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Contents

Figures

Tables

Abstract

During three years of drilling and sampling in the San Juan Basin, 524 coal core samples were collected from 149 drill sites located on approximate 2 mi centers in the Fruitland, Menefee, Crevasse Canyon, and Moreno Hill Formations. Most of these drill sites were placed along the lines parallel to the Late Cretaceous shorelines in areas where thickest coals are at depths of about 200 ft, i.e. potentially strippable. Eight drill sites in the Chacra Mesa field were drilled on a line perpendicular to the shorelines on 1 mi centers; the Moreno Hill Formation sites in the Salt Lake field and the Fruitland Formation in the Fruitland field were drilled on trends perpendicular to the Late Cretaceous shorelines.

The Fruitland Formation coals analyzed were from the Fruitland, Bisti, and Star Lake fields; the upper coal member of the Menefee Formation coals were from the Chacra Mesa and La Ventana fields; the Cleary Coal Member of the Menefee Formation coals were from the La Ventana, Chacra Mesa, San Mateo, and Standing Rock fields; and the remaining Menefee coals analyzed were from the Monero field. Cleary—Gibson, Gibson, and Dilco Coal Member coals of the Crevasse Canyon Formation were cored and analyzed from the Gallup and Crownpoint fields, and coals from the Moreno Hill Formation were collected and analyzed from the Salt Lake field.

Significant aspects of chemical, quality, coal rank, thickness trends, stratigraphic—depositional features, and petrographic composition are presented in this report. Petrographic analyses indicate a difference in maceral content between the Fruitland coals and the other older formations sampled. The Fruitland coals have a higher percentage of liptinite, in particular the resinite constituent of the liptinite group is much higher than for the Menefee and Crevasse Canyon coals. In general, the Fruitland coals have a higher hydrogen/volatile matter ratio which is in part influenced by the resinite content. The Moreno Hill Formation coals in the Salt Lake field have the highest inertinite content of all the formations sampled, indicating oxidation during coal development.

The Fruitland coals tend to be the most economically viable because of their thickness, relative continuity, and overall quality, albeit having a high ash yield. The Menefee Formation coals do not have the same degree of bed continuity or thickness as the Fruitland coals, but the ash yield is lower and the rank is equivalent to that of the Fruitland coals in the Bisti and Star Lake fields. The Menefee Formation coals, with the exception of those in the San Mateo field, have a relatively high (>1%) sulfur content. Of the Menefee Formation coal fields investigated, the San Mateo field has the best economic potential because of the thickness of the coals and the low sulfur and ash values. The Cleary—Gibson coals in the Gallup area have the greatest economic potential of the Crevasse Canyon fields examined. This coal-bearing sequence has both multiple coal beds and relatively thick coals. The Cleary—Gibson coals also have low ash and sulfur values which enhance their economic potential.

Of the remaining fields drilled, the upper coal member Menefee coals in the La Ventana field and the Crevasse Canyon coals in parts of the Crownpoint field may have economic potential. The La Ventana upper member coals are relatively thick and have a low ash yield. In the Crownpoint field the coals are thickest in the area northwest of the town of Crownpoint and near Borrego Pass.

Significance of the study

(Frank E. Kottlowski)

Even with a lesser demand for electricity, one of the brighter facets of New Mexico's presently depressed mineral industry is the production and use of coal. While the demand for coking coal has dropped drastically, usage of steam coal continues. During 1991, statistics gathered by Kay Hatton of the New Mexico Energy, Minerals, and Natural Resources Department showed New Mexico's coal production at 21.5 million short tons, having a total value of $509 million.

Although the use of electricity is not increasing at as high a rate as predicted a decade ago, its consumption is continuing to increase. The area served by New Mexico coals, principally the Southwest, has had a somewhat larger increase in the use of electricity than have most other parts of the country. Therefore, it is reasonable to project a corresponding increase in the demand for New Mexico's coal.

The largest occurrence of coal is in the San Juan Basin in the northwestern corner of the state. In addition, there are significant resources in north-central New Mexico and local areas of both strippable and deep coal in the west-central and central parts of the state. The total estimated tonnage of reserves of strippable coal depends somewhat on the parameters used to classify strippable coal resources, but the amount available under present methods of mining to a depth of 250 feet exceeds six billion tons, with most of it being located in the San Juan Basin. Underground resources, a legacy for future generations, probably total more than 200 billion tons.

Much is known about the distribution and quality of coals throughout the state. However, the data, particularly those pertaining to quality, tend to be concentrated in relatively small, specific project areas, with relatively large intervening areas of no data to very sparse data. Another problem has been a lack of consistency of data resulting from (1) variable sampling techniques and procedures or (2) lack of uniform analytical procedures. Ultimately, without more uniform, more detailed, and more reliable quality data, the competitiveness of New Mexico's coal in future regional, national, and international markets will be reduced.

Our project recognizes a need for a systematic assessment of coal quality in the state as a means to (1) provide data that will supplement the previous, sometimes misleading and sometimes totally erroneous information presently available, (2) add to the coal data base for use by industry, and (3) aid in the basic understanding of the geologic principles that affect the vertical and lateral variations in coal quality. Standard analytical procedures have been applied uniformly to carefully collected coal core samples. These analyses can be compared and contrasted with analyses of samples from earlier investigations, some of which were taken from weathered outcrops or were selectively hand-picked samples from old mines, prospects, or coal storage piles, and were used indiscriminately to characterize coal quality over large areas.

Even in recent years, many core samples have not been properly handled. There have been significant losses of natural moisture resulting in serious distortion of the quality data. A few years ago, before the advent of the split-core barrel, it was quite difficult (1) to either recover a sufficient percentage of the cored coal in some situations or (2) to know whether the sample was representative of the coal bed that was cored because of fragmentation of the coal core.

Although coal production in New Mexico fell to an all-time low in 1958, a revival of interest in New Mexico coal resulted in a renewed intensity of exploration and development activity in the state during the mid-1960s. Knowledge of the state's major and lesser coal deposits has been available for many years in varying degrees of comprehensiveness and reliability. However, except for clusters of detailed information in the present mine lease and PRLA areas, we do not have an overall picture of the chemical and physical properties of the coal deposits, and thus we cannot accurately project the suitability of New Mexico's coal for the various potential uses that may arise in the future. The chemical and physical properties and the consistency of the coals bear greatly on their utilization. More accurate data on calorific value, sulfur, ash, and even the minor constituents and trace elements are necessary for the design of boiler facilities. Only some New Mexico coals have coking characteristics, but the chemical and physical quality of these coking coals must be determined for this use as well. Minor elements are of even more importance in liquification or gasification and in dealing with environmental constraints.

Coals are composed of varying parts of different organic substances, and each type of substance or "maceral" can be determined by its existing chemical and physical properties. The maceral composition relates to the various economic characteristics of the coal, such as suitability for gas and liquid conversion products, coking properties, combustion, and others. Petrographic determinations thus aid in assessing the economic characteristics of coal seams. Also, as the maceral composition is a function of both the original environment of deposition and thermal alteration of the coal, these measurements provide a basis for classifying the coals and for correlating the various economic characteristics of the coal beds within a region. Sporadic petrographic analyses have been made on a few of the strippable coal seams in New Mexico; this is the first project in which the petrographic data have been collected in a systematic and uniform manner. Direct information relative to the economic characteristics of the coals is thus obtained, and the data aid in developing predictive models to explain lateral and vertical variations of the coal-seam composition over broad areas of the coal fields in New Mexico.

Acknowledgments—The idea for the project was advanced mainly by Frank Campbell, Ed Beaumont, and Gretchen Hoffman (Roybal) during a review of the general studies of coal being done in New Mexico in 1983. Ed, with his many years of experience working on the coal deposits of New Mexico and adjoining areas, first as geologist with the U.S. Geological Survey and then during the last 30 years as a coal consultant, was the senior planner, particularly in the location of the core sampling sites and in assisting with the contracts and with obtaining permission from companies and individuals. Ed was aided in the drill-siting by Gretchen Hoffman and Kevin Cook.

The core-sampling program was directed by Gretchen Hoffman with the assistance of Ed Beaumont and with active field participation by Brian Arkell, Kevin Cook, Mark Bowie, and James Barker. Analytical laboratory procedures were directed by Frank Campbell with contributions by Cecilia McCord, Barbara Popp, Jeanne Verploegh, and numerous New Mexico Tech students working as part-time employees for the New Mexico Bureau of Mines & Mineral Resources. Analyses of core samples in 1988 were completed by Jeanne Verploegh, Lynn Brandvold, and Barbara Popp, with the assistance of student employees.

Petrographic work was done by Frederick J. Rich and Robert B. Finkelman of Environmental and Coal Associates, Art Cohen, and Fred Kuellmer and his New Mexico Tech students Terrell Jones and Courtney Hesse (1987). Petrographic work (1988) was done by Deborah A. and Kenneth W. Kuehn of Western Kentucky University. Analysis of the petrography was done by Diane Bells and Art Cohen. The project was directed by Frank E. Kottlowski.

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Reports for the New Mexico Research and Development Institute (NMRDI) were prepared mainly by Gretchen Hoffman (Roybal), aided by Ed Beaumont, Kevin Cook, Jeanne Verploegh, and Frank Kottlowski, with major chapters by Beaumont (Geologic Setting), Hoffman (Coal-Bearing Sequences and Drilling), Frank Campbell (Analyses), and Fred Rich, Robert Finkelman, Fred Kuellmer, Diane Bellis, and Art Cohen (Coal Petrography). Typing was done by Judy Vaiza, Lynne Hemenway, Norma Baca, and Theresa Lopez.

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Geologic setting

(Edward C. Beaumont)

Introduction

The San Juan Basin occupies an area of about 26,000 mi^2 in northwestern New Mexico and southwestern Colorado. Along its southwestern margin, the basin extends slightly into eastern Arizona. The Cretaceous portion of the basin has a north—south dimension of about 180 mi and is about 150 mi wide (Fig. 1). Elements of the structural San Juan Basin have been present to some degree from at least as early as mid-Paleozoic time, but the present configuration is largely a Laramide phenomenon. The structural axis has a northerly and westerly arcuate trend that is nearer the eastern and northern margins.

Rocks of Cretaceous age are present at the surface throughout most of the San Juan Basin. An area of about 5300 mi^2 in the central part is covered by younger, Tertiary rocks. The thickness of the Cretaceous strata deposited and preserved is about 6000 ft. Sedimentation began as an initial invasion of the region by the late Early Cretaceous and Late Cretaceous sea as it moved from the east toward the west and southwest. This event was followed by successive regressive and transgressive migrations of the shoreline northeastward (seaward) and southwestward (landward) through much of Late Cretaceous time. Each successive major transgressive—regressive cycle resulted in a gradual seaward shift of the maximum transgressive position of the shoreline until the sea withdrew for the last time during middle to late Pierre time. The result is a jagged wedge of nonmarine rocks in the southern part of the basin interfingering with a correspondingly irregular wedge of marine strata to the north (Fig. 2). The transitional strata, the barrier beach, the shore-marginal swamps, and the other lower coastal-plain deposits migrated through time as they accumulated in the region.

Structural framework

In New Mexico and Arizona three structural elements account for much of the present configuration of the San Juan Basin. The eastern flank of the basin is sharply defined where Cretaceous rocks are steeply dipping to overturned near the Nacimiento uplift (Fig. 3). The southern margin of the basin is structurally less abrupt as the Cretaceous strata rise gradually toward the ancient Zuni uplift which was reactivated during Laramide time and now corresponds approximately with the present-day Zuni Mountains. The western side of the basin is rather sharply defined by the north-trending sinuous Defiance monocline associated with the much older positive area, the Defiance uplift.

These major structural elements provide rather clear definition of the structural basin along their margins, but the limits of the basin are much less distinct in between these major tectonic features. The northwest margin of the San Juan Basin is poorly defined in one respect, yet very sharply delineated in another. The Hogback monocline, which can be traced for more than 50 mi in a northeastward direction from the west-central part of the basin to the Colorado—New Mexico state line and for another 80 mi around the north flank of the basin, clearly defines the northwest and northern margins of the central basin. West and northwest of the Hogback monocline there is a broad area of slightly undulating Cretaceous rocks which is known as the Four Corners platform (Fig. 3). North of the Nacimiento uplift the Archuleta arch separates the central San Juan Basin from a smaller and shallower basinal feature, the Chama embayment. To the south of the Nacimiento uplift, the southeast margin of the basin is indistinctly marked by a faulted area that merges with the Puerco fault belt along the western margin of the Rio Grande trough.

Southeast of the Zuni uplift and beneath the volcanic rocks associated with Mt. Taylor there is a shallow, south-trending embayment, the Acoma sag. Cretaceous strata in the Acoma sag connect southward with those in the Datil Mountains coal field. A corresponding structural depression between the Zuni and Defiance uplifts is known as the Gallup sag or embayment. The Gallup sag (also known as the Gallup—Zuni embayment) is separated at the surface from the Salt Lake coal field by a thin band of Quaternary basalt (Fig. 1). In all probability the Zuni uplift is surrounded by Cretaceous strata, although this relationship is obscured on the south by a broad cover of Quaternary basalt (Fig. 1).

The Chaco slope in the southern part of the San Juan Basin is an area of gently northeast-dipping Cretaceous rocks lying between the central basin and the Zuni uplift. The Chaco slope is interrupted by several minor structural features and scattered normal faults.

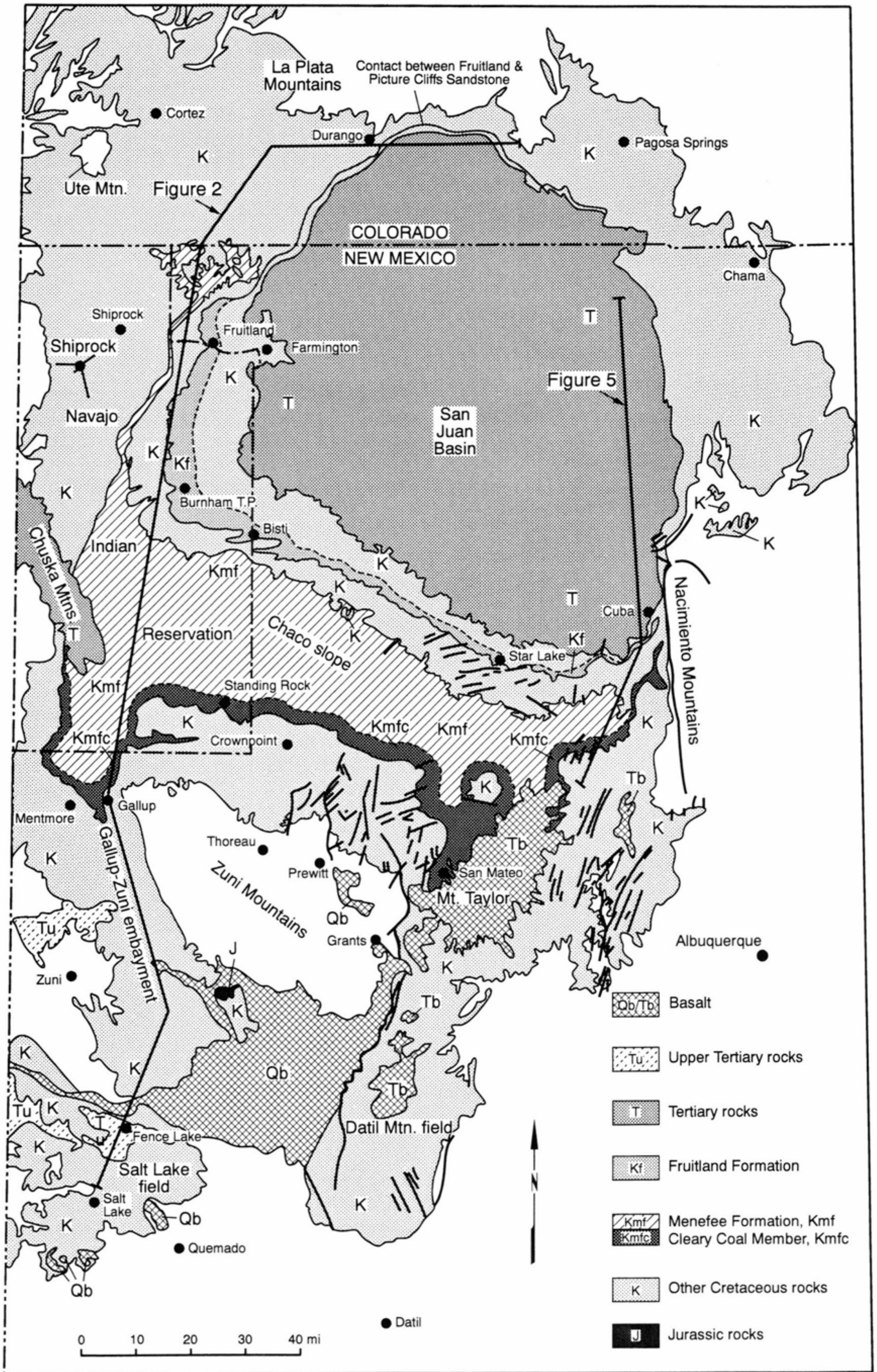

FIGURE 1—Index map for coal deposits in San Juan Basin and adjacent areas of New Mexico and Colorado. After Dane and Bachman, 1965.

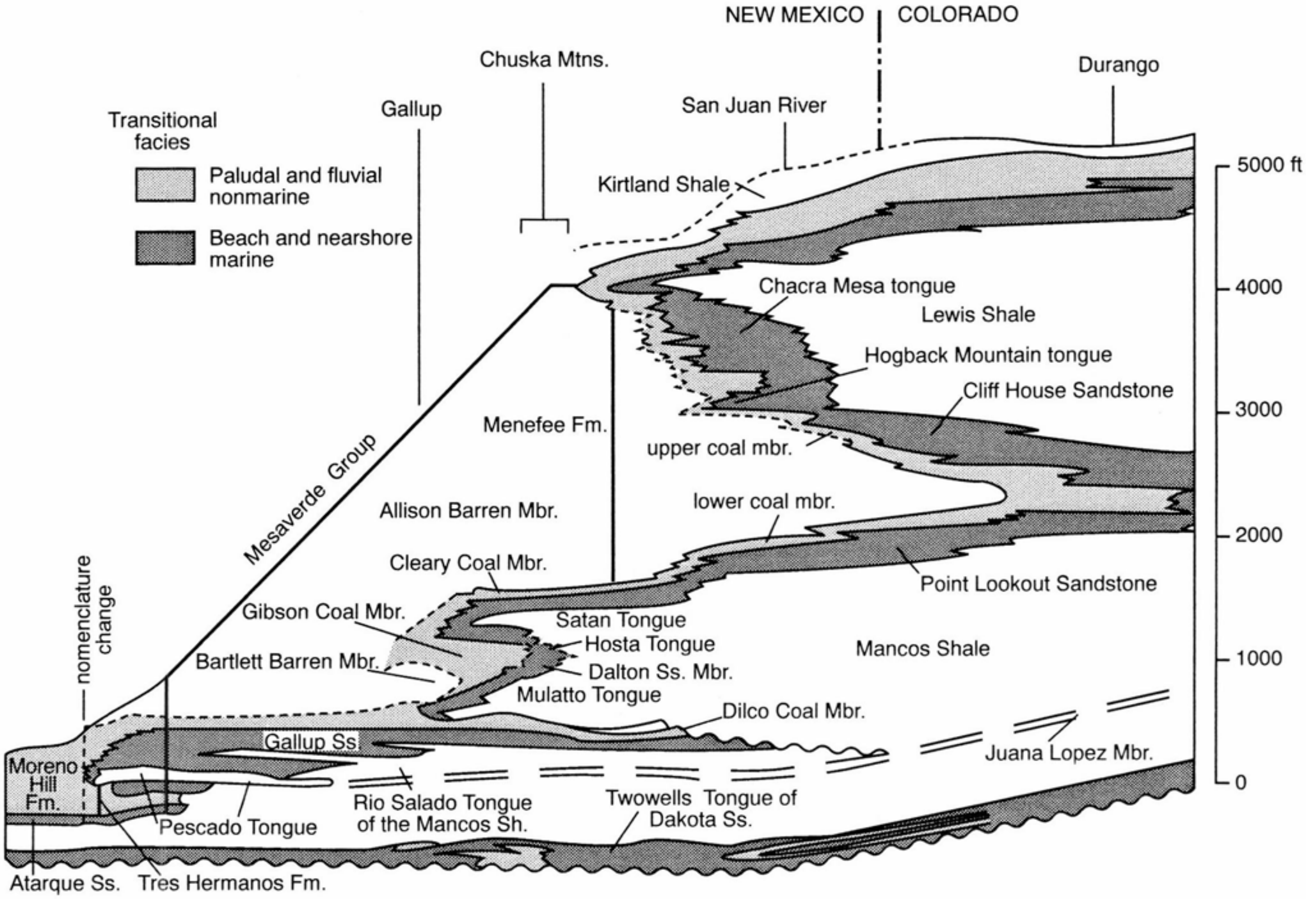

FIGURE 2—Stratigraphic diagram showing sequence, thickness, and nomenclature of Cretaceous rocks in San Juan Basin, New Mexico and Colorado. Modified from Beaumont, 1982, fig. 2.

Most of the faults have throws measured in a few tens of feet, but several are known to have displacements of between 100 and 200 ft at the surface. The Chaco slope, which contains outcrops of the two major regressive coal-bearing units, is highly favorable for coal development because of the low structural relief, the gentle dip of the beds, and the sparsity of faulting.

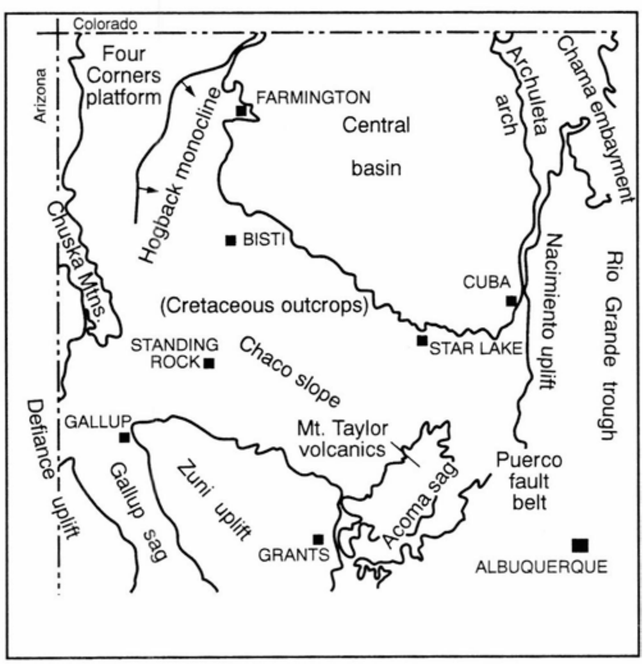

FIGURE 3—Tectonic map of San Juan Basin in New Mexico. From Beaumont, 1982, fig. 3.

Stratigraphic influences

As discussed briefly in the introduction, the nature of Cretaceous sedimentation was such that the lower coastal-plain paludal and fluvial environments shifted landward and seaward through time, leaving an almost unbroken record of transgressive and regressive deposits. Although the broader sedimentary facies are nearly continuous, individual lithic types, including coal, vary greatly over short distances. Figure 2 is a diagrammatic cross section based on surface and subsurface data through the western and northern parts of the basin. Although highly exaggerated vertically, the scale is constant throughout and the sequence of units is fairly accurate with respect to the sequence and thickness at any given locality.

In this diagram, the patterned units represent those that are transitional between the wholly marine depositional environment on the right (north) and the wholly nonmarine environment on the left (south). These transitional units contain the coal resources of the region; furthermore, the units that are deposited during regressive conditions are more important. Regressively deposited coal beds appear to have had better chances for preservation, whereas transgressively deposited peats, especially those deposited in shore-marginal swamps, appear to have been largely destroyed by the encroaching shoreline.

A second factor, equally important to the development of the coal resources, is the reverse order of the sequence of lithologies. Regressive deposits, such as the Cleary Coal Member of the Menefee Formation and the Fruitland Formation, contain coal beds underlain by the thick and, in most instances, massive barrier beach and nearshore sandstone units. These strata are overlain by mixed lower coastal-plain lithologies that include a high percentage of easily eroded mudstone and shale. This combination of lithologic sequences in low-dip areas such as the Chaco slope and along the west side of the San Juan Basin provides broad bands of relatively shallow coal. Much of the coal preserved in the transgressive units, such as the Gibson Coal Member of the Crevasse Canyon Formation and the upper coal-bearing member of the Menefee Formation, is deeply buried close to the outcrop by the overlying massive, cliff-forming sandstones of the barrier-beach and nearshore facies.

Rate of shoreline shift

An apparent control affecting the presence or absence of potentially economic coals in the San Juan Basin was the rate of shift of the shoreline which in turn appears to have affected the relative stability of the transitional environments. Localization of sedimentation resulting from a balance between sediment supply and subsidence appears to have resulted in relatively thick accumulations of peat in the shore-marginal swamp and fluvial environments as well as in the barrier-beach and nearshore transitional marine deposits. Conversely, rapid shoreline shifts brought about by sudden changes in sea level resulted in thin transitional facies with a paucity of coal accumulation (Fig. 4). An example is found in the Cleary Coal Member of the Menefee Formation along the west side of the San Juan Basin north of Gallup. For a distance of about 50 mi the Cleary (equals the lower coal-bearing member in the northern part of the basin) is present, although it is thin. This unit is characterized by an absence of significant coal beds. Likewise, the underlying Point Lookout Sandstone is correspondingly thin.

It is also significant in this area that there is an apparent absence of the intertonguing which marks minor reversals in major depositional modes and has the effect of providing temporary localization of sedimentary conditions. A rapid shift in shoreline position is recorded in the deposition of units of the Cliff House Sandstone in the southeastern part of the San Juan Basin. Following a period of shoreline oscillation and nearly vertical accumulation of marine transitional sands, a sudden landward shift in the position of the shoreline resulted in coaly, nonmarine sediments in the upper part of the Menefee Formation being overlain directly by marine shale, with the normally intervening transitional sandstone unit locally absent.

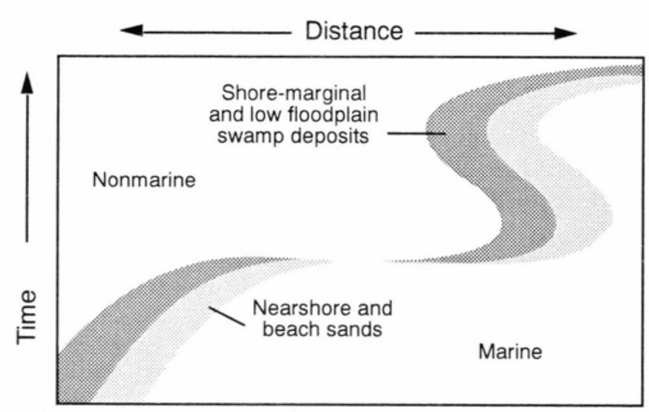

FIGURE 4—Response of transitional facies to varying rates of shoreline shift. After Shomaker et al., 1971, p. 184.

Finally, a major control associated with the rate of shoreline shift is the stillstand phenomenon observed in association with major reversals in sedimentary modes. Concentrations of coals occur in connection with the direction reversal of shoreline movement from the transgressively deposited Gibson Coal Member of the Crevasse Canyon Formation to the regressively deposited Cleary Coal Member of the Menefee Formation. The inertia associated with this reversal has produced some of the most economically desirable coal in the San Juan Basin in the area south of the pinchout of the Point Lookout Sandstone (Fig. 2). These coals are being mined by the Pittsburg & Midway Coal Mining Co. in their McKinley mine. The same sequence of events is responsible for the coal presently being mined by Peabody Coal Co. in the Black Mesa Basin of northeast Arizona.

Variations in coal with respect to shoreline orientation

Considering the constantly shifting nature of the depositional environments as they are controlled by the migration of the shoreline, it is not surprising that the resulting coal beds vary markedly over short distances normal to the shoreline. Through much of the Late Cretaceous time the strandline direction was northwest—southeast, with an average trend of about N50°W. Toward the end of the Pictured Cliffs—Fruitland deposition the emergence of source areas to the north caused the final withdrawal of the sea to shift to a more easterly direction.

Normal to the shoreline, continuity of coal beds would appear to have been principally a function of the balance between the rate of sediment accumulation and rate of shoreline shift. What are for practical purposes single coal beds, may in fact be complex beds composed of overlapping lenses which cross time boundaries normal to the depositional strike. Complex coal beds deposited under regressive conditions would thus be presumed to become younger northward. If there is an imbalance in the depositional system, the coal beds will be irregular and discontinuous in thickness and extent.

Parallel to the shoreline, continuity of coal units is in some instances remarkably good for fairly long distances, but the shore-marginal swamps which have produced the thicker, more widespread coals were interrupted at varying intervals by fluvial and deltaic deposits as the rivers in the region released their clastic loads in these low-energy environments. Near the swamp margins channel scouring is a common phenomenon, and coal beds may be locally either abruptly thinned or absent altogether.

Owing to differential compaction, the complex, thick coal beds of the central swamp area tend to be splayed vertically as the component coal units interfinger with fluvial or deltaic sands. These lateral interruptions in the swamp environments tend to be rather complete, thus suggesting that the river channels maintained their approximate positions throughout the period in which the coal-bearing strata were being deposited nearby.

General observations

The coal-bearing stratigraphic units that have been drilled and sampled in the San Juan Basin include, in some degree, nearly all of the named units, but the emphasis has been on those formations and members that have the greatest potential for commercial development. For reasons mentioned above, the units with the greatest potential are sequences deposited under regressive conditions. These units are examined and the direction of the shoreline shift presented in stratigraphically descending order as follows (see Fig. 2):

Fruitland Formation: Mainly regressive, with minor transgressive movements.

Menefee Formation

- Upper coal member: Primarily transgressive, with long periods of transgressive—regressive oscillations where adjacent to massive vertical buildup.
- Cleary Coal Member: Regressive, with minor transgressive episodes.
- Cleary—Gibson Coal Members: Regressive in upper (Cleary) part, transgressive in lower (Gibson) part. Entire undifferentiated interval represents major stillstand and reversal of shoreline movement.

Crevasse Canyon Formation

- Gibson Coal Member: Principally transgressive, but also regressive in lower part.
- Dilco Coal Member: Probably only regressive where investigated (vicinity of Gallup).

Moreno Hill Formation

- Lower member: Principally regressive.

Minor coal-bearing units that might be considered to have some potential economic value but have not been sampled during the course of this investigation are, in descending order, as follows:

(1) Lower coal member of the Menefee Formation: This extension of the Cleary Coal Member into the northwestern San Juan Basin contains scattered beds of potentially economic coal from the vicinity of the San Juan River northward into the Mesaverde Plateau region of southern Colorado. Very little potential for surface mining.

(2) Gallup Sandstone: In the original description of the Gallup Sandstone (Sears, 1925, p. 17) major mineral coal beds in the vicinity of Gallup were put in the Gallup Sandstone.

(3) Dakota Sandstone: Scattered lenses of coal are found in the Dakota in New Mexico, but the area of economic promise is in southwestern Colorado.

The following paragraphs summarize some of the broader aspects of the Fruitland, Menefee and Crevasse Canyon, and Moreno Hill sedimentation based on results of the present investigation and the writer's long-term experience with these units.

Fruitland Formation

This unit is essentially the coal-bearing facies deposited under shore-marginal swamp and fluvial conditions during the final withdrawal of the Late Cretaceous sea. Bauer (1916) originally distinguished between the Fruitland and the overlying Kirtland Shale on the basis of the greater sandstone content of the Fruitland, but at the same time he recognized that the boundary between the two units is gradational. A bit of the frustration in trying to typify the lithology of the Fruitland is expressed by Bauer and Reeside (1921, p. 167) when they describe the unit as consisting "of sandstone, shale, and coal . . . with every conceivable intermediate phase of sandy shale and shaly sandstone." These early workers mapped the Fruitland—Kirtland boundary on the basis of surface outcrops, and in much of the outcrop area of the Fruitland the coal beds are poorly exposed. Thus, the principal criterion for distinguishing between the Fruitland Formation and the Kirtland Shale became the larger percentage of sandstone in the Fruitland. Present usage, based on drill holes where lithologies are more clearly observable, is likely to restrict the Fruitland to the coal-bearing interval. As a result of these different methods of choosing the formational boundary, the thickness of the Fruitland determined in the drill hole is apt to be 50 to 100 ft less than the thickness observed in the outcrop. A possible offsetting factor, however, may be the greater ability to detect thinner, more obscure coal beds higher in the section in the drill cuttings and the geophysical logs. In this investigation the Fruitland is restricted to the coal-bearing interval.

The Fruitland Formation contains the thickest coal beds in New Mexico, although these coals, for reasons discussed above, are not spread evenly throughout the region. On the eastern side of the basin the Fruitland, most of the overlying Kirtland Shale, and the underlying Pictured Cliffs Sandstone are absent. This condition is in part due to depositional thinning but also results from pre-Ojo Alamo (Paleocene) erosion (Fassett and Hinds, 1971, p. 29). The absence of these units persists along the east side of the basin to within about 10 mi of the New Mexico—Colorado state line (Dane, 1945).

Upper coal member of Menefee Formation

The thickness of the Menefee Formation increases southward from about 500 ft near the New Mexico—Colorado state line to about 1000 ft at the San Juan River, and finally at its maximum development to more than 2000 ft in the vicinity Newcomb. Although there is some northward stratigraphic rise in the Point Lookout Sandstone, the major increase in Menefee thickness is accounted for by rise in the Cliff House Sandstone—Menefee Formation contact as the shoreline migrated in irregular pulses to the south. This contact is marked by a series of tongues that have been mapped (Hayes and Zapp, 1955; Beaumont, 1955). The Chaco Tongue of the Menefee can be traced southward from about the point where the Chaco River breaches the Mesaverde hogback west of Farmington for a distance of 8 mi. The massive Cliff House Sandstone that forms the backbone of Hogback Mountain thins southward and eventually loses its identity among the nonmarine sandstone beds of the Menefee. This single intertonguing event accounts for a stratigraphic rise of about 300 ft in the top of the Menefee.

Each of these reversals in the major transgressive episode involves either a reduction in the rate of basin subsidence or an increase in sediment availability that permits progradation of the shoreline. Whatever the reason might have been, it appears that there was sufficient localization of the shoreline to allow for relatively thick deposits of peat to accumulate.

In the eastern and southeastern parts of the San Juan Basin the rate of shoreline shift appears to have swung from one extreme to the other. The effect is seen in the thickness of the accumulations of the transgressive transitional units, the Cliff House Sandstone and its component members and the subjacent coal-bearing upper coal member of the Menefee Formation. The thinness of the Cliff House and the upper coal member between Regina and Cuba suggests another rapid transgression. In the vicinity of La Ventana the advance of the shoreline appears to have slowed down to the point of a virtual balance between subsidence and sediment supply. Sand accumulated in a nearly vertical pile along the sea margin, intertonguing on the north with the offshore silts and muds that comprise the Lewis Shale and on the south with the shore-marginal swamp and fluvial deposits that make up the upper coal member (Fig. 5).

This period of stagnation was followed by another surge of the sea in a landward direction at such a rapid rate as to nearly preclude the development of transitional units. This condition would approximate the theoretical relationships depicted in Figure 4, where horizontal shoreline shift is nearly instantaneous. The upper coal member becomes quite thin and individual coal beds are both thin and sparse, the nearshore and beach-sand fades are nearly absent, and the marine Lewis Shale thus rests almost directly on the barren Menefee. Following this sudden shoreline shift of approximately 10 mi, the balance between subsidence and sediment supply was again re-established, resulting in the deposition of a thick, localized sand pile which is often referred to as the unnamed tongue of the Cliff House Sandstone (Fassett, 1977) or Chacra Mesa tongue (Beaumont and Hoffman, 1992). Farther west this sandstone unit is known as the Tsaya Canyon sandstone member of the Cliff House (Fassett et al., 1977, p. 9). It is in this more western area that the Cliff House can be mapped to the position where the Lewis Shale pinches out and the Cliff House and the Pictured Cliffs merge. Some coal-bearing strata are found intertonguing with the Chacra, but for the most part the upper coal member on the landward (south) side of the Chacra has been removed by erosion.

Cleary Coal Member of Menefee Formation

The Point Lookout Sandstone regression, which began when the shoreline was within a few miles of the

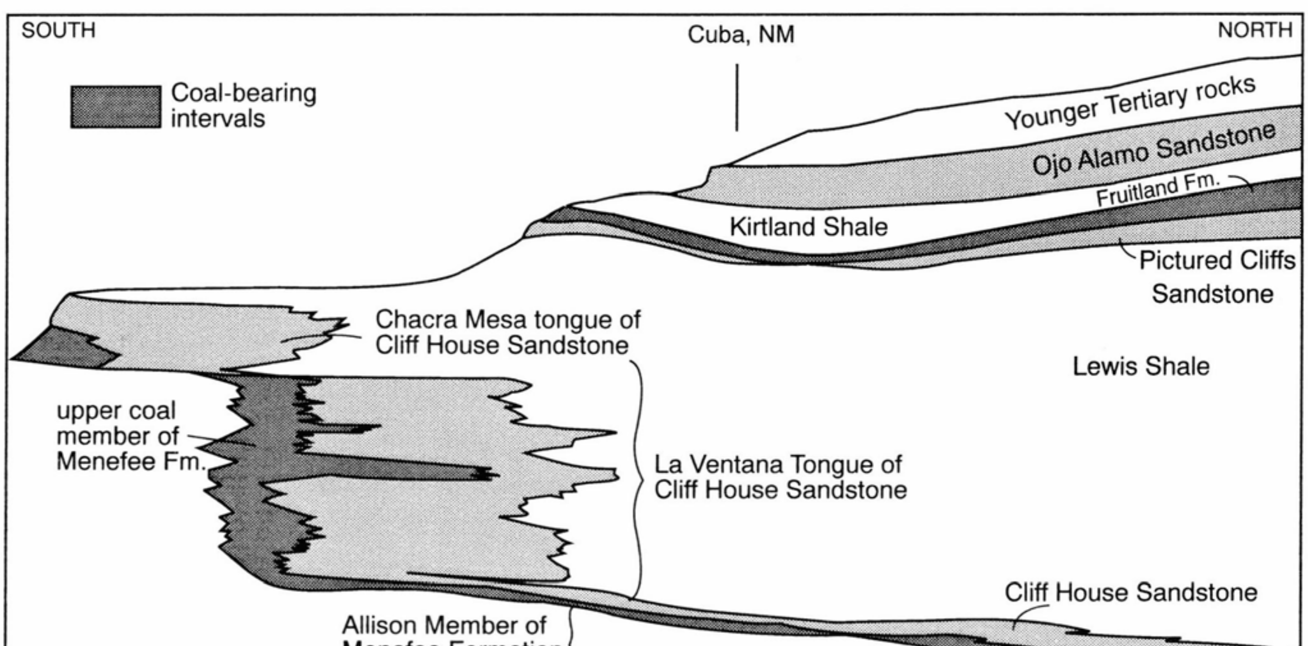

FIGURE 5—Cross section showing relationship of Cliff House Sandstone and upper part of Menefee Formation. Modified from Shomaker et al., 1971, fig. 7.

present site of Gallup, at first proceeded slowly, as is evidenced by the presence of numerous intertongues between the barrier-beach nearshore-sand facies and the shore-marginal swamp and other lower coastal-plain facies that constitute the Cleary Coal Member.

As discussed previously, the Point Lookout—Cleary regression seemed to move rather rapidly through the west-central part of the basin, as is evidenced by the relative thinness of both transitional units. Along the north flank of the Zuni uplift, however, detailed exploration drilling suggests that present-day, relatively small positive features such as the San Mateo and San Miguel Creek domes in the Lee Ranch area were somewhat positive during deposition of the Cleary sediments. Perhaps these features were not sufficiently elevated to serve as major sediment sources, but it seems that they, along with the larger Zuni positive area, probably controlled the shoreline configuration, and thus locally controlled the rate of shoreline shift and, in turn, the distribution and thickness of the resulting coal beds.

From the vicinity of the San Juan River northward into Colorado, intertonguing is common between the Point Lookout and the Cleary equivalent, the lower coal-bearing member of the Menefee. Coal beds up to 8 ft in thickness are found associated with these tongues (Hayes and Zapp, 1955). Numerous small mines have been developed in these coals immediately north of the San Juan River, but the surface-mining potential is essentially nonexistent because the lower coal-bearing member is involved at the surface in the steeply dipping Hogback monocline. As the monoclinal axis swings eastward, the Menefee is exposed along the margins of the mesas which are part of the Mesaverde Plateau. The area is within the Navajo Indian and Ute Mountain Ute Reservations, and very little is known of the coal potential.

As is true with the Fruitland Formation, the areas of well-developed coal are intermittent as the paludal environments were interrupted by lower flood-plain and deltaic deposition. Areas of potentially economic coal deposits have been delineated in the southeast part of the Navajo Indian Reservation near the village of Standing Rock, along the Continental Divide in the area referred to as the South Hospah area, and on the Lee Ranch where Santa Fe Pacific Coal Corp. is presently extracting about four million tons of coal a year from a surface-mining operation, the Lee Ranch mine.

Cleary Coal Member of Menefee Formation and Gibson Coal Member of Crevasse Canyon Formation, undivided

Throughout most of the area of their occurrence, these two units are separated by (descending) the Point Lookout Sandstone, the Satan Tongue of the Mancos Shale, and the Hosta Tongue of the Point Lookout. Southward, toward the Zuni Mountains, the Mancos Shale tongue thins to a feather edge and the Point Lookout and Hosta Tongue coalesce to form the massive, resistant sandstone that is responsible for the west—northwest-trending Mesa de los Lobos south of Crownpoint. This massive nearshore and barrier-beach sand, containing elements of both transgressive and regressive deposition, in turn pinches out southward, allowing the two coal-bearing units to come together (Fig. 6).

The two members, belonging to different formations, are not separable in the absence of the Point Lookout, and thus must be considered as a single, undifferentiated coal-bearing stratigraphic unit. For purposes of brevity, the combined members are referred to throughout this report as the Cleary—Gibson Coal Members. This facies does not extend very far southward, but in its area are found some of the most favorable coal deposits in the southern San Juan Basin. The writer has interpreted this area of favorable coal as directly related to the relatively stable shoreline at the time a major transgressive phase was brought to a halt and a correspondingly major regressive phase was slowly initiated.

Gibson Coal Member of Crevasse Canyon Formation

In the vicinity of the Continental Divide north of Borrego Pass is a moderately large area of potentially surface-minable Gibson Coal Member. Though only a few hundred feet thick, the Gibson represents both transgressive (upper part) and regressive (lower part) conditions. As a consequence, the coal-bearing sediments are sandwiched between the overlying transgressive Hosta Tongue of the Point Lookout Sandstone and the underlying regressive Dalton Sandstone Member of the Crevasse Canyon Formation. In the area of investigation both the Hosta Tongue and the next overlying sandstone unit in the sequence, the Point Lookout, are relatively poorly developed and separated by a northward-thickening wedge of slope-forming shale, the Satan Tongue of the Mancos Shale. Farther south, in the vicinity of Gallup, the upper and lower parts of the Gibson are separated by the Bar tleti Barren Member of the Crevasse Canyon. In the area of investigation the thickness of the Gibson is such that no identifiable barren interval is recognizable (Fig. 6).

