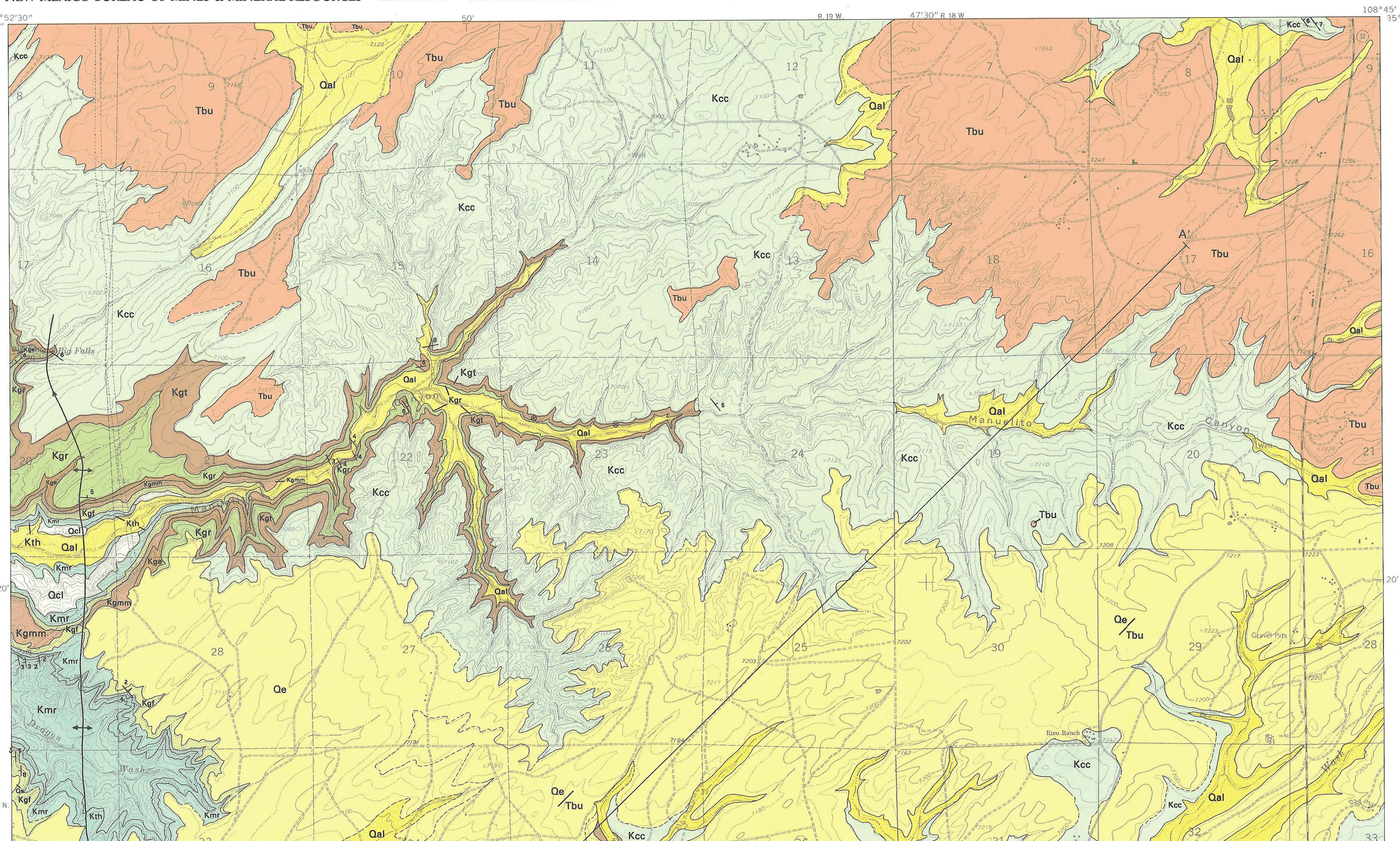


Base from U.S. Geological Survey
Geology by O. J. Anderson, 1984–85

SCALE 1:24 000

1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 KILOMETER

Geologic color separations and layout by Monte M. Brown
Edited by J. C. Love

CORRELATION OF UNITS

Qal, Qe, Qcl	HOLOCENE / PLEISTOCENE
Tbu	PLIOCENE
Kcc, Kgt, Kgr, Kge, Kgmm, Kgf, Kmr (Kth beds), Kmr, Kdt, Kmw, Kd	UPPER CRETACEOUS
unconformity	
Jz	MIDDLE JURASSIC

DESCRIPTION OF UNITS

Qal — **Alluvial deposits (Quaternary)**—sand, silt, and clay in the major drainages, their tributaries, and floodplains

Qe — **Mostly eolian deposits (Quaternary)**—very fine grained windblown sand as sheet deposits on upland surfaces; no recognizable dune forms

Qcl — **Colluvium and landslide debris (Quaternary)**—commonly covers slopes developed on Mancos Shale; includes some toreva blocks

Tbu — **Upper member of Bidahochi Formation (Pliocene?)**—consists of moderately reddish-brown to light-brown argillaceous sandstone, some mudstone, and two white rhyolitic ash beds; 0–140 ft thick

Kcc — **Crevasse Canyon Formation (Upper Cretaceous, Coniacian)**—an interbedded sequence of mudstone, shale, very fine to medium-grained crossbedded sandstone, carbonaceous shale, and minor lenticular coal beds; nonmarine; 0–800 ft thick but not all exposed

Kgt — **Torrivio Member of Gallup Sandstone (Upper Cretaceous, Coniacian?)**—distinctive, medium- to coarse-grained feldspathic sandstone, commonly reddish brown with pronounced crossbedding; paleoflow directions to north, northeast, and east; considered to be a braided-stream deposit; base is generally sharp; 30–50 ft thick

Kgr — **Ramah unit of Gallup Sandstone (Turonian)**—variable sequence of mudstone, fluvial-channel sandstone, carbonaceous mudstone, and minor coal; one coaly zone reaches 5.4 ft in thickness but is not persistent; unit overlies uppermost marine Gallup; 110–150 ft thick

