1,078
Wilcox	subtotal	3,647	8,606	8,539	16,570
Jackson	east	368	550	2,015	4,499
Jackson	south	0	434	748	757
Jackson	subtotal	368	984	2,763	5,256
Yegua	east	282	836	895	1,551
Total		4,297	10,426	12,197	23,377

[a]Perkins and Lonsdale (1955), reported in Fisher (1963), prorated here to 200 ft.
[b]Kaiser, 1974a.
[c]Kaiser, 1978a.
[d]This study.

Table 16. Percentage of near-surface resources by geologic unit, 1955 to 1980.

	Wilcox	Jackson	Yegua
1955	85	8	7
1974	83	9	8
1978	70	23	7
1980	71	22	7

doubled with each major increase in geologic understanding and data availability (table 15). The percentage of Texas lignite contributed by the Wilcox has declined, while that of the Jackson increased significantly; the Yegua percentage has held steady (table 16). The 1980 estimate is larger because it is calculated from a superior data base. The 1974 and 1978 estimates were based largely on geologic evidence and projection and were purposely made conservative because of data limitations. This philosophy is reflected in the large difference between 1978 productive and potential acreage (table 17). A less conservative assessment of productive acreage would be reflected in a smaller difference and a larger resource estimate. In fact, the 1980 estimate may be conservative if net thickness of lignite is compared with that calculated for earlier estimates (table 18). In retrospect, earlier estimates were essentially reserve base estimates.

8. The exploration model is predictive; no important lignite-bearing lands were overlooked in the 1978 estimate (compare figs. 6, 11, and 17 with 24, 25, and 27). Though smaller, the 1974 and 1978 estimates were realistic and of the same order of magnitude as the current resource estimate. Sparse data together with depositional models can be used to make resource estimates that meet the public need in long-range planning, setting research priorities, and making policy.

9. Most of the productive acreage in the Wilcox is leased; unleased acreage remains in the Jackson and Yegua and is mainly in the National Forest lands. The difference between the two partly reflects relative potential for finding additional lignite. Consequently, most of the Wilcox near-surface lignite has been discovered, whereas future discoveries can be expected in the East Texas Jackson and Yegua.

10. Approximately 6 to 7 billion tons (5.4 to 6.3 billion t) of lignite reserves must be committed by 2000 to fuel, over a 35-year life span, the equivalent of at least 30,000 MW of lignite-fired capacity, which is projected for construction by electric utilities and industry in Texas. Reserves of 8.6 to 11.1 billion tons (7.8 to 10.1 billion t) calculated in this study are adequate to meet these needs into the next century. Remaining uncommitted

Table 17. Near-surface lignite acreage.

Acreage type	Wilcox east-central	Wilcox northeast	Wilcox Sabine Uplift	Wilcox south	Wilcox subtotal	Jackson east	Jackson south	Jackson subtotal	Yegua east	Total
Productive (1974)	216,960	336,313	164,129	96,349	813,751	69,510	50,451	119,961	114,285	1,047,997
Productive (1978)	196,397	242,426	314,294	83,000	836,117	149,056	89,137	238,193	95,904	1,170,214
Productive (1980)	632,320	701,440	597,120	122,880	2,053,760	435,200	74,880	510,080	248,960	2,812,800
Leased (1979)	693,874	625,802	536,695	143,912	2,000,283	191,883	94,425	286,308	92,356	2,378,947
Potential (1978)	648,320	962,560	1,334,320	356,487	3,301,687	510,720	325,120	835,840	615,680	4,753,207

Table 18. Calculated net lignite thickness in seams greater than 3 ft thick.[a]

Region		1974[b]	1978[c]	1980[d]
Wilcox	east-central	7.5	8.6	5.8
Wilcox	northeast	5.7	6.0	4.2
Wilcox	Sabine Uplift	6.0	4.5	3.7
Wilcox	south	4.0	3.8	5.0
Wilcox	overall	6.0	5.8	4.6
Jackson	east	4.5	7.7	5.9
Jackson	south	4.9	4.8	5.8
Jackson	overall	4.7	6.6	5.9
Yegua	east	4.1	5.3	3.6
Statewide		5.7	6.0	4.7

[a]Tons ÷ productive acres = tons per acre ÷ 1,750 tons per ac-ft = total thickness.
[b]Kaiser, 1974a.
[c]Kaiser, 1978a.
[d]This study.

reserves would be available for production of synthetic fuels and chemical feedstocks. The standard synthetic fuel plant producing 50,000 barrels of oil or 250,000,000 ft^3 (7,080,000 m^3) of synthetic natural gas per day requires over its lifetime minimum reserves of 600 million tons (540 million t). No individual deposit in Texas is this large. Thus, the potential for large synthetic fuel plants is limited to one or two such plants. The outlook for medium-Btu gasification for industrial boilers and chemicals production is favorable. Low-Btu gasification, both aboveground and underground, at industrial energy parks and smaller mine-mouth operations, is also possible. Reserves are ample to support a number of small gasifiers.

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