Dilco Coal Member of Crevasse Canyon Formation

The lowermost coal-bearing sequence investigated in the San Juan Basin is the Dilco Coal Member (Fig. 6). This unit overlies, and is coupled with, the regressive Gallup Sandstone in the Gallup embayment and along the northern flank of the Zuni Mountains. The Dilco was penetrated and sampled only in three drill holes, thus the analytical data to be gained from this coal member are minimal. The Dilco—Gallup contact is indistinct and the Gallup Sandstone, contrary to the other marginal-marine sandstone units in the San Juan Basin, contains coal in the upper part, as originally described by Sears (1925, p. 17). It probably would have been a better procedure had Sears attributed the coal in the Gallup to a tongue of the Dilco, but this was not done and the Gallup thus is considered a coal-bearing unit.

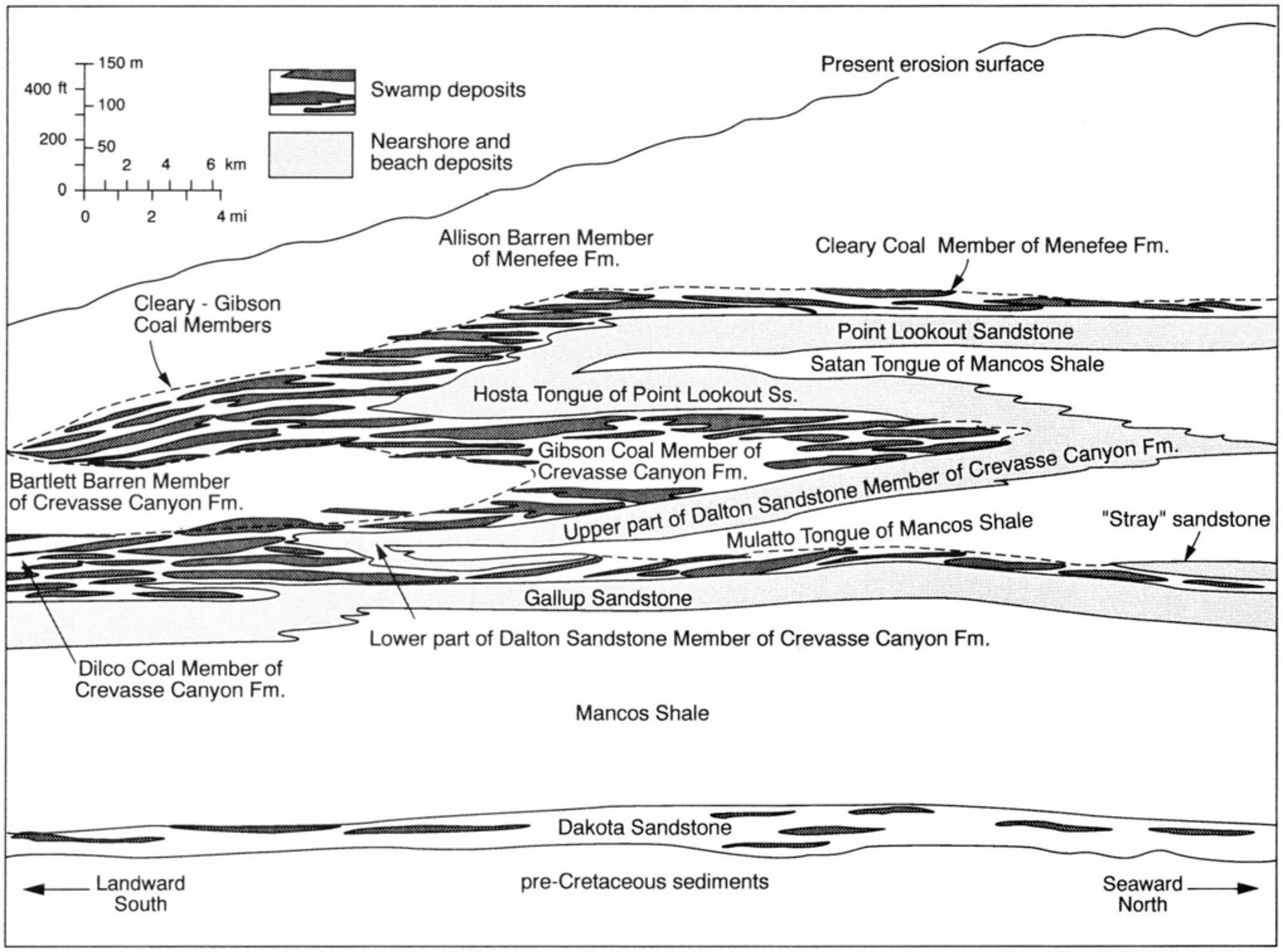

FIGURE 6—Cross section of coal beds near Gallup, New Mexico. From Shomaker et al., 1971, p. 183.

Moreno Hill Formation

The Moreno Hill Formation is the regressive continental coal-bearing sequence in the Salt Lake coal field. This formation was named by McLellan et al. (1984) while the U.S. Geolgoical Survey (USGS) and NMBM&MR personnel were mapping quadrangles in the area. This unit is 490 ft in the eastern part of the field and thins to 100 ft toward the west. The Moreno Hill Formation is divided into three members. The lower member is a fluvial sequence of sandstone, siltstone, mudstone, and coal, and is considered to be equivalent to the Tres Hermanos Formation (Hook et al., 1983; Fig. 2). This member has three recognizable coal zones (Campbell and Roybal, 1984) which have been named (ascending) the Antelope, Cerro Prieto, and Rabbit zones. The Antelope zone coals overlie the marine Atarque Sandstone and generally occur along the western edge of the Salt Lake field. The coals of the Cerro Prieto and Rabbit zones were deposited farther inland from the shoreline as the seas retreated to the northeast and occur north and east of the Antelope zone coals. The middle member of this formation is a feldspathic medium- to coarse-grained sandstone which possibly represents a braided-stream deposit. Campbell (1981) believed this sandstone to be equivalent to the Torrivio Member of the Gallup Sandstone. The upper member consists predominantly of siltstones and mudstones, with a few sandstones and a few coals near the base. It is considered to be equivalent to the lower part of the Crevasse Canyon Formation in the San Juan Basin (Fig. 2).

Logistics of the drilling program

(Gretchen K. Hoffman)

Introduction

Drill sites were initially located by Edward C. Beaumont on two-mile centers approximately along the 200 ft overburden line for the uppermost qualifying coal. Locations of drill sites in the Salt Lake field were determined by Gretchen Hoffman (formerly Roybal). Land ownership was obtained from the Bureau of Land Management (BLM) plats and county records for these preliminary locations. The access routes to these tentative sites were examined with respect to their feasibility. Based on this information, some initial drill-site locations were changed by NMBM&MR personnel because of inaccessibility, problems of land ownership, or various environmental and archeological constraints.

Throughout the three drilling seasons (1985, 1986, 1988) NMBM&MR continued the cooperative agreements established during the first-year drilling with both the Bureau of Land Management (BLM, Farmington, Albuquerque, Rio Puerco, Socorro, and Taos offices), the New Mexico State Land Office, and Energy, Minerals, and Natural Resources Department, Mining and Mineral Division (MMD) to drill on federal and state lands. The BLM and NMBM&MR extended the Memorandum of Understanding initiated in 1985 for the 1986 and 1988 drilling projects that provided for drilling on BLM lands with archeological clearance and environmental assessment done by BLM staff. The NMBM&MR agreed to follow BLM guidelines for the reclamation of drill sites. The New Mexico State Land Office entered into a similar agreement that allowed the NMBM&MR to drill on state lands with the stipulation that archeological clearance and reclamation procedures would be in accordance with the State Historical Preservation Office and the State Engineer's regulations. A drilling exploration permit was also obtained from the MMD in Santa Fe. Both federal and state agreements required the NMBM&MR to obtain written permission from the lessees of surface or mineral rights and to notify grazing lessees of intentions to drill. In some instances written permission was unattainable or refused, and a few drill sites had to be moved or deleted from the program.

Maps of the drill-site locations were sent to BLM and state agencies after most of the foreseen changes in site locations had been made. Archeological survey of the sites was conducted by a BLM archeologist or a contract archeologist. In some instances the locations were changed in the field because of inaccessibility caused by changes in the roads and trails after the time the topographic map of the area was made, or because of the presence of archeological artifacts in the 300 ft^2 area surveyed around the drill site. Archeological surveys of potential drill sites on state land were done by independent archeologists (David Snow of Santa Fe in 1986 and Division of Conservation Archeology at Farmington in 1988). BLM archeologists (Dave Simmons, Charles Carroll, and Paul Williams) surveyed potential drill sites on federal land. An archeological report was submitted to BLM on each site surveyed by the BLM archeologist. An archeological report of the state sites was submitted to the State Historical Preservation Office (SHIPO) for approval. The environmental (EA) and the threatened and endangered species assessments (T&E) were completed by BLM personnel when all the sites had been staked and the appropriate agencies had been notified of any changes in site locations. Upon completion of the assessments and archeological reports and receipt of written permissions from the lease holders at the BLM and State Land offices, drilling could begin.

The NMBM&MR sent invitations to bid on drilling and geophysical logging to a minimum of three contractors each. For both of these bids, the contractors were required to have experience working in western coals and to provide three references. Specific information, such as the geophysical logs to be run, coring equipment to be used, number of rigs, water-truck capacity, and number of personnel required were listed in the bids. Mo-Te Drilling in Farmington (1985, 1986, and part of 1988) and Stewart Brothers (1988) were selected for the drilling contracts. Century Geophysical (1985) and Southwest Surveys of Farmington (1986, 1988) were selected for the geophysical-logging contracts. These contractors were the lowest qualified bidders. For the redrilling of four locations in the Torreon area (1988) the bidding process was repeated because of the increased depth and small number of holes. Mo-Te received the drilling contract and Southwest Surveys received the geophysical-logging contract for these drill sites.

During the 1985 and 1986 drilling projects Mo-Te supplied two drill rigs, each of which was accompanied by a water truck. To maximize the use of technical personnel and minimize the sometimes lengthy drives for water, a feeder water truck supplied water to both rigs. Each rig was equipped with a 15 ft long, 3 in diameter, split-tube core barrel fitted with a carbide core head. One drilling rig with a water truck and a feeder truck were sufficient for the 1988 drilling project.

One Century Geophysical logging truck was used during the 1985 drilling program. In 1986, Southwest Surveys supplied two geophysical logging trucks for drilling in the Cuba—Torreon area. A logging truck was assigned to each drill rig to eliminate travel time on the sometimes difficult routes between the rigs, in order to maximize the efficiency of the operation. In the Crownpoint and Gallup areas (1986) one Southwest Surveys logging truck was used for both rigs because the travel distance from site to site was not as great nor was the terrain as difficult. One Southwest Surveys logging truck was used for the entire 1988 drilling project. All the geophysical-logging trucks used (1985, 1986, 1988) had a gamma, bulk-density, caliper, and resistivity logging tool and a neutron—gamma logging tool.

The 1985 drilling season began on June 4 northeast of Farmington in the Fruitland Formation, with a ten-days-on—four-days-off schedule, which varied occasionally. The average time spent at each drill site, depending on depth and occasional drilling problems, was 1.37 days for a total of 40 days to drill 65 sites (pilot and core hole) with two drill rigs. Temporary breaks in drilling were due to wet weather and delays in paperwork or permission to drill. Drilling of 46 Fruitland Formation and 19 Menefee Formation sites was completed on September 7, 1985.

The 1986 drilling season began on July 29 southwest of Cuba in the Menefee Formation, La Ventana coal field. A ten-days-on—four-days-off schedule was followed with some variation. The average time spent at each drill site, depending on the depth and occasional drilling problems, was 1.47 days for a total of 38 days to drill 56 sites using the two rigs. The average number of drilling hours at each site was slightly over nine. In many cases, travel time from one site to the next amounted to a large percentage of the time spent in the field. The weather and permissions from land owners or government agencies did not cause any delays. Drilling was completed on September 18, 1986.

The 1988 drilling season began on May 16 northwest of Quemado, in the Salt Lake field. A five-days-on—two-days-off schedule was followed with the exception of the last 12 days with no time off. The average time spent at each drill site, depending on the depth and drilling problems, was 1.45 days for a total of 35 days to drill 24 sites using the one rig. Again, moving the rig from one site to the next was a large factor in the amount of time spent in the field. There were no delays due to weather or waiting for permission to drill from land owners or government agencies. The initial 24 drill sites were completed on June 30. Four locations in the Chacra Mesa area near Torreon (three locations drilled in 1986 and one earlier in 1988) were redrilled to 725 ft for stratigraphic and correlation purposes. No coals of qualifying thickness were encountered at the greater depths and therefore no coring was done at these sites. Drilling of these four sites began on August 23 and was completed on August 27.

Field procedures

Each drill site potentially consisted of a pilot hole and a core hole. A core hole was drilled if coals of qualifying or greater thickness were encountered in the pilot hole. A minimum of 1.5 ft was chosen as the qualifying thickness for the 1986 and 1988 drilling seasons; a 2.5 ft minimum was used for a qualifying coal thickness in the 1985 season. The change in the minimum qualifying coal thickness was based on the opinion that the coal-bearing sequences sampled in 1986 and 1988 (Menefee, Crevasse Canyon, and Moreno Hill Formations) generally would contain thinner coal beds than those drilled in 1985. Using the 2.5 ft minimum thickness would have resulted in large areas that would not have been sampled, and the coal-quality characteristics thus would not have been ascertained.

Drill-site locations were designated by using the township, range, and section, i.e. 15N18W34 would be in T15N, R18W, sec. 34. Core holes were designated in the same way with a "C" following the location description. Core samples were labeled alphabetically, starting with "A" for the shallowest sample.

Wherever possible, the pilot hole was drilled through the entire coal-bearing sequence and at least 40 ft into the underlying formation. The Fruitland Formation is underlain by the Pictured Cliffs Sandstone, the Cleary Coal Member of the Menefee Formation is underlain by the Point Lookout Sandstone, and the Gibson Coal Member of the Crevasse Canyon Formation is underlain by the Dalton Sandstone. In the Salt Lake field, the Moreno Hill Formation is underlain by the Atarque Sandstone. The formational contacts between these coal-bearing units and the underlying, distinctive marine sandstones are easily identified. In the upper part of the Menefee Formation and in the Cleary—Gibson Coal Members (undivided) the contacts with underlying units are gradational and ambiguous, making it difficult to determine when the total coal-bearing sequence has been penetrated. In these situations the geologist chose to have the hole drilled through an additional 100 ft of non-coal-bearing strata or to the maximum depth permitted by the available drill pipe (about 500 ft). In most of the upper Menefee drill sites the maximum amount of drill pipe was used as the cut-off depth, whereas in the Cleary—Gibson drill sites an additional 100 ft of non-coalbearing rocks were drilled below the coal-bearing sequence.

Drill cuttings at 5 ft intervals were sampled from the pilot hole and examined to determine the lithology and when the coal-bearing sequence and the underlying unit have been penetrated. The pilot hole was conditioned, filled with water, and geophysically logged in two separate runs to obtain the necessary suite of logs. Only intervals containing coal beds thicker than 2.5 or 1.5 ft were cored. Depths to core the coal beds were determined from the geophysical logs on the criterion that only coals equal to or thicker than the qualifying coal thickness (2.5 or 1.5 ft) were to be sampled. Coring was done with water or mist and the cores generally included at least 0.5 ft of rock above and below the sampled coal. Coring commonly included a greater thickness below the bottom coal bed so that the base of the coal could be recorded on the geophysical log.

After the core was taken, the core barrel was placed on a core stand and opened in the presence of a geologist. Whenever possible, cores were not cut late in the day in order to ensure that the geologist had enough light to properly describe the core. Before description, the core was measured and compared to the interval on the geophysical log to determine if there was any core loss. If there was less than 5% loss of core and it could be clearly determined that it did not occur within the coal, the core was usually accepted for description and sampling. If the coal recovery was poor, less than 95%, or the coal core was broken, or if there appeared to be a differential recovery of the coal, the core was rejected and the interval was recored.

After measuring the core, the depth was marked off on the core in one-foot intervals with a lumber crayon. Changes in lithology were noted with a lumber crayon of a different color. Descriptions of lithologies were recorded for intervals measured to the nearest five hundredths of a foot. After the description was completed, coal beds generally thicker than 5 ft were divided into two or more samples, so that the maximum sample interval was limited to about 5 ft. Partings of 0.8 ft or more within the coal beds were considered to be removable. Such partings normally would not be included with the coal during the mining process, and, therefore, were not included in the coal samples. During 1985, a 0.5 ft interval above and below the coal as well as any removable partings in the coal bed were sampled separately for analyses. This practice was discontinued the second year because of the lack of variability in the data obtained from these samples. The coal samples were double-bagged in 6 ml polyethylene bags to ensure preservation of the moisture content. Identifying information such as the hole number, sample designation, and depth interval were written on the bag, on a card placed between the two bags, and on an aluminum tag tied to the bag. The bag was tied with cord and the top of the bag was folded over and tied again to protect against moisture loss. The accumulated samples were sent back to the NMBM&MR Coal Lab in Socorro for preparation and analysis every fifth day during the drilling program.

The core hole was geophysically logged with the gamma-ray, caliper, density, and resistivity tool. This was done to ensure an accurate log of the cored interval. In some instances, especially in the Menefee and Crevasse Canyon Formations, the cored coals differed in thickness, depth, and log signature from the coal intervals interpreted from the geophysical logs of the pilot hole.

Both the pilot and core holes were cemented with Portland Type II 100 ft above and below any coals deeper than 250 ft and thicker than 2.5 ft, or when an aquifer was encountered. Occasionally a hole was cemented from top to bottom because of an aquifer or multiple qualifying coals (>2.5 ft). If neither of these conditions was encountered, the hole was back-filled with the cuttings. All holes have a 5 ft cement (Quikrete) plug at the top. A metal stake with a flat cap or tag was placed in the cement to mark the site. The drill-hole number was stamped on the cap or tag for future reference. Drill sites were reclaimed and seeded by the drilling contractor with the seed mixture specified for both state and federal lands. After drilling was completed, the sites were surveyed by a contract surveyor (Jerry Nickels of JNS, Albuquerque).

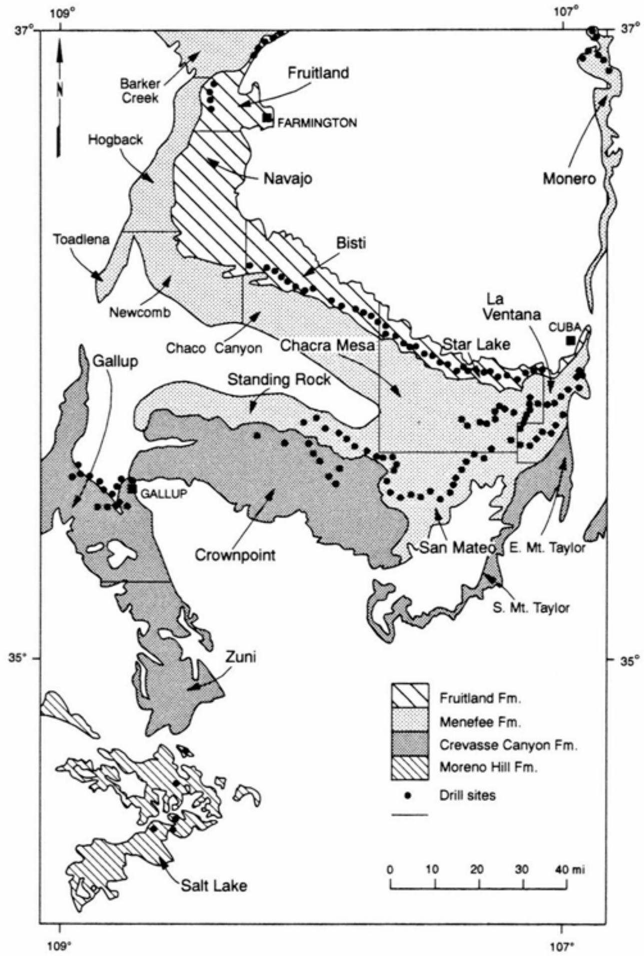

FIGURE 7—Generalized map of drill-site locations, San Juan Basin coal fields and Salt Lake field.

Drill-site locations

Sixty-five drill sites were completed in 1985. Forty-six of these were in the Fruitland Formation of the Fruitland, Bisti, and Star Lake fields. The remaining 19 sites were in the Menefee Formation of the San Mateo and Standing Rock fields (Fig. 7, Table 1).

The 56 drill sites completed in 1986 were located in six coal fields in the southern San Juan Basin (Fig. 7, Table 1). Most of these locations were in the Menefee Formation of the La Ventana, Chacra Mesa, and San Mateo fields. A few drill sites were located in the Crownpoint, Gallup, and Star Lake fields.

The 28 sites drilled in 1988 were confined to four coal fields in northwestern New Mexico (Fig. 7, Table 1). Seven of the locations were in the Monero field on the northeast edge of the San Juan Basin. Eight of the initial drill sites and the four redrilled locations were in the Chacra Mesa field. Four drill sites were located in the Gallup field in the southwest corner of the San Juan Basin. The remaining five drill sites were in the Salt Lake field, in west-central New Mexico (Fig. 7). Descriptions of cuttings, cores, analytical data, and geophysical logs for all 149 drill sites are available in NMBM&MR Open-file Report 377 (Hoffman, 1991).

Description of coal-bearing sequences

(Gretchen K. Hoffman)

Fruitland Formation

Forty-nine sites were drilled in the Fruitland Formation of the Fruitland, Bisti, and Star Lake fields in 1985 and 1986 (Fig. 7). Sixty-five percent of these sites were located on lands having federal surface and/or mineral rights, while those located on state land (24%) were secondary. Only a few sites were located on patented land. At the time of drilling, 63% of the sites in the Fruitland Formation were on existing coal leases or Federal Preferential Right Lease Application land (PRLA's) (Table 2).

The Fruitland Formation is a nonmarine sequence of interbedded shale, sandstone, siltstone, carbonaceous shale, and coal. Shale is the dominant lithology in both the Fruitland and Bisti fields, but sandstone and siltstone form a greater portion of the sequence in the Star Lake field.

The Pictured Cliffs Sandstone underlies the Fruit-

TABLE 1—Number of drill sites completed by year and formation* and by field and formation.

Year	No. of drill holes	Formation			
		Fruitland	Menefee	Crevasse Canyon	Moreno Hill
1985	65	46	19		
1986	56	3	34	18	
1988	28		19**	4	5
Total	149	49	73	22	5

Field	No. of sites	Year	Formation	Member
Fruitland	9	1985	Fruitland	
Bisti	16	1985	Fruitland	
Star Lake	21	1985	Fruitland	
	3	1986	Fruitland	
La Ventana	5	1986	Menefee	Upper
	10	1986	Menefee	Cleary
Chacra Mesa	10	1986	Menefee	Upper
	8	1988**	Menefee	Upper
	2	1986	Menefee	Cleary
Standing Rock	8	1985	Menefee	Cleary
San Mateo	11	1985	Menefee	Cleary
	8	1986	Menefee	Cleary
Monero	7	1988	Menefee	
Crownpoint	8	1986	Crevasse Canyon	Gibson
Gallup	9	1986	Crevasse Canyon	Gibson
	2	1988	Crevasse Canyon	Gibson
	1	1986	Crevasse Canyon	Dilco
	2	1988	Crevasse Canyon	Dilco
Salt Lake	5	1988	Moreno Hill	Lower
Total	149			

* See Tables 2–5 for detailed description of drill sites, field, ownership, and location.
** Four of these were drilled to greater depth at previous drill-site locations.

land Formation and is a readily recognizable sandstone unit. It is a sub- to well-rounded, fine- to medium-grained, quartz-dominated marine sand, which differs from the generally silty, fluvial sandstones in the Fruitland Formation. The Pictured Cliffs is very friable and tends to yield unconsolidated cuttings. In the Star Lake field, the contact between the Pictured Cliffs Sandstone and the Fruitland Formation is difficult to identify because of the increased intertonguing of the two units, which is more prevalent in the Star Lake area than in the northwest Fruitland outcrop areas.

Fruitland field

The Fruitland field is delineated by the outcrop pattern of the Fruitland Formation from the New Mexico—Colorado state line south to the San Juan River, an area of roughly 206 mi^{1} (Fig. 7). The field is bordered on the east by the Kirtland Shale and on the west by outcrops of the Pictured Cliffs Sandstone. The dip of the beds in the southern part of this field is only 1-3° to the east, but gradually increases to the north. In T31N the Fruitland Formation is influenced by the steeply dipping Hogback monocline and the dip is 18-40° to the southeast from here north to the Colorado state line.

Nine sites were drilled in the Fruitland field in 1985 (Fig. 8). Most of these sites were on federal land (55% surface ownership, 77% mineral ownership), with the remainder on private land (33% surface, 11% mineral) (Table 2). Most of the sites were located on properties of the La Plata, Black Diamond, and San Juan mines. One drill site was not on an existing mine property nor on an active coal lease.

As defined, the Fruitland Formation ranges from the top of the Pictured Cliffs to the uppermost coal. It is approximately 300 ft thick in the northern Fruitland field and thins to 200 ft in the southern area of the drill sites (Fig. 9). The Fruitland sequence in the Fruitland field is dominated by shale (sandstone : shale ratio = 0.09 : 0.96). Sandstone generally forms a minor part of the section, particularly in the southernmost drill sites (30N15W34, 30N15W28, 30N15W4). Carbonaceous shales also are minor (average 3%) in the sequence.

Four coal zones (sequences of coal beds separated by significant amounts of shale, siltstone, and sandstone) were recognized in the Fruitland field, but generally only three of them contained qualifying coals (>2.5 ft). Two coal zones were cored in the southern end of the field. The lowest coal zone is just above or within 30 ft of the Pictured Cliffs Sandstone contact. This zone is the thickest and most continuous of the three zones cored. The total coal thickness is greatest at drill site 32N13W28, where a total of 60 ft of coal was cored. One to four coal beds in the lower zone average 11.3 ft in thickness, with a range from 3.3 to 28.1 ft (individual seams are hard to identify on the

TABLE 2—Ownership and map designation of drill-site locations, Fruitland Formation.

Fruitland Formation	Ownership		Figure Map No.
Fruitland field	Surface	Mineral	Fig. 8
32N12W8	Federal	Federal	1
32N13W13	Federal	Federal	2
32N13W14	Federal	Federal	3
32N13W28	Private	Private	4
31N13W5	Private	Federal	5
30N15W4	Federal	Federal	6
30N15W16	State	State	7
30N15W28	Federal	Federal	8
30N15W34	Private	Federal	9
Bisti field			Fig. 8
24N13W31	Federal	Federal	10
23N13W2	State	State	11
23N12W6	Federal	Federal	12
23N12W4	State	Federal	13
23N12W3	State	Federal	14
23N12W12	Federal	Federal	15
23N11W19	State	Federal	16
23N11W29	State	Federal	17
23N11W27	Federal	Federal	18
23N11W36	State	State	19
22N10W17	Federal	Federal	20
22N10W23	Federal	Federal	21
22N9W19	Federal	Federal	22
22N9W29	Federal	Federal	23
22N9W27	Federal	Federal	24
22N9W36	Federal	State	25
Star Lake field			Fig. 8
21N8W7	Federal	Federal	26
21N8W17	State	Federal	27
21N8W22	Federal	Federal	28
21N8W36	Federal	State	29
20N7W8	Federal	Federal	30
21N7W33	Federal	Federal	31
20N7W10	Federal	Federal	32
20N6W18	State	Federal	33
20N6W28	State	State	34
20N6W26	State	Federal	35
20N5W31	Federal	Federal	36
20N5W32	State	State	37
20N5W28	Federal	Federal	38
20N5W34	Federal	Federal	39
20N5W36	Federal	Federal	40
19N5W1	Federal	Federal	41
20N4W32	State	State	42
19N4W3	Federal	Federal	43
19N4W1	Federal	Federal	44
19N3W8	Bankhead Jones	Federal	45
19N3W9	Private	Federal	46
19N3W3	Bankhead Jones	Federal	47
20N3W36	Federal	Federal	48
19N2W6	Federal	Federal	49

scale used in Figure 9). Sixty-eight coal samples were obtained from the lower zone. Partings (parting thickness/seam thickness) in these coal beds averaged 6%, which is the smallest percentage of all the coal zones cored in the Fruitland field.

The middle zone is recognized in the five northernmost sites and in three of the southern sites. This zone is 75 to 128 ft above the top of the lower zone and averages 17 ft in thickness. There are several coals within this interval that are less than the minimum qualifying thickness of 2.5 ft. One to three coal beds of this zone qualify, having an average thickness of 5 ft, and 11 samples were taken from these coals. The middle zone coal beds have the largest average percentage of partings (19.2%) of all the Fruitland field coals.

The upper zone is 180 to 250 ft above the top of the Pictured Cliffs Sandstone and its average thickness is

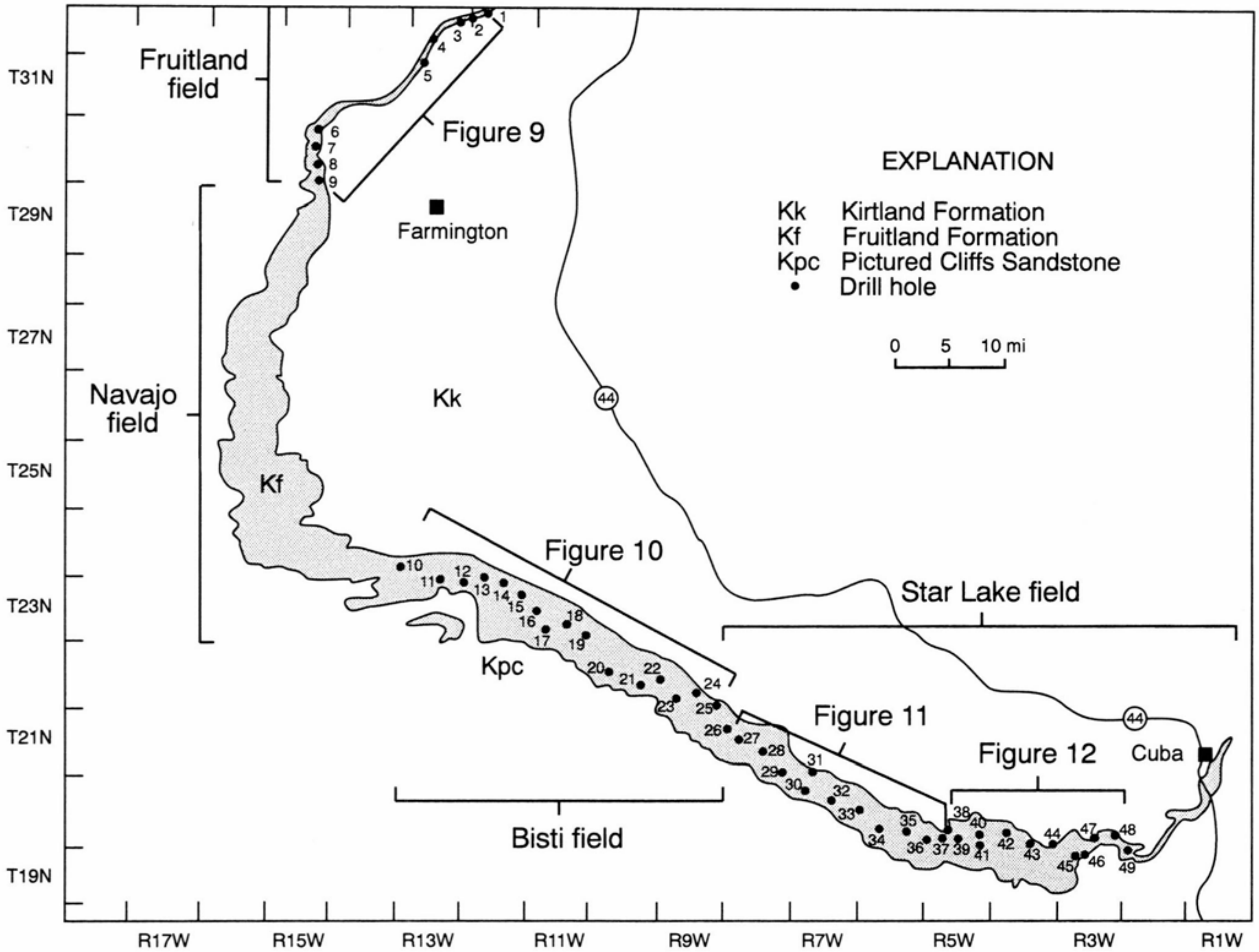

FIGURE 8—Fruitland Formation drill-site locations, Fruitland, Bisti, and Star Lake fields. Base map modified from Shomaker et al., 1971. See Table 2 for corresponding drill-site designations.

13 ft. A small number of coal beds in this zone did not meet the qualifying thickness (2.5 ft) for coring. The coals that qualify average 5 ft in the two beds sampled in this interval. Ten coal samples were taken from this zone. The upper-zone coal beds typically had two partings per sample, constituting an average of 10.7% of the total coal bed. The thickest interval of coal in the upper zone is at drill site 32N13W28. No coals are present in this zone in the southern part of the Fruitland field.

The Fruitland field coals are generally hard, banded with a high percentage of vitrain and good cleat. They are thickest, most abundant, and have the most areal continuity in the northern part of the Fruitland field. Previous data collected through a cooperative project for data entry into the USGS National Coal Resource Data System (NCRDS) and data from this study confirm a decrease in the number of beds in the coal-bearing sequences to the southwest in the Fruitland field.

Because the lower-zone coals have the greatest continuity and thickness in the Fruitland section, and typically are within a few feet of the marine Pictured Cliffs Sandstone, they probably represent deposits of a relatively stable back-barrier swamp environment. This environment appears to have been most stable in the northeast part of the Fruitland field. Coals higher in the Fruitland Formation probably accumulated during shorter standstills in the shoreline, resulting in a stacking of thinner coals. The frequency of partings in the middle-zone coals is indicative of a swamp that had recurrent invasions of clastic sediments.

Bisti field

The Bisti field is defined by the Fruitland Formation outcrop from the eastern boundary of the Navajo Reservation to the eastern edge of T21 + 22N, R9W, approximately 270 mi^1 (Figs. 7, 8). The southern border of the Bisti field is shared with the Chaco Canyon field at the outcrop of the Pictured Cliffs Sandstone. The northern edge of this field is at the Ojo Alamo and Fruitland—Kirtland outcrop. The structure in this area of the San Juan Basin, on the Chaco slope (Fig. 3), is simple and the general dip of the beds is 3-5° north—northeast.

Sixteen sites were drilled in the Bisti field in 1985 (Fig. 8). The Bisti Wilderness Area and the Ah-She-Sle-Pah Wilderness Study Area are within the Bisti area, but were avoided in the line of the Bisti drill locations; therefore, the spacing is not strictly on two-mile centers. These drill sites were predominantly on federal surface ownership (62%) and federal mineral ownership (81%). The remaining drill sites were on

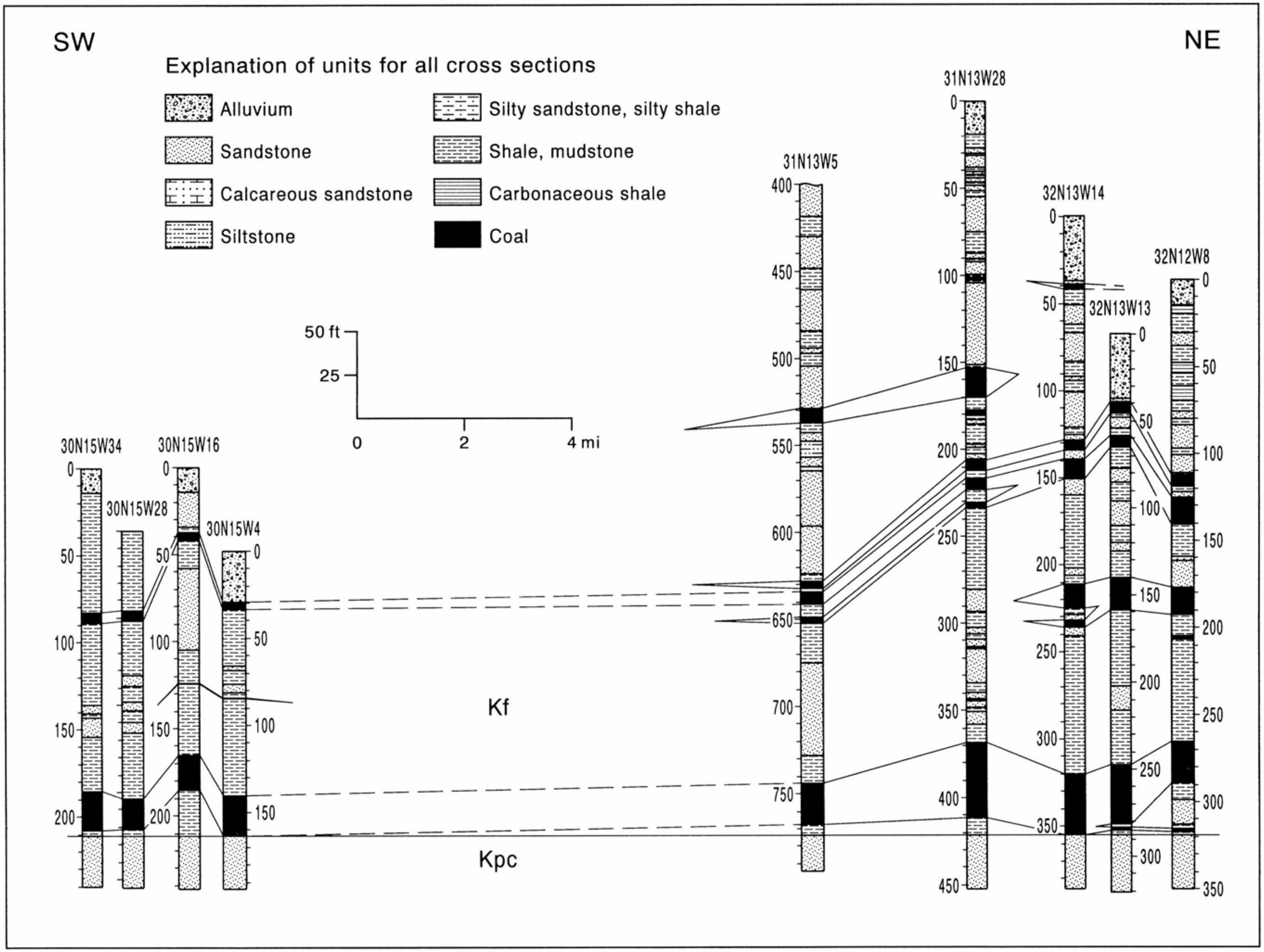

FIGURE 9—Explanation of graphic representations of pilot holes, and correlation of pilot holes in Fruitland field. Kpc = Pictured Cliffs Sandstone, Kf = Fruitland Formation.

state surface (38%) and state minerals (19%) (Table 2). All but two of the locations were on leased land or PRLA's at the time of drilling. None of the drill sites were in active-mine areas.

The Fruitland Formation penetrated in the Bisti field drill holes ranges from 120 to 380 ft in thickness (Fig. 10), which is partially because of the variation in distance between drill sites down-dip from the cropline resulting from access problems or denial of permission from the land owner.

Shale is the predominant lithology in all but one of the Bisti drill locations (22N9W29) where siltstone is dominant. The sandstone/shale ratio ranges from 0.03 to 0.77, with sandstone increasing to the southeast. Carbonaceous shale and impure coal are minor constituents in these sections. The total coal thickness within the Fruitland Formation in the Bisti field varies from 10 to 54 ft at the sites drilled. The total coal thickness at each location drilled for this study is generally greater than indicated by the previous data collected through the NCRDS project, presumably because this study's drill holes penetrated the entire Fruitland section and were completed in the Pictured Cliffs Sandstone. The coals are most often associated with shale but in some places are directly overlain or underlain by siltstone or sandstone. The coal zones within the section are typically separated by siltstone- or sandstone-dominated sequences. The coals tend to be in the lower 150 ft of the Fruitland sequence, and only a few thin coal beds are found in the upper part of the section (Fig. 10).

Three to four separate coal zones are recognized in the Fruitland Formation in the Bisti field. The stratigraphic position and thickness of these zones varies considerably throughout the field. Two to three zones are typically present and the coal beds in these zones commonly thin to the southeast. The lower zone is typically 15 ft thick and lies approximately 5 to 14 ft above the top of the Pictured Cliffs Sandstone, a barrier-beach deposit. This zone is the most laterally continuous but is also the thinnest in the Bisti field. One or two coal beds in this interval frequently are 7.8 ft thick, while the thickest coal bed is 17.3 ft thick at drill site 23N11W36. Fourteen of the 25 coal samples taken from the lower zone contained partings. These coals had an average of two partings per bed, constituting an average of 5% of the total coal-bed thickness, although one coal bed consisted of 17% partings.

The middle coal zone is 26 to 93 ft above the Pictured Cliffs Sandstone and typically is 26 ft thick. This zone commonly is stratigraphically higher in the Fruitland section to the southeast. From drill sites 23N11W19 to 22N10W23, the middle zone contains the thickest coals of the entire field. Previous data and this study's data confirm that the standard coal thickness is greatest in the T's 22-23 N, R's 10-11 W. The mean coal-bed thickness in the middle zone is 8.9 ft, ranging from 1.4 to 34.6 ft, the thickest coal penetrated at drill site 23N11W27 (34.6 ft). These coals were deposited farther away from the shoreline, possibly in a moderately stable flood-plain environment. The thickness of these coals is perhaps indicative of a minor standstill in the shoreline to the northeast. Forty-three samples were taken from the middle coal zone, of which 29 samples have partings averaging 11.5% of the total bed thickness. One coal bed contained partings amounting to 44.5% of the total bed thickness.

The upper coal zone is 64 to 185 ft above the toF of the Pictured Cliffs Sandstone and is stratigraphically higher in the southeastern part of the field. The thickness of this zone is extremely variable, ranging from 2 to 62 ft. The only coal beds thick enough tc core, at drill sites 22N9W19 and 22N9W29, were in the upper zone. Typically, one or two coals occur in this zone, with a bed thickness of 6 ft. The upper zone coals are thickest in the northwestern part of the field. The coals in this zone are generally associated with mudstone, siltstone, and an occasional channel sandstone indicating a fluvial environment. Eight of the seventeen samples taken in this zone have one to twc partings that on the average make up 8% of the total coal-bed thickness.

The Fruitland Formation coals in the Bisti field are hard, densely fine- to medium-banded with vitrain, slightly resinous, and with good cleat characteristics. Eighty-five coal samples were taken from the cored intervals in this field. The coal beds are thickest in the middle zone. The upper coal zone has the thinnest qualifying coal beds and is the least laterally continuous of all the zones in the Bisti field. The middle coal zone has the most samples with partings, and these partings constitute the highest mean percentage (10.6%) of the total coal-sample thickness. The upper zone has the smallest percentage of samples with partings, and they make up the smallest amount of the total sample thickness. The lower zone has the least variation in stratigraphic position within the Fruitland Formation and the most consistent coal-bed thickness throughout the Bisti field. All the zones in this field show a general thinning to the southeast, toward the Star Lake field. The Fruitland coal-bearing sequence in the Bisti field does not have as thick or as many coals as the Fruitland field. It appears, particularly in the southeastern Bisti area, that the depositional environment of the Fruitland was changing at a relatively rapid rate from a back-barrier swamp to an upper flood-plain sequence, possibly due to differential subsidence in this part of the basin (Hunt, 1984).