Kge — **E sandstone member of Gallup Sandstone (Turonian)**—very pale orange and grayish-orange, very fine to fine-grained quartzose sandstone; three generally coarsening-upward sequences, each up to 30 ft thick; sandstone units tend to be crossbedded in upper half; burrows, including *Ophiomorpha*, are common; bioturbated zones; locally, fining-upward sequences with opposed crossbed sets and clay drapes are present, indicating tidal influence; a 20–25-ft-thick paludal shale separates the two lower sandstone units; *Inoceramus dimidius* found at top of upper unit; *I. dimidius* also found in the more massively bedded overlying third sandstone unit; 75–110 ft thick

Kgmm — **Middle part of main Gallup Sandstone (Turonian)**—gray mudstone and shale with minor carbonaceous mudstone and coal representing deposition on the lower coastal plain in a backswamp environment; contains a 3-ft-thick coal bed in south-central part of quadrangle; 60–70 ft thick

Kgf — **F sandstone member of Gallup Sandstone (Turonian)**—very pale orange, grayish-orange, and yellowish-gray, very fine to fine-grained quartzose sandstone; consists of two coarsening-upward units, each ranging from 12 to 20 ft thick and separated by 10–18 ft of mudstone, carbonaceous mudstone, and high-ash coals; basal sand unit generally has gradational base through an 8-ft-thick zone of intercalated fine-grained sandstone and mudstone (transition-zone sediments); both sandstone units contain numerous burrows, including *Ophiomorpha*, and are locally bioturbated in lower part; basal part of upper sand unit is transgressive on coal-bearing paludal mudstones; 44–50 ft thick

Kmr / Kth beds / Kmr — **Rio Salado Tongue of Mancos Shale (Cenomanian and Turonian)**—gray to brownish-gray shale and arenaceous shale; base generally sharp on top of Twowells Tongue; 40 ft above base, platy limestone beds of Bridge Creek Limestone Member of Greenhorn Formation may be recognized (SW1/4 sec. 16, T12N, R19W); 100 ft below top, thin, yellowish-gray sandstone beds containing *Collignoniceras woollgari* are recognized as equivalent to basal Tres Hermanos Formation and were mapped separately as *Kth*; the portion of *Kmr* above the *Kth* beds is 40–44 ft thick and contains large (up to 2 ft in diameter) dark-brown to reddish-brown limestone concretions

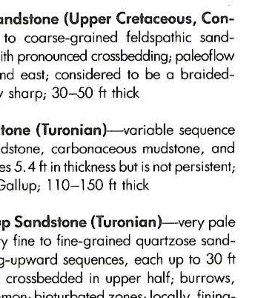
Kdt — **Twowells Tongue of Dakota Sandstone (Cenomanian)**—tan and very pale orange, lower very fine grained to lower medium-grained quartzose sandstone; bioturbated and burrowed, including *Ophiomorpha* and *Thalassinoides*; ripple laminations preserved locally in middle and lower parts; flat-bedded base; planar and trough-type crossbedding present in upper part; represents single progradational event; 25 ft thick maximum

Kmw — **Whitewater Arroyo Tongue of Mancos Shale (Cenomanian)**—gray to olive-gray silty shale; the oyster *Exogyra trigeri* is present, though not in abundance; base of unit is sharp; 60–80 ft thick

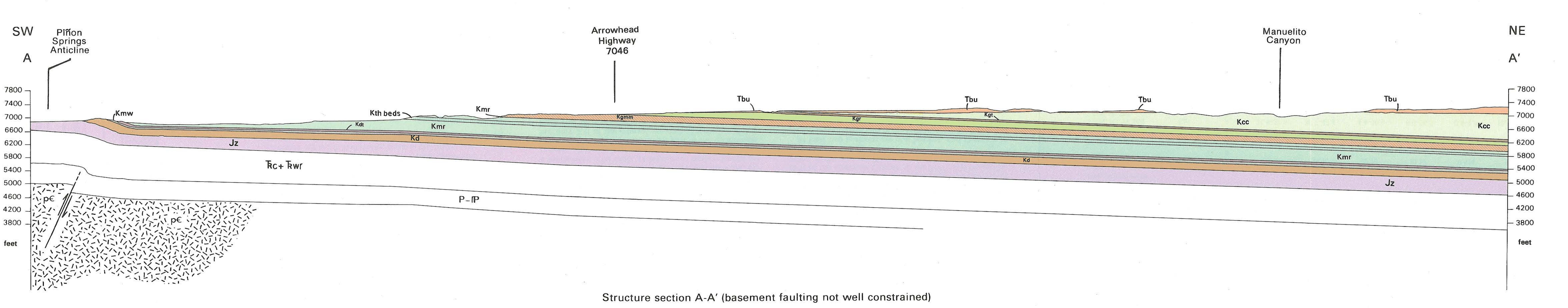
Kd — **Main body of Dakota Sandstone (Upper Cretaceous, Cenomanian)**—grayish-orange and very pale orange, fine- to coarse-grained sandstone, conglomeratic sandstone, mudstone, carbonaceous mudstone, and coaly carbonaceous mudstone; basal sandstone rests unconformably on Jurassic rocks and contains a quartzite- and chert-pebble conglomerate in lower 4 ft; basal sandstone is of fluvial origin and reaches 45 ft thick maximum; the overlying mudstone and carbonaceous unit is of paludal origin and ranges up to 80 ft thick with the greater thicknesses coming at the expense of underlying sandstone; the upper part consists of an interbedded sequence of arenaceous shale and fine- to very fine grained quartzose sandstone containing smooth-walled, small-diameter burrows with affinities to *Skolithos* and *Thalassinoides*; the very top, 12-ft-thick, coarsening-upward sandstone, containing the oyster *Exogyra levis* and the gastropod *Turritella* sp., may be the equivalent of the Paguate Tongue; total thickness of upper part is 30 ft; overall thickness for main body Dakota is 115–120 ft