Star Lake field

The Star Lake is defined by the outcrop of the Fruitland Formation in T19-21N, R1-9W (Fig. 8). This field extends from the Bisti field east toward the town of Cuba. The general dip of the Fruitland Formation is 1-5° northeast to northwest, toward the deepest part of the basin.

Twenty-four sites have been drilled in the Star Lake field, 21 of them in the 1985 season (Fig. 8). These sites are on federal (67%), state (24%), and private (9%) surface ownership. Eighteen sites have federal mineral ownership and three sites have state mineral ownership (Table 2). Eight locations have existing coal leases or PRLA's and two are within mine areas that were not active at the time of drilling. Seventeen sites were cored, and the remaining four sites lacked coals of qualifying thickness (2.5 ft).

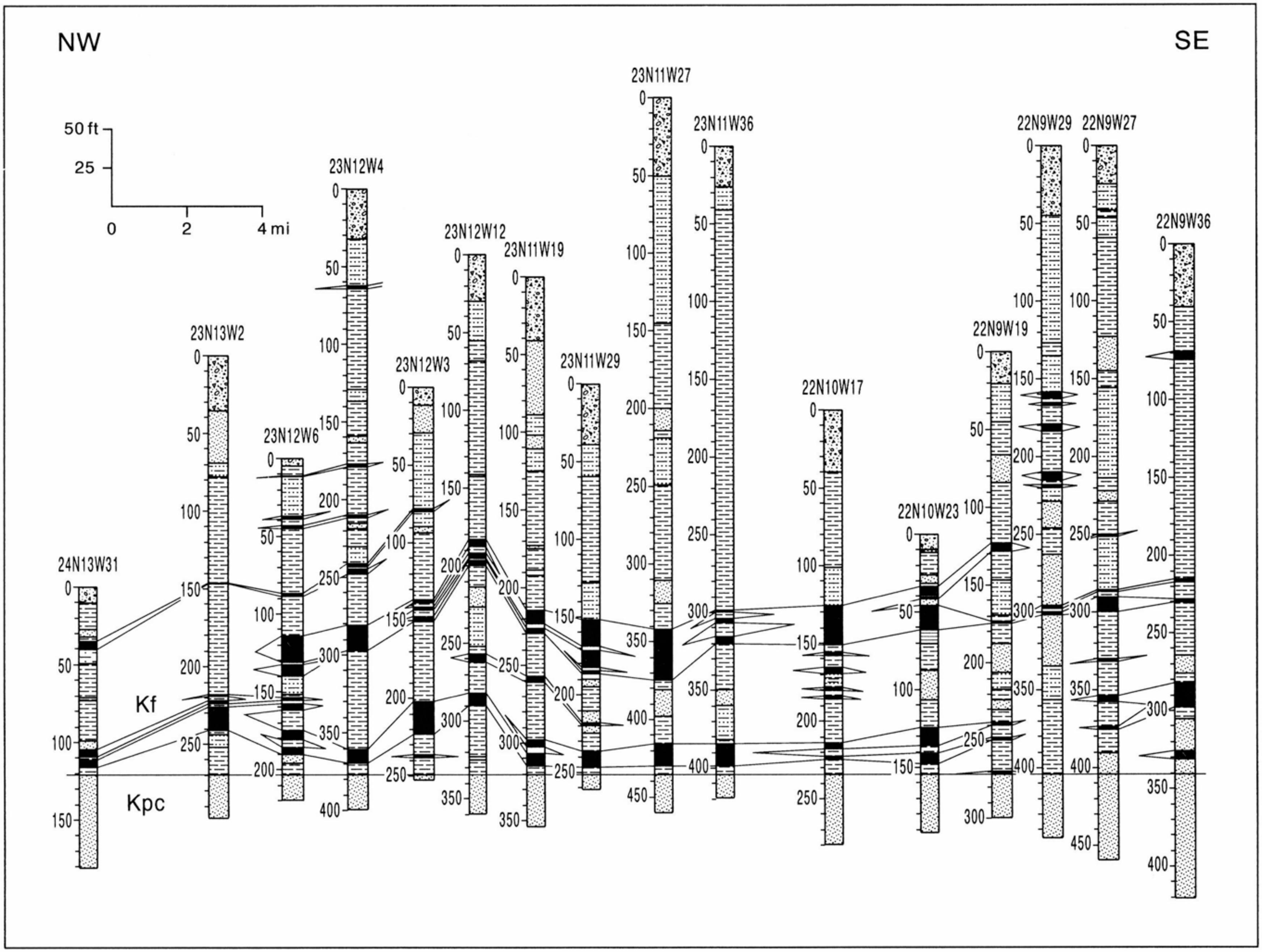

FIGURE 10—Correlation of pilot holes in Bisti field. Kpc = Pictured Cliffs Sandstone, Kf = Fruitland Formation.

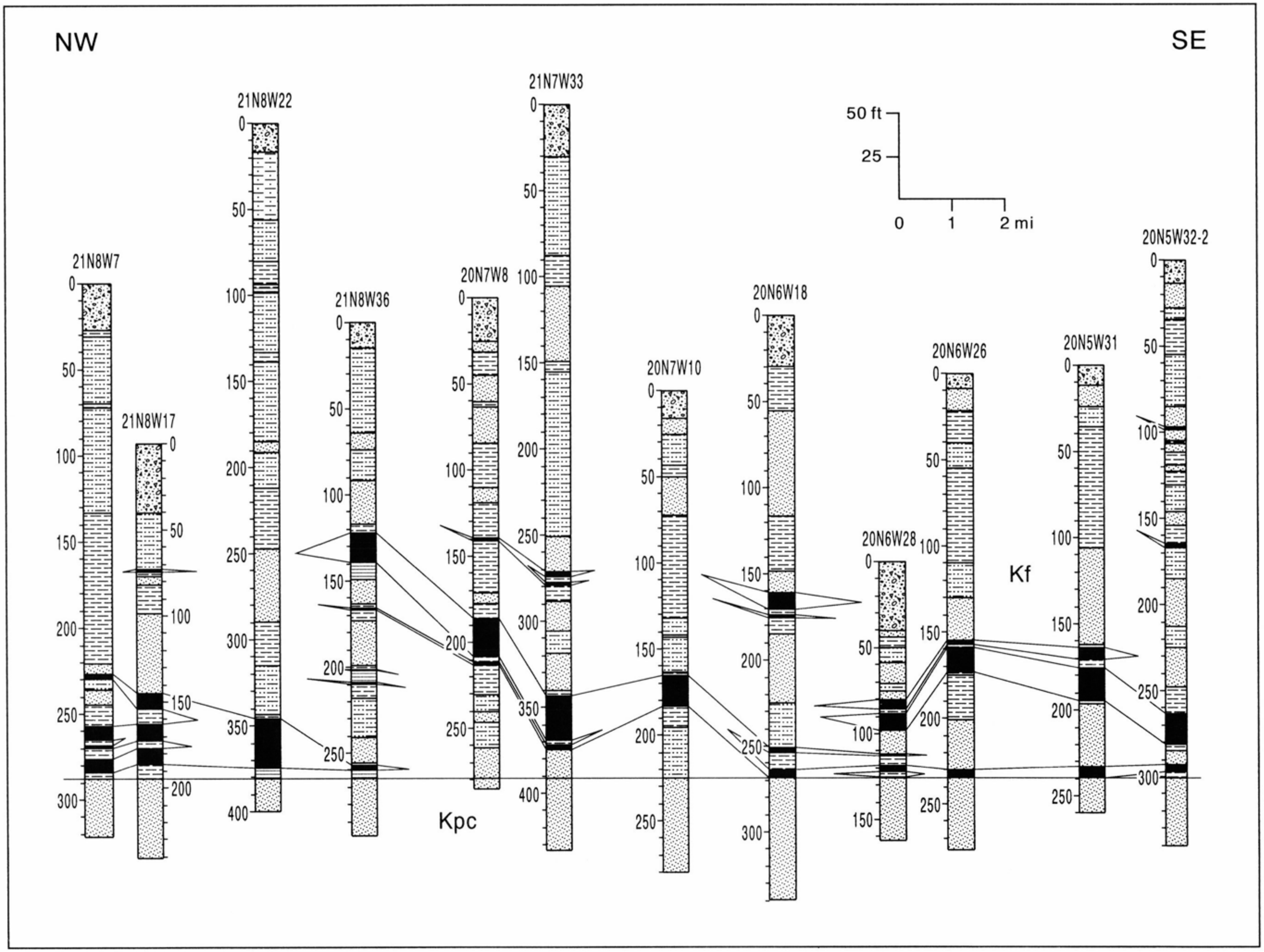

FIGURE 11—Correlation of pilot holes in Star Lake field, West. Kpc = Pictured Cliffs Sandstone, Kf = Fruitland Formation.

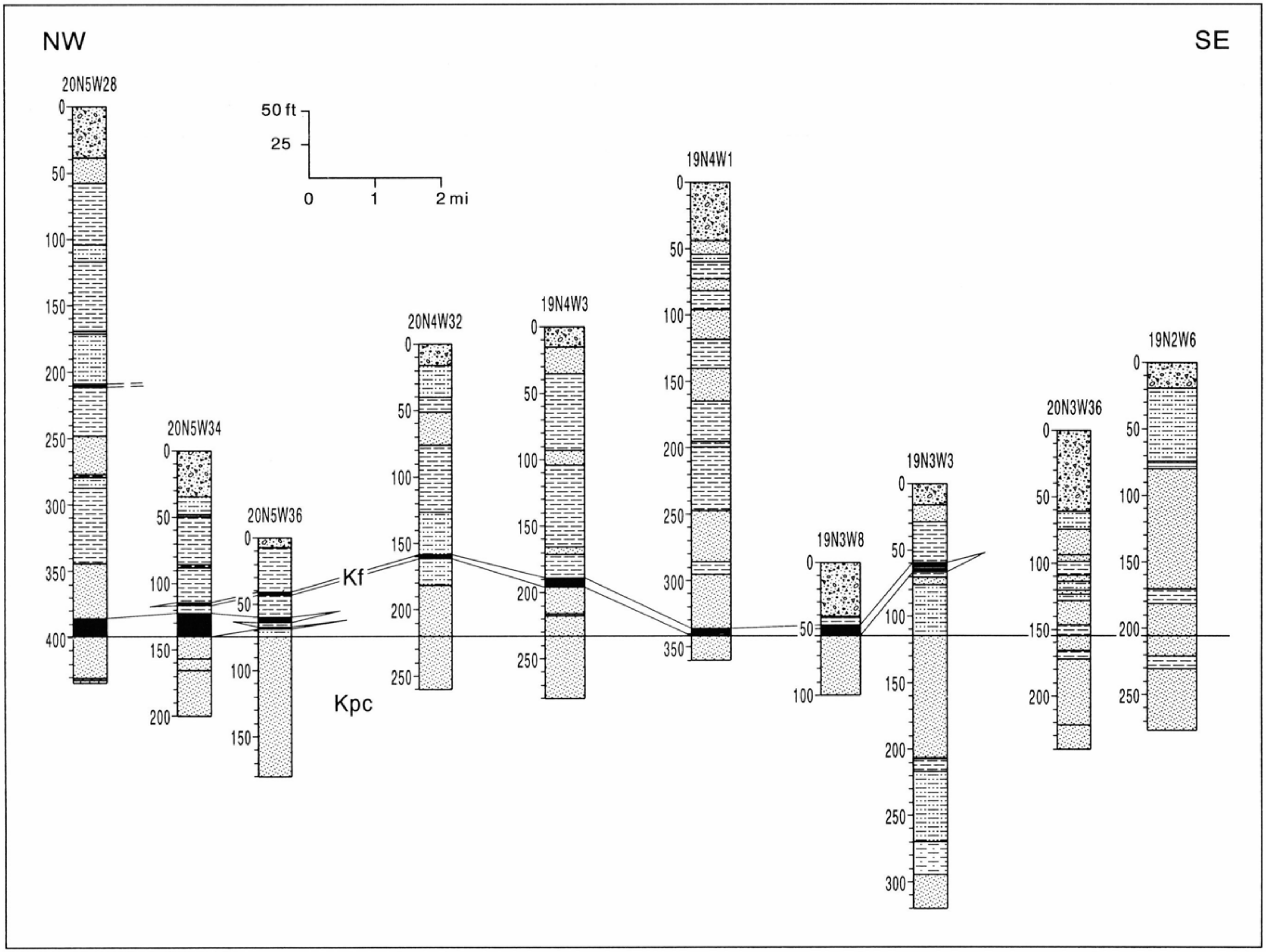

FIGURE 12—Correlation of pilot holes in Star Lake field, East. Kpc = Pictured Cliffs Sandstone, Kf = Fruitland Formation.

Three additional sites were drilled in 1986 to fill gaps in the data obtained during the 1985 drilling season (Fig. 8). One site was drilled on private surface with federal mineral ownership (19N3W9); another one on federal surface and mineral ownership (20N5W36); and the third one on state surface and mineral ownership (20N5W32). Two of these sites had qualifying coals (by 1985 criteria) and six coal samples were collected.

The Fruitland Formation penetrated in the Star Lake drill holes is 13 to 364 ft thick, with an average of 217 ft (Figs. 11, 12). The Fruitland sequence consists of sandstone, siltstone, shale, and coal. Sandstone is dominant, with sandstone-shale ratios of 0.13 to 7.72, a typical ratio being 1.99. The dominance of sandstone in the Star Lake field contrasts with the shale-dominated sequences of the Fruitland and Bisti fields. The Fruitland Formation in the Star Lake field is primarily a flood-plain deposit, which apparently has been more influenced by a positive source of sediment than the Fruitland sequences in the Bisti or Fruitland fields.

The average coal thickness in this field is 6.5 ft (0.5-31.2 ft), with the thickest beds occurring near the base of the section. The concept of coal zones does not readily apply to the Fruitland coal-bearing sequence in the Star Lake field. As seen in the cross sections (Figs. 11, 12), the coals vary greatly in depth and show a tendency to begin higher in the section and migrate toward its base going from west to east.

The coals are hard, clean, with numerous bands of vitrain and good cleat, containing more shale partings to the east. Seventy-four coal samples were collected from this field. The thickest coal beds were near the base of the Fruitland, although a greater number of seams occurred higher in the section. Fifty-four of these samples contained partings that on the average comprised 10% of the total bed thickness. When compared to previous data collected through the NCRDS grant, the data from this study indicate thicker coal beds occurring at greater depths in most of the field. This discrepancy probably results from many of the previous drill holes being very shallow (>150 ft) and, therefore, not penetrating the entire coal-bearing sequence nor reaching the Pictured Cliffs Sandstone. Because many of the thicker coals are in the basal Fruitland, they were not reached by these shallow drill holes. Many of the thick basal coals in the Star Lake field were deposited in a back-barrier swamp environment, behind the barrier-beach Pictured Cliffs Sandstone. Minor oscillations in the shoreline caused intertonguing of the Pictured Cliffs and the Fruitland Formations and occasionally allowed for peat development. Much of the Fruitland sequence in the Star Lake field was deposited during a relatively rapid retreat of the shoreline, with only minor peat development resulting from differential subsidence in this area of the basin (Hunt, 1984).

Summary

The Fruitland Formation is thickest in the northern part of the Fruitland field and thins to the southeast. The Fruitland generally maintains a thickness of 200300 ft in the Fruitland, Bisti, and Star Lake fields, but is extremely thin at the southeast end of the Star Lake field.

The coals in the Fruitland Formation are generally associated with shale sequences and are concentrated in the lower 150-200 ft of the formation. The Fruitland field has the thickest coals of all surface-minable coal areas in the Fruitland Formation. The Fruitland coals are hard and have significant amounts of vitrain, minor amounts of resin, and good cleat. The total coal thickness in the Fruitland diminishes from the northwest to the southeast. Four separate coal zones are recognized in the Fruitland and Bisti fields, but typically only three zones have coal beds 2.5 ft thick or thicker in these Fruitland Formation fields. The lower zone is within 30 ft of the contact with the Pictured Cliffs Sandstone and is the most consistent throughout the Fruitland Formation. In the Fruitland and Star Lake fields the coal beds are thickest near the base of the formation. The lowermost coal has similar thicknesses in the Bisti and Star Lake fields, but the middle-zone coal beds are thicker in the Bisti field. The coals deposited just above or within a few feet of the Pictured Cliffs are most likely back-barrier swamp deposits that developed behind a relatively stable shoreline. Some areas, particularly in sections of the Bisti field, may represent delta-front deposits (Flores and Erpenbeck, 1981). Subsequent coal deposits in the Fruitland Formation represent either minor oscillations and standstills of the shoreline (i.e. Fruitland field) or flood-plain deposits. It appears that a relatively rapid retreat of the shoreline occurred in the Star Lake field, which limited coal development in the swamps just behind the retreating shoreline (Hoffman et al., 1992).

Menefee Formation

In 1985 nineteen sites were drilled in the Cleary Coal Member of the Menefee Formation in portions of the San Mateo and Standing Rock coal fields (Figs. 7, 13, 21; Table 1). The San Mateo drill sites were predominantly on patented surface ownership (91%) with federal mineral ownership (100%) (Table 3). The remaining surface ownership in this field was federal. Most of the locations in the Standing Rock field had private surface ownership (50%) and state mineral ownership (36%). One-fourth of the locations was on federal surface and mineral ownership, and the remaining locations were on state surface (25%) and private mineral ownership (16%). At the time of drilling none of the locations in the San Mateo field were on leased land, although 25% of those in the Standing Rock field were on land with leased minerals (Table 3). One site (17N9W34) in the San Mateo field was within a mine-plan area, and two sites (Phillips Uranium, Nose Rock-18N12W11, 18N12W16) in the Standing Rock field were in mine areas.

Thirty-four sites were drilled in the Menefee Formation in 1986 (Table 1), 15 of them in the upper Menefee and 20 in the Cleary Coal Member of the Menefee Formation. The upper Menefee drill sites were located in the La Ventana and Chacra Mesa coal fields (Figs. 13, 14) and all were on federal land with the exception of one private surface location (Table

TABLE 3—Ownership and map designation of drill-site locations, Menefee Formation.

Menefee Formation upper coal member	**Ownership**		**Figure Map No.**
La Ventana field	Surface	Mineral	Fig. 14
20N1W33	Private	Federal	1
19N1W8	Federal	Federal	2
19N1W30	Federal	Federal	3
18N2W3	Federal	Federal	4
18N2W5	Federal	Federal	5
Chacra Mesa field			Fig. 13
18N3W3_1	Federal	Federal	1
18N3W3_2	Federal	Federal	2
18N3W11	Federal	Federal	3
18N3W10	Federal	Federal	4
18N3W16	Federal	Federal	5
18N3W21	Federal	Federal	6
18N3W21	Federal	Federal	7
18N3W28	Federal	Federal	8
18N3W32	Federal	Federal	9
18N4W13	Federal	Federal	10
18N4W10	Federal	Federal	11
18N4W10A	Federal	Federal	12
18N4W17	Federal	Federal	13
18N4W20	Federal	Federal	14
18N5W25	Federal	Federal	15
18N5W26	Federal	Federal	16
18N5W33	Federal	Federal	17
18N5W19	Federal	Federal	18

Menefee Formation Cleary Coal Member	**Ownership**		**Figure Map No.**
La Ventana field	Surface	Mineral	Fig. 14
19N1W4	Federal	Federal	6
19N1W21	Federal	Federal	7
19N2W35	Federal	Federal	8
18N2W23	State	Federal	9
18N2W34	Private	Federal	10
17N2W9	Private	Federal	11
17N2W7	Federal	Federal	12
17N3W14	Federal	Federal	13
17N3W22	Federal	Federal	14
17N3W20	Federal	Federal	15
Chacra Mesa field			Fig. 13
17N4W13	Federal	Federal	19
17N4W32	State	State	20
San Mateo field			Fig. 13
16N5W2	Federal	Federal	21
16N5W4	Federal	Federal	22
16N5W17	Federal	Federal	23
16N5W24	Federal	Federal	24
16N6W36	Federal	Private	25
15N6W2	Federal	Private	26
15N6W15	Federal	Private	27
15N6W20	Private	Federal	28
15N7W26	Private	Federal	29
15N7W22	Private	Federal	30
15N7W20	Private	Federal	31

TABLE 3 continued

Menefee Formation Cleary Coal Member	Ownership		Figure Map No.
15N8W24	Private	Federal	32
15N8W22	Private	Federal	33
15N8W20	Private	Federal	34
15N8W6	Private	Federal	35
16N8W28	Private	Federal	36
16N8W22	Private	Federal	37
16N8W10	Federal	Federal	38
16N8W6	Private	Federal	39
Standing Rock field			Fig. 21
16N9W1	Private	Private	1
17N9W34	Private	Federal	2
17N10W16	State	State	3
17N10W7	Private	Private	4
17N10W6	Private	Private	5
18N12W24	State	Federal	6
18N12W11	Federal	Federal	7
18N12W16	Federal	State	8
Monero field			Fig. 23
32N1W14	Private	Private	1
32N1W24	Private	Private	2
31N1W35	Private	Federal	3
31N1W10	Private	Federal	4
31N1E6	Private	Federal	5
31N1E9	Private	Federal	6
31N1E21	Private	Private	7

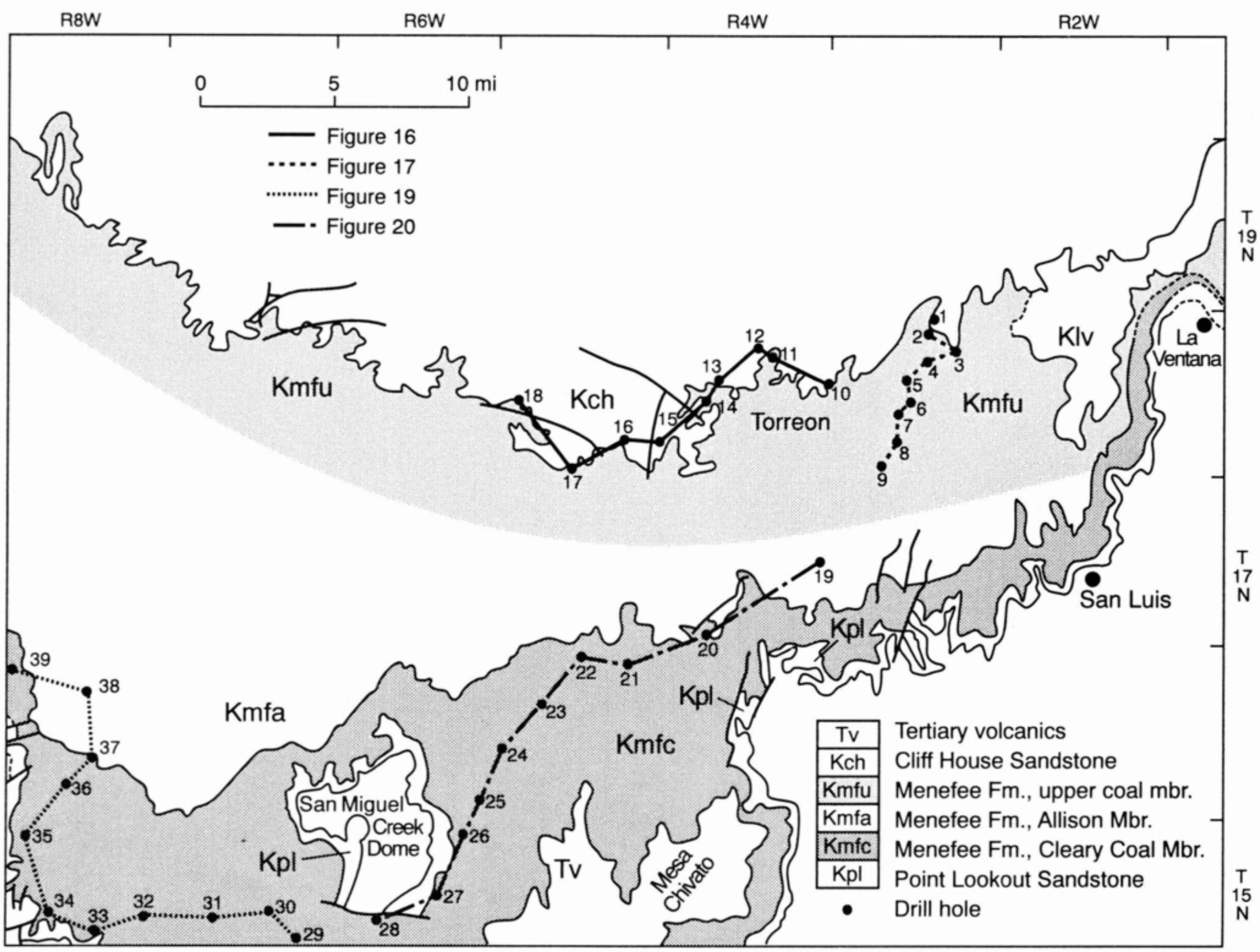

FIGURE 13—Menefee Formation drill-site locations in Chacra Mesa and San Mateo fields. Base map modified from Shomaker et al., 1971. See Table 3 for corresponding drill-site designations.

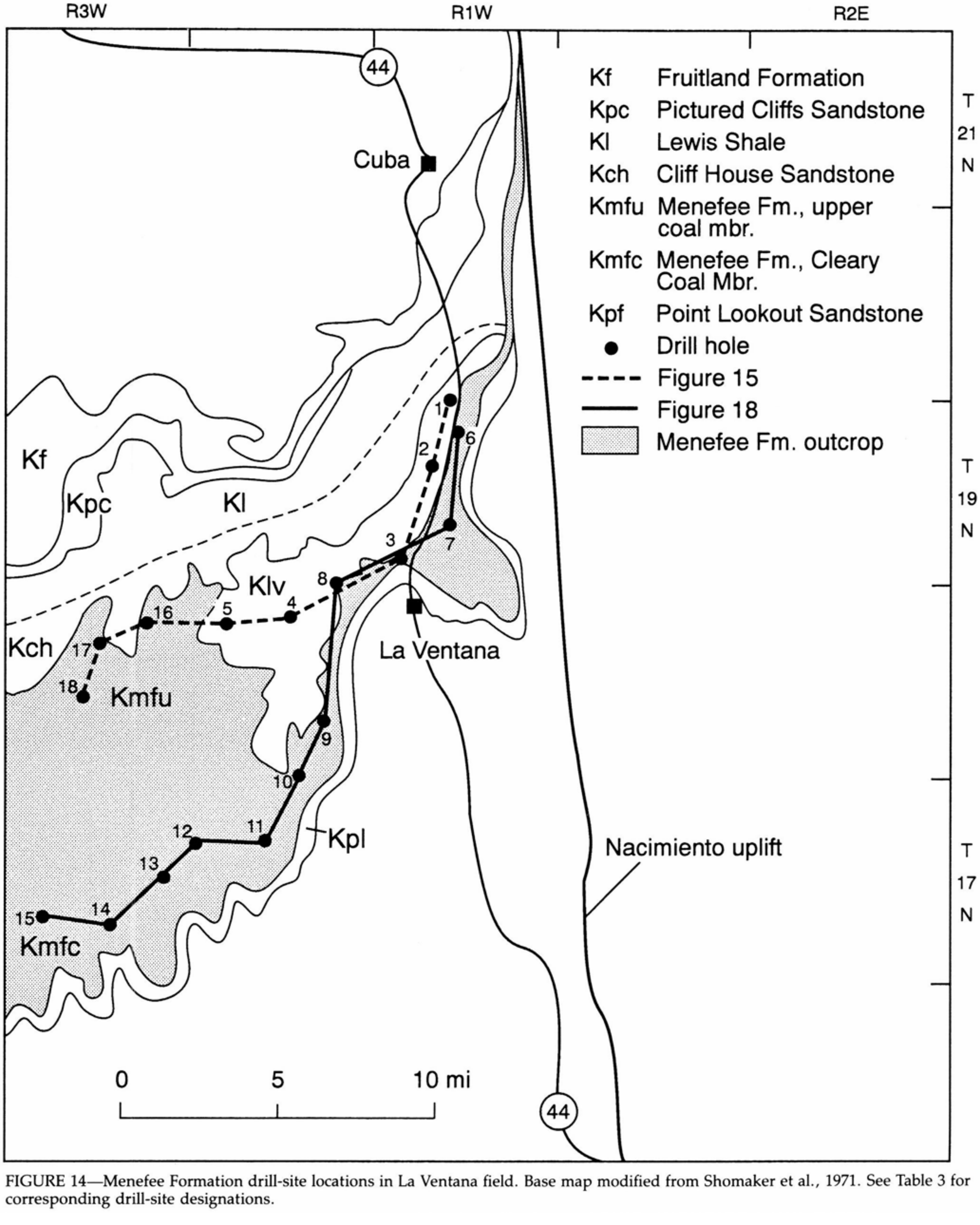

FIGURE 14—Menefee Formation drill-site locations in La Ventana field. Base map modified from Shomaker et al., 1971. See Table 3 for corresponding drill-site designations.

3). The Cleary Coal Member drill sites were in the La Ventana, Chacra Mesa, and San Mateo fields (Figs. 13, 14). Seventy-five percent of these sites were on federal surface with federal minerals; the remaining sites were on patented (15%) and state (10%) lands (Table 3).

Of the locations staked for drilling in the Menefee Formation, one upper Menefee site was not drilled because of inaccessibility and one Cleary Coal Member site was not drilled because of a denial of permission by the land owner. Two of the upper Menefee sites and three (1985 and 1986) of the Cleary sites contained no qualifying coals. The remaining 49 drill sites were cored for coal samples.

Initially, eight drill sites (1988) were completed in the Chacra Mesa field in T18N, R3 + 4W. These sites were located on one-mile centers (Fig. 13, nos. 1, 2, 5, 6, 8, 9, 11, 13) along two northeast-southwest trends perpendicular to the Late Cretaceous shoreline. One transect began at the northernmost outcrops of the La Ventana Tongue sandstones of the Cliff House, and the other at outcrops of the Cliff House Sandstone. All sites in the Chacra Mesa field were on federal surface and mineral land. These locations were drilled to obtain more coal samples in a poorly documented coal area and to better define, geographically and stratigraphically, the extent of the coal-bearing sequence.

After drilling the initial eight sites and comparing the geophysical logs for correlations, it was decided that three of the sites drilled in 1986 (18N4W10A, 18N3W11A, 18N3W10A), along or near the 1988 transects, and one of the sites drilled in 1988 (18N3W21A) needed to be drilled deeper. Each of these sites was redrilled in mid-August.

Seven sites were drilled in the Monero field in 1988 (Figs. 7, 23). These drill sites were spaced approximately 2 mi apart, from the Colorado-New Mexico state line south toward the town of Monero. Two of the seven drill sites were located west of Monero and southeast of Lumberton. Three of these sites were on private surface and mineral land and four sites were on private surface and federal mineral land (Table 3).

Description of coal fields

The La Ventana field includes portions of T16-21N, R1-3W. The northern boundary of this field is defined by the outcrop of the La Ventana Tongue of the Cliff House Sandstone (Figs. 7, 14). The southern boundary is defined by the outcrop of the Point Lookout Sandstone. The dip of the Menefee Formation in the northeast part of the La Ventana field is steep, with some overturned beds and faulting because of the proximity of the area to the Nacimiento uplift (Fig. 3). In the areas drilled, the dip varied from 15° to the west-northwest to 2° to the north-northeast.

The San Mateo field extends westward from the La Ventana field in T13-16N, R4-8W (Figs. 7, 13). The southern boundary of the field is defined by outcrops of the Point Lookout Sandstone. The drill sites were located along the southern border of the San Mateo field where the dip is gentle. There is some normal faulting present, especially in the vicinity of the San Miguel Creek dome.

North of the San Mateo field, the Chacra Mesa field is defined by outcrops of the Menefee Formation in T17-19N, R3-8W (Figs. 7, 13). The northern boundary of the field is defined by the outcrop of the Cliff House Sandstone. The general dip of the beds in this area is 1-5° to the north-northeast. Some normal faulting occurs in the Chacra Mesa field, with the beds down-dropped to the north (Dane, 1936).

The Standing Rock field extends over portions of T16-19N, R9-17W (Figs. 7, 21). The southern edge of the field is the contact of the Point Lookout Sandstone and the Cleary Coal Member of the Menefee Formation. The northern boundary is the northernmost outcrop line of the Cleary Coal Member of the Menefee Formation. The total area of this field is approximately 350 me. This area is dominated by simple structure with gently north-dipping beds.

The Monero field is located on the northeast edge of the San Juan Basin, between the Archuleta arch and the Chama embayment (Fig. 3). This field is defined by the north-south-trending outcrops of the Mesaverde Group extending from the Colorado state line south to T26N, R1E (Fig. 23). The dip of these outcrops is moderately steep in the northern part of the field, and several northwest-trending faults create large mesas. The coal-bearing Menefee Formation is defined by the overlying Cliff House Sandstone and the underlying Point Lookout Sandstone in the vicinity of the towns of Monero and Lumberton. North of this area the Menefee consists almost entirely of sandstones and is indistinguishable from the surrounding Cliff House and Point Lookout Sandstones.

Upper coal member of Menefee Formation

The upper coal member of the Menefee Formation is 250 to 480 ft thick in the sections drilled (Figs. 1517). This sequence is overlain by, and intertongues with, the sandstones of the La Ventana Tongue of the Cliff House Sandstone in the La Ventana field. The upper coal member represents a nonmarine sequence deposited shoreward of the La Ventana Tongue coastal-barrier sand buildup during a stillstand of the shoreline (Molenaar, 1977). In the Chacra Mesa field (west of R4W) the upper Menefee is overlain by, and inter-tongues with, the Cliff House Sandstone. The Cliff House does not show as extensive a buildup of sandstone here as the La Ventana Tongue to the east, but there is some stacking of barrier sandstones and intertonguing with the upper Menefee. The lesser buildup of Cliff House sandstones is sometimes referred to as the unnamed or Tsaya Canyon tongue (Fassett, 1977), or the Chacra Mesa tongue (Beaumont and Hoffman, 1992; see Fig. 2). The nonmarine upper Menefee Formation associated with the Cliff House Sandstone has fewer and thinner coals as a result of this difference in depositional environments (Fig. 16).

In the 15 sites drilled parallel to the shoreline (1986), the upper Menefee Formation is a sequence of shale, sandstone, siltstone, carbonaceous shale, and coal. Sandstone often dominates or equals the amount of shale in the upper Menefee. The sandstone is dominant in the La Ventana field (sandstone/shale ratio = 1.62 avg. in R1-3W vs. 0.94 avg. in R4-5W) upper Menefee drill sites, probably due to the intertonguing

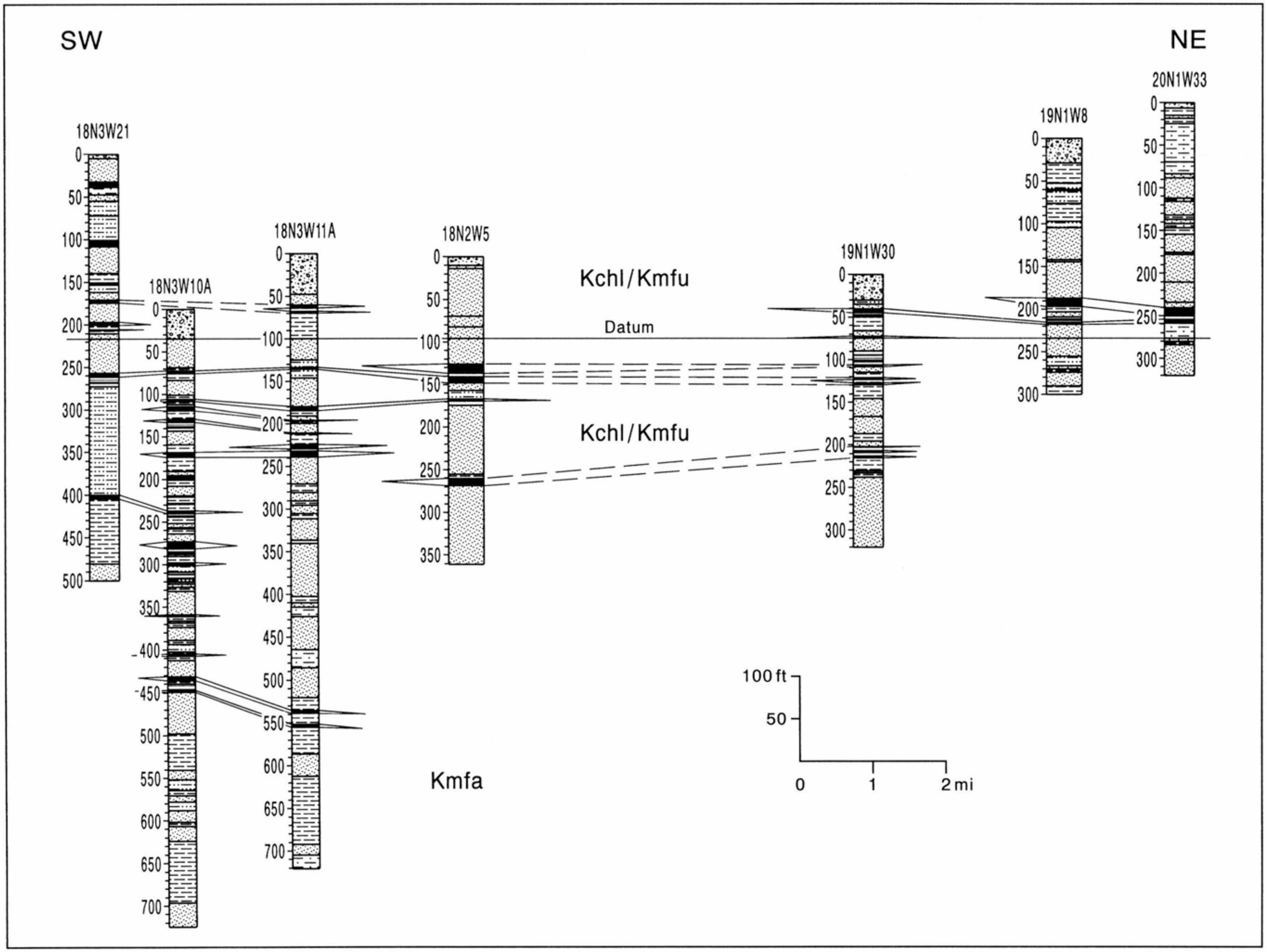

FIGURE 15—Correlation of pilot holes in upper Menefee Formation and Cliff House Sandstone, La Ventana Tongue, La Ventana field. Kmfa = Allison Member of Menefee Formation, Kmfu = upper coal member of Menefee Formation, Kchl = La Ventana Tongue of Cliff House Sandstone.

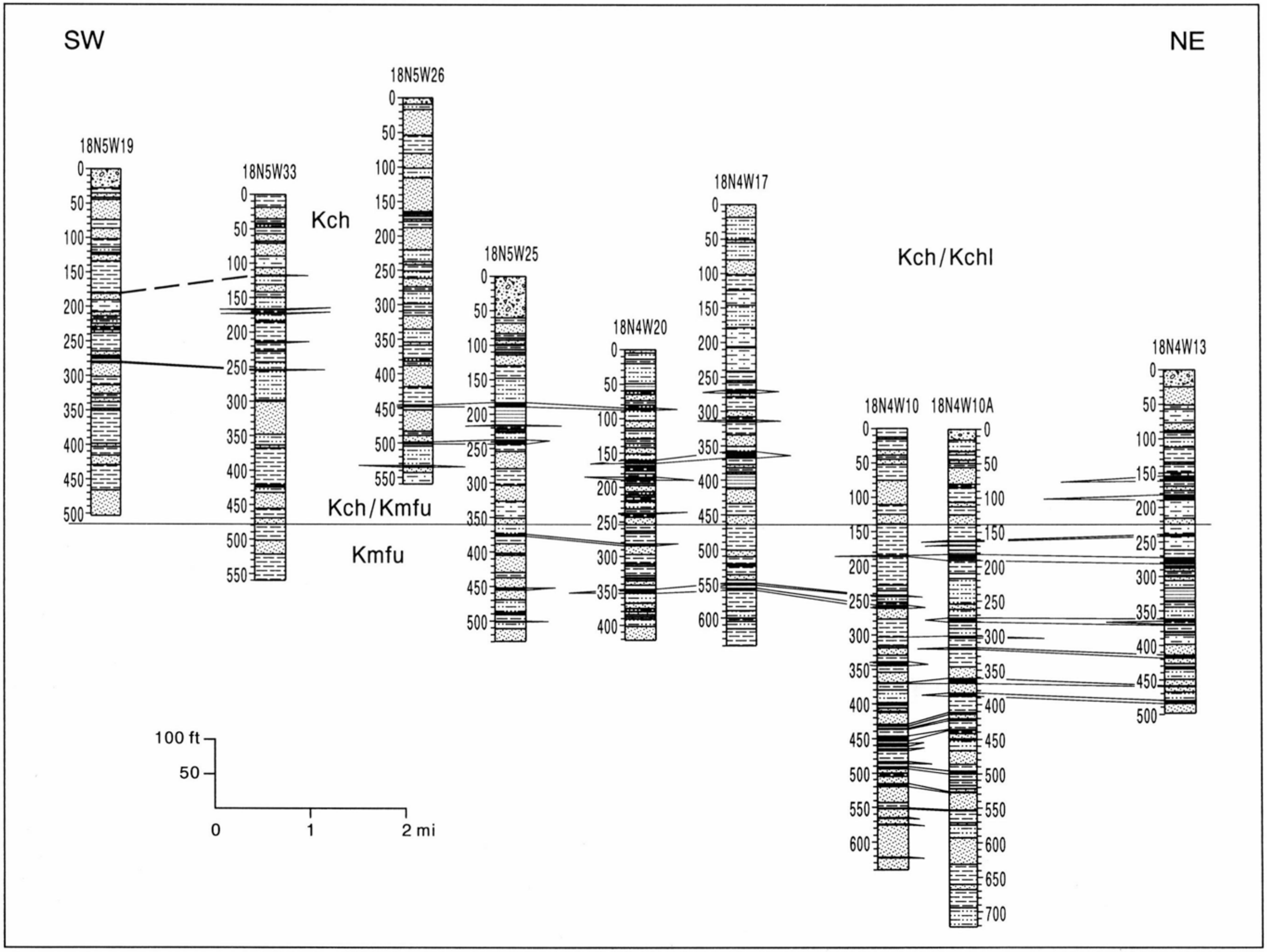

FIGURE 16—Correlation of pilot holes in upper Menefee Formation and Cliff House Sandstone, Chacra Mesa tongue, Chacra Mesa field. Kmfu = upper coal member of Menefee Formation, Kch = Cliff House Sandstone, Kchl = La Ventana Tongue of Cliff House Sandstone.

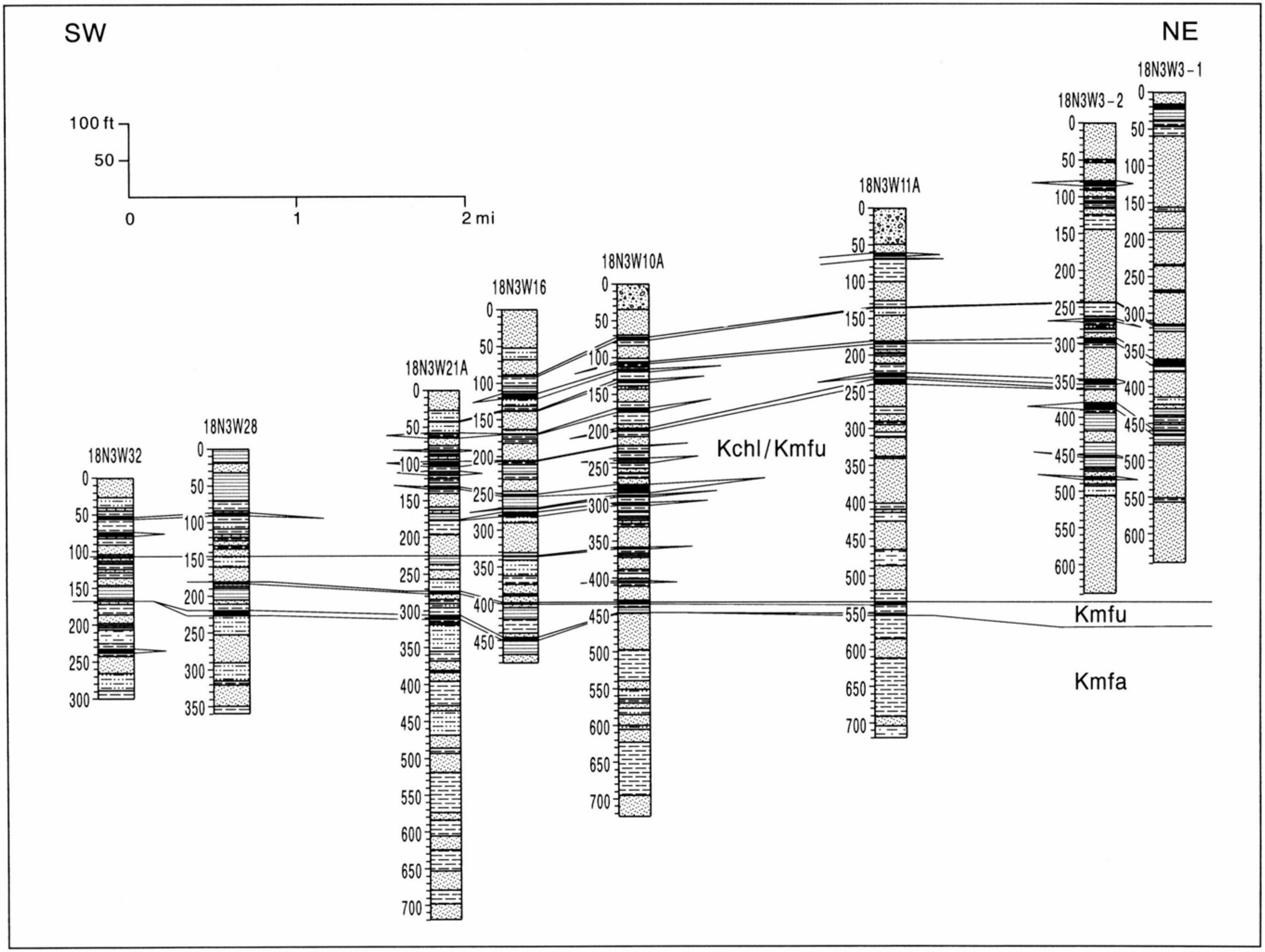

FIGURE 17—Correlation of pilot holes along a trend perpendicular to shoreline, upper Menefee Formation and Cliff Sandstone, La Ventana Tongue. Kmfa = Allison Member of Menefee Formation, Kmfu = upper coal member of Menefee Formation, Kchl = La Ventana Tongue of Cliff House Sandstone.

of the La Ventana Tongue sandstones (Fig. 15). These sandstones are massive, relatively well-sorted, predominantly quartzitic, and have sharp upper and lower contacts on the geophysical logs. Generally the sandstones within the coal-bearing sequence are finer-grained and show a fining-upward trend, particularly in the Chacra Mesa field drill sites (18N4W13- 18N5W19, Fig. 16). In the Chacra Mesa field (west of R4W) the upper Menefee sequence tends to have about equal amounts of shale and sandstone (0.51 to 1.86 sandstone/shale ratio), with siltstone becoming a more significant portion of the section to the west (Fig. 16).

The drill sites in the Chacra Mesa field were spudded above at least one of the Cliff House Sandstone tongues and often the drill holes began in the overlying Lewis Shale (Fig. 16). The upper coal member of the Menefee is 330 to 430 ft thick and thins to the southwest, away from the shoreline. This sequence contains fewer sandstones than in the La Ventana field and the sandstone/shale ratios (1.25 to 0.47) reflect a more clay- and silt-dominated sequence.

Most of the coals in the two upper Menefee Formation-Cliff House Sandstone sites drilled in 1988 (18N4W10 and 18N4W17) are deep and were not cored. Drill hole 18N4W10A, shown in Figure 16, was re-drilled to a greater depth in 1988; the coals in this section were cored in 1986. The bed thicknesses for these three sites range from 1.9 to 2.85 ft. The thickest coal beds at these locations are 4, 5, and 8.5 ft, and each thins to the southwest. Drill site 18N4W10 has the most beds (19) concentrated in a 100 ft section, which become carbonaceous shales to the east. Several of the coal beds have shale above and below, but a few are overlain by sandstones.

Sixty-seven coal samples (1986, 1988) were taken from the upper Menefee Formation. Ten of them contained partings that comprised 7.3% of the total coal-bed thickness. The upper-member coals have variable lithologic characteristics. The coal beds in the La Ventana field drill sites tend to contain more vitrain and to have better cleat development than the upper Menefee coals in the Chacra Mesa field. The La Ventana field coals also tend to have calcite on the cleat surfaces. All the upper Menefee coals cored have some pyrite, often found on the cleat surfaces, some have resin, and some have fine to medium banding. A few of the upper Menefee coals smelled strongly of hydrogen sulfide when first exposed to the atmosphere.

Coal beds in the upper Menefee are most frequently associated with shale, although many of the thicker coal beds are associated with both sandstone and shale (Figs. 15-17). In the Chacra Mesa field the coals are commonly found in a sequence of sandy shale, shaly sandstone, and siltstone and tend to be impure due to a high silt content of the sequence. These coal beds are thinner (1.25-5 ft) than those associated with the La Ventana Tongue in the La Ventana field (7-11.5 ft). The thickness of individual upper Menefee coal beds at our drill sites ranges from 0.77 to 11.5 ft, which compares favorably with previous data collected through the NCRDS grant. The number of coal beds in the upper Menefee section varies from one to twelve. Generally the coal beds are thicker where only six or less of them occur. The sections with fewer but thicker coals suggest a more stable environment that allowed time for thicker deposits of peat to develop in the swamps landward of the thick marine-sandstone buildups of the La Ventana Tongue (Beaumont and Hoffman, 1992). The thinner, more numerous coal beds would indicate a more landward position of development, probably on a lower coastal plain (Beaumont and Hoffman, 1992). Very few of the coals in the upper Menefee show any recognizable continuity between drill sites, although there seems to be some correlation between the thicker beds in the eastern drill sites. Many of these thicker coal beds underlie a massive, marine La Ventana sandstone whose geophysical-log signature can be correlated among the first three easternmost sites (20N1W33-19N1W30; Fig. 15). These thicker seams are probably what has been called the "Padilla seam," named for the coal bed mined at the Padilla mine near the town of La Ventana, southwest of Cuba (Nickelson, 1988, p. 175; McCurdy and Schofield, 1978).

Upper Menefee drill sites perpendicular to the shoreline—These drill sites along the upper Menefee-La Ventana Tongue trend were located at the base of one of the many prominent La Ventana Tongue sandstones. The coal-bearing part of the upper Menefee Formation is 180 to 500 ft thick in the sections associated with the La Ventana Tongue of the Cliff House Sandstone (Fig. 17). This sequence thins away from the shoreline, in part because of a thinner coal-bearing section to the southwest and in part because of erosion of the less resistant upper Menefee where it is not overlain by the La Ventana Tongue sandstones. The northeastern drill sites in this trend contain thick, massive, moderately well-sorted, quartz-dominant sandstones (La Ventana Tongue) interbedded with thinner sections of shale, carbonaceous shales, and coal (upper coal member of Menefee Formation). The sandstone/shale ratios (3.32 to 0.74) decrease away from the shoreline and the sandstones are thin and silty, with thicker shale and carbonaceous-shale sequences to the southwest. The upper Menefee coals along this trend are thicker near the shoreline, indicating a stability of the environment not present farther inland. There are more (11 to 15) and thicker (averaging 2.75 to 3.25 ft) coal beds toward the mid-section of this transect. The thickest coals (6 to 12 ft) occur in the five northernmost drill sites, although many of these coals are at depths greater than 250 ft. Many of the coals sampled had shale both above and below; a few coals, particularly from the northeastern holes, are overlain by tongues of the La Ventana sandstone deposited during minor transgressive pulses of the shoreline.

Twenty-two coal samples were taken from the upper Menefee Formation that intertongues with the La Ventana Tongue of the Cliff House Sandstone. These coals are vitrain-rich and have moderate to good cleat, with fine to medium banding. Most of the coal beds sampled had some pyrite on the cleat faces and were resinous. The coal beds themselves did not appear shaly, and only the thicker beds had shale partings.

The upper Menefee Formation that intertongues with the La Ventana Tongue of the Cliff House Sandstone has more and generally thicker coal beds than the upper Menefee that intertongues with the Cliff House Sandstone west of R3W. The sandstone/shale ratio is greater (i.e. relatively more sandstone) in the upper Menefee sections associated with the La Ventana Tongue. These relationships resulted from longer stillstands with only minor oscillations of the shoreline; therefore, a greater part of the section reflects the intertonguing between the La Ventana Tongue of the Cliff House Sandstone and the upper coal member of the Menefee Formation (Beaumont and Hoffman, 1992).

Cleary Coal Member of Menefee Formation

(Kevin Cook and Gretchen K. Hoffman)

The Cleary Coal Member is 88 to 290 ft thick in sections drilled during the 1985 and 1986 drilling programs. This unit of the Menefee Formation comprises the coal-bearing sequence that lies above the shore-marginal regressive Point Lookout Sandstone and beneath the nonmarine beds assigned to the Allison Member of the Menefee (Fig. 2). The Cleary contains a sequence of paludal carbonaceous shale, coal, fluvial sandstone, and shale that were deposited on the landward side of the Point Lookout Sandstone (Molenaar, 1977, 1983).

La Ventana field—Ten sites were drilled in the Cleary Coal Member in the La Ventana field from T19N, R1W to T17N, R3W (Figs. 14, 18). Seven of the 10 drill sites were on federally owned surface and mineral land. Two of the drill sites were on private surface and federal minerals, and one site was on state land with federal minerals (Table 3). At one location (19N2W35) no coring was done because of a lack of qualifying coal beds (1.5 ft). The Cleary coal-bearing interval is 108 to 260 ft thick, thinning from the southwest to the northeast. In locations 17N2W7, 17N3W14, 17N3W20, and 18N2W23 the upper 300 to 380 ft drilled are part of the barren Allison Member of the Menefee Formation; there are very few coals in this part of the nonmarine section and they are very thin (less than 1.5 ft). The Cleary sequence is composed of sandstone, siltstone, shale, carbonaceous shale, and coal; it is dominated by shale, with only three sections having a sandstone/shale ratio greater than 1.0. Fine-grained, silty sandstones are typical for the Cleary coal-bearing sequence in the La Ventana field.

The Cleary coals in the La Ventana field are typically associated with shale, but the coal in the southwestern drill sites (17N2W9-17N3W20) is just as frequently associated with sandstone and shale (Fig. 18). The coal-bed thickness varies from 1.4 to 3.3 ft, with two to ten seams in each section. From 17N2W9 to 17N3W20 there are six to ten coal beds in the section, which is a much higher mean than in the locations to the northeast, and, generally, these sites have the thicker Cleary coal beds in the La Ventana field, the thickest being 6 ft at 17N2W9. The thicker coal beds in any of the sections are typically at the base of the Cleary Coal Member, within 20 ft of the Point Lookout Sandstone contact. The average thicknesses of the La Ventana field coal beds measured in this study compare well with the previous data collected through the NCRDS grant, but the seams are at depths greater than predicted on the previous data.

The Cleary coals in the La Ventana field are hard, contain moderate to high amounts (bands) of vitrain, and have poor to good cleat. These coals tend to have fine to moderately thick banding and contain moderate to abundant amounts of pyrite. Thirty-two coal samples were taken from the 10 drill sites in this area, of which only six had partings less than 0.8 ft thick. The percentage of partings in these samples ranged from 6.23 to 14.8% of the total bed thickness (8.9% average).

Chacra Mesa and San Mateo fields—Two sites were drilled in the Cleary Coal Member of the Menefee in the Chacra Mesa field (17N4W13, 17N4W32). These locations are in the southeast corner of this field and are part of the line of drill sites from the La Ventana to San Mateo field. These sites are discussed jointly with the San Mateo drill sites because of their limited number. Nineteen sites were drilled (1985 and 1986) in the San Mateo field. Over half of these sites were on patent surface (52%), with 80% of all the drill sites on federal minerals land. The remaining locations were on federal surface (43%) and private minerals (14%), and one location had state surface and mineral ownership (Table 3). Two of the San Mateo sites drilled in 1985 were not cored because they lacked qualifying coal beds (1985 criterion of 2.5 ft).

The Cleary Coal Member in the Chacra Mesa–San Mateo area is 88 to 290 ft thick (Figs. 19, 20). The sequence is composed of sandstone, siltstone, shale, carbonaceous shale, and coal. Sandstone becomes a greater part of the sequence to the west and northwest because of a greater influx of sediment. The mean sandstone/shale ratio is 0.93 in the eastern 10 drill sites (17N4W13 to 15N6W20). The remaining 11 drill sites have an average sandstone/shale ratio of 1.22 (0.30-2.83). Fine-grained, silty sandstones are common in the eastern part of this area, with a few moderately well-sorted, fine- to medium-grained sandstones found in the sequence to the west. The Cleary sequence decreases in fine-grained sediments and increases in thicker coal deposits from east to west. The depositional environment in the eastern San Mateo field appears to have been less conducive to the development of coals because of short-lived peat-swamp environments possibly resulting from variable rates of subsidence over this large area (Beaumont, this report).

The coals in the Chacra Mesa–San Mateo area are typically associated with shale. A few coals are overlain and/or underlain by a combination of sandstone and shale or siltstone and shale. Only three coals in 15N8W24 had sandstone above and below. The coal-bed thickness varies from 1.6 to 5.9 ft, with an average of six seams in each section. The thickest coal bed is 19 ft in 15N8W24, and the area of thicker coals (more than 6 ft for the thickest coal bed and more than 2.9 ft for the average bed thickness in a section) is from 15N7W26 to 15N8W22. The San Mateo and San Miguel Creek domes are interpreted as having been positive areas during the deposition of the Cleary sequence (see Beaumont, this report) that would have influenced the position of the shoreline in this area (T15N,

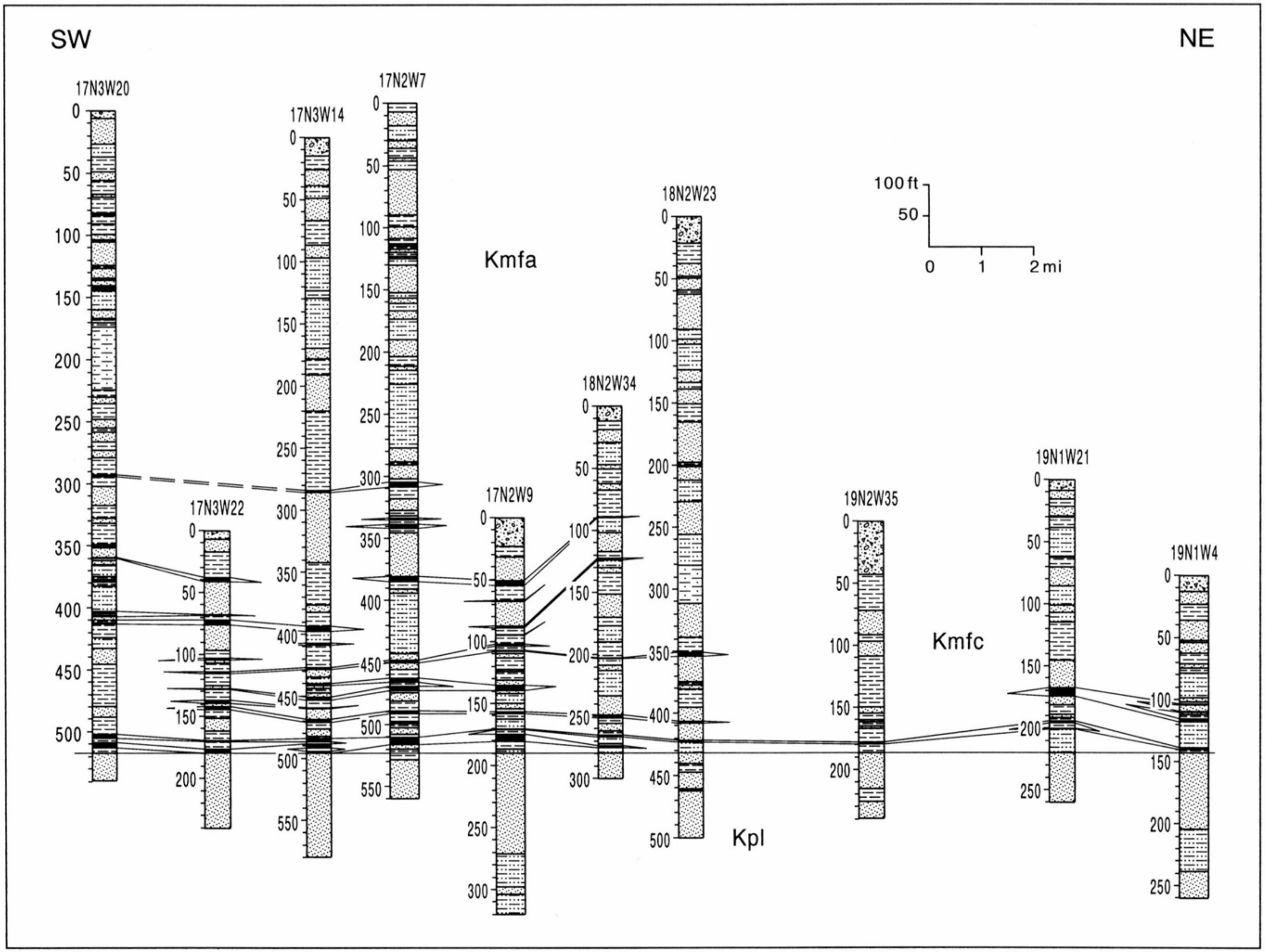

FIGURE 18—Correlation of pilot holes in Cleary Coal Member of Menefee Formation, Chacra Mesa and La Ventana fields. Kpl = Point Lookout Sandstone, Kmfc = Cleary Coal Member of Menefee Formation, Kmfa = Allison Member of Menefee Formation.

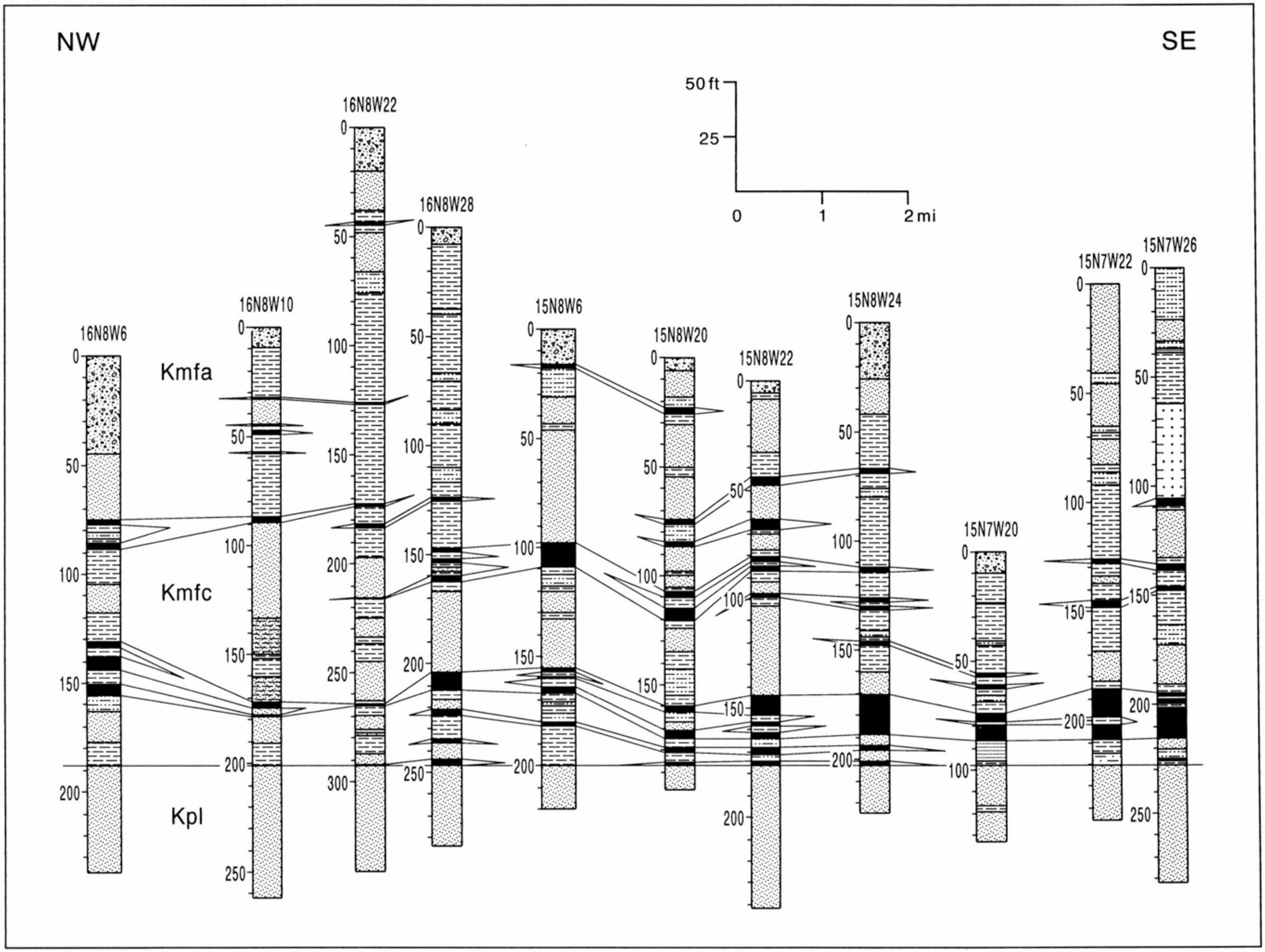

FIGURE 19—Correlation of pilot holes in San Mateo field, West. Kpl = Point Lookout Sandstone, Kmfc = Cleary Coal Member of Menefee Formation, Kmfa = Allison Member of Menefee Formation.

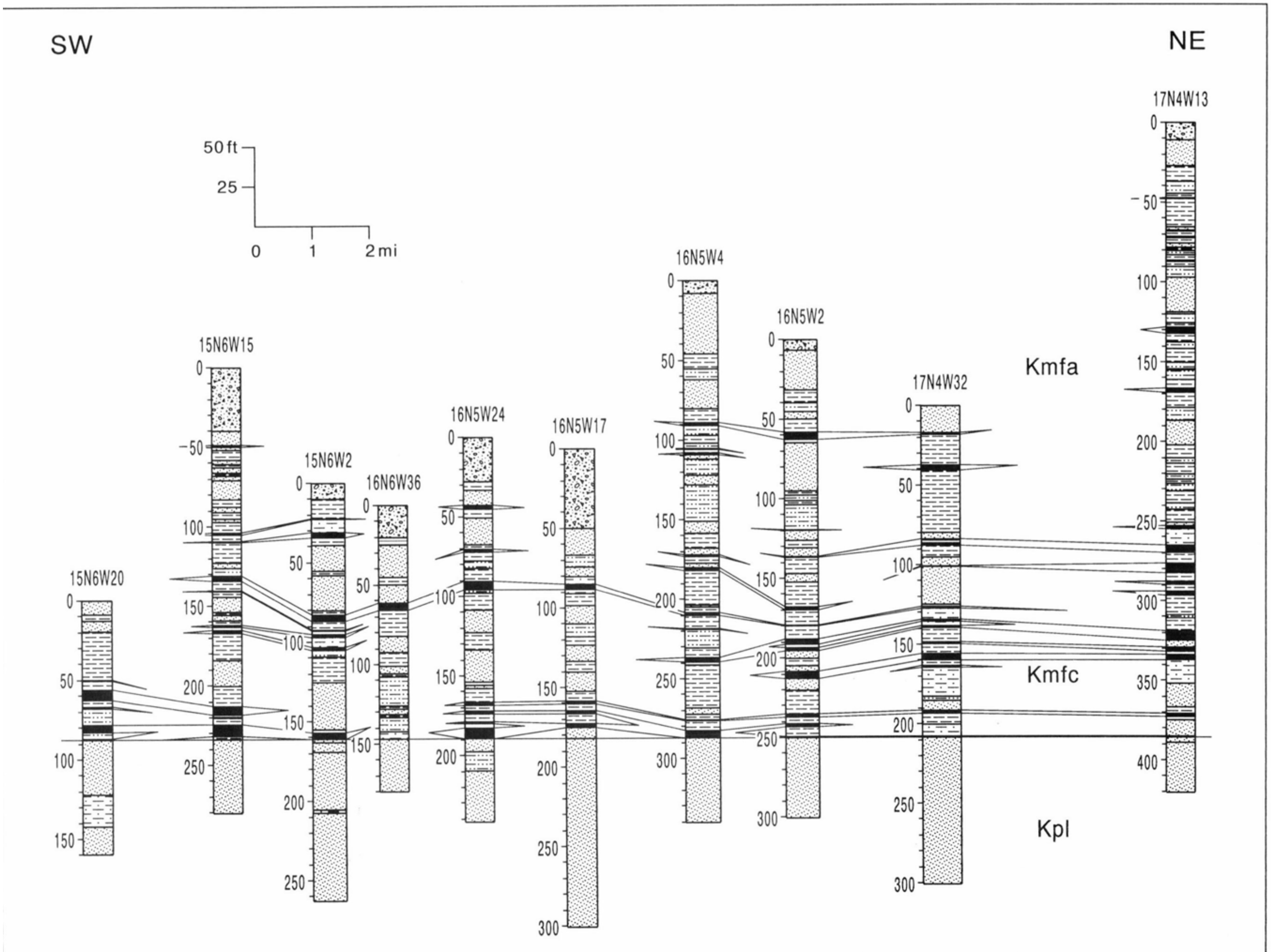

FIGURE 20—Correlation of pilot holes in San Mateo field, East. Kpl = Point Lookout Sandstone, Kmfc = Cleary Coal Member of Menefee Formation, Kmfa = Allison Member of Menefee Formation.

R7 + 8W) and subsequently the coal development. Northeast and northwest of this area the coal beds thin but the total number of seams within the sequence does not change significantly. The Cleary coals in the Chacra Mesa-San Mateo area are thickest at the base of the coal-bearing sequence, within 20 ft of the Point Lookout Sandstone contact. The average coal-bed thickness measured in this study is similar to that obtained through the NCRDS project, but the typical depth of the coals is greater in drill sites of this study, probably due to the longer distance from the outcrop.

Cleary coals in the Chacra Mesa-San Mateo fields have moderate amounts of vitrain and poor to good cleat. These coals are fine- to medium-banded and commonly exhibit a hackly fracture. Pyrite blebs, pyrite along the cleat face, and resin are more abundant in the San Mateo field coal samples than in the coals from the Chacra Mesa field. Some of the lower coal seams in the San Mateo field drill sites are associated with sandstones that have relatively high gamma readings, indicative of uranium. Nineteen of the 56 coal samples (33%) taken from these sites had non-removable partings constituting an average of 11% of the total coal-bed thickness, which is the highest average percent in the Cleary coals.

Standing Rock field—Eight locations in the eastern portion of the Standing Rock field were drilled in 1985 (Fig. 21). Some gaps exist in the spacing of these locations as a result of ownership problems. These sites are on private (50%), federal (25%), and state (10%) surface. Three sites were on land with private mineral, three on state mineral, and two on federal mineral ownership. Two sites had existing coal leases and two were within inactive mine areas (Table 3).

The Cleary Coal member of the Menefee Formation is 93 to 290 ft thick in the eastern part of the Standing Rock field (Fig. 22). The coal-bearing sequence consists of sandstone, siltstone, shale, carbonaceous shale, and coal. Sandstone is the most dominant lithology in the sequence, followed by shale or siltstone. Five of the eight sections have sandstone/shale ratios greater than 1.0, but there is no geographic trend in the percentage of sandstone within the sequence.

The coals in the Standing Rock sections are typically within a shale-dominated interval but several are overlain or underlain by siltstone or sandstone. In many of the sections (18N12W11, 18N12W16, 18N12W24, 17N10W7, 16N9W1) coal is directly above

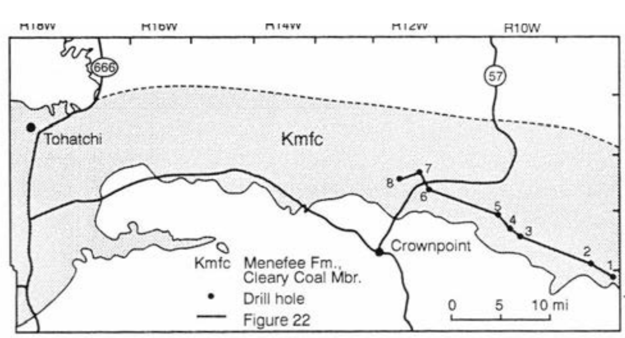

FIGURE 21—Menefee Formation drill-site locations in Standing Rock field. Base map modified from Shomaker et al., 1971. See Table 3 for corresponding drill-site designations.

or within a foot of the Point Lookout Sandstone contact. Most of the coals are within 75 ft of the Point Lookout Sandstone. At each site there are three to seven coals in the Cleary coal-bearing sequence, but most of them are thin and only two beds were cored. Some liberty was taken with the qualifying seam thickness (2.5 ft) to obtain samples from every locality. Coal beds sampled were 2.0 ft to 5.7 ft thick, with a mean of 3.96 ft. The typical coal thickness and depth measured in this study are comparable to previous data collected through the NCRDS project. There is no discernible trend in thickening or thinning of the coals, and, given the spacing of the drill sites and the lenticularity of the coal, individual coal beds cannot be traced.

The coals have variable amounts of vitrain, poor to good cleat, and fine to medium banding; they are pyritic, resinous, and commonly shaly. Fourteen coal samples were taken from the eight Standing Rock drill sites. Six of these samples (43%) had partings less than 0.8 ft thick, on the average comprising 5% of the total bed thickness, which is the lowest percentage in all of the Cleary coal samples.

Summary

The total thickness of the Cleary Coal Member shows little variation from the La Ventana to the Standing Rock fields, although the section does thin slightly to the northeast. Lithologically, the Cleary changes from a shale-dominated sequence in the northeast to a sequence with more sandstone and siltstone in the western San Mateo and Standing Rock areas, indicating a greater sediment influx and possibly proximity to a source area.

The Cleary Coal Member has multiple coal beds (generally six per section) throughout the areas drilled. The thickest coals are in the San Mateo field, southwest of the San Miguel Creek dome, and there is a general thinning of the coal beds to the northeast and northwest of this prominent feature. The San Miguel Creek dome area appears to have been a stable section in the shoreline where retreat of the sea was delayed, allowing for thicker peat accumulation. The coals in the Cleary Member are commonly pyritic; in the San Mateo area they tend to have more pyrite and resin and more partings. The thickest coals are within 20 ft of the coastal-barrier sandstones of the Point Lookout Sandstone, in a nearshore, more stable environment better suited for peat development than that higher in the section. The Cleary coals higher in the section are lenticular and mostly thin, indicating a short-lived swamp environment. These coals probably developed in a lower coastal-plain to fluvial setting, in peat swamps of limited extent (Beaumont, this report).

Monero field, Menefee Formation—Seven drill sites were completed in the Monero field near the towns of Monero and Lumberton, and extending northward toward the New Mexico-Colorado state line (Fig. 23). Three of these sites were on private surface and mineral ownership and four sites were on private surface and federal mineral ownership (Table 3). Only two sites, south of Lumberton and south of Monero, had qualifying coals (1.5 ft, 1988 standard).

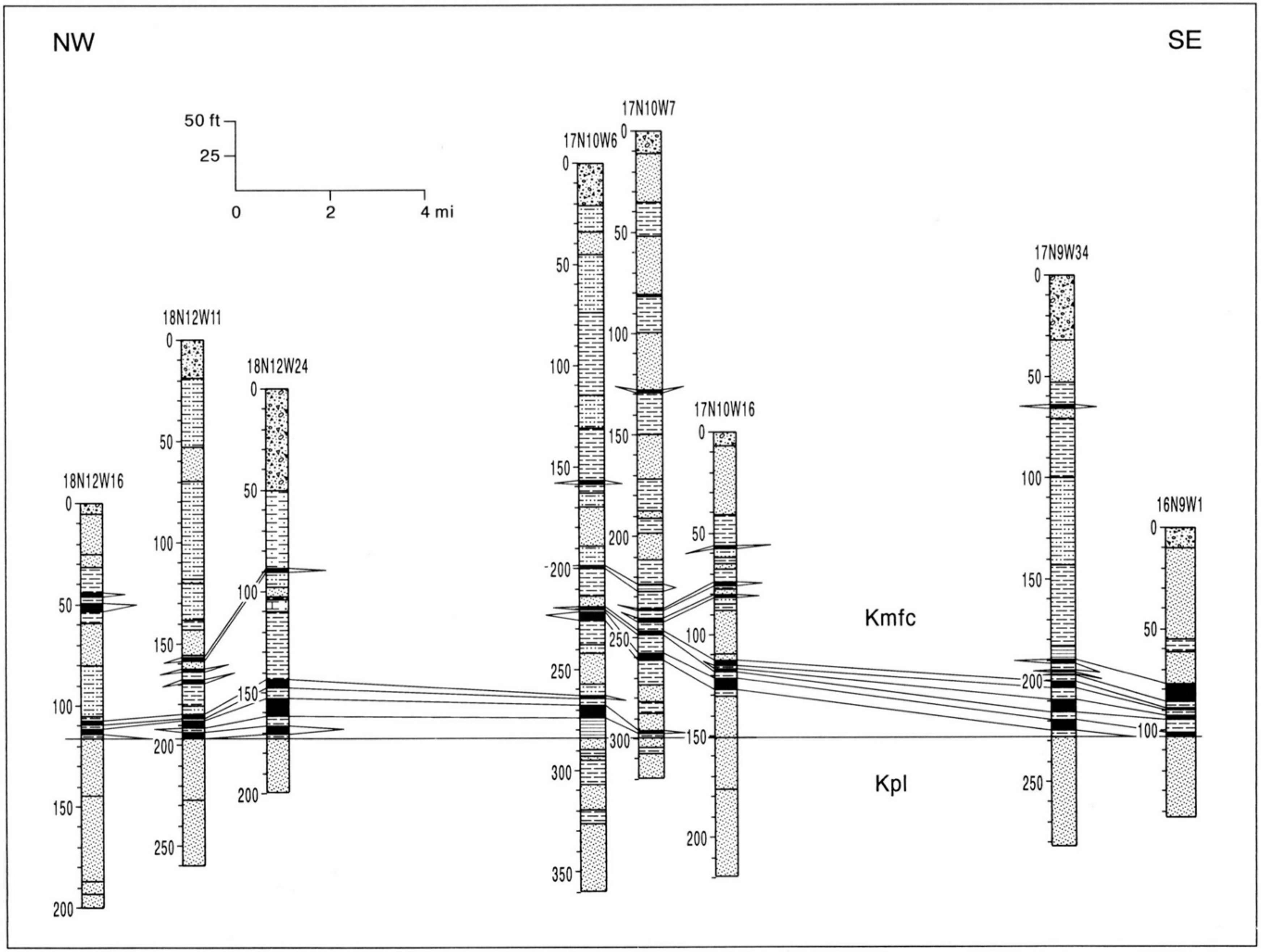

FIGURE 22—Correlation of pilot holes in Standing Rock field. Kpl = Point Lookout Sandstone, Kmfc = Cleary Coal Member of Menefee Formation.

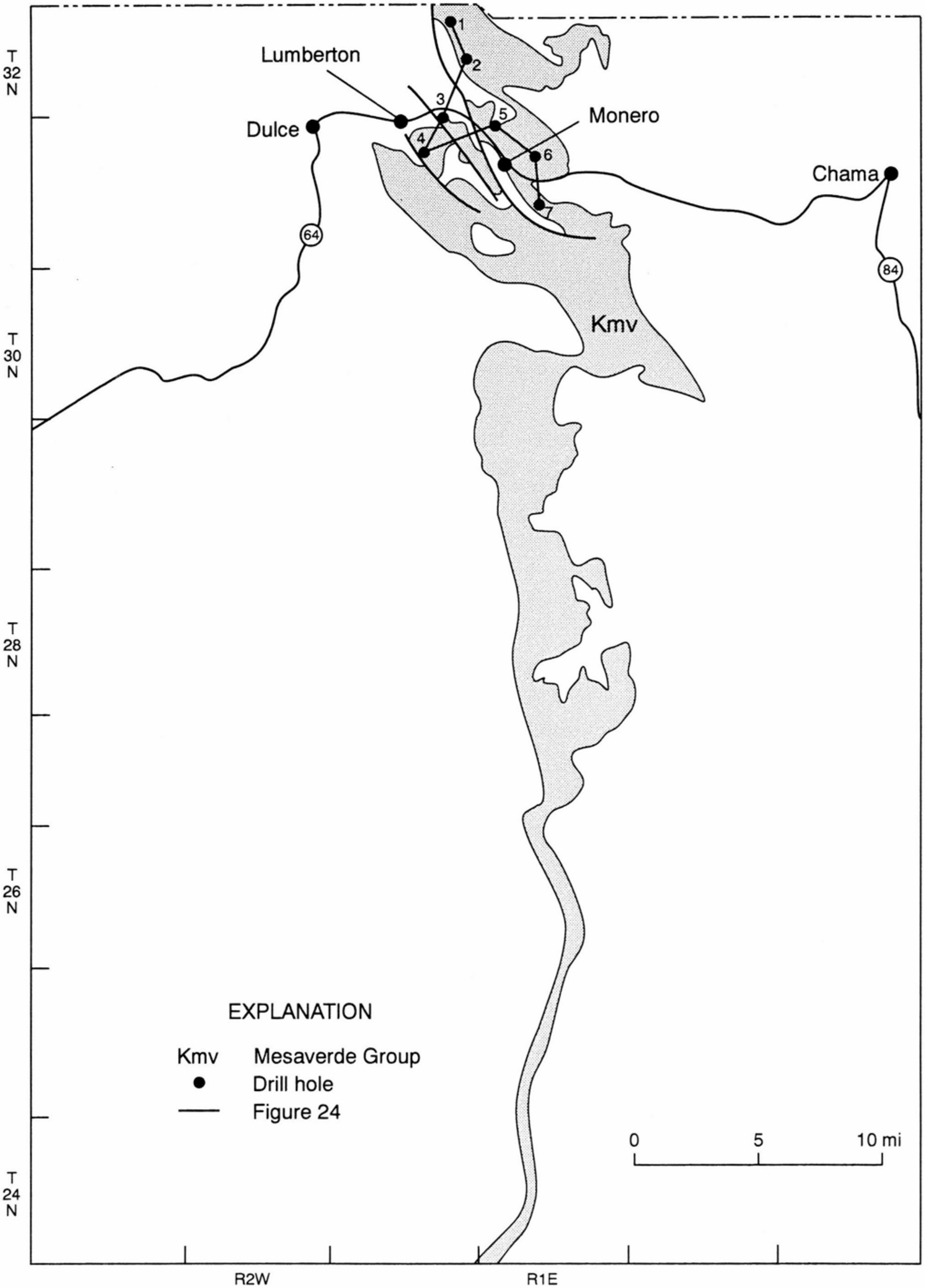

FIGURE 23—Mesaverde Group drill-site locations in Monero field. Base map modified from Shomaker et al., 1971. See Table 3 for corresponding drill-site designations.

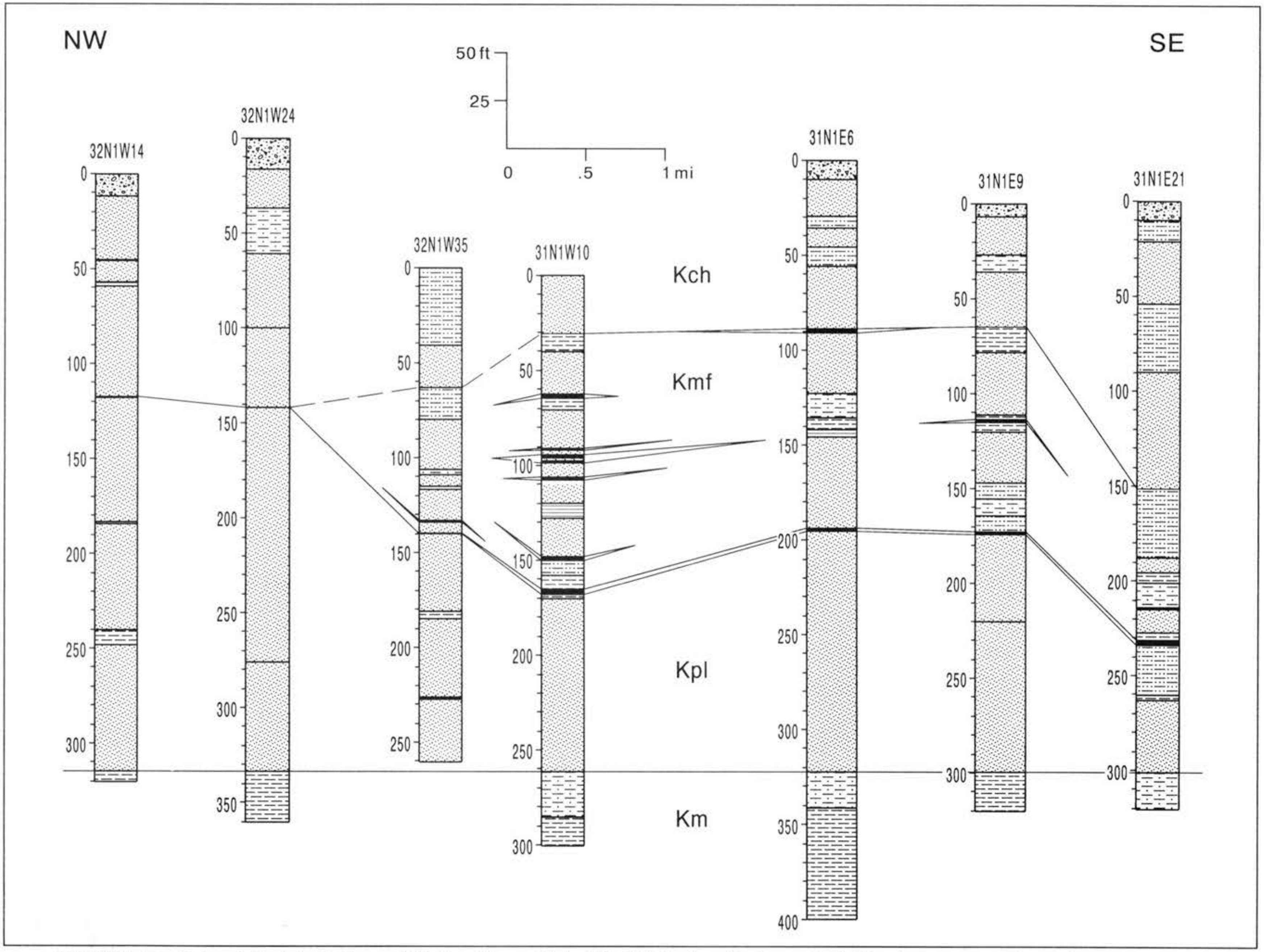

FIGURE 24—Correlation of pilot holes in Monero field. Km = Mancos Shale, Kpl = Point Lookout Sandstone, Kmf = Menefee Formation, Kch = Cliff House Sandstone.