Jz — **Zuni Sandstone (Middle Jurassic)**—very fine to medium-grained, white to pinkish-gray, quartzose eolian sandstone characterized by thick sets of planar and planar–tangential, high-angle crossbeds; crossbed-dip direction variable, but southeast is most common; upper part equivalent to Cow Springs Sandstone; total thickness locally up to 500 ft

TRUE NORTH
MAGNETIC N.
13°
APPROXIMATE MEAN DECLINATION, 1980



INDEX MAP OF NEW MEXICO



Structure section A-A' (basement faulting not well constrained)

Geology and coal resources of Vanderwagen quadrangle, McKinley County, New Mexico

by Orin J. Anderson, 1990
New Mexico Bureau of Mines & Mineral Resources, Socorro, NM 87801

Abstract

A portion of the east flank of the Piñon Springs anticline crosses the extreme southwest corner of the Vanderwagen 7½-min quadrangle, and it is the dominant structural feature. The anticline brings Jurassic rocks to the surface, but throughout most of the quadrangle Upper Cretaceous rocks are at the surface although veneered extensively with sediments of the late Tertiary Bidahochi Formation and with Recent eolian sand. For the most part the Upper Cretaceous rocks dip gently northeastward, 1°–4°, toward the axis of the asymmetric Zuni Basin. These rocks range from the Dakota Sandstone (Cenomanian) through the Crevasse Canyon Formation (Coniacian).

Three Cretaceous units are coal bearing, the Dakota Sandstone, the Gallup Sandstone, and the Dilco, but only the latter two contain coal of sufficient quality and in beds thick enough to be considered a resource.

The Vanderwagen quadrangle encompasses the southernmost area of the Zuni Basin, in which the Tres Hermanos Formation and the Pescado Tongue of the Mancos Shale are neither recognized nor mapped as a distinct regressive–transgressive sequence below the Gallup Sandstone. The landward pinchout of the Pescado Tongue occurs in the subsurface a few miles to the east and southeast of the quadrangle, and thus no basis exists for differentiating a lower (Tres Hermanos) from an upper (Gallup) regression. Accordingly, all nearshore, shoreface, and back-barrier sandstones deposited at the close of and immediately following the Greenhorn cycle of sedimentation were mapped as Gallup Sandstone.

INTRODUCTION

The Vanderwagen 7½-min quadrangle lies 12–20 mi south of Gallup in the northern half of the Zuni Basin. The area is accessible via NM–32, a paved road that passes along the eastern margin of the quadrangle (Fig. 1). No cities, large towns, or major installations are present, but the small village of Vanderwagen, on NM–32 in the southeast corner, lends its name to the quadrangle. The abandoned village of Two Wells is located in the southwest corner of the quadrangle near the type section of the Twowells Tongue of the Dakota Sandstone.

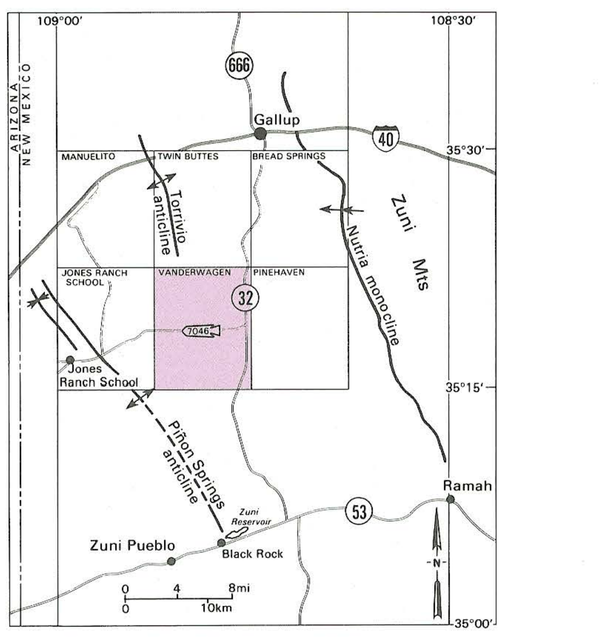


FIGURE 1—Index map of north half of Zuni Basin showing location of Vanderwagen quadrangle, surrounding quadrangles, and major geologic and geographic features.

Elevations range from a low of approximately 6,650 ft in the northwest, where Manuelito Creek crosses the quadrangle boundary, to a high of 7,283 ft in the northeast corner. Manuelito Canyon is incised approximately 350 ft below the upland surface, and the canyon walls provide the best outcrops of Gallup Sandstone in the quadrangle. The floor of Whitewater Arroyo, where it crosses the Piñon Springs anticline in the southwest corner, is at an elevation of approximately 6,800 ft. Except for the broader alluvial-valley floors and the very well drained uplands with their veneer of eolian sediment, the area carries a cover of piñon and juniper.

No perennial streams cross the area; however, two major tributaries of the Rio Puerco of the West, commonly known as the Puerco River, drain the quadrangle. The Manuelito Canyon tributary drains the northern half of the quadrangle and joins the Puerco River on the New Mexico side, whereas Whitewater Arroyo (type locality of the Whitewater Arroyo Tongue of the Mancos Shale) drains the southern half of the quadrangle and joins the Puerco River approximately 10 mi inside the Arizona border. All these drainages in the Vanderwagen quadrangle are anaclinal in that they flow against structural dips.

Previous work in the area includes that of Darton (1910), who included the Zuni Basin in a regional study, Sears (1925), who discussed Cretaceous stratigraphy and coal resources of the Gallup–Zuni Basin, and Shomaker et al. (1971), who included the Zuni Basin in a regional evaluation of strippable coal resources. More recently Tabet (1981), assisted by subsurface data, mapped and reported on the coal resources of the adjacent Pinehaven 7½-min quadrangle. Most recently Molenaar (1983) and Hook et al. (1983) described in detail the Gallup Sandstone and the Tres Hermanos Formation and added greatly to our understanding of the intertongued marine–nonmarine sequence in the Zuni Basin.