All of the drill holes in the Monero field were spudded near the top of the Mesaverde Group. The locations were based on Dane's (1948) map and field observations made while staking the sites. The holes were completed in the Mancos Shale to ensure that the entire Mesaverde Group was penetrated.

The Mesaverde Group consists of 285 to 330 ft of sandstone, siltstone, and minor amounts of shale and coal (Fig. 24). The sequence thickens and becomes sandier toward the New Mexico—Colorado state line. The Menefee Formation can be delineated only in the drill sites near the towns of Monero and Lumberton. The Menefee Formation is distinctive in this area, and the sandstone/shale ratios (2.5 to 7.3) indicate the dominance of sandstone in these sections. The sandstone/shale ratio is lowest (2.5 and 2.64) at the two locations that have coal beds of qualifying thickness (31N1W10, 31N1E21).

Only one or two coal beds were present in most of the sections drilled in the Monero field. An exception is the drill site south of Lumberton (31N1W10), which had seven coals within the section. The coals of the Monero field are thin, ranging from 1.25 to 3 ft, with a mean bed thickness of 1.7 ft. The thickest coal beds cored in the Monero field were 3 ft. The coal beds are generally associated with shale or mudstone, but several of the thinner coals occur above, below, or between sandstones.

Four coal samples were taken from the two locations. The cored coals were hard and banded with moderate amounts of vitrain. The coal sampled at the location south of Monero (31N1E21) was highly fractured and only about one-third the thickness anticipated from the geophysical log. This coal was cored twice because of the discrepancy, but both samples were fractured and thinner than expected, probably because of proximity to a faulted area.

The Monero field drilling confirmed the mapping and descriptions by Dane (1948). The Mesaverde Group becomes sandier to the northwest and the best coal areas are near the towns of Monero and Lumberton where the old underground mines were located. A very thin section of the coal-bearing Menefee was deposited in the Monero field. This region was very close to the seaward extent of the regressive deposits behind the coastal-barrier sandstones of the Point Lookout and was quickly covered by the transgressive deposits of the Cliff House Sandstone (Molenaar, 1983). The rate of shoreline shift seems to have been relatively fast in the Monero area, with very few oscillations in the overall shoreline movement to the northeast.

Menefee and Crevasse Canyon Formations in Gallup field

The Gallup field includes all of the coal-bearing sequences of the Mesaverde Group in T12-19N (Fig. 25). This field extends to the western boundary of the Crownpoint field in the northeastern part of the Gallup—Zuni embayment. The eastern edge of the field is delineated by the steeply dipping outcrops of the Mesaverde strata along the Nutria monocline (Fig. 25). In the central part of the Gallup—Zuni embayment the attitude of the rocks is locally controlled by the Gallup and Torrivio anticlines and the intervening syncline, the Gallup sag. The western margin of the field is marked by relatively steeply dipping beds associated with the sinuous, north-trending Defiance uplift.

Fourteen sites were drilled in the Gallup coal field north and northwest of Gallup (Fig. 25). Ten of these locations penetrated the coal beds in the Cleary—Gibson Coal Members. One drill site (15N18W18, No. 5 in Fig. 25), the location of which was controlled by surface and mineral ownership, proved to be too high in the stratigraphic section so that only thin coals were encountered at depths greater than 430 ft. Most of the Cleary—Gibson drill locations (except 16N20W27, 15N18W31, 15N18W33; nos. 11, 4, and 3 in Fig. 25) probably started in the overlying barren Allison Member. Three drill sites (15N18W4, 15N18W34, 15N19W35; nos. 12, 13, and 14 in Fig. 25) penetrated the Dilco Coal Member of the Crevasse Canyon Formation. All of the Gallup field locations were on private surface and private minerals (Table 4). Three of these drill sites (15N19W11, 16N19W35, 16N19W29) are in a permitted coal-mine area. One of the locations (15N18W34; no. 13 in Fig. 25) was in a permitted inactive coalmine area.

Cleary—Gibson Coal Members of the Menefee and Crevasse Canyon Formations, undivided

The Cleary and Gibson Coal Members of the Menefee and Crevasse Canyon Formations are the nonmarine sequence shoreward of the pinchout of the marine Point Lookout Sandstone which separates the Cleary Coal Member from the Gibson Coal Member northeast of the Gallup coal field (Fig. 2). The Cleary—Gibson Coal Members consist of shale, sandstone, siltstone, carbonaceous shale, and coal that are from 53 to 204 ft thick in the sites drilled (Fig. 26). The thickness at 16N18W26 (129 ft) is misleading because circulation was lost at 117 ft in this hole when a mined-out area was encountered. The section at 15N18W31 (53 ft) is also deceptive because, as a result of access problems, the location was not at the top of the coal-bearing sequence and, therefore, some coals were missed. Sandstone or shale dominate the sequence, and in five of the sections (16N18W26, 15N19W11, 16N19W29, 15N18W31, 15N18W33) siltstone beds constitute 23% or more of the coal-bearing interval. The average sandstone/shale ratio in the 11 Cleary—Gibson sections is 1.2, varying from 0.25 to 3.3. Generally the sections with the largest percentage of sandstone are in the eastern part of the area drilled (16N18W26, 16N18W28, 15N18W33). The sandstone beds in the Cleary—Gibson are medium- to fine-grained and show a sharp basal contact and a fining-upward pattern on geophysical logs, indicating floodplain deposits.

The total coal thickness in the Cleary—Gibson Coal Members is usually greatest in shale-dominated sequences. An exception to this statement is noted in two of the northeastern drill sites (16N18W26, 16N18W28) that have 17-18 ft of total coal and are in sandstone-dominated sequences. The thickest coal beds

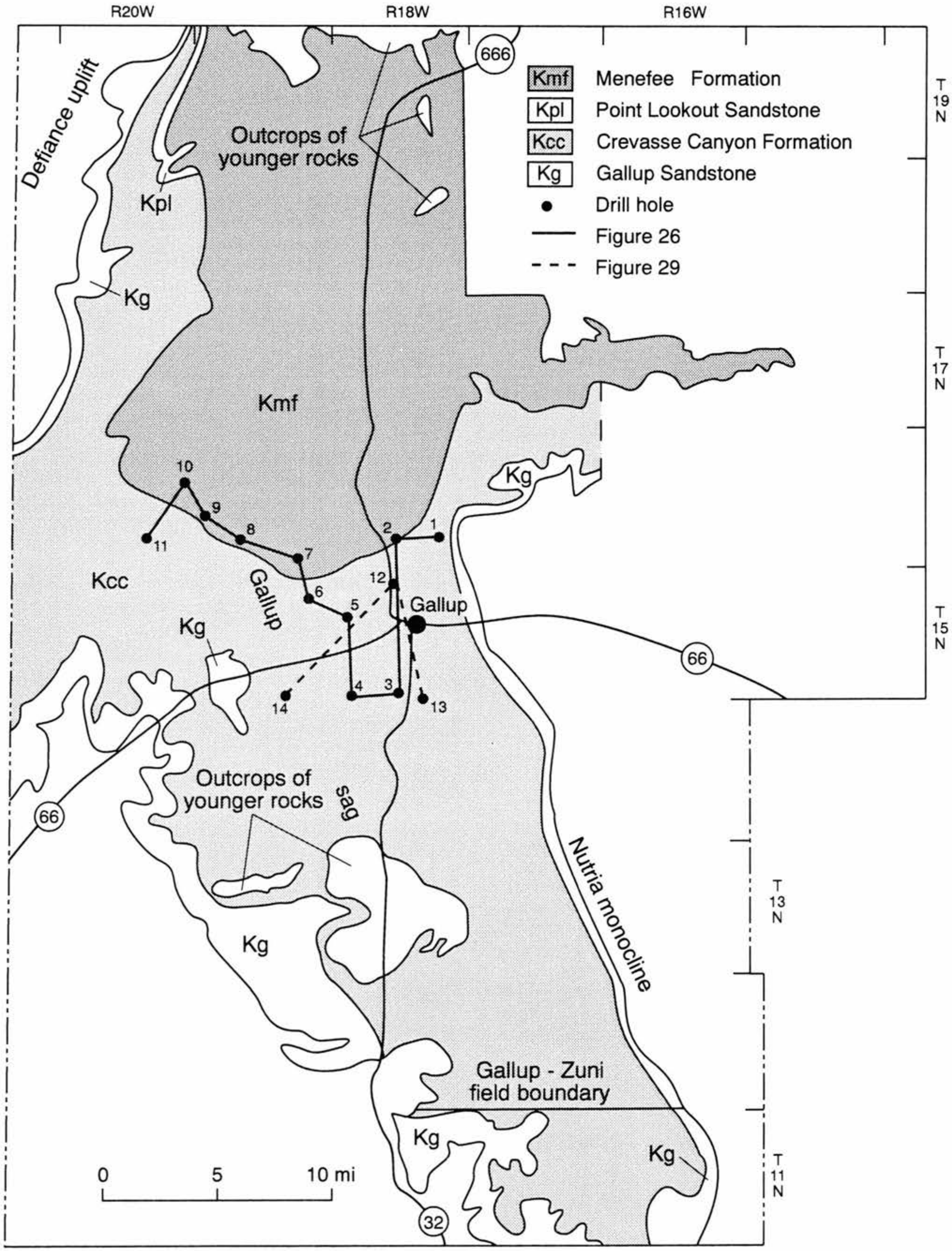

FIGURE 25—Crevasse Canyon Formation drill-site locations in Gallup field. Base map modified from Shomaker et al., 1971; and Thaden and Zech, unpubl. See Table 4 for corresponding drill-site designations.

TABLE 4—Ownership and map designation of drill-site locations, Crevasse Canyon Formation.

Crevasse Canyon Formation Cleary – Gibson	Ownership		Figure Map. No.
Gallup field	Surface	Mineral	Fig. 25
16N18W26	Private	Private	1
16N18W28	Private	Private	2
15N18W33	Private	Private	3
15N18W31	Private	Private	4
15N18W18	Private	Private	5
15N19W11	Private	Private	6
16N19W35	Private	Private	7
16N19W29	Private	Private	8
16N19W19	Private	Private	9
16N20W13	Private	Private	10
16N20W27	Private	Private	11
Gibson Coal Member			
Crownpoint field			Fig. 27
16N10W33	Private	Private	1
16N10W29	Private	Private	2
16N10W16	State	State	3
16N11W2	Federal	Federal	4
17N11W34	Federal	Federal	5
17N11W16	Private	Private	6
17N12W16	State	State	7
17N13W12	Private	Private	8
Dilco Coal Member			
Gallup field			Fig. 25
15N18W4	Private	Private	12
15N18W34	Private	Private	13
15N19W35	Private	Private	14

in the eastern half of the Gallup field tend to be associated with sandstone and siltstone (16W18W26, 16N18W28, 15N19W11), whereas the thickest coal beds in the western half are associated with shale (16N19W19, 16N20W13). Throughout the Gallup field, the thickest coal bed in a section varies from 2.15 to 6.6 ft, and coal beds within a section range from one to 3.5 ft, which agrees with data collected for the NCRDS grant. The number of coals in the Cleary—Gibson sections ranges from three to 16 coals, with typically eight coal beds in a section. In the sections with nine or more seams, the average thickness is 2.36 ft. Most of the coals in these sections are associated with shale and are in shale-dominated sequences. The sections with less than nine seams have thinner coal beds (1.82 ft average) and are in sandstone-dominated sequences. The sections south of Gallup have fewer coals (three or four seams per section), and these coal beds are thinner (2.5 to 3.5 ft) than those in the sandstone-dominated sequence to the northeast.

Forty-two coal samples were taken from the Cleary—Gibson sections. Seven of them had partings constituting an average of 8% of the total coal-bed thickness. The coals that were cored showed the same general characteristics throughout the area covered. They were hard, possessed a well-developed cleat, and contained large to moderate amounts of vitrain banded with clarain and durain. The banding tended to be fine to medium, and the coals contained some resin and pyrite. Very few of these coal samples were shaly.

The coal beds are more continuous in the Carbon Coal/Gamerco property drill sites, west of Highway 666 (15N19W11, 16N19W35, 16N19W29), extending to the westernmost drill site (16N20W27; Fig. 26). Both the coal-bearing sequence and the coal-bed thicknesses tend to thin to the west, diagonal to the direction of pinchout of the entire coal-bearing sequence, and to the south, away from the shoreline. The section at drill site 16N20W27 misses some of the upper Cleary—Gibson coals because it is located south of the uppermost coal outcrop. The coals penetrated in this section are thinner than those to the east and northeast, although the general sandstone/shale sequence appears to correlate with that penetrated at drill site 16N20W13. The thinness of most of these beds would appear to indicate an unstable environment not well suited for peat development, but the number of beds also demonstrates multiple occurrences of coal-producing peat environments during the time of deposition of the Cleary—Gibson sequence (Sears, 1925, p. 24; Roybal, 1989).

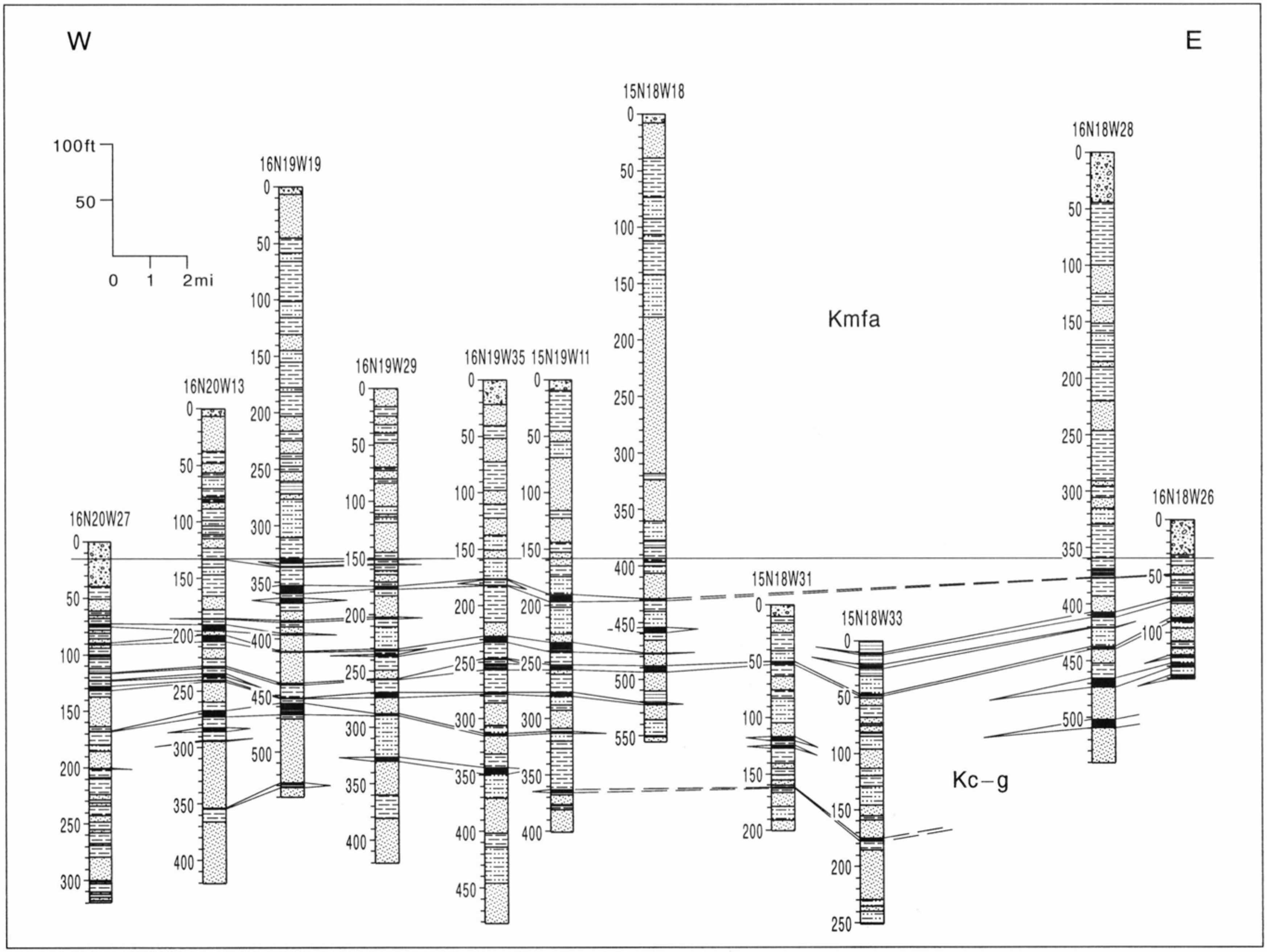

FIGURE 26—Correlation of pilot holes in Cleary–Gibson Coal Members, Gallup field. Kc–g = Cleary–Gibson Coal Members (undivided), Kmfa = Allison Member of Menefee Formation.

Crevasse Canyon Formation

Gibson Coal Member, Crownpoint field

The Crownpoint field covers T12-18N, R8-17W (Figs. 7, 27). The northern and eastern boundaries are defined by exposures of the Point Lookout Sandstone, and the southern boundary is delineated by the southernmost outcrop of the Crevasse Canyon Formation in the San Juan Basin. The structure in the drilled segment of the field is simple, being within the Chaco slope where the beds dip gently to the north.

Eight sites were drilled (1986) in the Gibson Coal Member of the Crevasse Canyon Formation in the Borrego Pass—Crownpoint area (Fig. 27). The number of sites was limited because of the predominance of Indian-owned land in this area. Drill sites were on private (50%), state (25%), and federal (25%) lands (Table 4). Most of the drill holes started in the overlying Hosta Tongue of the Point Lookout Sandstone and penetrated the Gibson Coal Member, continuing into the underlying Dalton Sandstone. One hole drilled northeast of Crownpoint did not contain any qualifying coals.

The Gibson Coal Member of the Crevasse Canyon Formation is 150 to 240 ft thick in the sections drilled (Fig. 28). This sequence is thinnest east of the town of Crownpoint (17N12W16), and is composed of sandstone, shale, coal, and a few siltstone beds, with shales being the predominant lithology. The sandstone/shale ratio mean is 0.95, with a range of 0.49-1.65. The sandstone beds tend to be thicker in the western part of the area drilled (17N13W12-17N11W16), have a strong resistivity-log signature, and are quartz-rich and moderately well sorted, suggestive of channel sands. Possible intertonguing between the nonmarine Gibson Coal Member and marine sandstones of the Hosta Tongue of the Cliff House Sandstone also may be a factor.

The Gibson Coal Member and its coals show a few trends within the area drilled in this study. In the western half sandstone beds occur above or below the coals more commonly than shale (i.e. 17N13W12-17N11W16; Fig. 28). The geophysical-log signatures of sandstones associated with the coals show the grain size to be either consistent throughout or coarsening upward. These coals may represent back-barrier swamp deposits associated with barrier-beach sandstones deposited during several oscillations of the shoreline. The frequency of sandstone above or below the coals lessens to the southeast as more coals are present within shale sequences. Some of the coals in the Borrego Pass area (16N11W2, 16N10W16) are associated with sandstones that show fining upward. The coals

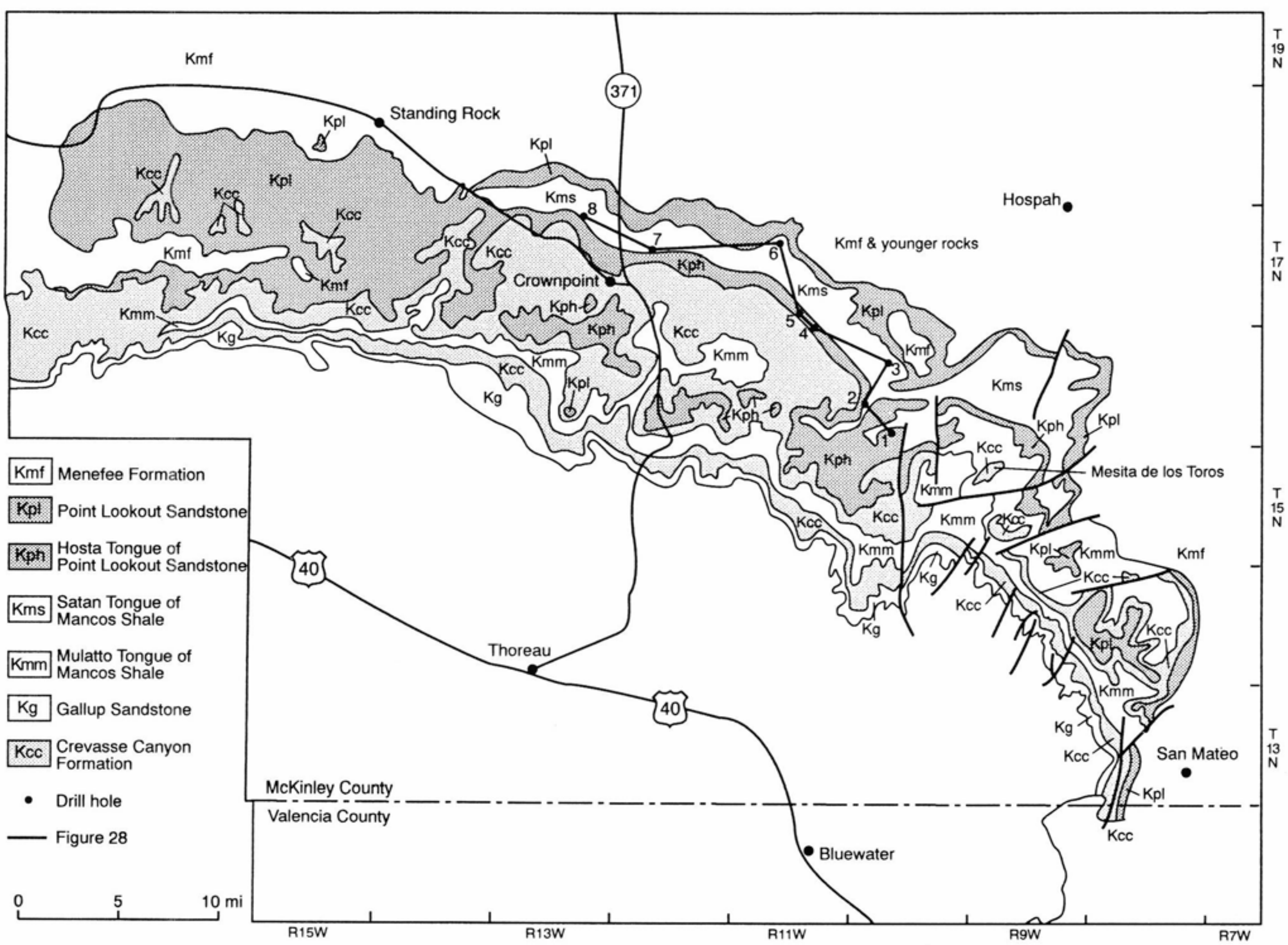

FIGURE 27—Crevasse Canyon Formation drill-site locations in Crownpoint field. Base map modified from Shomaker et al., 1971. See Table 4 for corresponding drill-site designations.

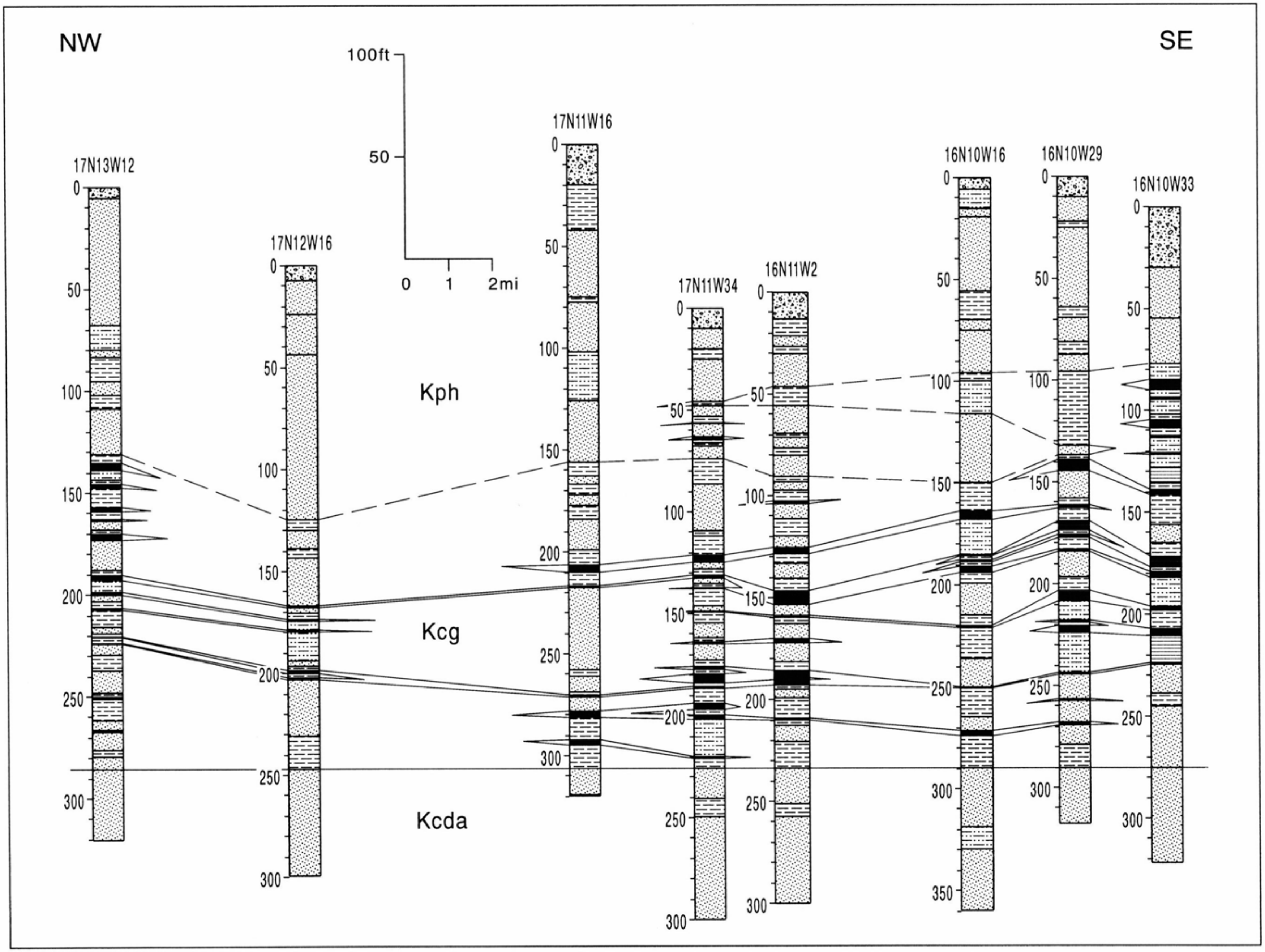

FIGURE 28–Correlation of pilot holes in Gibson Coal Member of Crevasse Canyon Formation, Crownpoint field. Kcda = Dalton Sandstone, Crevasse Canyon Formation, Kcg = Gibson Coal Member of Crevasse Canyon Formation, Kph = Hosta Sandstone Tongue of Point Lookout Sandstone.

associated with the finer-grained sandstones and shales probably represent flood-plain deposits. Most of the thicker coals in the Gibson Coal Member are in shale sequences at the Borrego Pass drill sites (16N10W16, 16N10W29, 16N10W33). The Borrego Pass area may have been located landward of the Dalton-Hosta shoreline during a reversal. This position would have allowed a relatively stable swamp environment to develop, resulting in thicker coal beds. It should be noted that the northwestern drill site 17N12W13 may be on the edge of another area of good coal development farther to the west, which is indicated by the number of seams (nine), the average coal thickness (2.0 ft), and the sandstone/shale ratio (0.49).

Thirty coal samples were taken from the cored intervals of the Crevasse Canyon drill sites. Five of these samples had nonremovable partings ranging from 8 to 13% of the total coal-bed thickness. The coals are moderately clarain-rich, hard, with fair to moderate cleat, and contain variable amounts of pyrite and resin. The seam thicknesses vary from 1.0 to 2.7 ft in the drilled sections, which is consistent with the bed thicknesses from data collected for the NCRDS project. The thickest coal bed encountered in the Gibson coal sequence was 6 ft (16N10W29; Fig. 28).

Some correlation within the Gibson coal-bearing sequence is possible using characteristic log signatures. Coal beds are most continuous in the southeast part of the section from 17N11W34 to 16N10W33 (Fig. 28). The entire coal-bearing section is thickest at 16N10W33 and 17N13W12, and thins dramatically in 17N12W16. Because of the thick sandstone sequence, this drill site probably represents an inter-swamp stream deposit.

Dilco Coal Member, Gallup field

Three drill holes (15N18W4, 15N19W35, 15N18W34; Fig. 29) penetrated the Dilco Coal Member of the Crevasse Canyon Formation in the Gallup coal field. The upper 125 to 300 ft of these drill holes were in the Bartlett Barren Member of the Crevasse Canyon Formation. Because of the depth of the coal-bearing sequence at 15N18W4 and 15N18W34 (>300 ft), no coal beds less than 2.5 ft thick were cored at these locations (Fig. 29).

The Dilco Coal Member is a nonmarine sequence of sandstone, siltstone, shale, carbonaceous shale, and coal. This sequence is shale-dominated, with sandstone/shale ratios of 0.12 to 0.61. The sandstone beds in this sequence are shaly to silty and tend to have a fine- to very fine-grained matrix. A maximum of 236 ft of the Dilco coal-bearing sequence was penetrated in any of these sections, which contained seven to nine coals.

The coals in the Dilco are generally thin (1-2 ft), with the exception of two coal beds at drill site 15N18W4, which are 7.95 and 8.3 ft thick. Both of these thick beds are in sandstone- and siltstone-dominated sequences rather than in the usual shale-dominated sequence. These thicker coal beds are thought to be equivalent to the previously mined Black Diamond and Otero coal seams mentioned in Sears (1925). The thickest Dilco coal penetrated south of Gallup was 5.85 ft in drill site 15N18W34. None of the coals encountered in the Dilco were close to the marine Gallup Sandstone contact. The shoreline was to the northeast and the coals were formed in swamps on a coastal floodplain. The coals in these drill holes were deposited during minor stillstands of the shoreline farther to the northeast (Roybal, 1989).

Thirteen coal samples were taken from the cored intervals. The Dilco coals tend to be shaly, pyritic, with moderate amounts of vitrain. Little or no resin was observed. Cleat was variable, ranging from poor to good, and the banding was thickest in the deepest coal bed (samples D and E, 15N18W34).

Moreno Hill Formation, Salt Lake field

The Salt Lake field is defined by the outcrop pattern of the Moreno Hill Formation. The field extends from the western border of New Mexico east to R15W and from T1N to T6N (Fig. 30). The structure in the area is simple with 3-5° dips to the southeast and a few minor flexures resulting from volcanic activity in the area. There are a few faults in the area, but none are significant.

Five sites were drilled in the Salt Lake field along a southwest-northeast trend (Fig. 30). These locations were on lands with private surface and federal mineral ownership (Table 5). All of the drill sites had qualifying coals (1.5 ft, 1988 standard) in the lower member of the Moreno Hill Formation. The drill sites selected were located at the base or above the middle sandstone member of the Moreno Hill Formation and were completed in the Rio Salado Tongue of the Man-cos Shale, stratigraphically below the marine Atarque Sandstone.

The coal-bearing sequence of the lower member of the Moreno Hill Formation is 115 to 183 ft thick in the sections drilled and thins toward the northeast (Fig. 31). The sequence consists of sandstone, siltstone, mudstone, and coal. The sandstone/shale ratio (0.87 to 13.67) increases to the northeast.

The coals in the lower member are within 120 ft of the underlying Atarque Sandstone and within 260 ft of the surface. The number of coal beds ranges from two to five in each section. Most of the coals in this sequence are thin, ranging in thickness from 1.2 to 2.5 ft, and, because of the scale, they do not appear as individual coals in the cross section (Fig. 31). The greatest frequency of coals in these sections is within 50 ft of the Atarque Sandstone. Coals just above the Atarque Sandstone are in the Antelope zone (Campbell, 1989). The thickest coals (5.4 and 7.4 ft) are near the base of the lower member and are present in the two holes near the geographic center of the field (3N17W1, 5N16W30). These beds are generally the second coal above the Atarque Sandstone, probably coals in the Cerro Prieto zone (3N17W14, 3N17W1, 5N16W30; Campbell, 1989). The thin coals in the upper part of the lower member are in the Rabbit zone (5N16W30, 6N16W33; Campbell, 1987).

The coal beds in the lower part of the sequence are associated with shales, whereas the coals higher in the section are often associated with siltstones and

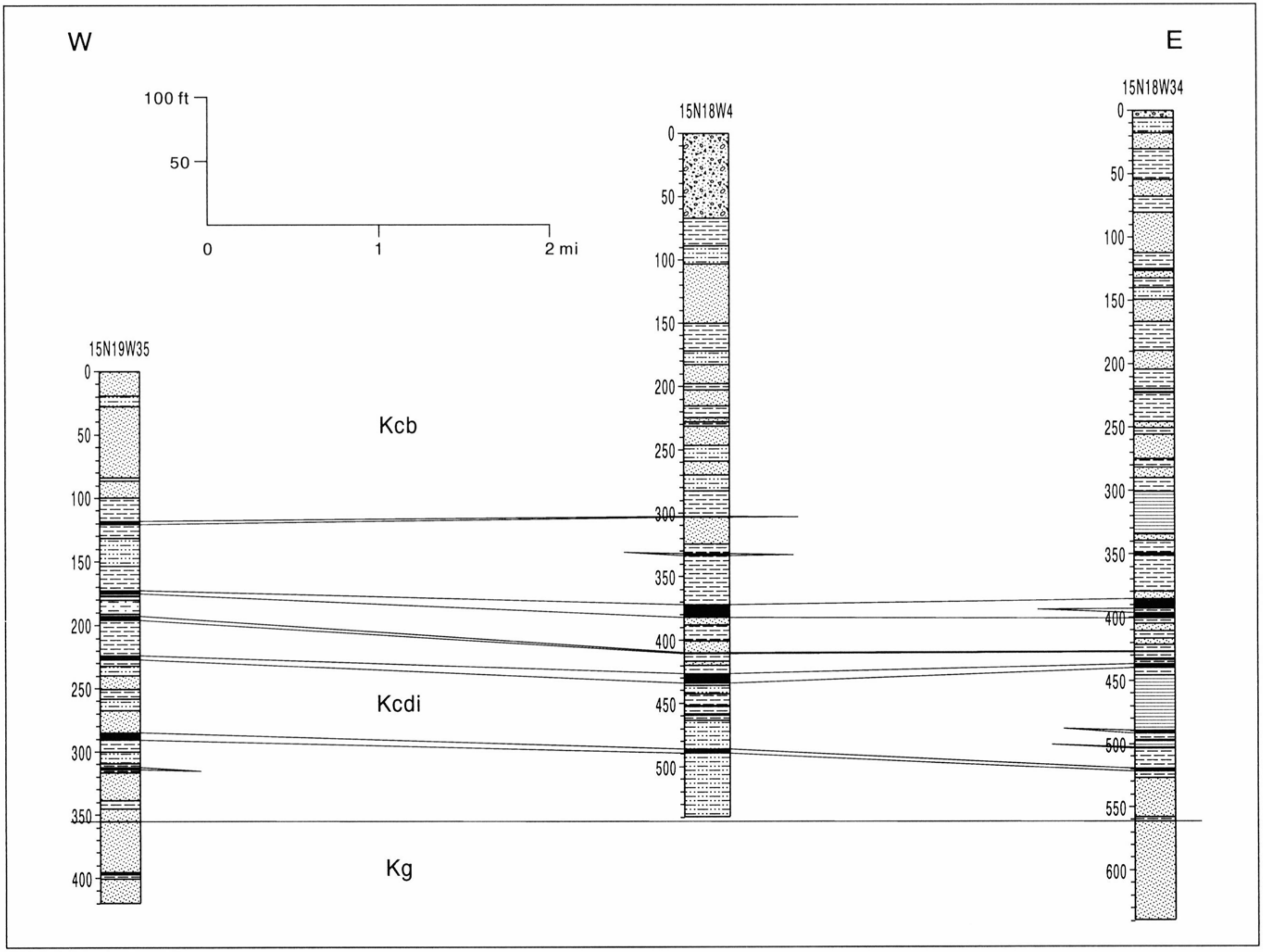

FIGURE 29—Correlation of pilot holes in Dilco Coal Member of Crevasse Canyon Formation, Gallup field. Kg = Gallup Sandstone, Kcdi = Dilco Coal Member of Crevasse Canyon Formation, Kcb = Bartlett Barren Member of Crevasse Canyon Formation.

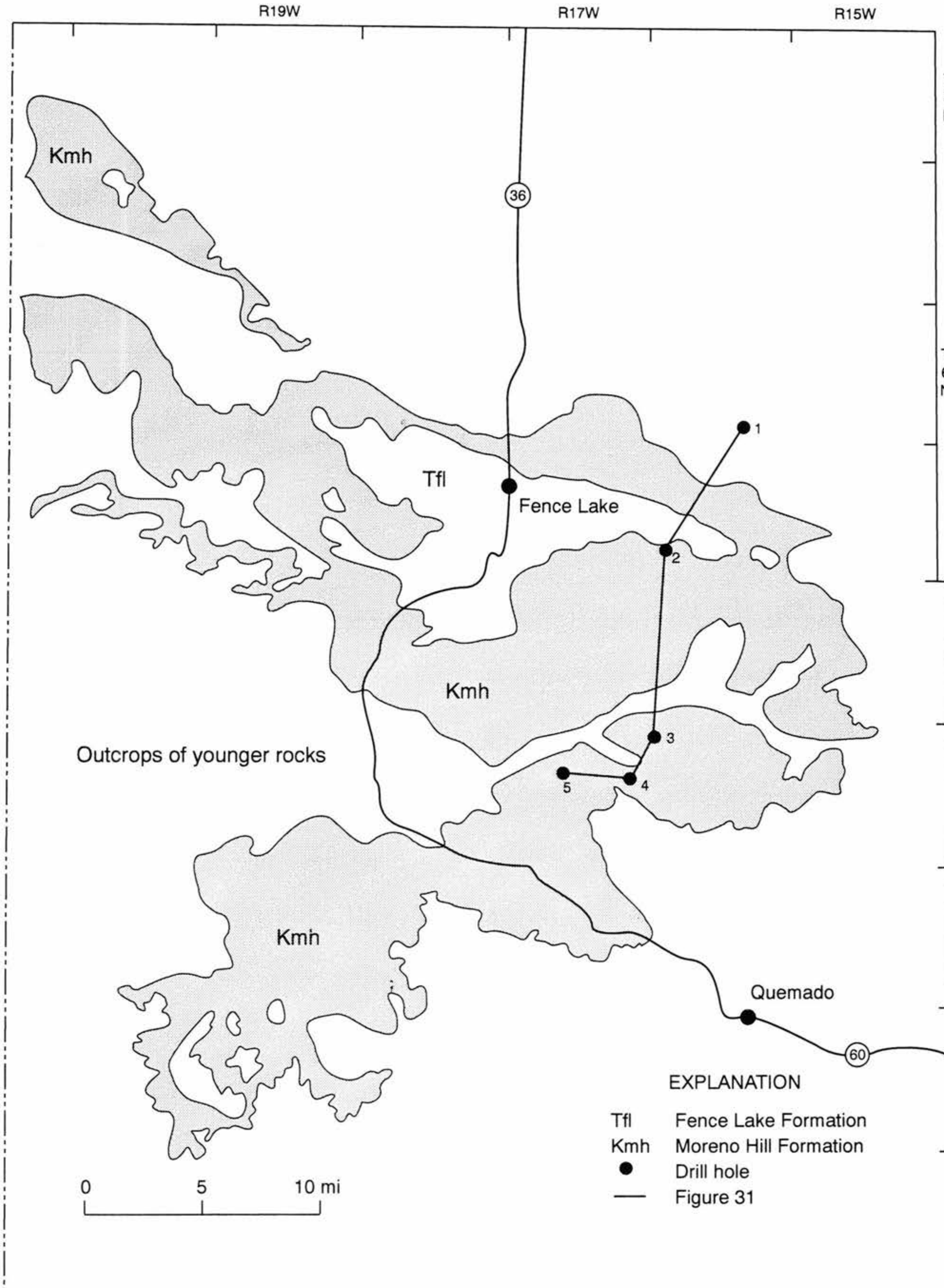

FIGURE 30—Moreno Hill Formation drill-site locations in Salt Lake field. Base map modified from Dane and Bachman, 1965. See Table 5 for corresponding drill-site designations.

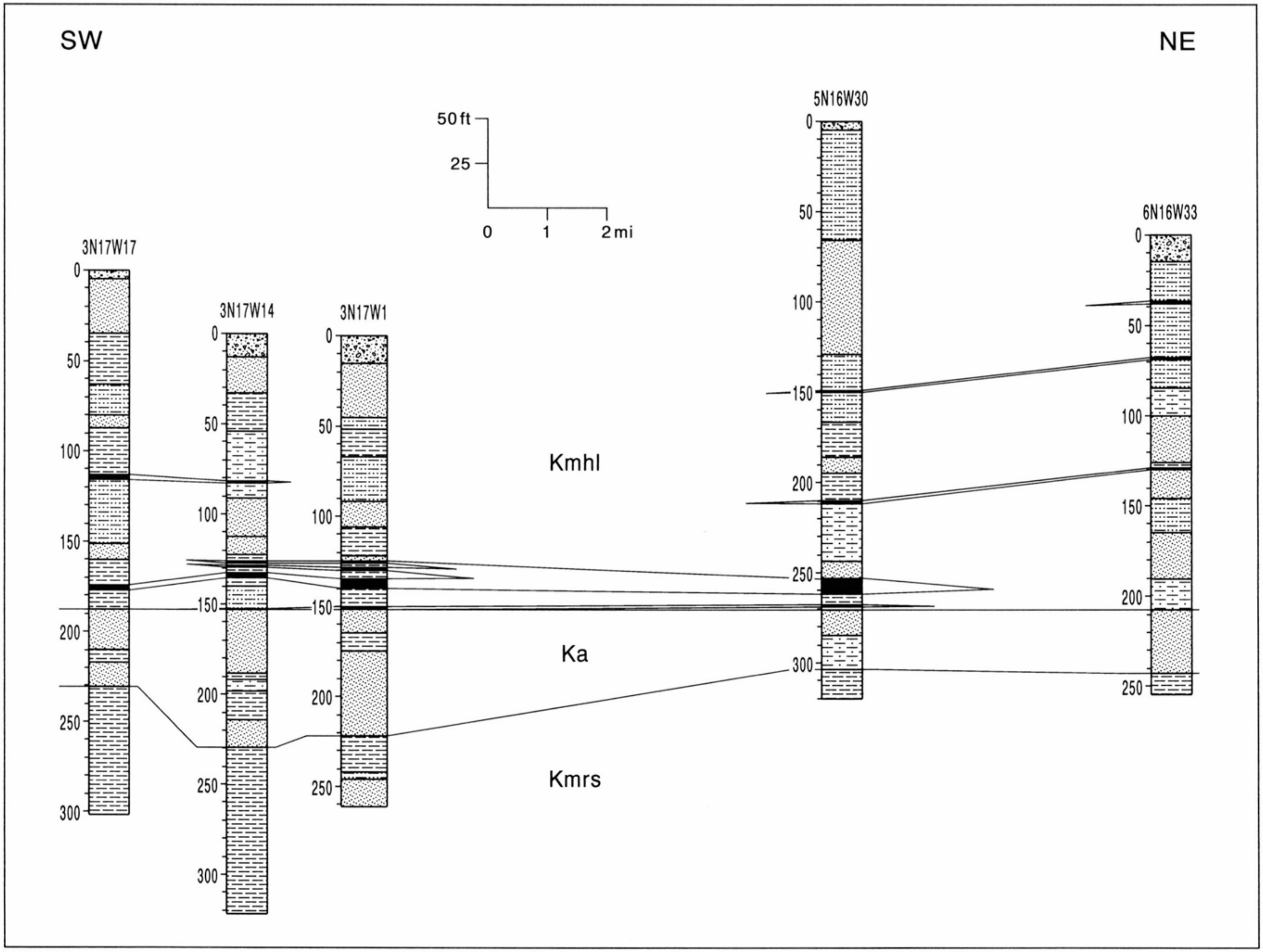

FIGURE 31—Correlation of pilot holes in Moreno Hill Formation, Salt Lake field. Kmrs = Rio Salado Tongue of Mancos Shale, Ka = Atarque Sandstone, Kmhl = lower member of Moreno Hill Formation.

TABLE 5—Ownership and map designation of drill-site locations, Moreno Hill Formation.

Field	Ownership		Figure Map No.
Salt Lake field	Surface	Mineral	Fig. 30
6N16W33	Private	Federal	1
5N16W30	Private	Federal	2
3N17W1	Private	Federal	3
3N17W14	Private	Federal	4
3N17W17	Private	Federal	5

the entire sequence becomes more siltstone- and sandstone-dominated upward. The stratigraphically lower Antelope zone coals, in close proximity to the marine Atarque Sandstone, are probably back-barrier swamp deposits (Anderson and Stricker, 1987), while the Cerro Prieto and Rabbit zone coals are of a fluvial origin (Campbell, 1987).

Eleven coal samples were taken from the Salt Lake field. The Moreno Hill coals have moderate banding, abundant vitrain, some pyrite, and good cleat. The thicker coals often contain a thin parting of claystone or tonstein. The persistence of tonstein partings in the thicker Cerro Prieto zone coal has been documented by Campbell (1987).

Chemical analytical procedures

(Frank W. Campbell)

Drilling in northwestern New Mexico resulted in a total of 749 samples collected, including 524 coal samples from 149 drill sites. All coal samples were double sealed in 6 mil plastic bags in the field to prevent moisture loss during transportation from the San Juan Basin to Socorro. Complete analyses, including proximate, ultimate, forms of sulfur, etc. were performed on all coal samples which included partings less than 0.8 ft between two coal layers of greater thickness. Short proximate analyses were run on the 0.5 ft interval above or below the coal as well as sampled partings (>0.8 to 2.5 ft) within a seam. Partings, underburden, and overburden were sampled only in the first year of drilling.

Coal samples were weighed upon arrival at the laboratory. The plastic bag was weighed, air-dried, and weighed again to determine the amount of moisture lost from the coal. This value was added to the air-dried loss of the coal to determine the total air-dried loss of the fresh coal. After drying, the sample was crushed to $^1/2$ x $^1/4$ mesh size; 1500 g were split for paired-run analyses and the reminder of the sample was sealed in 6 mil plastic bags. The samples for analyses were reduced to — 8 mesh. Samples too wet to be crushed were spread in a thin layer, weighed, and exposed to air to partly dry and then ground to —16 mesh for equilibrium moisture analyses. The remaining coal sample was further reduced to —100 mesh and split for paired runs of the other analyses.

Coal samples were additionally analyzed for proximate, ultimate, calorific value, forms of sulfur, major oxides, and trace elements. The analytical techniques were performed according to the ASTM (American Society of Testing Materials, 1983) standard procedures and the same techniques were used for all three field seasons except where noted in the subsequent discussion. For determination of major oxides, forms of sulfur, chlorine, and CO_2, the following analytical procedures were used. Chlorine was in concentrations less than the detection limit of the chlorine electrode. Therefore, a Volhard Titration (see ASTM D236166 5.4.2, chlorine) was employed, allowing for sensitivity at the ppm level. The nitrobenzene stage of the Volhard Titration was also dropped as no significant difference was observed when it was used. In the latter part of this study chloride was determined by oxygen-bomb combustion and ion chromatography. The ion chromatography was chosen over the electrode method because it had a higher degree of selectivity. In the first two years of the study sulfur analyses were performed with a Fisher Sulfur analyzer using 0.50 to 0.03% standards (ASTM D 4239). In the third year bomb calorimetry and ion chromatography were employed to determine sulfur. Forms of sulfur were determined using the ASTM method (D2492), except the final result was determined on the ion chromatograph instead of gravimetrically. The ultimate analysis was done using a LECO 600 CHN analyzer. The instrument was calibrated using dry reference materials (C = 71.24%, H = 5.10%, N = 1.56%).

Major oxides on ashed coal samples were done by x-ray fluorescence (D4326). The trace elements were done by atomic-absorption spectroscopy on the ash with the exception of phosphorus and titanium which were determined calorimetrically (Sandell, 1981), and silica which was determined gravimetrically (Jeffrey and Hutchison, 1981). Phosphorus was run on some samples the first year and was found to be below detection limits. Initially the oxide analyses were prepared using HF-Aqua Regia perchloric-acid digestion. This proved to be a very tedious and slow procedure. Instead of this technique, oxides were determined using a lithium-metaborate fusion (Boar and Ingram, 1970). This proved to be fast and reliable, and it permitted the silica analysis to be run using atomic-absorption spectroscopy. Manganese was to be originally run as a major oxide, but was found to be in quantities less than 0.01% and therefore was run as a trace element.

Standards (NBS 1633) were run with each batch of oxide samples. Whenever the summation of the oxides was less than 99% or greater than 101%, the batch was rerun. The results of these analyses are not normalized to equal 100%, but are reported in their determined quantities. All of the individual chemical analyses from this study are presented in New Mexico Bureau of Mines & Mineral Resources (NMBM&MR) Open-file Report 377 (Hoffman, 1991). These analyses were done at the NMBM&MR Coal Laboratory by Frank Campbell and his staff.

The NMRDI coal analyses are compared to coal analyses from other studies in the following sections. For both sets of data a ceiling of 33% ash yield was adopted for coal samples (Wood et al., 1983). The oxygen reported for both data sets is calculated and represents the sum of the other ultimate analyses plus ash subtracted from 100. The two sets of data were compared statistically using a two-tailed t-test with a pooled standard deviation. The t-values were compared at 0.025 and 0.005 significance levels using the individual degrees of freedom ($n_1 + n_2 — 2$). The t-values in Tables 6-18 are for those analyses where the critical t-value was exceeded, resulting in a statistically significant difference. As-received moisture statistically differs for almost all field comparisons between the NMRDI data and data from other studies. Data from other studies are from core coal samples or mine samples. The apparent low rank of these coals (sub-bituminous to high-volatile bituminous) and differences in collection techniques make it difficult to obtain reliable as-received-moisture content (ASTM-D388). Equilibrium moisture would be the preferred basis for comparison of these data, but the data from the other studies do not always include equilibrium-moisture analyses. To avoid influencing the other analytical results with the moisture values, the data are presented on a dry basis, except to determine apparent rank, where equilibrium moisture, mineral-free (eqmmf) is used. A weighted-average comparison on a seam basis of the two data sets, NMRDI and data from other studies, was done to determine if statistical differences in the analytical values would be the same or different from a straight sample-to-sample comparison. The differences between these two statistical analyses are included in the following discussions.

Description of analyses

(Frank W. Campbell, Gretchen K. Hoffman, and Jeanne Verploegh)

Introduction

Drilling of the Fruitland Formation and part of the Cleary Coal Member of the Menefee Formation in 1985 resulted in a total of 522 samples collected, of which 282 samples were coal. Of these coal samples 240 were from the Fruitland Formation fields and 42 were from the Cleary Coal Member of the Menefee Formation fields.

Samples from the summer 1986 drilling phase of this NMRDI coal-characterization project were from three formations, Menefee (113 samples), Crevasse Canyon (75 samples), and Fruitland (six samples). The Menefee Formation drilling included both the upper coal member and the Cleary Coal Member coals. The Crevasse Canyon drilling included coals in the Gibson and Dilco Coal Members.

The drilling during 1988 concentrated in four coal fields: the Monero and Chacra Mesa fields (Menefee Formation), the Gallup field (Crevasse Canyon Formation), and the Salt Lake field (Moreno Hill Formation). Drilling in both the Chacra Mesa and Gallup fields extended the areas sampled in 1986. Forty-six coal samples were collected for analysis.

Fruitland Formation

coals Fruitland field

The Fruitland Formation is the youngest coal-bearing sequence in the San Juan Basin. This Late Cretaceous unit contains some of the thickest coals in the basin and they are generally concentrated within the first 100 ft above the Pictured Cliffs Sandstone contact. The entire length of the Fruitland outcrop in the basin, except for that on the Navajo Indian Reservation, was drilled and cored for this investigation. The following table outlines the number of coal samples taken during this study.

FIELD	No. OF SAMPLES	YEAR COLLECTED
Fruitland	90	1985
Bisti	88	1985
Star Lake	68	1985
Star Lake	6	1986
Total	252	

The results of analyses from this study and data available from other studies are presented in Table 6 (see footnote 1, Table 6). A sample-to-sample comparison of these two sets of data indicates that equilibrium moisture, as-received moisture, oxygen, and sulfide (dry basis) differ statistically. When the weighted averages are compared for these two data sets, only the equilibrium moisture is statistically different (t-value = 3.09, degrees of freedom = 32). These results indicate that variations within the seams are highlighted when comparing sample-to-sample analyses, but most of the statistical differences disappear when the weighted-average analyses of these two data sets are compared. The equilibrium moisture is significantly less (avg. 7.59) for this study, indicating a possible difference in sampling techniques between the two data sets.

TABLE 6—Analyses of Fruitland field coals*.

	NMRDI data			Other studies[1]			t-test values	
	No. of samples	Mean	Std. dev.	No. of samples	Mean	Std. dev.	t-values	Degrees of freedom
Eq. moisture	80	7.61	3.18	42	9.8	2.21	5.59	120
Moisture	81	6.70	1.76	195	8.39	4.85	3.47	274
Ash	81	22.24	7.02	195	21.36	6.48		
Volatile matter	81	35.46	3.42	163	35.87	3.89		
Fixed carbon	81	42.29	5.29	163	42.17	4.09		
Calorific value	81	10646	1590	195	11041	1164		
EQMMFBTU	79	12907	683	14	13201	535		
Carbon	81	62.41	6.2	54	62.77	3.94		
Hydrogen	81	4.88	0.43	53	4.74	0.64		
Nitrogen	81	1.30	0.18	54	1.31	0.14		
Oxygen	81	8.21	3.97	53	10.10	3.36	4.56	132
Total sulfur	81	0.97	0.70	195	1.56	0.48		
Sulfide	81	0.37	0.40	12	0.70	0.48	4.13	91
Sulfate	39	0.01	0.03	7	0.02	0.01		
Organic sulfur	81	0.59	0.38	11	0.86	0.83		
Ashed oxides								
SiO_2	58	58.07	7.12	49	53.56	8.50	3.82	105
Al_2O_3	58	24.98	5.10	49	23.88	6.06		
TiO_2	56	0.96	0.30	19	1.10	0.33		
Fe_2O_3	58	3.61	2.58	49	3.60	2.57		
MgO	58	0.72	0.46	49	0.87	0.37		
CaO	58	5.19	4.62	49	4.74	6.18		
K_2O	57	0.41	0.19	49	0.63	0.52	3.79	104
Na_2O	58	0.78	0.59	49	1.28	0.64	5.37	105
Total oxides		94.72			89.66			

*Analyses on dry basis except as-received moisture, eq. moisture, and EQMMFBTU. All values in percent except calorific value and EQMMFBTU.
[1] Sources of data from other studies: Cimmarron Coal Co.; Western Coal Co.; Bureau of Land Managment coal studies; and confidential data.

The major oxides in the Fruitland coals collected for this study differ statistically for silica, potassium, and sodium from other studies on a sample-to-sample comparison. Except for the sodium values (t-value = 2.73, degrees of freedom = 25), all of these statistical differences disappear when these analyses are compared on a weighted-average basis. The samples with the highest sodium-oxide values for both data sets are concentrated in the southern part of the Fruitland field. A greater percentage of the data from other studies comes from drill sites in the southern Fruitland field; therefore, the average for this data set is biased toward these higher Na_2O_3 values. Sodium content in coal is often influenced by ground water (Harvey and Ruch, 1986) and often the deeper coals in these data sets have greater Na_2O_3 values, particularly in the southern Fruitland field where the coal bearing sequence is near a major discharge area, the San Juan River.

Bisti field

Eighty-six samples were taken from the Bisti field in this study, and 83 of them had less than 33% ash (Table 7). A maximum of 62 coal analyses from this field are available from other studies (see footnote 1, Table 7). Statistical differences on a sample-to-sample comparison are noted for the equilibrium moisture, volatile matter, calorific value (equilibrium moisture, mineral-matter-free basis, eqmmf), hydrogen, oxygen, sulfate, and organic sulfur. A comparison of weighted averages indicates the statistical differences between these two data sets occur for the calorific values, and pyritic and organic-sulfur values. All other statistical differences apparent from the sample-to-

TABLE 7—Analyses of Bisti field coals*.

	NMRDI data			Other studies[1]			t-test values	
	No. of samples	Mean	Std. dev.	No. of samples	Mean	Std. dev.	t-values	Degrees of freedom
Eq. moisture	83	14.88	1.18	5	16.40	1.26	4.15	86
Moisture	83	13.81	2.97	60	13.91	3.95		
Ash	83	21.32	6.81	60	23.31	8.16		
Volatile matter	83	36.93	2.81	60	35.15	4.30	4.01	141
Fixed carbon	82	41.71	5.28	60	41.69	6.20		
Calorific value	83	10187	1097	62	10336	1236		
EQMMFBTU	83	10811	483	5	11457	400	4.35	86
Carbon	83	59.24	6.24	46	58.40	7.19		
Hydrogen	83	4.85	0.39	46	5.31	1.06	4.97	127
Nitrogen	83	1.09	0.16	46	1.05	0.31		
Oxygen	83	12.92	2.11	46	10.54	3.13	7.18	127
Total sulfur	83	0.59	0.14	62	0.61	0.15		
Sulfide	83	0.08	0.11	26	0.13	0.07		
Sulfate	24	0.01	0.01	16	0.03	0.01	9.75	38
Organic sulfur	83	0.50	0.09	26	0.44	0.13	4.02	107
Ashed oxides								
SiO_2	81	57.28	4.26	53	57.10	6.05		
Al_2O_3	81	27.04	2.79	53	23.16	3.85	9.19	132
TiO_2	80	0.97	0.32	53	0.93	0.21		
Fe_2O_3	81	3.48	1.86	53	3.10	1.87		
MgO	81	0.69	0.46	53	0.70	0.19		
CaO	81	3.76	2.57	53	2.14	1.05	5.92	132
K_2O	80	0.51	0.41	53	0.79	0.45	5.03	131
Na_2O	86	2.33	1.42	53	1.73	0.46	4.04	132
Total oxides		96.06			89.65			

*Analyses on dry basis, except for as-received moisture, eq. moisture, and EQMMFBTU. All values in percent except calorific value and EQMMFBTU.

[1] Sources of data from other studies: Shomaker et al., 1971; Cherokee and Pittsburg coal studies; Schneider et al., 1979; Wilson, and Jentgen, 1980; and Bureau of Land Management coal studies.

sample comparison appear to be artifacts of this type of correlation. The differences in the mean calorific values on a dry basis, although statistically significant, do not change the apparent rank (subbituminous A) for both sets of data. The most meaningful statistical and practical differences are in the forms of sulfur. These differences may have to do with the spatial form of the coal seams and the geographic and stratigraphic distribution of the data.

Differences in the proportion of sulfide + sulfate to organic sulfur may be a function of the maceral content (Chou, 1990) and therefore the type of organic material (i.e. trees or shrubs and grasses) which is dependent on conditions within the swamp that may vary laterally and vertically (Chou, 1990; Ferm et al., 1989). The sulfide + sulfate to organic-sulfur ratio could also be attributed to factors affecting the bacterial activity, such as pH and availability of iron in the swamp (Cecil et al., 1982). The NMRDI data are distributed over the entire length of the Bisti field and throughout the entire coal-bearing interval of the Fruitland Formation, but the other data set is drawn from a few densely sampled areas and taken from shallower drill-hole depths that did not penetrate the entire Fruitland Formation, such as mine-plan areas. The shallow depths of the coal samples and the higher sulfate values indicate a possible weathering of the coal.

The four oxides that differ between the two Bisti data sets are calcium, aluminum, sodium, and potassium. All of these statistical differences are removed when the two data sets are compared on a weighted-average basis. These differences might be explained by different methods of dealing with partings. This study considered any parting thicker than 0.8 ft to be removable, whereas the other studies may have used a different scheme to determine if a parting was to be included in the coal sample or separated from the coal before analyses for specific mining purposes. When the weighted averages of these two data sets are compared, these artifacts of sampling disappear.

Star Lake field

Seventy-two samples were collected from the Star Lake field during the NMRDI drilling seasons of 1985 and 1986, and 66 of them have ash yields of less than 33%. Seventy-four coal samples from the Star Lake field are available from other studies (see footnote 1, Table 8). There are statistical differences in the equilibrium moisture, moisture, and oxygen analyses between the two data sets (Table 8). The statistical differences between the weighted averages of coal beds are in the moisture, calorific value, eqmmfBtu value, and the oxygen value. The oxygen values are calculated and therefore dependent on the other analytical parameters, which did appear to be within the same statistical population. The deviation in the equilibrium-moisture and the moisture values is probably because of differences in sample collection and preparation. The difference between the NMRDI equilibrium-moisture and the NMRDI as-received moisture values is significant (t-value = 5.26, degrees of freedom = 129) and indicates that the as-received-moisture values for this data set should be higher, closer to the as-received-moisture value from the other studies (13.21%). The eqmmfBtu value is dependent on the calorific value and therefore the difference in cal-

TABLE 8—Analyses of Star Lake field coals*.

	NMRDI data			Other studies[1]			t-test values	
	No. of samples	Mean	Std. dev.	No. of samples	Mean	Std. dev.	t-values	Degrees of freedom
Eq. moisture	66	14.11	3.83	48	12.37	2.26	3.70	112
Moisture	65	11.34	1.85	74	13.21	1.72	7.63	137
Ash	65	25.62	6.11	74	25.01	5.75		
Volatile matter	65	35.77	3.12	74	36.71	2.60		
Fixed marbon	65	38.45	4.96	74	38.43	3.96		
Calorific value	65	9849	959	74	10118	1375		
EQMMFBTU	65	11253	554	48	11508	1569		
Carbon	64	56.14	5.26	73	57.67	4.95		
Hydrogen	64	4.64	0.36	73	4.89	0.82		
Nitrogen	64	1.08	0.15	73	1.16	0.26		
Oxygen	64	12.03	1.44	73	10.67	0.96	8.12	135
Total sulfur	66	0.63	0.17	74	0.64	0.13		
Sulfide	66	0.09	0.10	15	0.07	0.04		
Sulfate	13	0.03	0.03	10	0.01	0.00		
Organic sulfur	66	0.53	0.12	15	0.55	0.07		
Ashed oxides								
SiO_2	60	58.90	4.23	11	54.87	5.37	4.16	69
Al_2O_3	60	27.80	3.70	11	29.47	3.78		
TiO_2	59	0.98	0.37	11	1.20	0.20		
Fe_2O_3	60	2.59	1.11	11	3.18	0.98		
MgO	60	0.60	0.48	11	0.51	0.21		
CaO	60	2.74	1.59	11	3.21	2.92		
K_2O	60	0.61	0.65	11	0.58	0.41		
Na_2O	60	1.79	0.85	11	1.48	0.44		
Total oxides		96.01			94.50			

*Analyses on dry basis except for as-received moisture, eq. moisture, and EQMMFBTU. All values in percent except calorific value and EQMMFBTU.

[1]Sources of data from other studies: Shomaker et al., 1971; and Bureau of Land Management coal studies.

orific value is reflected in the eqmmfBtu. These values are lower for the NMRDI data and may be a factor of sampling; the NMRDI samples were taken throughout the Star Lake field, whereas data from the other studies are concentrated in mine-plan areas.

Statistical comparison of the major-oxide analyses indicates significant differences in the silica values. When the weighted averages of these two sets of analyses are compared, the aluminum values are statistically different (t-value = 5.2, degrees of freedom = 19). The probable cause of this dissimilarity is the localized nature of the samples from the other studies, which are from a single mine plan.

Comparison of **Fruitland Formation fields**

A total of 230 coal samples (less than 33% ash yield) were analyzed from the three Fruitland Formation coal fields (Fig. 7). Several relationships can be discerned when the analytical data are compared between the coal fields.

The most notable difference in the quality parameters of the Fruitland coals is the lower mean equilibrium-moisture value of the Fruitland field (weighted avg. 7.59% sd =1.96) compared to the Bisti (weighted avg. 13.95% sd = 1.43%) and Star Lake (weighted avg. 13.01% sd =1.06) fields. The lower equilibrium-moisture content is anticipated because the Fruitland field coals are higher in apparent rank (eqmmf-basis) as a consequence of being closer to the San Juan volcanic complex in southwestern Colorado, a source of heat and therefore a factor in the maturation of these coals (Clarkson and Reiter, 1987). Coals from the Bisti field show the greatest variation in equilibrium-moisture content with a range of 10.96 to 17.55%.

Ash yield is lowest in the Fruitland coals (weighted avg. 21.17% sd = 4.23), and highest in the Star Lake field (weighted avg. 26.38% sd = 2.94). Applying the t-test to the weighted averages of these three fields, the largest statistical difference of the mean ash yield is between the Fruitland and Star Lake ash yields (t-value = 3.67, degrees of freedom = 22). The high ash yields in the Star Lake field may have resulted from the inclusion of thin partings (less than 0.8 ft) in these relatively thin coal beds. The Star Lake coals have multiple partings that may be a result of these coals originating in swamps that were interrupted by crevasse splays and stream channels in an area where the shoreline was retreating relatively fast in comparison with the shoreline movement to the northwest. The rapid retreat of the shoreline is substantiated by the overall thinning of the Fruitland Formation and Pictured Cliffs Sandstone in the Star Lake field (Fassett, 1988).

Ash yields in samples from the Fruitland field are variable (weighted avg. 21.17% sd = 4.23) and coals with higher ash (>20%) commonly occur in the northern part of the field (Hoffman et al., 1992). One of the coal-zone samples in the northern Fruitland field had multiple partings totaling 18% of the entire coal seam. The multiple partings and subsequent higher ash in this coal zone are attributed to an influx of sediment, probably from a source to the north—northwest, into the coal swamps.

The volatile-matter content of coals from the Fruitland Formation shows statistical differences when compared on a weighted-average dry basis. T-values for the Fruitland and Bisti volatile-matter content and the Fruitland and Star Lake volatile-matter values are within the same statistical population. The Bisti and Star Lake volatile-matter values have a moderate statistical difference on the 0.025 significance level (t-value = 2.26, degrees of freedom = 30). The fixed-carbon content is slightly higher for the coals in the Fruitland field. Again, this is a function of the higher apparent rank of the Fruitland field coals. The mean values of fixed carbon in the Fruitland and Bisti coals are statistically within the same population. The difference between the fixed carbon in the Fruitland field and in the Star Lake field is probably the most statistically significant (t-value = 3.59, degrees of freedom = 22).

The Fruitland field coals have the highest dry-basis calorific value (10,581 Btu/lb). The calorific values for all three Fruitland fields are statistically different. The calorific values, on an eqmmf-basis, of the coals from these three fields show a general decrease in apparent rank from north to south. Coals from the Fruitland field are high-volatile B to C bituminous, the highest apparent rank in the Fruitland Formation. Coal samples from the Star Lake field are subbituminous A in apparent rank (eqmmfBtu = 10,732, weighted avg.), but extend into the high-volatile C bituminous range. The lowest apparent-rank coals are found in the Bisti field, where they are non-agglomerating, subbituminous A (eqmmfBtu = 10,308, weighted avg.).

The average total-sulfur content is highest in coals from the Fruitland field (weighted avg. 0.88%). This value differs statistically from the sulfur content of the Bisti and Star Lake coals, which are about equal (weighted avg. 0.59% and 0.64%, respectively). Sulfur values from the Fruitland field also show the greatest range in values (2.58 to 0.47%). Based on the data from this project, 56% of the total sulfur in the Fruitland field is present as organic sulfur. The sulfide content is highest in the Fruitland field (weighted avg. 0.32% sd = 0.11). X-ray diffraction analyses indicate that pyrite is the primary sulfide. In the Bisti and Star Lake fields the sulfide content is less than 16% of the total sulfur (weighted avg. 8% and 12%, respectively), and pyrite is the primary sulfide. In all three Fruitland Formation fields most of the partings thicker than 0.8 ft showed a higher sulfide content than that present in the coals which included thin (less than 0.8 ft thick) partings.

The oxide analyses indicate a marked increase in the sodium content from the Fruitland field (weighted avg. 1.00) to the Star Lake (weighted avg. 1.68) and Bisti (weighted avg. 2.04) fields. Average percent of $CaCo_3$ decreases from the Fruitland field coals (weighted avg. 5.94) to the Bisti and Star Lake coals (weighted avg. 3.15 and 2.79, respectively). X-ray diffraction analyses indicate the dominant clay fraction for coal intervals to be kaolinite, whereas partings are richer in illite/montmorillonite. The high percentage of $CaCo_3$ in the Fruitland coals may be a result of the calcite along the cleat surfaces, a common feature mentioned in the core descriptions.

Menefee Formation

The Menefee Formation contains two coal-bearing members, the Cleary Coal Member at the base of the unit, just above the Point Lookout Sandstone, and the upper coal member at the top of the formation, which intertongues with the Cliff House Sandstone (Fig. 2). The Menefee Formation fields were sampled in all three years of this study. The following table outlines the number of drill sites in each field, the year, and the member of the Menefee Formation drilled.

FIELD	No. OF SAMPLES	YEAR COLLECTED	MEMBER
Standing Rock	14	1985	Cleary
W. San Mateo	29	1985	Cleary
La Ventana	47	1986	Cleary, upper
Chacra Mesa	32	1986	Cleary, upper
E. San Mateo	28	1986	Cleary
Chacra Mesa	22	1988	upper
Monero	4	1988	undivided
Total	176		

Upper coal member of Menefee Formation

La Ventana field—The analyses of 15 coal samples from the NMRDI project are compared to 31 analyses from other studies in Table 9 (see footnote 1, Table 9). Statistically significant differences between the two data sets for the proximate and ultimate analyses occur for mean as-received-moisture, hydrogen (dry basis), and nitrogen (dry basis) values. A comparison of the weighted averages of these samples indicates that statistical differences are present between the hydrogen, nitrogen, and volatile-matter values of the two data sets. The mean as-received-moisture value from the other data set appears to be low for these coals when compared to the moisture and equilibrium-moisture values of the NMRDI study, although this value does not appear to be statistically different on a weighted-average comparison. The hydrogen analyses are significantly lower for this study, and the nitrogen is higher both on a sample and weighted-

TABLE 9—Analyses of La Ventana field, upper coal member coals*.

	NMRDI data			Other studies[1]			t-test values	
	No. of samples	Mean	Std. dev.	No. of samples	Mean	Std. dev.	t-values	Degrees of freedom
Eq. moisture	15	17.90	1.52	0				
Moisture	15	17.09	1.62	31	15.12	3.37	2.32	44
Ash	15	7.89	1.86	31	9.81	4.92		
Volatile matter	15	45.70	4.89	31	44.11	6.97		
Fixed carbon	15	46.40	4.21	31	47.10	7.60		
Calorific value	15	12645	443	31	12195	780		
EQMMFBTU	15	11187	38	0				
Carbon	15	72.49	2.07	9	69.90	3.31		
Hydrogen	15	5.14	0.12	9	7.08	0.47	17.56	22
Nitrogen	15	1.48	0.08	9	1.35	0.09	4.20	22
Oxygen	15	11.43	1.13	9	11.81	2.72		
Total sulfur	15	1.57	1.01	31	1.42	0.99		
Sulfide	15	0.46	0.49	0				
Sulfate	15	0.06	0.07	0				
Organic sulfur	15	1.03	0.59	0				
Ashed oxides								
SiO_2	13	44.97	10.00					
Al_2O_3	15	16.49	3.56					
TiO_2	13	0.99	0.29					
Fe_2O_3	13	10.03	6.86					
MgO	13	2.81	0.97					
CaO	13	11.71	5.39					
K_2O	13	0.36	0.21					
Na_2O	13	1.15	0.29					
Total oxides		88.51						

*Analyses on dry basis except for as-received moisture, eq. moisture, and EQMMFBTU. All values in percent except calorific value and EQMMFBTU.

[1]Sources of data from other studies: Ellis, 1936; Shomaker et al., 1971; La Ventana Mine Plan; and Tabet and Frost, 1979.

average comparison. The variation in analytical results may be a function of differences between the techniques employed.

The organic sulfur constitutes 68% of the total sulfur content of the NMRDI analyses in the La Ventana field. The mean sulfate appears high (0.06%) because of four samples with sulfate values more than 0.1%, probably resulting from oxidation of the samples. Removing these four analyses from the data set, the mean sulfate content is 0.02% (sd = 0.02%). No forms of sulfur analyses were available from other sources for comparison.

Chacra Mesa field—The NMRDI program acquired 50 samples from this field for analyses. Only six analyses from other studies were available for the upper member coals (Table 10, see footnote 1). Comparing these two data sets, statistical differences are apparent between the as-received moisture and dry-basis hydrogen. These statistical differences disappear when the weighted averages of these two data sets are compared. The problem with this comparison is the small number of weighted averages from other studies, which makes the results suspect. The moisture values for the Chacra Mesa coals likely should be closer to the value obtained in this study, given the much larger number of samples in the NMRDI data set and the relatively good match between the equilibrium-moisture and as-received-moisture values.

Forty-three of the 50 samples of the NMRDI study were analyzed for the major oxides. Silica, aluminum, potassium, and sodium values are significantly higher than the values from La Ventana field upper coal member (Table 9). No major-oxide data from other studies were available for comparison.

TABLE 10—Analyses of Chacra Mesa field, upper coal member coals*.

	NMRDI data			Other studies[1]			t-test values	
	No. of samples	Mean	Std. dev.	No. of samples	Mean	Std. dev.	t-values	Degrees of freedom
Eq. moisture	50	16.84	2.38	0				
Moisture	50	16.10	3.04	6	11.70	1.02	4.90	54
Ash	50	10.30	5.18	6	11.78	8.29		
Volatile matter	49	42.89	4.02	6	40.60	2.43		
Fixed carbon	50	48.61	9.34	6	47.58	6.10		
Calorific value	50	12062	875	6	12054	1304		
EQMMFBTU	50	11085	759	0				
Carbon	49	71.54	4.87	6	68.90	7.68		
Hydrogen	49	5.14	0.46	6	4.59	0.43	4.41	53
Nitrogen	48	1.41	0.15	6	1.49	0.15		
Oxygen	50	10.59	2.16	6	11.97	1.27		
Total sulfur	50	0.97	0.70	6	1.26	0.99		
Sulfide	50	0.23	0.39	0				
Sulfate	39	0.07	0.18	0				
Organic sulfur	49	0.69	0.33	0				
Ashed oxides								
SiO_2	41	60.96	9.21					
Al_2O_3	41	20.61	5.97					
TiO_2	41	0.91	0.14					
Fe_2O_3	41	5.50	4.79					
MgO	41	1.30	0.76					
CaO	41	3.76	4.19					
K_2O	41	0.89	0.46					
Na_2O	41	2.87	1.38					
Total oxides		96.80						

*Analyses on dry basis except as-received moisture, eq. moisture, and EQMMFBTU. All values in percent except calorific value and EQMMFBTU.
[1]Sources of data from other studies: Tabet and Frost, 1979.

Cleary Coal Member of Menefee Formation

Standing Rock field—Fourteen samples were analyzed from the Standing Rock field and compared to the 42 from other studies (see footnote 1, Table 11). The majority of NMRDI analyses agree with those from previous studies (Table 11). One exception is the oxygen values, which are calculated. The weighted-average comparison agrees with the sample-to-sample comparison of the two data sets, although the statistical difference in the oxygen values disappears.

The major-oxide analyses from this study show a high percentage of iron, calcium, and sodium. The high iron content could result from pyrite or siderite and the high calcium value is probably indicative of the calcite that occurs on the cleat faces of these coals, which was noted in the core descriptions. No major-element oxide analyses from other studies were available for comparison.

Chacra Mesa field—Only two analyses of coals from the NMRDI study are from the Chacra Mesa field. These analyses have been grouped with the San Mateo field samples.

San Mateo field—Sampling during the NMRDI drilling doubled the number of available analyses for the San Mateo field (Table 12). The NMRDI data have statistically lower mean equilibrium-moisture and as-received-moisture values than the mean of other studies for both the sample-to-sample and weighted-average comparisons. In the two data sets there is a greater variance between as-received-moisture values than between the equilibrium-moisture values. The true moisture content of these coal samples is probably closer to the previous data sets, because the equi-

TABLE 11—Analyses of Standing Rock field, Cleary Coal Member coals*.

	NMRDI data			Other studies[1]			t-test values	
	No. of samples	Mean	Std. dev.	No. of samples	Mean	Std. dev.	t-values	Degrees of freedom
Eq. moisture	14	16.10	2.98	0				
Moisture	14	16.92	2.50	42	16.99	1.17		
Ash	14	15.66	6.05	42	15.80	4.03		
Volatile matter	14	41.27	2.33	42	40.80	1.79		
Fixed carbon	14	43.06	4.85	42	43.43	2.85		
Calorific value	14	11187	871	42	11530	673		
EQMMFBTU	14	10919	437	0				
Carbon	14	65.73	4.92	42	62.70	8.27		
Hydrogen	14	5.19	0.29	41	4.92	0.73		
Nitrogen	14	1.16	0.21	42	1.13	0.60		
Oxygen	14	10.98	1.33	42	13.11	2.29	3.49	54
Total sulfur	14	1.28	0.57	42	1.22	0.68		
Sulfide	14	0.51	0.42	41	0.47	0.49		
Sulfate	12	0.03	0.03	32	0.03	0.04		
Organic sulfur	14	0.73	0.21	42	0.73	0.29		
Ashed oxides								
SiO_2	11	55.50	4.80					
Al_2O_3	11	23.34	3.52					
TiO_2	11	0.87	0.28					
Fe_2O_3	11	8.43	3.43					
MgO	11	0.79	0.33					
CaO	11	4.79	1.56					
K_2O	11	0.56	0.39					
Na_2O	11	2.09	0.48					
Total oxides		96.36						

*Analyses on dry basis except as-received moisture, eq. moisture, and EQMMFBTU. All values in percent except calorific value and EQMMFBTU.
[1]Sources of data from other studies: Shomaker et al., 1971; and confidential data.

TABLE 12—Analyses of San Mateo field, Cleary Coal Member coals*.

	NMRDI data			Other studies[1]			t-test values	
	No. of samples	Mean	Std. dev.	No. of samples	Mean	Std. dev.	t-values	Degrees of freedom
Eq. moisture	56	14.21	1.80	52	15.41	1.43	4.81	106
Moisture	56	12.66	2.54	78	15.61	2.11	8.76	132
Ash	56	15.29	5.54	78	13.97	6.47		
Volatile matter	56	42.12	2.58	57	41.35	3.22		
Fixed carbon	56	42.58	4.13	57	43.35	5.25		
Calorific value	56	11695	941	78	12011	1059		
EQMMFBTU	56	11736	684	52	11596	515		
Carbon	56	67.34	4.98	67	67.29	5.94		
Hydrogen	56	5.07	0.29	67	5.93	1.04	7.30	121
Nitrogen	56	1.21	0.16	67	1.18	0.12		
Oxygen	56	10.10	2.91	65	10.33	2.74		
Total sulfur	56	0.99	0.51	78	1.08	0.68		
Sulfide	55	0.32	0.30	55	0.42	0.55	3.07	108
Sulfate	36	0.03	0.03	32	0.04	0.07		
Organic sulfur	55	0.63	0.39	55	0.62	0.23		
Ashed oxides								
SiO_2	25	64.60	7.78	23	53.74	6.62	6.15	46
Al_2O_3	25	21.96	6.32	23	22.99	3.73		
TiO_2	25	1.19	0.24	23	1.05	0.11	3.04	46
Fe_2O_3	25	5.59	3.05	23	6.16	2.54		
MgO	25	0.86	0.33	23	1.02	0.33		
CaO	25	3.04	2.42	23	6.45	3.48	4.21	46
K_2O	25	0.79	0.54	23	0.54	0.34		
Na_2O	25	1.79	0.51	23	1.17	0.93	3.44	46
Total oxides		98.03			93.12			

*Analyses on dry basis except as-received moisture, eq. moisture, and EQMMFBTU. All values in percent except calorific value and EQMMFBTU.
[1]Sources of data from other studies: Tabet and Frost, 1979; and Bureau of Land Management coal drilling, 1982.

librium moisture for the NMRDI data, although statistically different from the other data set, is closer to the moisture values (equilibrium and as-received) in the other set (Table 12, see footnote 1).

The ultimate analyses show significant statistical differences for the hydrogen values on a dry basis, for both the sample-to-sample and weighted-average correlations. Nitrogen values appear to be statistically different for the weighted averages. The mean sulfide from this study is statistically lower than the mean sulfide in the other data set, possibly due to the geographic distribution of the two data sets, although this difference does not appear in the weighted-average comparison of the two data sets. This would suggest that inter-seam variations in the sulfide values are the reason for the statistical variation in the t-test of the samples.

T-test comparison of the major ashed oxides for the samples in the San Mateo field shows statistical differences between silica, titanium, calcium, and sodium. The weighted-average t-test shows differences between silica, aluminum, iron, potassium, and sodium, a set slightly different from that found in the t-test sample comparison. Analyses from other studies are concentrated in the Lee Ranch mine area (Table 12, footnote 1). The NMRDI analyses were from coal cores northeast and northwest of this area and do not geographically overlap with the other data set. For all the oxides that are statistically different in the two data sets, with the exception of aluminum the NMRDI values are higher. Most of these oxides are often constituents of clay minerals, and the SiO_2 probably indicates a higher percentage of quartz. The clay and quartz likely are of a detrital origin, indicating a greater influx of sediment into the peat swamps northeast and northwest of the Lee Ranch mine. As mentioned in the lithologic section of this report, several of the coals sampled in the San Mateo field had a high percentage (avg. 11%) of nonremovable partings (less than 0.8 ft thick). The inclusion of partings could in part explain the higher silica content, and some of the silica may be quartz that is finely disseminated throughout the coal bed.

La Ventana field—The 30 samples from NMRDI drilling in the La Ventana field double the number of available analyses for this area (Table 13). The equilibrium-moisture values from this study differ statistically from the mean equilibrium-moisture value of the other studies (see footnote 1, Table 13), although the as-received-moisture values are statistically within the same population. The equilibrium-moisture value is not statistically different for the weighted average t-test.

The ultimate analyses of the two data sets show statistical differences for hydrogen, nitrogen, and oxygen. The hydrogen and oxygen differences probably are significant as these values are statistically different also for the weighted average t-test. The differences in these values may be due to the variance in geographical distribution between the two data sets. The data from other studies are concentrated in two areas of the La Ventana field, whereas the NMRDI data cover the entire area.

The average dmmf (dry, mineral-matter-free basis) hydrogen value from the other studies is high for the apparent rank (high volatile C biuminous) of the coal (Damberger et al., 1984), but the average nitrogen value does not show a large difference between the

TABLE 13—Analyses of La Ventana field, Cleary Coal Member coals*.

	NMRDI data			Other studies[1]			t-test values	
	No. of samples	Mean	Std. dev.	No. of samples	Mean	Std. dev.	t-values	Degrees of freedom
Eq. moisture	30	15.75	2.09	34	17.94	4.36	2.96	62
Moisture	30	15.40	2.59	41	16.63	3.98		
Ash	30	13.92	6.41	41	13.63	5.29		
Volatile matter	30	41.38	3.23	41	42.25	2.82		
Fixed carbon	30	44.69	3.82	41	45.01	6.54		
Calorific value	30	12078	1202	41	12447	1003		
EQMMFBTU	30	11668	689	34	11730	1147		
Carbon	30	69.24	6.43	38	73.53	7.85		
Hydrogen	29	4.74	0.32	38	6.29	0.64	13.88	65
Nitrogen	30	1.35	0.17	38	1.48	0.12	4.32	66
Oxygen	30	9.70	2.40	32	5.08	5.84	4.78	60
Total sulfur	30	1.21	0.74	41	1.64	1.26		
Sulfide	30	0.47	0.50	14	0.73	1.16		
Sulfate	26	0.04	0.04	26	0.09	0.22		
Organic sulfur	29	0.73	0.40	35	0.90	0.62		
Ashed oxides								
SiO_2	29	59.27	7.97					
Al_2O_3	29	20.13	5.40					
TiO_2	29	1.03	0.20					
Fe_2O_3	29	8.28	5.22					
MgO	29	1.24	0.43					
CaO	29	4.26	4.48					
K_2O	29	0.99	0.48					
Na_2O	29	2.75	1.11					
Total oxides		97.95						

*Analyses on dry basis except as-received moisture, eq. moisture, and EQMMFBTU. All values in percent except calorific value and EQMMFBTU.
[1]Sources of data from other studies: Tabet and Frost, 1979; Arroyo Mine Plan; and Bureau of Land Management coal studies, 1986, 1987.

two sets of analyses. Combined with a lower nitrogen, the lower hydrogen of the NMRDI analyses results in a higher oxygen content. Although the mean total sulfur and sulfide in the two data sets appear to be different, the t-test values for both the sample and weighted-average comparisons indicate that both are within the same population; this may be the result of the wide range of values, as indicated by the high standard deviation.

Menefee Formation, Monero field

Four core samples were collected from the Monero field, providing some new data in addition to the 43 predominantly mine samples from other studies (Table 14, see footnote 1). Most of the data from the NMRDI coal samples are statistically within the same population as the data from the other studies. The only statistical difference for both the sample and weighted-average t-tests is that between the fixed-carbon values. The NMRDI mean fixed-carbon value is lower than the mean from other studies. Fixed carbon is calculated using the ash, moisture, and volatile-matter values; therefore, minor differences in these values, when combined to calculate the fixed carbon, could account for the difference in values between the two data sets.