ACKNOWLEDGMENTS—This geologic map is the result of encouragement from Frank Kottlowski, Director of the New Mexico Bureau of Mines and Mineral Resources, to extend our investigations of Cretaceous rocks and coal resources northwestward from the Pinehaven area to the Manuelito area. The New Mexico Bureau of Mines and Mineral Resources provided the support for the field work and laboratory analyses. Special thanks go to Stephen C. Hook of Texaco, Inc. and William A. Cobban of the U.S. Geological Survey for identification of the molluscan fauna and for helpful suggestions, to Donald L. Wolberg and William A. Cobban for reviewing and improving the text, to Richard M. Chamberlin for reviewing the map and cross sections, to Frank Campbell for proximate analysis of the coal samples, and to Lynne McNeil, who typed the manuscript. The author is most grateful to all the local ranchers and landowners who gave their permission to enter, map, and collect samples on their property; these include Frank and Charlene Montaño, Glen Adekai, Darrell Olson, and Wilson Skeets.

STRATIGRAPHY

The composite stratigraphic column (Fig. 2) illustrates the Jurassic through Tertiary units exposed in the quadrangle. It is based on detailed measured sections made at 17 localities throughout the quadrangle. Emphasis was on the Gallup Sandstone and overlying, coal-bearing section, but thicknesses were established for all units except the Zuni Sandstone and the Rio Salado Tongue of the Mancos Shale. A thickness of 350 ft is estimated for the Rio Salado Tongue.

Jurassic rocks

The Jurassic System is represented by the Zuni Sandstone (*Jz*; Middle Jurassic) as defined by Anderson (1983). It is a very fine to medium-grained, white to pinkish-gray, quartzose sandstone. It is characterized by thick sets of planar and planar–tangential, high-angle crossbeds. The crossbeds generally are accepted to be of eolian origin but locally reworked. Crossbed-dip directions, although variable, are commonly to the southeast. Locally the Zuni approaches 500 ft in thickness and commonly has a medial notch or reentrant formed in a 1-ft-thick, dark reddish-brown mudstone. The notch may represent the Todilto interval; thus, the section below the notch is probably equivalent to the Entrada Sandstone and that above is probably equivalent to the Cow Springs Sandstone of Harshbarger et al. (1957). Only the upper part of the section, approximately 180 ft, is exposed in the map area.

Topographic expression of the unit varies from moderately steep slopes to cliffs, depending on degree of induration. Induration varies with sorting; the well-sorted, cleaner zones tend to be well indurated; the poorly sorted zones tend to be more friable, and thus many hollows and irregular reentrants are common in areas of good exposure.

In the adjacent quadrangles to the west and south, as far south as Plumasano Basin quadrangle (Anderson, 1987), significant interbeds of reddish-brown mudstone begin to appear in the upper part of the Zuni Sandstone. This results in a marked change in topographic expression. The mudstones represent extensive interdunal Wanakah deposition along the margins of the basin. It is known that this part of the section intertongues with the Wanakah Fm. farther to the northwest (Condon and Huffman, 1984, p. 102).

Upper Cretaceous rocks

Dakota–Mancos sequence

The Dakota Sandstone (*Kd*; Cenomanian) forms the base of the Upper Cretaceous sequence in the Zuni Basin. It consists of a basal, medium- to coarse-grained, grayish-orange, crossbedded sandstone that ranges up to more than 45 ft in thickness. Commonly, a pebbly conglomeratic zone occurs at or very near the base with clasts primarily of chert and quartzite. Overlying this cliff-forming sandstone is a mudstone and shale sequence ranging from 40 to 80 ft thick, which generally contains one or more fluvial-channel sandstones on the order of 5–15 ft thick. Carbonaceous zones are common in the mudstone–shale, and some are coaly, but there are no coal beds in the resource category (14 inches or more thick). At places where the cliff-forming sandstone pinches out, this mudstone unit, which represents overbank deposits in a backswamp floodplain setting, rests directly upon a surface of low relief cut in the Zuni Sandstone.

The uppermost 30 ft of the Dakota consists of marine and marginal-marine strata. Backswamp and floodplain deposition ultimately gave way to shoreface and offshore deposits of the interior seaway, which encroached from the east. The basal 10–12 ft of this marine unit is an interbedded sequence of arenaceous shale and flat-bedded, fine to very fine grained sandstone containing small-diameter, smooth-walled, vertical burrows with affinities to *Skolithos* and perhaps *Thalassinoides*. These ichnofossils exhibit a tolerance for a broad range of substrate conditions. The upper part of the marine unit is not well exposed in this quadrangle but locally consists of an 8–10-ft-thick arenaceous shale that is overlain by a 12-ft-thick coarsening-upward sandstone containing abundant *Exogyra levis* and *Turritella* sp. This uppermost sandstone may be the equivalent of the Paguate Tongue. Further discussion of the Dakota Sandstone is not undertaken here as outcrops are very limited in this quadrangle, mainly restricted to sec. 17, T12N, R19W. The reader is referred to Anderson (1989, in press) for a more detailed treatment of the Dakota outcrops in the adjacent quadrangles.

Equally as restricted in this quadrangle are outcrops of the overlying Whitewater Arroyo Tongue of the Mancos Shale(*Kmw*), which crops out in an arcuate band that defines the northeast limb of the Piñon Springs anticline in the southwest corner of the quadrangle. An excellent outcrop in the NE1/4 sec. 17, T12N, R19W on the west side of the Whitewater Arroyo water gap provides the type section, described and named by Owen (1966). As described by Owen (1966), the Whitewater Arroyo Tongue is a "well defined, persistent tongue of marine shale separating the Twowells Tongue from the rest of the Dakota Sandstone in the southwestern part of the San Juan Basin." At the type locality the strata are dipping 16° to the northeast, and Owen (1966) measured a thickness of 80 ft of "gray to olive gray, silty, oyster-bearing shale." The present investigation indicates that this is a reasonable figure for the thickness of this shale; however, the oysters *Exogyra trigeri* are widely scattered, disarticulated fragments, and thicknesses as low as 40 ft were found in the vicinity (Anderson, 1989). Thin, orange-weathering bentonite beds are common in the middle part of the Whitewater Arroyo Tongue.