The NMRDI analyses for major oxides are the only data available for the Monero field. The iron (Fe_2O_3) content appears to be high and may be a consequence of the high sulfur content. The two samples that were analyzed for major oxides have pyritic-sulfur values of 1.08% and 0.78%, higher than the average pyritic sulfur for the field (0.65%). The Fe_2O_3 content of these two samples is 19.53% and 18.48%, respectively. Pyrite was mentioned in the core descriptions from the Monero field as being concentrated along the cleat faces of the coals.

TABLE 14—Analyses of Monero field, Menefee Formation coals*.

	NMRDI data			Other studies[1]			t-test values	
	No. of samples	Mean	Std. dev.	No. of samples	Mean	Std. dev.	t-values	Degrees of freedom
Eq. moisture	4	5.69	3.67	0				
Moisture	4	4.49	2.38	18	3.44	1.43		
Ash	4	15.07	2.98	12	11.43	5.94		
Volatile matter	4	39.20	0.87	12	38.60	1.72		
Fixed carbon	4	45.72	2.43	12	51.69	2.36	4.31	14
Calorific value	4	12527	354	16	12745	1229		
EQMMFBTU	4	14089	891	0				
Carbon	4	71.92	2.18	9	72.12	4.14		
Hydrogen	4	5.76	0.29	9	5.62	0.17		
Nitrogen	4	1.62	0.21	9	1.57	0.11		
Oxygen	4	5.60	2.20	10	8.83	5.59		
Total sulfur	4	2.19	1.71	18	2.31	1.53		
Sulfide	4	0.65	0.346	0				
Sulfate	3	0.02	0.01	0				
Organic sulfur	4	1.52	1.37	0				
Ashed oxides								
SiO_2	2	57.54	0.13					
Al_2O_3	2	17.54	0.81					
TiO_2	2	1.06	0.11					
Fe_2O_3	2	19.01	0.52					
MgO	2	0.23	0.10					
CaO	2	0.68	0.27					
K_2O	2	1.07	0.01					
Na_2O	2	0.98	0.16					
Total oxides		98.11						

*Analyses on dry basis except as-received moisture, eq. moisture, and EQMMFBTU. All values in percent except calorific value and EQMMFBTU.
[1]Sources of data from other studies: Ellis, 1936; Shomaker et al., 1971; and Rochester Coal Co.

Comparison of Menefee Formation fields

The ash yields of the Menefee coals appear to vary considerably (7.89-15.66%, dry basis), although a weighted-average comparison by the t-test shows no difference in the mean ash yields from the three Cleary Coal Member fields sampled. The upper coal member ash yields from the Chacra Mesa and La Ventana fields are within the same population, but have statistically lower ash yields (7.89-10.3%) than the Cleary Coal Member coals and the Monero field Menefee coals.

The calorific values (dry basis) for these Menefee Formation fields are essentially equal, except for the Standing Rock field coals which have a statistically significant lower calorific value (11,187 Btu/lb) than all the other Menefee Formation coals sampled in this study. This statistical difference disappears upon comparison of the weighted averages. The Monero field samples have the highest average calorific value (12,527 Btu/lb, dry basis). Recalculating the Monero field average calorific value to a moist, mineral-matter-free basis (equilibrium moisture) yields an apparent rank of high-volatile A bituminous. The coals in the Monero field, on the northeast edge of the San Juan Basin (Figs. 7, 23), have been influenced by depth of burial and by heat from the San Juan volcanic complex, possibly transmitted by heat advection from ground water (Clarkson and Reiter, 1987), which seems to have increased their thermal maturity (Crist et al., 1989).

The Standing Rock field (apparent rank) subbituminous A coals have the lowest calorific value (10,919 eqmmfBtu). The weighted-average calorific value for the Standing Rock (10,356 eqmmfBtu) is slightly higher than that for the La Ventana Cleary Coal Member coals sampled (10,330 eqmmfBtu). The apparent rank of samples collected from the upper coal member of the Menefee (La Ventana and Chacra Mesa fields) is also subbituminous A. The mean calorific values of the Cleary Coal Member samples from all three fields (Standing Rock, La Ventana, San Mateo) are of the apparent rank of subbituminous A.

The average sulfur values of coals from the Cleary Coal Member fields are statistically within one population. The upper member coals of the Chacra Mesa and La Ventana fields show a significant difference on a sample comparison at the 0.025 confidence level (t-value = 2.61) for the total-sulfur values, although this difference is somewhat alleviated in the weighted-average t-test. The organic-sulfur values are statistically different for the weighted averages, with higher values in the La Ventana field. The sulfur content of the Monero field samples is statistically higher than the Cleary Coal Member sulfur values. The upper coal member coals and the uppermost coals in the Monero field were deposited during a transgressive sequence and overlain by marine Cliff House sandstones (Hoffman, 1991), which may explain the higher percentage of sulfur in these coals. The sampled Cleary coals have statistically different sulfide values between the San Mateo and Monero, the Chacra Mesa and Standing Rock, and the Chacra Mesa and La Ventana fields. The Chacra Mesa and San Mateo sulfide values are low (0.21 and 0.32%, weighted average, dry basis), and the Standing Rock and La Ventana values are high (0.42 and 0.39%, weighted average, dry basis). All the fields sampled have sulfate values of 0.1% or less. Organic sulfur is the dominant sulfur form in the Menefee coals. The upper member coals in the La Ventana and Monero fields have the highest organic-sulfur values (1.02% and 1.83%, respectively, weighted average, dry basis) in the Menefee Formation fields. The organic-sulfur values in the Cleary Coal Member are statistically different between the Monero and La Ventana, and Standing Rock and San Mateo fields; and those in the upper coal member are statistically different between the La Ventana, Chacra Mesa, and Monero fields. The upper coal member coals are often overlain by marine sandstones (Cliff House Sandstone) and were deposited behind a transgressive shoreline. The presence of overlying marine units probably is a large factor in the predominance of organic sulfur in these coals. The Monero field Menefee coals were deposited near the turn-around of the shoreline; therefore, the higher organic-sulfur content is probably a result of marine influence (Hoffman, 1991a).

Some statistical differences are apparent when a comparison of major-oxide analyses is done between the Menefee fields on a sample comparison, but most of these differences are alleviated by a weighted-average t-test. All of the Cleary Coal Member fields have oxide values within the same population. In the upper coal member samples the most striking difference occurs between the La Ventana and Chacra Mesa fields. The only oxide values that did not differ between these two fields were those of TiO_2. Many of the Chacra Mesa coals are associated with a buildup of the Cliff House Sandstone (referred to as Chacra Mesa tongue in Fig. 2) during a time of relative stability that followed the transgressive interval which terminated the La Ventana Tongue (of the Cliff House Sandstone) buildup. The coals in the La Ventana field are associated with the stratigraphically lower La Ventana Tongue sandstones. The later buildup of the Cliff House Sandstone developed farther to the south and west than the La Ventana Tongue buildup (Beaumont and Hoffman, 1992), and the source areas of sediments introduced into the swamps in these two adjacent coal fields may have been different.

Crevasse Canyon Formation

The Gibson Coal Member is the uppermost coal-bearing unit of the Crevasse Canyon Formation, overlain by the Point Lookout Sandstone in the Crown-point field. The Crevasse Canyon Formation in the Gallup field is not separated from the overlying Menefee Formation because the landward extent of the Point Lookout Sandstone is northeast of this field. Consequently, in the Gallup field there is no division between the Cleary Coal Member of the Menefee Formation and the Gibson Coal Member of the Crevasse Canyon Formation (Fig. 2). This coal-bearing unit is referred to as the Cleary—Gibson Coal Members of the Menefee—Crevasse Canyon, undivided. At the base of the Crevasse Canyon Formation is the Dilco Coal Member, a coal-bearing sequence above the Gallup Sandstone.

The following table lists the fields and numbers of coal samples taken during this study from the Crevasse Canyon Formation coal-bearing sequences.

FIELD	No. OF SAMPLES	YEAR COLLECTED	MEMBER
Crownpoint	30	1986	Gibson
Gallup	40	1986	Cleary—Gibson
Gallup	5	1986	Dilco
Gallup	2	1988	Cleary—Gibson
Gallup	8	1988	Dilco
Total	85		

Cleary—Gibson Coal Members, Gallup field

Forty samples were taken in the Gallup field in 1986 and two additional samples were collected in 1988; two of these samples had ash yields greater than 33% and are not included in Table 15. A maximum of 83 analyses from other studies were compared with the NMRDI analyses (Table 15, see footnote **1).** The t-test comparisons (sample and weighted average) of the proximate analyses indicate no significant differences between the two data sets. Statistical comparison of the ultimate analyses on a sample basis indicates significant variation for carbon (t-value = 4.09) and oxygen (t-value = 8.41). The weighted-average t-test displays statistical differences for carbon (t-value = 3.09), hydrogen (t-value = 3.04), and nitrogen (t-value = 2.66). The mean carbon, hydrogen, and nitrogen values (dry basis) of the NMRDI data are signficantly higher than the mean values of the other studies, although all values are within the range for the apparent rank (high-volatile C bituminous) of these coals. The oxygen content is a calculated value, therefore the values reflect the sum of differences from the other ultimate analyses. Given that in all the ultimate analyses the values differ (except for sulfur) for the two sets of

TABLE 15—Analyses of Gallup field, Cleary-Gibson coals*.

	NMRDI data			Other studies[1]			t-test values	
	No. of samples	Mean	Std. dev.	No. of samples	Mean	Std. dev.	t-values	Degrees of freedom
Eq. moisture	39	13.39	1.64	0				
Moisture	40	13.65	2.01	82	14.12	2.00		
Ash	40	10.67	6.07	83	8.88	4.48		
Volatile matter	40	44.18	3.37	81	44.47	2.99		
Fixed carbon	40	45.16	4.69	81	45.96	6.16		
Calorific value	40	12420	865	80	12538	834		
EQMMFBTU	40	11981	582	0				
Carbon	40	73.91	5.52	55	69.77	5.90	4.09	93
Hydrogen	40	5.34	0.33	55	5.66	0.93		
Nitrogen	39	1.30	0.12	55	1.24	0.21		
Oxygen	40	8.18	1.57	55	13.17	4.21	8.41	93
Total sulfur	40	0.64	0.52	83	0.59	0.12		
Sulfide	40	0.11	0.11	36	0.08	0.07		
Sulfate	37	0.02	0.07	7	0.06	0.05		
Organic sulfur	40	0.49	0.39	37	0.49	0.10		
Ashed oxides								
SiO_2	18	57.36	5.95	13	58.70	7.53		
Al_2O_3	18	21.22	5.95	13	20.24	4.21		
TiO_2	18	1.31	0.24	13	1.15	0.26		
Fe_2O_3	18	6.61	2.78	13	4.87	1.58		
MgO	18	1.32	0.44	13	1.06	0.25		
CaO	18	5.37	2.22	13	4.98	2.95		
K_2O	18	0.50	0.36	13	0.56	0.34		
Na_2O	18	3.31	1.38	13	2.01	1.18	3.20	29
Total oxides		97.00			93.57			

*Analyses on dry basis except as-received moisture, eq. moisture, and EQMMFBTU. All values in percent except calorific value and EQMMFBTU.
[1]Sources of data from other studies: Ellis, 1936; and confidential data.

data, it would appear that the analytical methods used have not been the same.

The major ashed oxides for the Cleary—Gibson coals show good statistical correlation between the two data sets. The only statistical difference for the sample comparison is between the sodium values, which are greater for the other studies. The weighted-average t-test indicates a statistical difference for Fe_2O_3 values (t-value = 2.57, degrees of freedom = 13). The NMRDI iron-oxide values are much higher (7.63 vs. 4.65, weighted average) than those of other studies. The source of Fe_2O_3 is probably pyrite.

Gibson Coal Member, Crownpoint field

Thirty NMRDI samples were collected from the Crownpoint field and compared with 12 analyses from other studies (Table 16, see footnote 1). The sample t-test values indicate that statistical differences occur between the total sulphur, organic sulphur, and the oxygen values, which are calculated. The weighted-average t-test indicates that hydrogen and organic sulfur are statistically different for the two data sets. The organic sulfur is much higher for the NMRDI data (weighted average 1.66%). These two data sets come from different locations; all the other data are from sites farther west or east than the data of this study. Because there is no overlap in geographic coverage, the difference in organic-sulfur values appears to be attributable to origination of the coal in different parts of the swamp environment.

Comparison between the Gallup Cleary—Gibson and Crownpoint Gibson ashed-oxide analyses indicates statistical differences for TiO_2, Fe_2O_3, and Na_2O values. The weighted-average comparison of the oxide analyses shows statistical differences for TiO_2 and Fe2O3

TABLE 16—Analyses of Crownpoint field, Gibson Coal Member coals*.

	NMRDI data			Other studies[1]			t-test values	
	No. of samples	Mean	Std. dev.	No. of samples	Mean	Std. dev.	t-values	Degrees of freedom
Eq. moisture	30	15.04	1.30	4	15.56	0.76		
Moisture	30	15.62	1.47	4	16.70	1.00		
Ash	30	13.13	6.39	4	11.51	4.93		
Volatile matter	30	42.64	2.78	4	44.42	2.43		
Fixed carbon	30	44.22	4.30	4	47.06	2.65		
Calorific value	30	11961	1178	4	12775	1038		
EQMMFBTU	30	11550	587	4	12039	508		
Carbon	30	72.02	5.87	4	76.49	5.14		
Hydrogen	30	5.19	0.44	4	6.22	0.31		
Nitrogen	30	1.25	0.35	4	1.31	0.05		
Oxygen	30	6.61	1.22	4	3.21	1.61	6.23	32
Total sulfur	30	1.85	1.11	4	1.26	0.53	1.28	32
Sulfide	29	0.46	0.69	4	0.51	0.36		
Sulfate	24	0.07	0.06	2	0.04	0.03		
Organic sulfur	29	1.32	0.82	4	0.73	0.18	1.73	32
Ashed oxides								
SiO_2	23	54.48	12.23					
Al_2O_3	23	18.62	4.22					
TiO_2	23	1.11	0.20					
Fe_2O_3	23	12.98	10.03					
MgO	23	1.33	0.34					
CaO	23	4.94	2.83					
K_2O	23	0.69	0.38					
Na_2O	23	1.94	0.97					
Total oxides		96.08						

*Analyses on dry basis except as-received moisture, eq. moisture, and EQMMFBTU. All values in percent except calorific value and EQMMFBTU.
[1]Sources of data from other studies: Bureau of Land Management coal studies, 1986.

values. The iron oxide is much higher in the Crownpoint field samples, in part probably due to the higher sulfur content of these coals.

Dilco Coal Member, Gallup field

During the NMRDI coal-quality study 12 samples were collected and analyzed from the Dilco Coal Member in the Gallup field. Twenty-seven coal analyses were available from other studies of the Dilco Coal Member (Table 17, see footnote 1). The only analyses that appear to be statistically within the same population are the moisture (as-received and equilibrium) and sulfur values (dry basis). When these two data sets are compared on a weighted-average basis, all the statistical differences except for nitrogen disappear. The t-test demonstrates how a weighted-average comparison can help to determine if variations within a seam are being overemphasized by compar ing samples instead of seams. Possible explanations for the difference in values between these two data sets on a sample basis are the variations in collection and analytical techniques, and that the data from the other studies are based almost exclusively on mine samples whereas the NMRDI data are all from cores. Many of the mine samples were only coal, with no partings included in the sample (Sears, 1925). To determine if the statistical differences could be attributed to the distinction between mine and drill-core samples, the 12 NMRDI analyses were compared to the two non-mine analyses of Tabet (1981). Although a comparison of these two analyses to the 12 from the NMRDI study is probably not statistically valid, statistical differences occurred between significantly fewer values (moisture, fixed carbon, nitrogen, and oxygen) than in the data set used for comparison in Table 17. The results of this statistical comparison indicate that sampling techniques probably do play

TABLE 17—Analyses of Gallup field, Dilco Coal Member coals*.

	NMRDI data			Other studies[1]			t-test values	
	No. of samples	Mean	Std. dev.	No. of samples	Mean	Std. dev.	t-values	Degrees of freedom
Eq. moisture	12	11.96	1.69	0				
Moisture	12	10.53	0.82	27	10.69	1.93		
Ash	12	19.67	7.12	27	7.48	1.99	8.85	37
Volatile matter	12	39.75	3.96	27	43.46	2.03	4.14	37
Fixed carbon	12	40.58	3.61	27	48.81	2.41	8.96	37
Calorific value	12	11058	1020	25	13106	366	9.63	35
EQMMFBTU	12	12035	301	0				
Carbon	12	64.86	5.94	12	73.11	2.39	4.53	22
Hydrogen	12	5.04	0.48	12	6.54	0.57	7.65	22
Nitrogen	12	1.27	0.14	12	1.13	0.05	3.58	22
Oxygen	12	8.18	1.51	12	10.63	0.82	5.42	22
Total sulfur	11	1.02	0.33	78	0.91	0.32		
Sulfide	11	0.29	0.19	0				
Sulfate	1	0.004	0.005	0				
Organic sulfur	11	0.75	0.22	0				
Ashed oxides								
SiO_2	9	65.56	6.82					
Al_2O_3	9	21.44	6.99					
TiO_2	9	1.36	0.20					
Fe_2O_3	9	5.15	1.58					
MgO	9	1.37	0.53					
CaO	9	2.58	2.59					
K_2O	9	0.62	0.31					
Na_2O	9	1.27	0.34					
Total oxides		99.35						

*Analyses on dry basis except as-received moisture, eq. moisture, and EQMMFBTU. All values in percent except calorific value and EQMMFBTU.
[1]Sources of data from other studies: Sears, 1925; Tabet, 1981.

an important role in the statistical divergence between the NMRDI and other values, and that comparison of weighted averages helps to alleviate many of these variations.

Comparison of Crevasse Canyon Formation fields

The Crevasse Canyon coals have many quality differences between the fields. Although the Gibson coals in Crownpoint field and the Cleary-Gibson coals in Gallup field might be similar because of their stratigraphically equivalent position (Fig. 2), they statistically differ in the moisture (as-received and equilibrium) and sulfur (total and forms) values. A comparison of samples from the Dilco Coal Member with samples of the Gibson coals in the Crownpoint field and the Cleary-Gibson sequence in the Gallup field indicates the same number of statistical differences, although the analyses are slightly different. Because of their equivalent stratigraphic position (Fig. 2), it might be presumed that analyses of the Cleary-Gibson coals in Gallup field would be closer in value to the analyses of samples from the Cleary Coal Member of the Menefee Formation, but a statistical comparison with the Cleary Coal Member coals in San Mateo field indicates that there are significant differences in t-tests between the samples and weighted averages for the two data sets. The variation in analyses of the Crevasse Canyon coals may be related to the depositional environments of the three coal-bearing sequences sampled (Fig. 2; see Beaumont, this report). The Dilco Coal Member of the Crevasse Canyon Formation developed during a regressive sequence, inland from the marine and coastal-barrier Gallup sandstones (Beaumont, 1968). The Cleary-Gibson coal-bearing sequence in the Gallup area developed inland of a major turn-around in the shoreline, allowing for several thick coals to develop during minor stillstands in the shoreline (Roybal, 1989). The lower coals of the Gibson Coal Member in the Crownpoint field were deposited during a regressive period, and the upper coal beds in this sequence were deposited as part of a subsequent transgressive cycle (Beaumont, 1968).

For the Crevasse Canyon Formation coals sampled in this study, the mean ash yield is highest (19.76%, dry basis, weighted average) in the Gallup Dilco coal and lowest in the Gallup Cleary-Gibson coals (10.32%, dry basis, weighted average). The apparent rank of these coals increases from subbituminous A in the Crownpoint field to high-volatile C bituminous in the Dilco and the Cleary-Gibson in Gallup field. The mean equilibrium-moisture content is lowest in the Dilco coals and highest in the Crownpoint coal samples. The Cleary-Gibson coal samples in the Gallup field have the lowest mean sulfur content (0.66%, dry basis, weighted average) and the Gibson coals in the Crownpoint field have the highest mean sulfur content (2.25%, dry basis, weighted average). The mean organic sulfur is more than 75% of the total-sulfur value in all of the Crevasse Canyon coals sampled.

Comparison of major oxides in the Crevasse Canyon fields shows some differences, but not as great a variation as in the quality characteristics. In the Gallup field the Dilco coals statistically differ from the Cleary-Gibson coals in calcium and sodium contents for the weighted-average correlation. Comparison of the Gallup field coals of both the Dilco and Cleary-Gibson sequences with the Gibson coals in the Crownpoint field indicates differences in the titanium and iron-oxide content. The high iron-oxide content in the Crownpoint field coals may be characteristic of the higher sulfide values in this field. The Dilco coals are statistically different in silica content from the Crownpoint field coals and have the highest average silica of all three sets of the Crevasse Canyon coal samples. The higher silica content in the Dilco coals may be attributed to a different source area for sediment and/or a greater influx of sediment during the development of these coals. The Cleary-Gibson coals in the Gallup field have the highest sodium content of all the Crevasse Canyon coals. Both the higher calcium and sodium content in the Cleary-Gibson coals in Gallup field and the Gibson coals in Crownpoint field may be indicative of calcite and clays which often occur on the cleat faces of brighter coals. Martin and Cavorac (1992) indicated that there is a correlation between some trace elements, including Ca, and the lithotypes. The bright coals, rich in vitrain and durain, show a higher concentration of authigenic and/or diagenetic minerals; and the duller coals, with greater percentages of durain and clarain, show a higher concentration of detrital mineral matter. The Cleary-Gibson coals have the lowest ash yield of all the Crevasse Canyon coals sampled and are described as bright to moderately bright in the core descriptions. Therefore, these coals would likely show the highest concentration of diagenetic or authigenic minerals, such as calcite.

Moreno Hill Formation, Salt Lake field

The samples collected in the Salt Lake coal field are from the Moreno Hill Formation (McLellan et al., 1984), the oldest coal-bearing formation sampled during the NMRDI coal-quality project. Eleven core samples were collected from the five holes drilled in this field in 1988. All three major coal-bearing zones (Antelope, Cerro Prieto, and Rabbit—Campbell, 1989) were sampled; however, the population sizes were not sufficient to compare the zones to each other. Table 18 presents a statistical summary of the analyses of the Salt Lake field coals and compares the NMRDI sampling to what was previously known about this area from other studies (see footnote, Table 18).

A sample comparison of the two data sets shows oxygen and all forms of sulfur to be statistically different. A weighted-average comparison of these two data sets does not indicate a statistical difference in the oxygen values, but does show differences in the hydrogen and all the sulfur values. In part, the differences in sulfur may be the result of 40% of the NMRDI samples having been taken from the coals just above the marine Atarque Sandstone in the Antelope zone (Campbell, 1989). The Antelope coals may have been influenced by a marine invasion and tend to have a higher percentage of total sulfur (avg. 1.09%) than the coals of the Cerro Prieto and Rabbit zones

TABLE 18—Analyses of the Salt Lake field, Moreno Hill Formation coals*.

	NMRDI data			Other studies[1]			t-test values	
	No. of samples	Mean	Std. dev.	No. of samples	Mean	Std. dev.	t-values	Degrees of freedom
Eq. moisture	11	15.86	3.28	0				
Moisture	11	14.30	0.92	104	14.09	4.28		
Ash	11	19.75	4.75	100	20.51	6.31		
Volatile matter	11	38.47	2.60	103	36.17	5.18		
Fixed carbon	11	41.77	2.81	103	42.18	7.96		
Calorific value	11	10524	788	104	10696	1086		
EQMMFBTU	11	10845	555	0				
Carbon	11	63.62	4.16	82	60.68	5.42		
Hydrogen	11	4.94	0.33	82	4.86	3.92		
Nitrogen	11	1.23	0.08	82	1.12	0.15		
Oxygen	11	9.23	0.52	82	11.90	2.26	3.98	91
Total sulfur	11	1.24	0.29	89	0.76	0.24	6.21	89
Sulfide	11	0.49	0.28	65	0.19	0.16	5.23	74
Sulfate	11	0.01	0.01	22	0.06	0.06	2.86	31
Organic sulfur	11	0.73	0.11	65	0.53	0.15	4.63	74
Ashed oxides								
SiO_2	10	61.09	8.33	57	57.63	4.73		
Al_2O_3	10	23.36	6.89	57	28.06	4.64	2.81	65
TiO_2	10	1.55	0.28	57	1.41	0.30		
Fe_2O_3	10	6.70	3.05	57	3.77	1.15	5.63	65
MgO	10	1.28	0.45	57	0.55	0.19	8.99	65
CaO	10	4.59	1.68	57	3.95	1.47		
K_2O	10	0.40	0.09	57	0.26	0.19	2.34	65
Na_2O	10	0.70	0.27	64	0.48	0.35		
Total oxides		99.67			96.35			

*Analyses on dry basis except as-received moisture, eq. moisture, and EQMMFBTU. All values in percent except calorific value and EQMMFBTU.
[1]Sources of data from other studies: Campbell, 1981; Roybal and Campbell, 1981; and confidential data.

(avg. 0.97%). The coals higher in the Moreno Hill Formation (Cerro Prieto and Rabbit zones; Campbell, 1989) were deposited in a fluvial environment and contain less sulfur. Most of the samples in the other data set are from these fluvial coal beds. The fluvial coals attain considerable thicknesses (avg. 4.2 ft, up to 13 ft) and extent (12-15 mi), particularly in the Cerro Prieto zone in the Salt Lake field, and are the economically significant coals in this field.

The Moreno Hill Formation coals in the Salt Lake field have moderately high ash yields that are similar to those of the Dilco Coal Member in the Gallup field. The Salt Lake field coals have an apparent rank subbituminous A and a moderate sulfur content, predominantly organic sulfur.

The sample t-test comparison of major ashed oxides for the Salt Lake field shows statistical differences between the aluminum, iron, magnesium, and potassium oxides. The weighted-average t-test indicates that iron and magnesium have valid statistical differences. The NMRDI samples are higher in Fe_2O_3 and MgO; the higher iron is probably tied to the higher percentage of sulfur in these samples.

Petrographic analyses: Assessment of methods and results

(Diane Bellis)

Introduction

This section is modified from the NMRDI report 2-76-5310 (Roybal et al., 1988). The maceral distribution has been determined on 136 samples and vitrinite reflectance has been measured on 158 coal and carbonaceous-shale samples of the 522 samples collected during the 1985, 1986, and 1988 field seasons. The individual petrographic analyses are part of NMBM& MR Open-file Report 377 (Hoffman, 1991). Average vitrinite reflectance varies little between formations or fields with the exception of the most northerly locations, the Monero and Fruitland fields being significantly higher. There are, however, interesting differences in maceral composition between fields and formations.

Methods

Vitrinite-reflectance analyses for this study were done by Frederick J. Kuellmer, New Mexico Institute of Mining & Technology (NMIMT); Arthur D. Cohen in conjunction with the Earth Sciences and Resource Institute (ECRI) of the University of South Carolina; Frederick Rich, formerly with the Environmental and Coal Associates (ECA); and Deborah A. and Kenneth W. Kuehn. Kuellmer's and Cohen's methods have been described elsewhere (Roybal et al., 1986, p. 80). Kuellmer determined mean-random reflectance in oil on 100 points per sample and the results were multiplied by 1.06 to approximate mean-max; Cohen's group determined mean-max reflectance in oil on 50 points per sample, each sample consisting of two pellets; ECA and Kuehn measured mean-max reflectance in oil on 100 points per sample. ASTM test method D 2798 (1986) recommends 50 readings on each of the two pellets. In the tables summarizing the petrographic analyses (Tables 19-22), vitrinite reflectance (R,) is the average of the reflectance determined by the various laboratories.

Maceral content for this study was analyzed by Kuellmer, Rich (ECA), and Kuehn. Kuellmer counted 400 points per sample; his methods have been described elsewhere (Roybal et al., 1987, p. 86); ECA and Kuehn counted 500 points per pellet, two pellets per sample as recommended by ASTM method D 2799 (1986). Different subdivisions were used by the groups for vitrinite, as shown below.

KUELLMER	ECA	KUEHN
pseudovitrinite	telinite	telinite
vitrinite 1	telocollinite	telocollinite
vitrinite 2	vitrodetrinite	desmocollinite
vitrodetrinite		corpocollinite

These vitrinite-group macerals are defined as follows:

Pseudovitrinite differs from vitrinite by a slightly higher reflectance, presence of telinitic structures, marked fissuration, somewhat higher relief, and absence of pyrite.

Vitrinite 1 is characterized by a relatively higher reflectance and is equivalent to telocollinite or sub hydrous vitrinite.

Vitrinite 2 is characterized by a lower reflectance and is equivalent to desmocollinite or perhydrous vi trinite.

Telinite, the maceral in which the former cellular structures of plant tissues are apparent, is rare anc often difficult to distinguish from collinite.

Telocollinite has a structureless appearance resulting from geochemical gelification of well-preserved tis sues or a similar reflectance between the cell wall; and cell infillings.

Desmocollinite is the structureless constituent of vi trinite and is found as infilling or groundmass.

Corpocollinite consists of massive, homogeneous spherical bodies of collinite which form in bituminous coals as a result of cell filling.

Vitrodetrinite is composed of fragments of vitrinite, indicating some early degradation.

Liptinite was subdivided into sporinite, resinite, and cutinite by Kuehn. Maceral compositions (%) of individual samples are averages of Kuellmer's and ECA's results. Liptinite- (exinite-) and inertinite-group macerals are as described in Stach et al. (1982).

Kuellmer applied a factor to the maceral count determined by ECA in order to compensate for differences between using fluorescent and ordinary visible light to determine the maceral content. The original maceral content of the samples was determined under visible light, which often causes the percentage of liptinitic material to be underestimated; then a fluorescent analysis was used to more accurately determine the percentage of liptinite. The point counts for each sample from both methods were compared to determine a correction factor, to obtain a corrected maceral count. The procedure for determining and applying the factor is described in Roybal et al. (1987, pp. 86-89).

Pellets were prepared according to ASTM method D2797 (1986) by Kuellmer, ECA, and Kuehn. Some pellets were repolished by ECRI, some were not. ECA prepared all the pellets for their analyses, and in the 1986 field season also pellets for some of the analyses done by the other laboratories. Kuehn prepared all the pellets in 1988.

Results

Summaries of petrographic analyses for 1985 and 1986 are organized by coal field (Table 19), by formation (Table 20, Fig. 32), and by eustatic environment (Beaumont, this report) in Table 21. The results of all petrographic analyses are summarized in Table 22.

Vitrinite reflectance ranges between 0.39 and 0.79% and averages 0.49% (Tables 19, 21). It is highest in samples from the northern areas sampled in the San Juan Basin, the Fruitland and Monero fields. These reflectance values correspond to ASTM apparent-rank

TABLE 19—Summary of petrographic data by field (in %).

	R_o	PVIT	VIT1	VIT2	VITD	TEL	TC	DC	CC	VD	VIT	SP	CUT	RES	LD	LIPT	FUS	SF	MIC	MAC	ID	SCL	INERT
Fruitland																							
Max	0.60	1	34	54	1	0	7	91	5		86	2	1	27	5	27	3	17		2	0	0	34
Min	0.47	0	22	24	0	0	2	83	3		50	0	0	4	0	8	0	1		0	0	0	2
Avg	0.54	0	28	38	0	0	4	86	4		69	1	1	17	2	14	1	8		0	0	0	18
No.	12	13	13	13	13	2	2	2	2		14	14	14	14	14	14	14	14		14	14	14	14
Std	0.04	0	4	9	0	0	3	4	1		10	11	0	7	1	6	1	4		0	0	0	10
Bisti																							
Max	0.51	5	26	60	0						86	2	2	27	3	15	1	13		3	1	0	31
Min	0.45	2	16	39	0						60	1	0	5	0	7	0	5		0	0	0	8
Avg	0.42	3	21	50	0						74	1	1	13	1	11	1	8		1	0	0	15
No.	6	6	6	6	6						6	6	6	6	6	6	6	6		6	6	6	6
Std	0.03	1	4	7	0						9	0	1	7	1	3	0	3		1	0	0	8
Star Lake																							
Max	0.53	7	26	57	0	1	7	83	6	0	83	4	2	24	3	23	2	18	0	3	2	0	29
Min	0.39	1	15	32	0	0	1	67	3	0	56	0	0	2	0	8	0	3	0	0	0	0	5
Avg	0.45	3	21	45	0	1	3	76	5	0	69	2	1	14	2	15	1	9	0	1	1	0	15
No.	44	11	11	11	11	3	3	3	3	3	13	13	13	13	13	13	12	13	13	13	13	13	13
Std	0.03	2	4	8	0	0	3	6	2	0	24	1	2	6	1	4	1	5	0	1	1	0	8
La Ventana																							
Max	0.56					2	8	84	18	0	88	6	1	2	0	16	3	13	1	0	4	0	18
Min	0.40					0	0	65	2	0	78	1	0	0	0	2	0	6	0	0	1	0	9
Avg	0.47					0	2	75	6	0	83	3	0	1	1	5	1	9	0	0	2	0	13
No.	11					15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Std	0.05					0	2	6	5	0	3	1	0	1	0	3	1	2	0	0	1	0	2
Chacra Mesa																							
Max	0.50					1	2	88	7	0	93	4	0	1	0	6	2	5	1	0	2	0	8
Min	0.44					0	0	79	2	0	88	1	0	0	0	2	1	3	0	0	0	0	4
Avg	0.47					0	1	84	5	0	91	2	0	1	0	3	1	4	0	0	1	0	6
No.	9					9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Std	0.01					0	1	3	2	0	2	1	0	0	0	1	0	1	0	0	1	0	1
San Mateo																							
Max	0.47						2	83	8		90	4	0	2	0	6	2	17	0		3		21
Min	0.41						0	71	1		71	2	0	1	0	3	1	4	0		2		6
Avg	0.45						1	78	4		82	3	0	1	0	4	1	9	0		3		13
No.	6						5	5	5		5	5	5	5	5	5	5	5	5		5		5
Std	0.03						1	4	3		6	1	0	1	0	1	0	5	0		1		5

TABLE 19 continued

	R_o	PVIT	VIT1	VIT2	VITD	TEL	TC	DC	CC	VD	VIT	SP	CUT	RES	LD	LIPT	FUS	SF	MIC	MAC	ID	SCL	INERT
Standing Rock																							
Max	0.50					1	4	80	5		86	3	0	2	0	5	1	9			2	0	12
Min	0.46					1	2	76	2		82	3	0	1	0	4	1	7			1	0	10
Avg	0.48					0	3	78	3		84	3	0	2	0	5	1	8			2	0	11
No.	2					1	2	2	2		2	2	1	2	1	2	1	2			2	2	2
Std	0.02					0	1	2	1		2	0	0	1	0	1	0	1			0	0	1
Monero																							
Max	0.79					15	19	48	8		73	6	1	6			1	22	4	1			26
Min	1					7	9	35	1		65	4	0	2			1	15	2	1			20
Avg	0.73					11	12	40	5		69	5	1	3			1	18	3	1			23
No.	4					4	4	4	4		4	4	4	4			4	4	4	4			4
Std	0.05					3	4	5	2		3	1	0	2			0	3	1	0			3
Crownpoint																							
Max	0.48					1	4	90	21		92	5	0	1	1	6	2	12	1	0	3	0	17
Min	0.41					0	0	63	2		79	1	0	0	0	2	0	3	0	0	1	0	4
Avg	0.45					0	1	78	7		86	3	0	1	0	4	1	7	0	0	2	0	10
No.	12					15	15	15	15		15	15	15	15	15	15	15	15	15	15	15	15	15
Std	0.02					0	1	6	5		3	1	0	0	0	1	0	2	0	0	1	0	3
Gallup																							
Max	0.49					0	3	84	8		89	4	0	4	0	7	1	14	0	0	3	0	18
Min	0.44					0	0	72	2		78	1	0	1	0	3	0	6	0	0	1	0	8
Avg	0.47					0	1	79	4		84	3	0	2	0	5	1	9	0	0	2	0	11
No.	8					10	10	10	10		10	10	10	10	10	10	10	10	10	10	10	10	10
Std	0.02					0	1	4	2		3	1	0	1	0	1	0	2	0	0	1	0	2
Salt Lake																							
Max	0.53					34	10	39	8		74	9	2	5			2	37	1	1			38
Min	0.44					16	1	29	1		54	4	1	1			0	16	0	0			17
Avg	0.49					22	4	33	4		63	6	1	3			1	25	1	0			27
No.	11					11	11	11	11		11	11	11	11			11	11	11	11			11
Std	0.03					5	3	3	2		7	1	1	1			0	7	0	0			6

Abbreviations:

R_o = percent vitrinite reflectance in oil
LD = liptodetrinite
SCL = sclerotinite
SP = sporinite
DC = desmocollinite
ID = indertodetrinite
VDET = vitrodetrinite
SF = semifusinite
RES = resinite
VIT1 = vitrinite 1
VIT = vitrinite
TC = telocollnite
MAC = macrinite
VIT2 = vitrinite 2
FUS = fusinite
CUT = cutinite
PVIT = pseudovitrinite
VD = vitrodetrinite
INERT = inertinite
MIC = micrinite
CC = corpocollinite
LIPT = liptinite
TEL = telinite

TABLE 20—Comparison of petrographic data by formation (in percent volume, on mineral-free basis).

	No.	Avg.	Std. dev.	No.	Avg.	Std. dev.	t-values*	Degrees of freedom
Fruitland				Menefee				
R_o	64	0.47	0.05	32	0.50	0.09	2.91	94
Vitrinite	33	70	10	35	84	7	8	66
Liptinite	33	14	5	31	4	3	12	62
Inertinite	33	16	9	35	12	6	3	66
Fruitland				Crevasse Canyon				
R_o	64	0.47	0.05	20	0.46	0.02		
Vitrinite	33	70	10	24	85	3	9	55
Liptinite	33	14	5	24	4	1	12	55
Inertinite	33	16	9	24	11	3		
Menefee				Crevasse Canyon				
R_o	32	0.50	0.09	20	0.46	0.02		
Vitrinite	35	84	7	24	85	3		
Liptinite	31	4	3	24	4	1		
Inertinite	35	12	6	24	11	3		
Moreno Hill				Crevasse Canyon				
R_o	11	0.49	0.03	20	0.46	0.62	3.57	29
Vitrinite	11	63	7	25	85	3	14	33
Liptinite	11	7	2	24	4	1	7	33
Inertinite	11	27	6	24	11	3	11	33
Moreno Hill				Menefee				
R_o	11	0.49	0.03	32	0.50	0.09		
Vitrinite	11	63	7	35	84	7	9	44
Liptinite	11	7	2	31	4	3	4	40
Inertinite	11	27	6	35	12	6	8	44
Moreno Hill				Fruitland				
R_o	11	0.49	0.03	64	0.47	0.05		
Vitrinite	11	63	7	33	70	10	2	42
Liptinite	11	7	2	33	14	5	5	42
Inertinite	11	27	6	33	16	9	4	42

* T-test values shown are for comparisons that represent statistically different populations.

TABLE 21—Petrographic data by eustatic environment (Beaumont, this report; in percent volume, on mineral-free basis).

	No.	Avg.	Std. dev.	No.	Avg.	Std. dev.	t-values*	Degrees of freedom
Primarily regressive								
Fruitland Formation				Cleary Coal Member				
R_o	64	0.47	0.05	19	0.46	0.04		
Vitrinite	33	70	10	17	83	4	7	48
Liptinite	33	14	5	17	5	3	9	48
Inertinite	33	16	9	17	13	4		
Primarily transgressive								
Upper coal member				Gibson Coal Member				
R_o	11	0.47	0.02	12	0.45	0.02	2.60	21
Vitrinite	14	89	4	15	86	3	3	27
Liptinite	14	3	1	15	4	1		
Inertinite	14	8	3	15	10	3		

* T-test values shown are for comparisons that represent statistically different populations.

TABLE 22—Summary of petrographic data from NMRDI coal-quality project (data in percent volume, on mineral-free basis).

Stratigraphic unit	R_o	Vitrinite	Liptinite	Inertinite
Fruitland Formation				
Max	0.60	86	27	34
Min	0.39	50	7	2
Avg	0.47	70	14	16
No.	64	33	33	33
Upper coal member				
Max	0.50	93	6	15
Min	0.44	81	2	4
Avg	0.47	89	3	8
No.	11	14	14	14
Cleary Coal Member				
Max	0.56	90	16	21
Min	0.40	71	2	6
Avg	0.46	83	5	13
No.	17	15	15	15
Cleary-Gibson Members				
Max	0.49	89	7	18
Min	0.44	78	3	8
Avg	0.47	84	5	11
No.	8	10	10	10
Gibson Coal Member				
Max	0.48	92	6	17
Min	0.41	79	2	4
Avg	0.45	86	4	10
No.	12	15	15	15
Moreno Hill Formation				
Max	0.53	74	10	38
Min	0.44	54	5	17
Avg	0.49	63	7	27
No.	11	11	11	11

classifications of subbituminous C to subbituminous A or high-volatile C bituminous (Stach et al., 1982).

Discussion

Samples for petrographic analysis were chosen to be geographically and stratigraphically representa

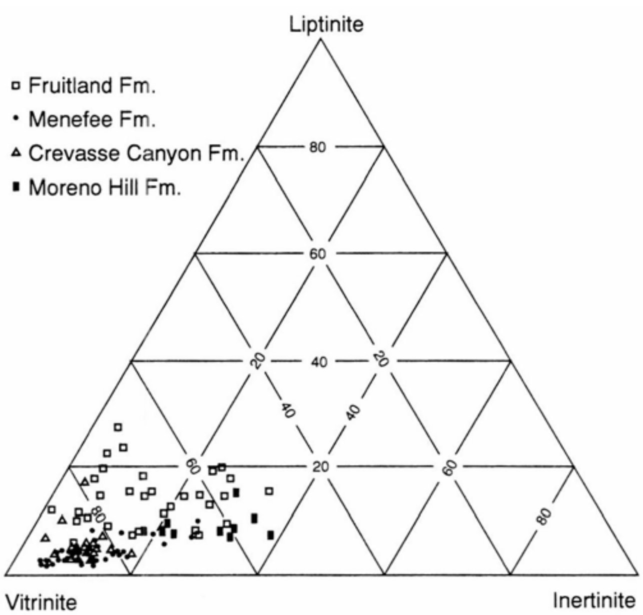

FIGURE 32—Maceral-group content by formation. Macerals are reported on a percentage basis.

tive, though there is a bias toward thicker seams. All the samples from the NMRDI project were taken from cores and collected in the same manner. Not all samples taken from a seam were petrographically analyzed, which makes it difficult to determine weighted averages for the petrographic data and therefore limits the interpretation of the data on a seam basis. Variations in petrographic analyses occurred in preparation, analytical techniques, and point counts by the different analysts; therefore, the data have been integrated and averaged without applying factors to compensate for determinate differences. Disparities in sample preparation most likely account for determinate differences in vitrinite reflectance between the petrographic laboratories. The differences are less than the reproducibility of the analysis and are compensated for by the number of samples. In all cases the range of reflectance of the samples from an individual core is greater than the range between cores, and in most cases between fields and formations. The difference between mean-random reflectance and mean-maximum reflectance is small for subbituminous coals, therefore the mean-random reflectance values were multiplied by 1.06 to approximate Rmax•

For comparative maceral analyses of samples on which 500 to 1000 points have been counted, results are acceptable if differences do not exceed 4% (Stach et al., 1982). These variations encompass inherent errors in the preparation of pellets as well as statistical errors and unavoidable errors in identification.