The Whitewater Arroyo Tongue of the Mancos represents deposition in deeper water, out beyond the transition zone, in a transgressive sequence. But the transgression was interrupted near the end of Cenomanian time by the deposition of a shelf sandstone—the Twowells Tongue of the Dakota Sandstone(*Kdt*).

The basal contact of the Twowells is sharp in the outcrop band provided by the Piñon Springs anticline in the NE 1/4 sec. 21, T12N, R19W, but elsewhere this contact is commonly gradational down through 6–10 ft of the Whitewater Arroyo Tongue. Here the Twowells is less than 25 ft thick and consists of a coarsening-upward sequence of flat-bedded to crossbedded sandstone. Bioturbation and burrowing are evident throughout, and horizons are intensively bioturbated. Ripple laminations and burrows, including *Ophiomorpha* and *Thalassinoides*, indicate a shallow-water shelf environment. During this depositional event sand was distributed as far as 50 mi seaward from this locality to the Ambrosia Lake area near Grants with no significant regression of the shoreline.

Overlying the Twowells Tongue are 350± ft of light-gray to dark-gray marine shale that is slightly calcareous in the lower half. The sharp basal contact suggests a rapid return

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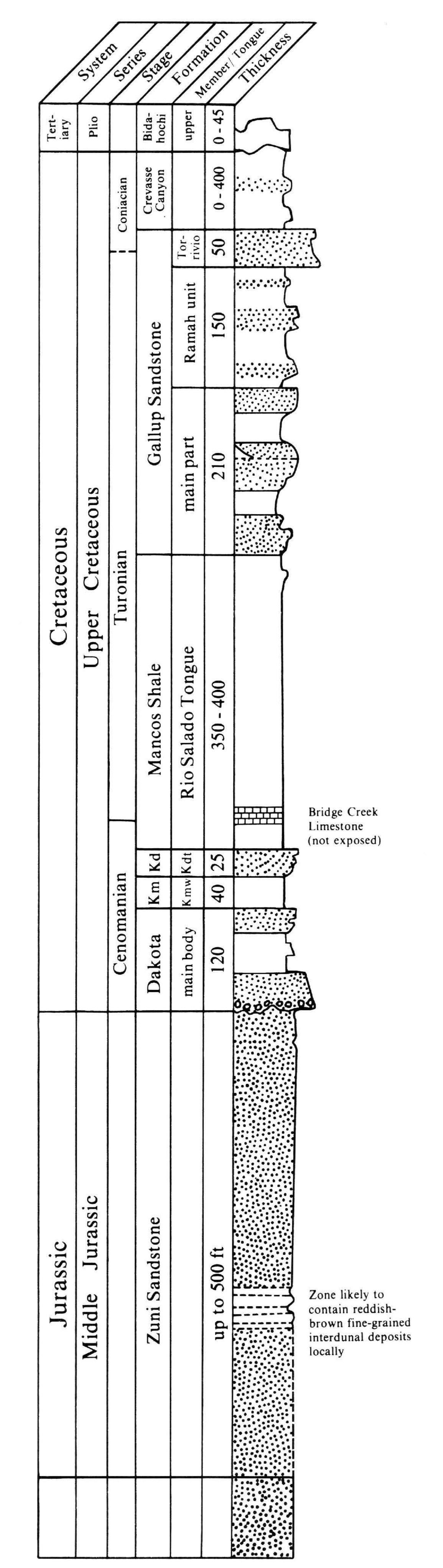

FIGURE 2—Composite stratigraphic column for Tertiary and older rocks.

to deep-water, open-marine conditions. This transgressive event apparently was triggered by a eustatic rise in sea level and represents a major and final pulse during the Greenhorn cycle of sedimentation. The name Rio Salado Tongue of the Mancos Shale (*Kmr*; Hook et al., 1983) is used for this shale tongue even though here it is overlain by the Gallup Sandstone, not the Tres Hermanos Formation as is the case in the type area. The Rio Salado Tongue, by definition, is overlain by and coextensive with the Tres Hermanos Formation or Atarque Sandstone. This, however, is a matter of nomenclature change related to the pinchout of the Pescado Tongue of the Mancos Shale and is not the result of any abrupt stratigraphic change that materially affects the nature of the upper boundary of the Rio Salado Tongue (Fig. 3).

Approximately 40 ft above the base of the Rio Salado Tongue, beds equivalent to the Bridge Creek Limestone Member of the Greenhorn Formation may be recognized in outcrops in the NE1/4 SW1/4 sec. 16, T12N, R19W. The Bridge Creek beds consist of a 25–30-ft-thick interval of interbedded calcareous shale and platy limestone beds 0.5–1 inch thick; the limestone beds contain abundant inoceramid debris. A limestone bed near the top of this calcareous interval in the Jones Ranch School quadrangle has yielded *Mytiloides mytiloides* (Anderson, 1989), an Upper Cretaceous guide fossil that occurs mainly in the early Turonian ammonite zone *Mammites nodosoides* (Cobban, 1984). Thus the limestone beds were deposited at or close to the time of maximum transgression during the Greenhorn cycle, an early Turonian event (Hook and Cobban, 1977).

Exposures higher in the section are poor, but somewhere within 100 ft above the Bridge Creek beds, the calcareous aspect of the Rio Salado Tongue is lost, and the upper part is a darker-gray, noncalcareous sequence.

Also near the top of the Rio Salado, beginning approximately 90 ft below the upper contact, is a 40–45-ft-thick sequence of from four to five thin sandstone beds. These beds are, for the most part, very fine grained and yellowish gray to light olive gray in contrast with the much darker shale. The thickest of these sandstones reaches a maximum of 6–7 ft and generally is near the middle of the sequence. Commonly one or more of the beds in the lower half are fossiliferous. Immediately east of the mouth of Skeets Wash in the SW1/4NE1/4 sec. 15, T12N, R19W, a sandstone bed 20 ft below the top of the sequence contains a coquina of gastropods, small bivalves, *Crassostrea soleniscus*, shark teeth, and crocodile scutes. A similar fauna, albeit without the shark teeth and scutes, was collected by Hook et al. (1983) from the base of the Tres Hermanos Formation in the Zuni Basin. They went on to describe it as a facies-controlled fauna occurring in nearshore marine sandstones, and they regarded it as "the characteristic fauna of the Tres Hermanos Formation."