Vitrinite reflectance

Reflectance correlates positively with increasing aromaticity, ring condensation, and n-alkane carbon maxima. These characteristics are in turn strongly dependent on thermal-maturation level. Vitrinite is used for reflectance studies because it is the most abundant maceral and is assumed to be representative of the reflectance and, therefore, the rank of the coal.

Increased reflectance at the north end of the San Juan Basin, noted in both the Fruitland and Monero coal fields in this study, most likely results from heat flow in the San Juan volcanic complex (Clarkson and Reiter, 1987), although depth of burial has also been suggested as an influence. At the shallow depths sampled in this study, the stratigraphically older coals in the basin do not have any higher reflectance (Table 20). The Moreno Hill coals, which are the oldest coals sampled, do show a slightly higher vitrinite reflectance than the Menefee and Crevasse Canyon coals. San Juan Basin coals, depending on the age and location within the basin, have been buried from 1000 to 4000 ft deep, with the depth of burial increasing to the north. Vitrinite reflectance measured on the deeper Fruitland and Menefee coals ranges from 0.5 to 1.45% (Rice, 1983; Fassett and Nuccio, 1990) and tends to show some increase in rank with depth and toward the northern part of the basin, in the vicinity of the San Juan volcanic complex.

Anomalously high vitrinite reflectance attributable to localized metamorphism was not observed in the coals sampled in this study, although very few areas sampled were directly adjacent to volcanics or intrusions. No statistical differences in vitrinite reflectance between transgressive and regressive coal-bearing sequences were noted, although there are statistical variations in the maceral content (Table 21).

Frequency diagrams of the vitrinite reflectance for the upper coal member of the Menefee Formation and the Cleary—Gibson sequence (Figs. 33, 34) are fairly symmetrical, whereas those for the Fruitland field and Moreno Hill Formation (Figs. 35, 36) are positively skewed. The Fruitland Formation coals in the Bisti

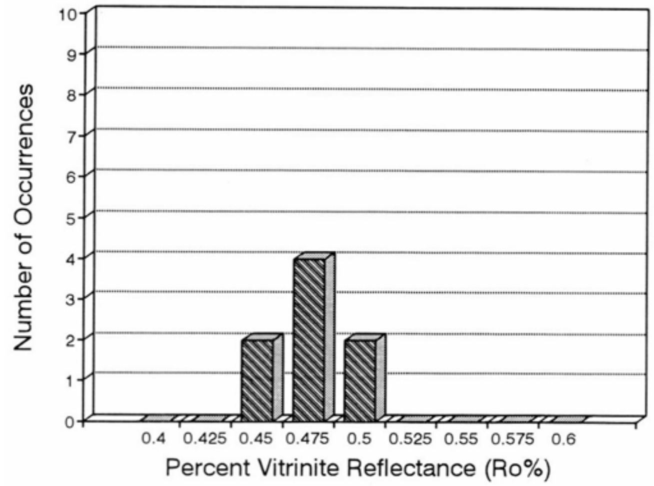

FIGURE 34—Frequency of vitrinite reflectance in Cleary–Gibson Coal Members, Gallup field. Average $R_o = 0.47$.

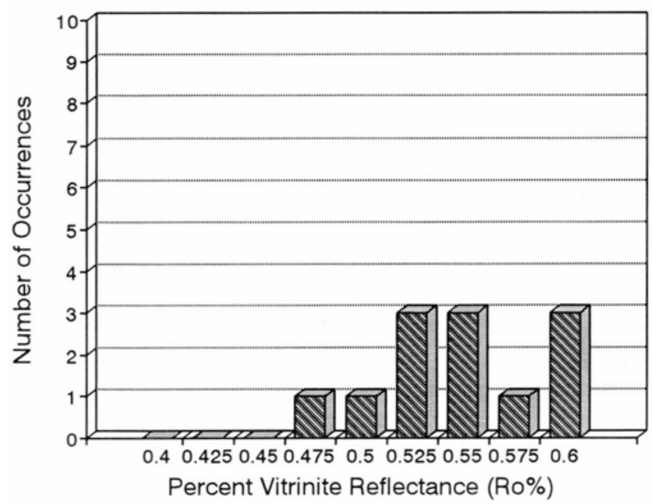

FIGURE 35—Frequency of vitrinite reflectance in Fruitland Formation, Fruitland field. Average $R_o = 0.54$.

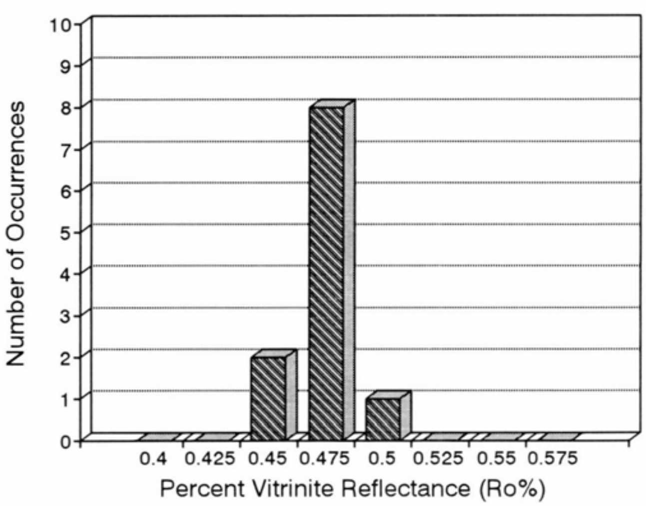

FIGURE 33—Frequency of vitrinite reflectance in upper coal member of Menefee Formation. Average $R_o = 0.47$.

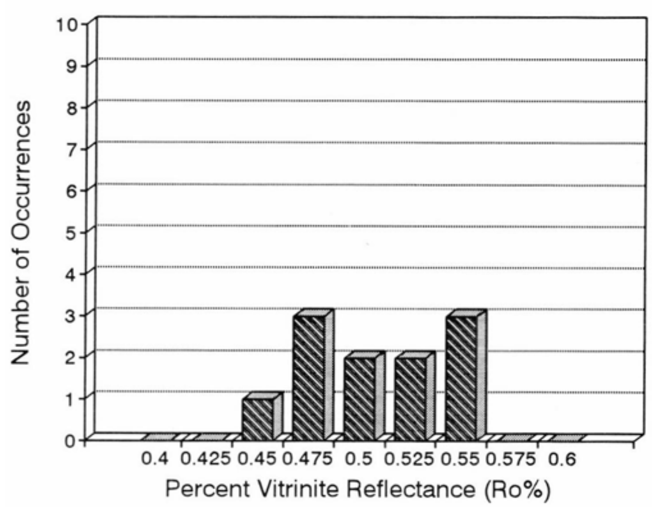

FIGURE 36—Frequency of vitrinite reflectance in Moreno Hill Formation, Salt Lake field. Average $R_o = 0.49$.

and Star Lake fields, the Cleary Coal Member, and the Gibson Coal Member coals show a negative skew (Figs. 37-39). In all the frequency diagrams the greatest number of occurrences of vitrinite reflectance is between 0.45 and 0.55, although the range of the values for the different formations varies significantly. This may be the result of variation in the number of samples taken from the field or formation and/or problems in the reproducibility of data. The Monero and Fruitland fields in the northern San Juan Basin have the highest average vitrinite reflectance (R_o) of the fields sampled (0.73 and 0.54, respectively). The Moreno Hill Formation coals, which are the oldest coals sampled, have the next highest average R_o (0.49). All the coals from the Menefee (excluding the Monero field) and Crevasse Canyon Formations have average vitrinite reflectance values of 0.46 to 0.47.

Maceral content

Maceral analysis measures the proportion by volume of the organically derived components in the coal samples. Vitrinite, derived from wood, leaf, or root tissue, is the dominant maceral in the San Juan Basin coals. It varies from a low of 50% to a high of 93% (Tables 18-22). The highest average percentage of vitrinite is in the Crevasse Canyon Formation coals (85%), and the lowest average is in the Fruitland Formation coals (69%). There is no statistical difference between the Menefee and Crevasse Canyon coals in percentage of vitrinite, but both of these are statistically different from the Fruitland Formation vitrinite content (Table 20). The frequency distributions of vitrinite are positively skewed for the Gibson Coal Member of the Crevasse Canyon Formation and the Cleary Coal and upper coal members of. the Menefee Formation (Figs. 40-42). The Fruitland Formation coals show a normal distribution in the Fruitland field (Fig. 43) and a bimodal frequency of vitrinite content in the Bisti and Star Lake fields (Fig. 44). The Moreno Hill Formation coals have a much lower and statistically different vitrinite percentage than all the other formations sampled (Table 19, Fig. 45).

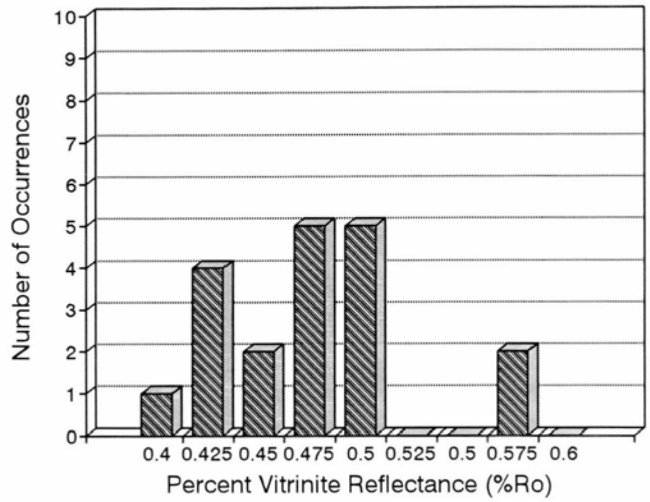

FIGURE 38—Frequency of vitrinite reflectance in Cleary Coal Member of Menefee Formation. Average $R_o = 0.46$.

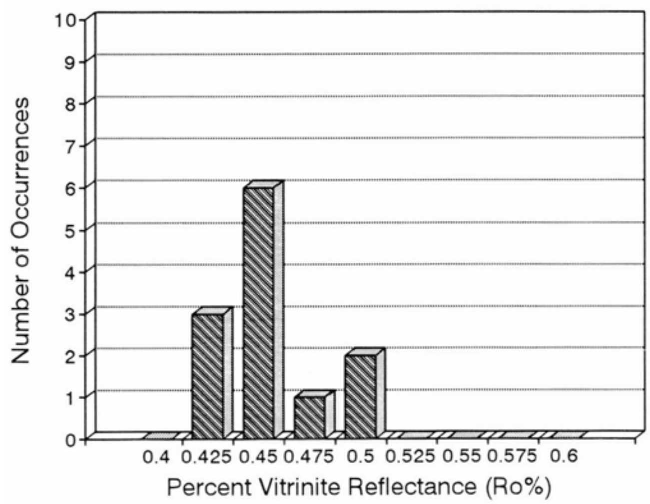

FIGURE 39—Frequency of vitrinite reflectance in Gibson Coal Member of Crevasse Canyon Formation. Average $R_o = 0.45$.

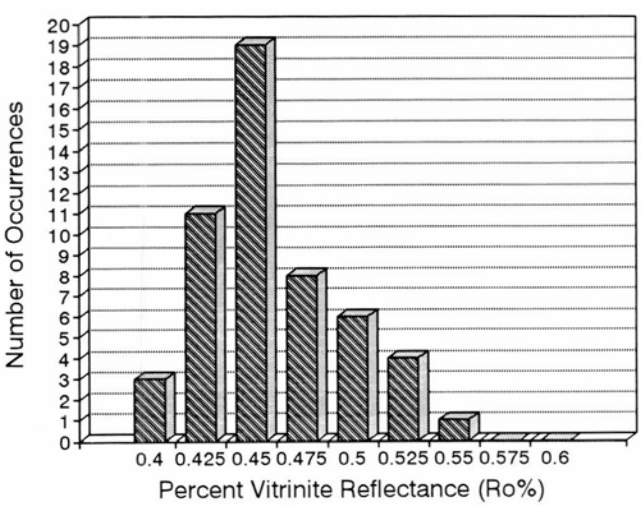

FIGURE 37—Frequency of vitrinite reflectance in Fruitland Formation, Bisti and Star Lake fields. Average $R_o = 0.45$.

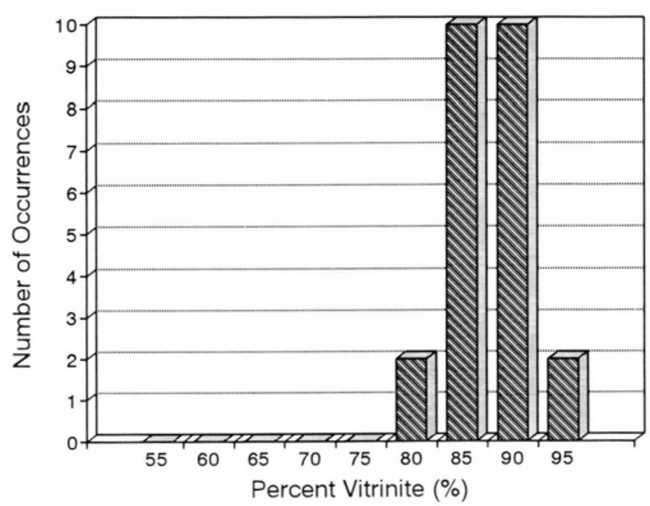

FIGURE 40—Frequency of vitrinite in Gibson Coal Member of Crevasse Canyon Formation. Average vitrinite = 86%.

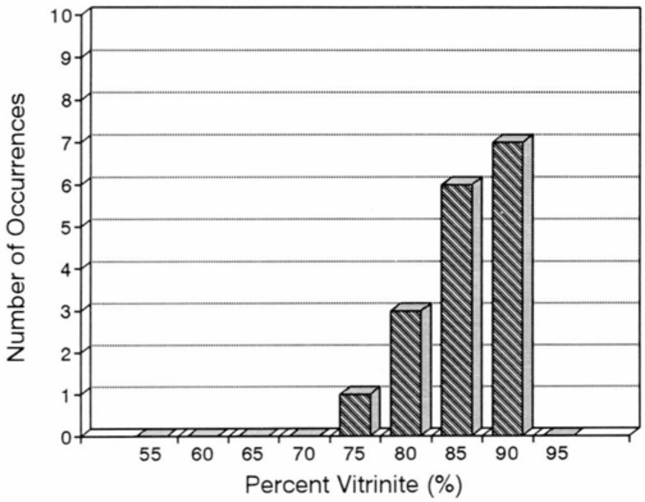

FIGURE 41—Frequency of vitrinite in Cleary Coal Member of Menefee Formation. Average vitrinite = 83%.

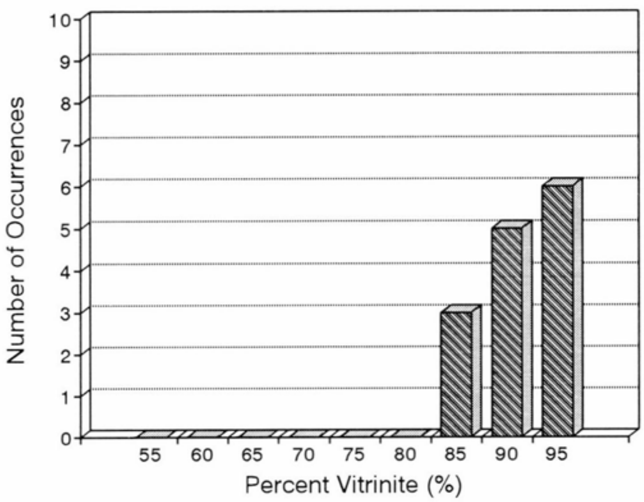

FIGURE 42—Frequency of vitrinite in upper coal member of Menefee Formation. Average vitrinite = 89%.

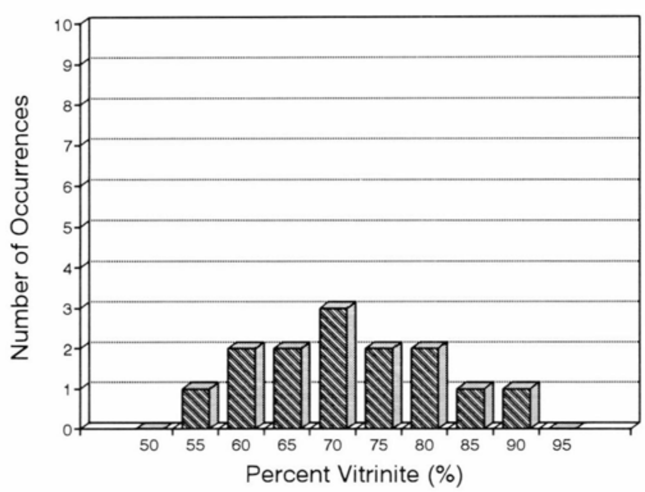

FIGURE 43—Frequency of vitrinite in Fruitland Formation, Fruitland field. Average vitrinite = 69%.

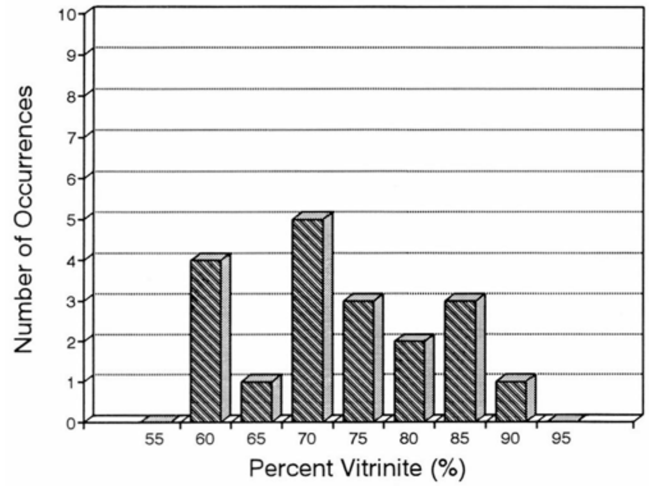

FIGURE 44—Frequency of vitrinite in Fruitland Formation, Bisti and Star Lake fields. Average vitrinite = 71%.

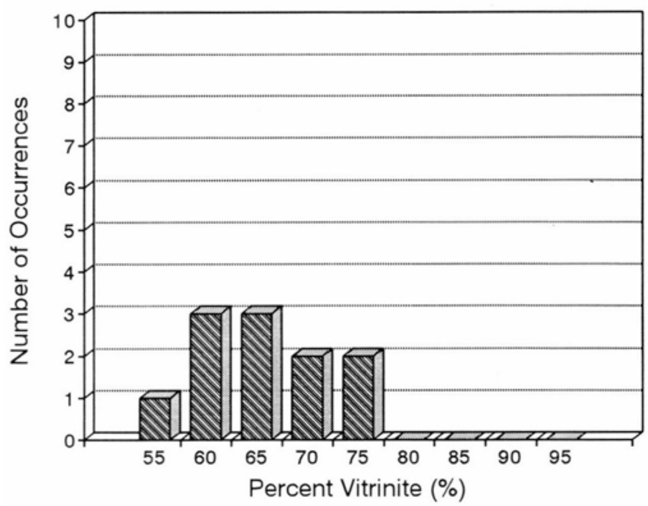

FIGURE 45—Frequency of vitrinite in Moreno Hill Formation, Salt Lake field. Average vitrinite = 63%.

Inertinite content ranges from 2 to 38% for all the fields sampled. Chemically and botanically, the source material of inertinite is the same as that of vitrinite, the cellulose and lignin from the cell walls of plants. However, this material has been oxidized either biochemically or by fire or desiccation early in its diagenetic history. All the coals sampled in this study have relatively low percentages of inertinite, between 8 and 27%, indicating that little of the plant material deposited in these swamps underwent oxidation. The average inertinite content in the Fruitland coals is 16% (Table 19), which is statistically higher than the percentage of inertinite in the Menefee and Crevasse Canyon (Mesaverde Group) coals (Fig. 32). The Menefee and Crevasse Canyon inertinite percentages are statistically within the same population (Table 20), which is illustrated by their grouping in Figure 32. The Moreno Hill Formation has the highest average percentage of inertinite (27%) of all the coals sampled and is statistically different from all the other fields. Most of the inertinite identified in the Moreno Hill coals is semifusinite, which is indicative of charring.

Liptinite macerals, coalified lipid plant material, comprise between 2 and 27% of the total and overall are the least abundant macerals in the coals sampled (Fig. 32). The widest range in maceral-group composition occurs in the Fruitland Formation, whereas the narrowest range occurs in the Mesaverde Group. The Fruitland coals have a higher percentage of resinite (13-17%) than the other coals sampled. Stach et al. (1982, p. 119) indicated that resinite has a high hydrogen content, although a direct correlation is not apparent from our analyses of the Fruitland Formation, probably because the overall liptinite content of these coals is a small percentage of the total maceral content. To test this relationship further, the hydrogen/volatile-matter ratio was compared to the resinite content. Generally the fields with high resinite (i.e. Fruitland, Bisti, Star Lake) do have a higher hydrogen/volatile-matter ratio (0.12) than the Menefee or Crevasse Canyon fields sampled.

A t-test comparison (Table 20) indicates that the Fruitland and Moreno Hill Formations are statistically different from the other formations sampled for vitrinite, liptinite, and inertinite content. These differences are clearly illustrated in the ternary diagram (Fig. 32). The Menefee and Crevasse Canyon coals are statistically within the same population for all three major maceral groups. Statistical differences in maceral content between the predominantly regressive Fruitland Formation and Cleary Coal Member are apparent for the vitrinite and liptinite content (Table 21). The percentage of vitrinite statistically varies between the transgressive sequences of the upper coal member of the Menefee Formation and the Gibson Coal Member of the Crevasse Canyon Formation. It would appear that there is no correlation between these depositional sequences and the maceral content of their coals.

Summary of petrographic data

The petrographic data from the NMRDI project do not indicate definite trends in the coals sampled, although several statistical differences exist between the formations. There is no clear geographic trend in the vitrinite reflectance, although the values are higher at the north end of the basin.

Maceral composition is affected by the nature of the plant material forming the peat as well as by oxidation of this material. The distribution of macerals in the Fruitland Formation coals differs significantly from that of older coals in the San Juan Basin (Tables 19, 20) in having a significantly higher liptinite-group (in particular resinite) content, suggesting an increasingly arboreal, liptinitic-rich flora over time (Fig. 32). The Moreno Hill Formation coals have a higher inertinite-group content than the other coals sampled, indicating that the swamps in which these coals formed were subjected to greater oxidation, perhaps due to burning, before burial.

Summary

Purpose and method of study

The purpose of this coal-quality study of surface-minable coals was to collect coal cores for quality analyses and to obtain lithologic and stratigraphic information from equally spaced drill sites in the major coal-bearing sequences of the San Juan Basin. The project was funded by the New Mexico Research and Development Institute (NMRDI) and several companies. During the three years of drilling and sampling, 149 drill sites on approximate two-mile centers were completed in the Fruitland, Menefee, Crevasse Canyon, and Moreno Hill Formations. Most of these drill sites were located along a line parallel to the Cretaceous shorelines. Eight drill sites in the Chacra Mesa field were drilled on a line perpendicular to the shorelines on one-mile centers. The Fruitland Formation sites in the Fruitland field and the Moreno Hill Formation sites in the Salt Lake field of west-central New Mexico were drilled on two-mile centers along lines perpendicular to the Late Cretaceous shorelines.

Forty-nine sites were drilled in the Fruitland Formation and 252 coal samples were analyzed from the Fruitland, Bisti, and Star Lake fields. The upper coal member of the Menefee Formation was penetrated at 23 locations and 65 coal samples were analyzed from the Chacra Mesa and La Ventana fields. The Cleary Coal Member of the Menefee Formation was cored at 39 drill sites, producing 107 samples from the La Ventana, Chacra Mesa, San Mateo, and Standing Rock fields. The seven remaining Menefee locations were in the Monero field and four coal samples were analyzed from these drill holes. The Cleary—Gibson, Gibson, and Dilco Coal Members of the Crevasse Canyon Formation were drilled at 22 sites in the Gallup and Crownpoint fields. Forty-two samples from the Cleary—Gibson in the Gallup area, 30 samples from the Gibson Coal Member in the Crownpoint field, and 13 samples from the Dilco Coal Member in the Gallup field were taken for chemical analyses. Five sites were drilled in the Moreno Hill Formation in the Salt Lake field and 11 samples were collected for chemical analyses. All the drilling data and chemical and petrographic analyses done during this study are available in the New Mexico Bureau of Mines & Mineral Resources Open-file Report 377 (Hoffman, 1991).

Lithologic and quality **characteristics**

Fruitland Formation

Most of the Fruitland Formation coals in the Fruitland, Bisti, and Star Lake fields are associated with shales and concentrated in the lower 150-200 ft of the coal-bearing sequence. Many of the thickest coals are just above the Pictured Cliffs Sandstone contact. The Fruitland field has some of the thickest (up to 30 ft) coal beds in the San Juan Basin. This area appears to have experienced several stillstands and minor reversals in the retreat of the shoreline, which allowed for thick peat development resulting in multiple, relatively thick coal beds. The frequency and thickness of the coals wane to the south and east in the Bisti and Star Lake fields. The increase in siltstones and sandstones in the Star Lake field and the smaller percentage of coals in the sequence indicate a relatively rapid retreat of the shoreline at this locality, possibly because of differential subsidence in this part of the basin (Hunt, 1984).

The Fruitland Formation coal-quality analyses indicate some geographic trends. The Fruitland field coals are higher in sulfur (0.88%, weighted avg., dry basis) than the Bisti or Star Lake field coals (0.59% and 0.64%, respectively, weighted avg., dry basis). The apparent rank of the Fruitland field coals is high-volatile B—C bituminous compared to high-volatile C bituminous to subbituminous A for the other fields. All three Fruitland areas have high ash yields (>20%, weighted avg., dry basis), although Star Lake has the highest ash (26%, weighted avg., dry basis) partially resulting from the large number of partings in these thin coal beds. Silica and aluminum are the major constituents of ash in the Fruitland coals, with minor amounts of calcium and sodium. Petrographic analyses indicate a difference in maceral content between the Fruitland coals and the other older formations sampled. These coals have a higher percentage of liptinite. Resinite, a constituent of the liptinite maceral group, is particularly high in the Fruitland field coals and there appears to be a general correlation between the increased resinite content and a higher hydrogen/volatile-matter ratio. The vitrinite reflectance in the Fruitland field is the highest (0.54) in this formation and higher than in all other fields sampled except for the Monero field. The volatile matter in the Fruitland field is also the lowest of all the fields sampled. These values indicate that the Fruitland field coals have a greater thermal maturity than other coals sampled farther south in the San Juan Basin. The increased coalification of the Fruitland field coals is attributed to the close proximity of the San Juan volcanic complex and heat advection by ground-water flow.

Menefee Formation

Coal-bearing sequences occur at the top and base of the Menefee Formation. The transgressive upper coal member was sampled in the La Ventana and Chacra Mesa fields along the southeast edge of the San Juan Basin. The upper coal member is 250-500 ft thick and in the La Ventana field intertongues with the La Ventana Tongue of the Cliff House Sandstone. The Chacra Mesa tongue of the Cliff House Sandstone in the Chacra Mesa field intertongues with the upper Menefee Formation. The regressive Cleary Coal Member is at the base of the Menefee, above the Point Lookout Sandstone. This coal member was drilled in the La Ventana, Chacra Mesa, San Mateo, and Standing Rock fields.

The upper coal member of the Menefee Formation is one of the few transgressive sequences in the San Juan Basin that contain some moderately thick coals (8-10 ft). The thickest coals are part of the intertonguing of the Menefee with the massive sandstone buildup of the La Ventana Tongue of the Cliff House Sandstone. In the Chacra Mesa field, where the Cliff House sandstones (Chacra Mesa tongue) are not as massive or as stacked as in the La Ventana Tongue, the upper coal member of the Menefee contains only a few thin, shaly coals.

The Cleary Coal Member of the Menefee Formation is a 100-300 ft thick coal-bearing sequence deposited behind the regressive barrier-beach sandstones of the Point Lookout Sandstone. The entire Cleary sequence displays an increase in sandstone and siltstone content east (La Ventana and Chacra Mesa fields) and west (Standing Rock field) of the San Mateo field. The thickest coals in the Cleary occur it the San Mateo area, with a concentration of thick beds (6-19 ft) southwest of San Miguel Creek dome. Coal beds thin northeast and northwest from this area. Beaumont (this report) believes that the San Miguel Creek dome and other similar small structures in this area influenced the Late Cretaceous shorelines and probably created a localized stable environment suited for a thicker peat development. Similarly to the Fruitland Formation, the thickest beds in the Cleary Coal Member are often near the base of the coal-bearing sequence, above the barrier-beach Point Lookout Sandstone contact.

The Monero field coal-bearing sequence (75-100 ft) includes both the upper and Cleary Coal members of the Menefee Formation and is an abbreviated version of the sequence in the southern San Juan Basin. The close proximity of the Monero field to the point of maximum transgression of the Point Lookout shoreline did not allow for a thick nonmarine sequence to develop before the subsequent regression of the sea and deposition of the Cliff House Sandstone (Hoffman, 1991a). Because of the limited thickness of the coal-bearing interval, the coal beds in the Monero field are thin (1-3 ft) and occur in a limited geographic area.

Stratigraphic and geographic quality differences occur in the Menefee Formation coals. The ash yield is lowest in the upper member coals (8-10%), and is significantly higher in the Cleary coals (13-15%) and the Monero field Menefee coals (15%). The ash yields of these Menefee coals are significantly lower than in the Fruitland Formation coals sampled, which is an artifact of their depositional environment. The iron-oxide content of all the Menefee coals is significant, higher than 5%, and in the Monero averages 18% of the total ashed oxides. Sulfur content of the La Ventana field coals in both the Cleary and upper members is above 1%. The sulfur values for all the Cleary Coal Member fields sampled (0.9-1.0%) show little statistical variation. In the upper member coals the sulfur values decrease from the La Ventana (1.57%) to the Chacra Mesa field (0.97%). The average sulfur is highest in the Monero field (2.19%), although not all of the coals sampled in the Monero field are high in sulfur. In the Menefee coals the sulfur content is significantly higher than in the Fruitland coals sampled in the Bisti and Star Lake fields. The Fruitland field mean sulfur values are comparable to the Menefee coal values except for the upper member La Ventana field coals and the Monero coals, which are statistically higher. Apparent-rank values of the Menefee coals range from subbituminous A in the Standing Rock field to high-volatile A bituminous in the Monero field. The higher rank of the Monero field is probably a function of its proximity to the San Juan volcanic complex and heat advection by ground-water flow. A greater thermal maturity is also indicated by the high vitrinite reflectance (avg. 0.73) of the Monero coals. Most of the Menefee coals sampled are in the subbituminous A to high-volatile C bituminous range.

Crevasse Canyon Formation

These coals are concentrated in the Gibson Coal Member and the Dilco Coal Member. The Gibson Coal Member was sampled in the Crownpoint field. The lower Gibson was deposited during a time of seaward advance and is underlain by the Dalton Sandstone of the Crevasse Canyon Formation. The upper Gibson is part of a transgressive phase overlain by the Hosta Tongue of the Point Lookout Sandstone. In the Gallup area the Crevasse Canyon and Menefee Formations are not separated by the Point Lookout Sandstone. The maximum extent of the Point Lookout is northeast of this area, and, therefore, the Cleary Coal Member and Gibson Coal Member are undivided in the Gallup field. This combined coal-bearing unit is a non-marine sequence deposited during a major reversal of the shoreline. The Dilco Coal Member is a regressive coal-bearing sequence deposited behind the marine Gallup Sandstone.

The 200 ft thick coal-bearing sequence of undivided Cleary—Gibson in the Gallup field is shale-dominated, although sandstones become prevalent in the eastern drill sites. There is a greater concentration of coals in the shale-dominated sequences and the thickest coals (up to 7 ft) are associated with shales. These coals were probably formed in a fairly stable lower coastal-plain environment, inland from the major reversal of the shoreline. South and west of the town of Gallup the number of coals in the Cleary—Gibson sequence decreases, away from the shoreline.

The Gibson Coal Member in the Crownpoint field is a shale-dominated sequence ranging in thickness from 150 to 240 ft. The frequency of sandstones in the coal-bearing sequence increases to the northwest, possibly because of intertonguing with the Hosta Tongue of the Point Lookout Sandstone. Coals encountered in the northwestern Crownpoint drill sites are often associated with Hosta Tongue sandstones, suggesting that a back-barrier swamp environment developed during times of stillstands and minor shifting of the shoreline. Southeast of the town of Crown-point, in the Borrego Pass area, the thicker coals (3.55 ft) are associated with shales probably representing a lower coastal-plain swamp environment. These thicker coals may have developed in a laterally equivalent position to the major shoreline reversal that allowed for a relatively greater accumulation of peat.

The Dilco Coal Member in the Gallup area is a 150-300 ft thick shale-dominated sequence with interbedded silty sandstones. The Dilco coals are thin and tend to be shaly, perhaps because of sediment influx into the swamp environment. The Dilco coal-bearing section sampled in the Gallup area appears to have been deposited during a relatively rapid retreat of the shoreline to the northwest, which did not promote a thick accumulation of peat.

The undivided Cleary—Gibson and the Gibson Coal Member (Crevasse Canyon Formation) coals have moisture contents (14-15%) comparable to those of the Cleary Coal Member coals in the Menefee Formation fields. The Dilco coals have a lower moisture content (11%, weighted avg., dry basis), possibly due to a greater depth of burial. The ash yield is higher for the Dilco coals (20%, weighted avg., dry basis) than for the Gibson or Cleary—Gibson coals (ash yield 10%, weighted avg., dry basis). The ashed-oxide analyses of the Dilco coals indicate that silica and aluminum form a higher percentage of the total ashed oxide (86%) than in the Cleary—Gibson and Gibson coals, probably due to a greater sediment influx into the swamps. The Gibson coals from Crownpoint field have a high iron-oxide content (13%), which probably is a function of the higher sulfide values of these coals. Average sulfur content is highest in the Gibson coals from Crownpoint field (2.25%, weighted avg., dry basis). The average sulfur content of the Dilco coals (0.95%, weighted avg., dry basis) and the Cleary—Gibson coals (0.66%, weighted avg., dry basis) is significantly lower. These differences in sulfur content may be indicative of the depositional environment and coal deposition during either a transgressive or regressive cycle, which would dictate the overlying strata to be either marine or nonmarine. The Crevasse Canyon Formation coals have an average sulfur content between the Fruitland coals and the Menefee coals of the San Juan Basin.

The apparent rank of the Crevasse Canyon coals averages high-volatile C bituminous for the Dilco and Cleary—Gibson coals sampled in the Gallup area. The Crownpoint Gibson coals are of a lower apparent rank, subbituminous A. The range in rank within the Crevasse Canyon Formation is similar to that of the coals in the Menefee Formation and the Bisti and Star Lake fields of the Fruitland Formation. There is very little variation in the vitrinite reflectance among these coals, the average Ro is 0.46 or 0.47. The maceral contents of the Menefee and Crevasse Canyon coals are very similar and statistically within the same population. Vitrinite makes up the largest portion (85%) of the Crevasse Canyon coals, with minor amounts of liptinite and inertinite.

Moreno Hill Formation

The Moreno Hill Formation is the oldest coal-bearing sequence sampled in this study. The lower Moreno Hill is equivalent to the Tres Hermanos Formation, and the middle and upper Moreno Hill are equivalent to the Gallup Sandstone and Crevasse Canyon Formation, respectively (Hook et al., 1983). Both the upper and lower members of the Moreno Hill Formation are coal-bearing, although the coals in the upper part are of little consequence. The lower Moreno Hill Formation is 115-183 ft thick in the area drilled. There are three coal zones in the lower member, the Antelope, Cerro Prieto, and Rabbit (Campbell, 1989). The lowermost coals are within 50 ft of the contact with the marine Atarque Sandstone. These coals are generally associated with shales and represent back-barrier swamp deposits (Anderson and Stricker, 1987). The second coal above the Atarque—Moreno Hill contact often is the thickest (5-7 ft). The upper part of the Moreno Hill sequence has a higher percentage of silt and sand and the coals are more often associated with sandstones or siltstones. The coals in the upper part of the lower member are thin (1-3 ft) and probably of fluvial origin (Campbell, 1987).

The Moreno Hill Formation coals sampled in this study have a moderately high moisture (15%, weighted avg.), ash yield (18%, weighted avg., dry basis), and sulfur content (1.4%, weighted avg., dry basis). The sulfur is higher in coals near the contact with the marine Atarque Sandstone. The apparent rank of these coals averages subbituminous A. The Moreno Hill coals have the highest percentage of inertinite maceral content of all the formations sampled. Inertinite is formed by oxidation of plant material that otherwise would be preserved as vitrinite. The predominance of semifusinite, a constituent of the inertinite group, in these coals indicates that the plant material was charred before burial. The vitrinite reflectance (0.49) is higher than the mean R_o for any of the Crevasse Canyon and Menefee coals in the southern San Juan Basin. Two factors could have influenced the thermal maturity of these coals, (1) time and (2) close proximity of Tertiary and Quaternary volcanics.

Conclusions

The Fruitland Formation coals tend to be the most economic coals because of their thickness, relative continuity, and overall quality, however their ash yield is high. The apparent rank and thermal maturity of the Fruitland field coals increase their economic importance, as is evidenced by surface-mining activity in this area and coalbed-methane interests to the east, where these coals are at greater depths. The Menefee Formation coals do not have the same degree of continuity or thickness as the Fruitland coals, but the ash is lower and the apparent rank is equivalent to that of the Fruitland coals in the Bisti and Star Lake fields (subbituminous A). The Menefee Formation coals, with the exception of the San Mateo field, have relatively high sulfur content (>1%). Of the Menefee Formation coal fields investigated, the San Mateo field has the best economic potential because of the thickness and relatively low sulfur and ash yields of the coals. The Cleary—Gibson coals in the Gallup area have the best economic potential of the Crevasse Canyon fields examined. This coal-bearing sequence has multiple coal beds and relatively thick coals. The Cleary—Gibson coals also have low ash and sulfur values that enhance their economic potential. As a consequence of the quality of these coals, the San Mateo and Gallup coal fields have active coal mining and/or active coal leases.

Of the remaining fields drilled, the upper member Menefee coals in the La Ventana field and the Crevasse Canyon coals in part of the Crownpoint field may be of economic interest. The La Ventana upper member coals are relatively thick and have low ash yields. The thick overburden of sandstone may be prohibitive to surface mining, but underground mining may have a potential, and has been investigated in the past (Nickelson, 1988, pp. 173-201, La Ventana field). The Crownpoint field, in particular the areas northwest of the town of Crownpoint and at Borrego Pass, has some economic potential. The coals are thickest in these two areas, although the average sulfur content is higher than 1% and the apparent rank is subbituminous A. Both the La Ventana field and especially the Crownpoint area would require more drilling and coal analyses to better determine the extent, thickness, and quality of the coals.

The quality data gained through this study greatly increase the amount of information available on all the fields investigated, in particular those areas where there has been little or no recent coal exploration. Although this study included elemental and petrographic analyses, these data sets are far from complete. The increased interest in environmental impacts of coal combustion and coalbed-methane production makes both elemental and petrographic analyses important sources of information. More complete data sets would allow researchers to determine stratigraphic and geographic trends, and changes in depositional environments, which could facilitate mining operations as well as exploration for coal and coalbed methane.

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Selected conversion factors*

TO CONVERT	MULTIPLY BY	TO OBTAIN
Length		
inches, in	2.540	centimeters, cm
feet, ft	3.048×10^{-1}	meters, m
yards, yds	9.144×10^{-1}	m
statute miles, mi	1.609	kilometers, km
fathoms	1.829	m
angstroms, Å	1.0×10^{-8}	cm
Å	1.0×10^{-4}	micrometers, μm
Area		
in^2	6.452	cm^2
ft^2	9.29×10^{-2}	m^2
yds^2	8.361×10^{-1}	m^2
mi^2	2.590	km^2
acres	4.047×10^{3}	m^2
acres	4.047×10^{-1}	hectares, ha
Volume (wet and dry)		
in^3	1.639×10^{1}	cm^3
ft^3	2.832×10^{-2}	m^3
yds^3	7.646×10^{-1}	m^3
fluid ounces	2.957×10^{-2}	liters, l *or* L
quarts	9.463×10^{-1}	l
U.S. gallons, gal	3.785	l
U.S. gal	3.785×10^{-3}	m^3
acre-ft	1.234×10^{3}	m^3
barrels (oil), bbl	1.589×10^{-1}	m^3
Weight, mass		
ounces avoirdupois, avdp	2.8349×10^{1}	grams, gr
troy ounces, oz	3.1103×10^{1}	gr
pounds, lb	4.536×10^{-1}	kilograms, kg
long tons	1.016	metric tons, mt
short tons	9.078×10^{-1}	mt
oz mt^{-1}	3.43×10^{1}	parts per million, ppm
Velocity		
ft sec^{-1} (= ft/sec)	3.048×10^{-1}	m sec^{-1} (= m/sec)
mi hr^{-1}	1.6093	km hr^{-1}
mi hr^{-1}	4.470×10^{-1}	m sec^{-1}

TO CONVERT	MULTIPLY BY	TO OBTAIN
Pressure, stress		
lb in^{-2} (= lb/in^2), psi	7.03×10^{-2}	kg cm^{-2} (= kg/cm^2)
lb in^{-2}	6.804×10^{-2}	atmospheres, atm
lb in^{-2}	6.895×10^{3}	newtons (N)/m^2, N m^{-2}
atm	1.0333	kg cm^{-2}
atm	7.6×10^{2}	mm of Hg (at 0° C)
inches of Hg (at 0° C)	3.453×10^{-2}	kg cm^{-2}
bars, b	1.020	kg cm^{-2}
b	1.0×10^{6}	dynes cm^{-2}
b	9.869×10^{-1}	atm
b	1.0×10^{-1}	megapascals, MPa
Density		
lb in^{-3} (= lb/in^3)	2.768×10^{1}	gr cm^{-3} (= gr/cm^3)
Viscosity		
poises	1.0	gr cm^{-1} sec^{-1} *or* dynes cm^{-2}
Discharge		
U.S. gal min^{-1}, gpm	6.308×10^{-2}	l sec^{-1}
gpm	6.308×10^{-5}	m^3 sec^{-1}
ft^3 sec^{-1}	2.832×10^{-2}	m^3 sec^{-1}
Hydraulic conductivity		
U.S. gal day^{-1} ft^{-2}	4.720×10^{-7}	m sec^{-1}
Permeability		
darcies	9.870×10^{-13}	m^2
Transmissivity		
U.S. gal day^{-1} ft^{-1}	1.438×10^{-7}	m^2 sec^{-1}
U.S. gal min^{-1} ft^{-1}	2.072×10^{-1}	l sec^{-1} m^{-1}
Magnetic field intensity		
gausses	1.0×10^{5}	gammas
Energy, heat		
British thermal units, BTU	2.52×10^{-1}	calories, cal
BTU	1.0758×10^{2}	kilogram-meters, kgm
BTU lb^{-1}	5.56×10^{-1}	cal kg^{-1}
Temperature		
°C + 273	1.0	°K (Kelvin)
°C + 17.78	1.8	°F (Fahrenheit)
°F − 32	5/9	°C (Celsius)

**Divide by* the factor number to reverse conversions.
Exponents: for example 4.047×10^{3} (see acres) = 4,047; 9.29×10^{-2} (see ft^2) = 0.0929.

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