In the Vanderwagen quadrangle this sandstone sequence also has yielded specimens of the early-middle Turonian ammonite *Collignoniceras woollgari* from two localities, the SE1/4NW1/4 sec. 9, T12N, R19W and the SW1/4NW1/4 sec. 33, T13N, R19W. The former locality yielded *C. woollgari* from the lower part of the sandstone sequence. A determination for the second locality was more difficult, but the specimen was apparently from the middle to lower part as the upper part had been removed by erosion. *C. woollgari* has been reported also from the base of the Atarque Member of the Tres Hermanos Formation in the Acoma Pueblo area, which is near the seaward (northeastward) limit of this unit (Hook et al., 1983).

A stratigraphic section measured by Molenaar (unpubl. field notes 1969) in Squash Canyon, 7 mi to the northwest of the above described sec. 33 locality and somewhat more seaward, yielded a specimen of *Spathites puercoensis*? from a similar sandstone sequence (Fig. 4). *S. puercoensis* is thought to occur in or just below the middle Turonian ammonite zone *Prionocyclus hyatti*, which in turn is just above the zone *C. woollgari* (Hook and Cobban, 1982).

Inasmuch as the nonmarine Carthage Member of the Tres Hermanos Formation, which overlies the Atarque Member throughout the Zuni Basin and southeastward, has been determined to be of middle Turonian age (Hook et al., 1983), it would appear that the sandstone sequence described above, including the Squash Canyon locality, is the time equivalent of both or parts of the Atarque Member and the nonmarine Carthage Member of the Tres Hermanos. Moreover, the sequence represents deposition at the seaward limit of a regression that was far more extensive to the southeast. The sequence of from four to five thin sandstone beds is treated here informally as the Tres Hermanos beds, unrecognizable as the formation-rank unit to the southeast in Pescado Creek (Fig. 3).

A 40–44-ft-thick marine shale, representing the uppermost part of the Rio Salado Tongue, overlies the Tres Hermanos beds. Dark-brown to reddish-brown calcareous concretions, up to 2 ft in diameter, occur in this upper part. No molluscan fauna was noted.

Gallup–Crevasse Canyon Formations

Overlying the Rio Salado Tongue, generally with a sharp basal contact, is the Gallup Sandstone. The Gallup Sandstone consists of as much as 210 ft of marine and marginal-marine sediments (*Kgm*) overlain by a nonmarine section up to 200 ft thick, which includes a distinctive coarse-grained, feldspathic, fluvial-channel sandstone unit at the top. The lower, mostly marine part (*Kgm*) is made up of a stacked sequence of shoreface sandstones interbedded with marine shale or mudstone and lagoonal, restricted-bay, and paludal sediments (Fig. 3). Mappable throughout much of the quadrangle is a 70-ft-thick, medial coal-bearing paludal shale (*Kgmm*). It divides the marine or "main Gallup" into a lower marine unit (*Kgf*), equivalent to the F sandstone of Molenaar (1983), and an upper marine unit (*Kge*), equivalent to the E sandstone of Molenaar (1983; Fig. 3). The stratigraphic relationships indicate that the middle part of the main Gallup (*Kgmm*) is equivalent, in part, to the Carthage Member of the Tres Hermanos Formation. However, the area is very near the northern limits of the geographic extent of the Carthage Member. These stratal relationships clearly suggest that this area was a pivot point on the middle Turonian shoreline. When it reached this area, the shoreline segment north of the pivot point ceased to regress, while the segment south of the pivot point continued to regress northeastward, swinging through a broad arc and eventually assuming a nearly east–west alignment (Fig. 5). Thus a nearshore coastal-plain and alluvial-plain sedimentary section, increasing in thickness to the southeast (Fig. 4), accumulated to form the Tres Hermanos Formation. To the northwest, the basal Gallup began accumulating as a sequence of stacked marine coastal barrier sandstones interrupted by offshore mudstones, bay-fill sequences, and coastal-plain deposits. This portion of the Gallup is older than it is at any place in the San Juan Basin. Inasmuch as the Pescado Tongue is the age equivalent of the Juana Lopez Member of the Mancos Shale, we can see that in the Manuelito Canyon area much of the marine Gallup Sandstone is equivalent to or older than the Juana Lopez (Fig. 4). In the San Juan Basin the Gallup is younger than the Juana Lopez. In the Whitewater Arroyo section (Fig. 4), the presence of the bivalve *Inoceramus dimidius*, a guide fossil to the lower and middle Juana Lopez (Hook and Cobban, 1980), near the top of the Gallup was of greatest importance in establishing these age relationships.

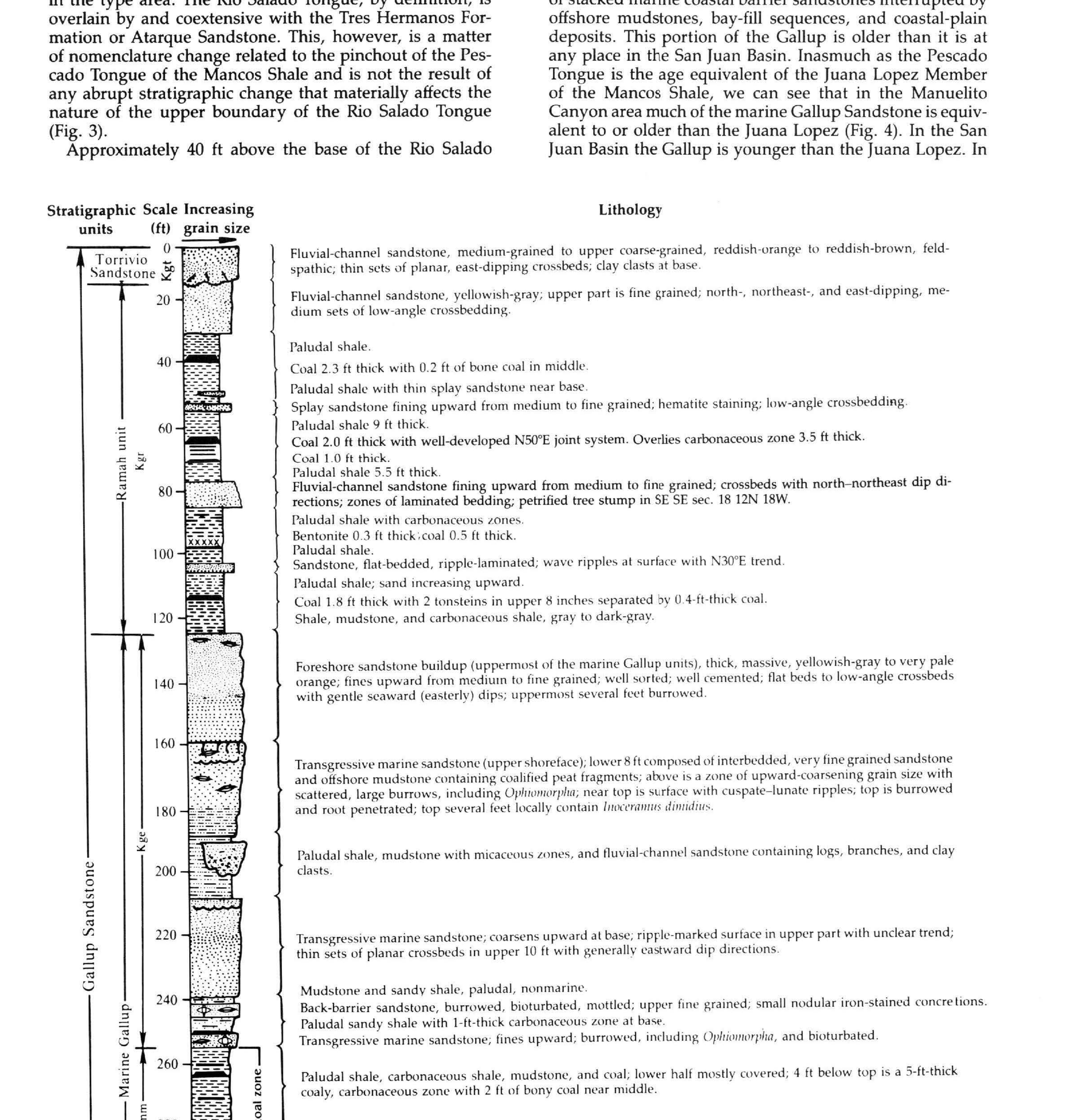

FIGURE 3—Composite measured section of Tres Hermanos Formation, Mancos Shale, and Gallup Sandstone for the Whitewater Arroyo–Nelson Wash area.

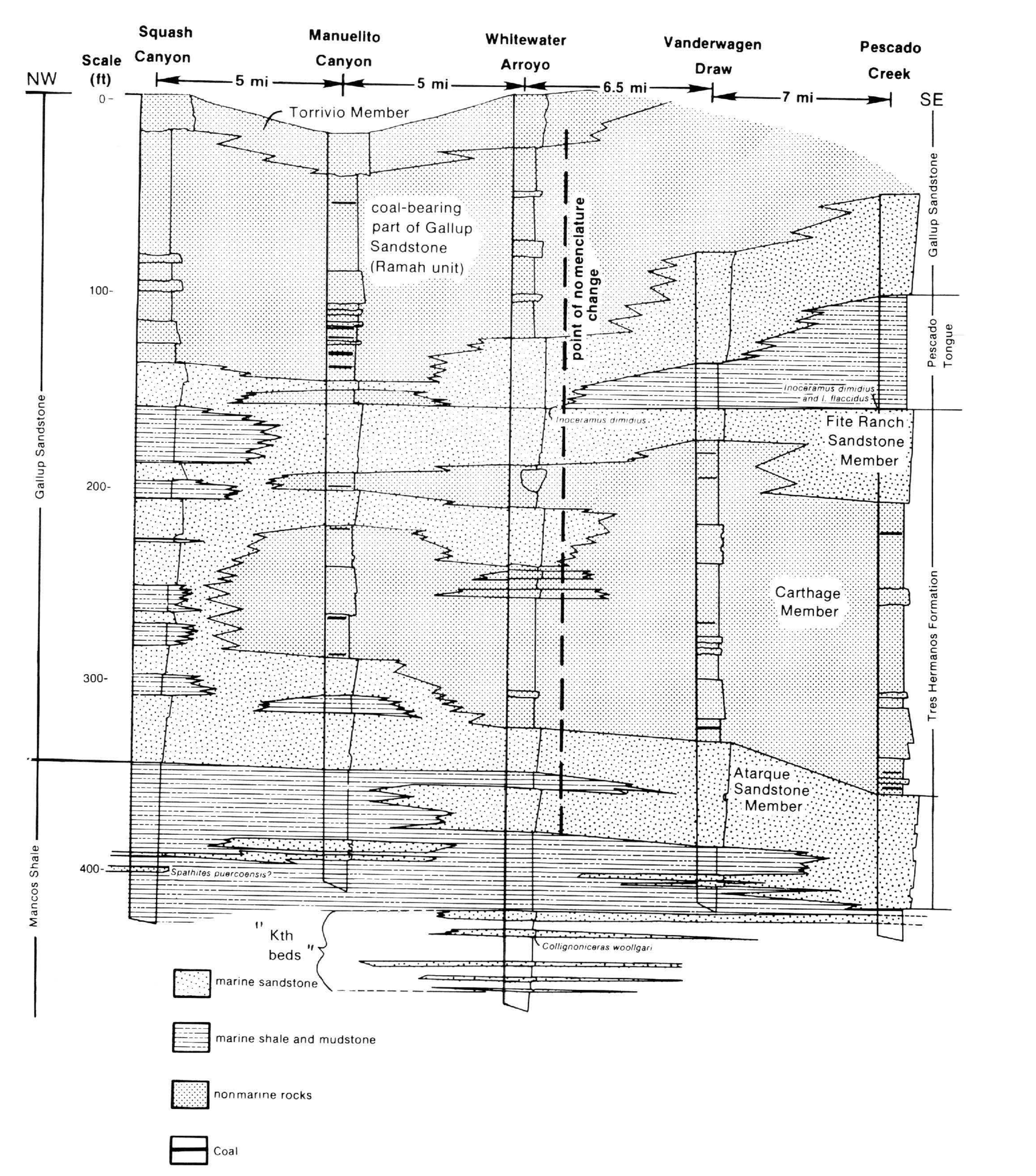

FIGURE 4—Stratigraphic cross section from Pescado Creek northwestward through Vanderwagen quadrangle showing relationship between Tres Hermanos Formation and Gallup Sandstone along depositional strike. Note pinchout of Pescado Tongue and undifferentiated Gallup–Tres Hermanos to northwest. Also note pinchout of lower nonmarine unit to northwest, which demonstrates pivotal point in Turonian shoreline.

Within the middle part of the main Gallup Sandstone (*Kgmm*), the mostly nonmarine unit between the F and the E sandstones, four coaly, carbonaceous shale intervals are present. One of these intervals reaches a maximum thickness of 7.5 ft in the southeastern part of the quadrangle, but only 3 ft of the interval are coal—2-ft-thick and 1-ft-thick coal beds separated by 3.2 ft of fine-grained carbonaceous sediment. All four intervals have been designated here collectively as the Adekai coal zone (Fig. 3). In Squash Canyon in the Manuelito quadrangle, several miles along depositional strike to the northwest, this zone is replaced by largely marine and marginal-marine sediments, suggesting an embayed shoreline.

Excellent outcrops of the F and E sandstones may be found along west-trending Manuelito Canyon. One of these, called the Powerline section for the Tucson Electric Power high-voltage line that crosses there, provides a good exposure of the F sandstone in the NW1/4SE1/4 sec. 29. T15N, R19W. One of the interesting characteristics of the regressive Gallup is the evidence for repeated minor reversals of the shoreline during the overall regression, and good examples are provided at this outcrop. Two horizons that overlie a shoreface sandstone provide evidence of the sea transgressing a back basin and depositing a shoreface or foreshore sand on back-barrier or paralic peat swamps. The resulting coal beds are thin, high ash, and thus subeconomic.

The E sandstone (*Kge*) forms the uppermost part of the marine Gallup. Locally it exhibits many of the sedimentary features associated with tidal-channel sandstones. Some of these features noted at the outcrops in sec. 20, T13N, R19W are: (1) a sharp base, (2) fining-upward sequence or sequences, (3) variable thickness, (4) opposed crossbedding, (5) the presence of clay clasts or clay drapes, and (6) burrows, including *Ophiomorpha*. The previously inferred highly embayed nature of the shoreline would be consistent with high tidal energy.

Overlying the marine Gallup throughout the Zuni Basin is a variable sequence of mudstones, fluvial-channel sandstones, carbonaceous shales, and coal that is referred to informally as the Ramah unit (*Kgr*; Anderson and Stricker, 1984) or as the coal-bearing part of the Gallup. The unit ranges in thickness from 110 to 150 ft within the quadrangle but thins somewhat to the north across the Torrivio anticline and thins dramatically to the east at the Nutria monocline. This is depositional thinning and strongly suggests some tectonism concurrent with sedimentation. If so, it occurred considerably prior to the classic Laramide deformation. Stricker and Anderson (1985) have referred to it as pre-Laramide tectonics and suggested that the subtle deformation influenced the configuration of Turonian–Coniacian shorelines.

The thickest coal in the quadrangle occurs in the upper part of the Ramah unit. The coal is well exposed at the small abandoned workings near the south quarter corner of sec. 2 and the north quarter corner of sec. 11, T12N, R19W. Here the coal interval is 5.4 ft thick with 1.1 ft of partings (including a tonstein), leaving a net coal thickness of 4.3 ft. This thickness is not laterally continuous, however, as the coal zone cannot be identified a few hundred feet to the west.

The coals of the Ramah unit were deposited in a lower alluvial-plain environment following withdrawal of the Gallup seaway. Thin fluvial-channel sandstones and crevasse-splay deposits are present in a mudstone-dominated sequence in the eastern part of the quadrangle. By contrast, in the western part, a thick (up to 40 ft) fluvial-channel sandstone is present in the upper half of the Ramah unit and replaces the 5.4-ft-thick coaly interval described above. This is thick for fluvial sandstones in the Ramah unit, and it may be argued that the sandstone genetically belongs with the overlying Torrivio Member; it is generally separated from the Torrivio by 6–12 ft of carbonaceous mudstone and is somewhat finer grained. Regardless of the stratigraphic assignment, this fluvial unit does represent sand backing up onto the coastal plain, perhaps during one of the reversals of shoreline movement during the Gallup regression.

The overlying Torrivio Member of the Gallup (*Kgt*) is distinctive in color, composition, and texture. It is a feldspathic, medium- to coarse-grained, well-cemented, commonly reddish brown, fluvial-channel sandstone that ranges up to 50 ft thick. Grain size, crossbedding characteristics, and the overall geometry of the unit suggest that it is a braided-stream deposit. Both trough and planar crossbeds are common, and both types indicate paleoflow directions to the north, northeast, east, and east–southeast. Lithogenetically, the Torrivio does not belong in the Gallup Sandstone; however, along the Nutria monocline, where Sears (1925) named the unit, the Torrivio lies much nearer to the main Gallup than it does in this more basinward location.

Braided streams commonly are associated with facies higher up in the alluvial plain, but a tectonic event in southeastern Arizona probably increased sediment supply during Torrivio deposition (Hayes, 1970). This event, dated at about 90 m.a., possibly marked the initiation of Laramide tectonics in southeastern Arizona and thrust the coarse clastics of the Bisbee Group into a series of northwest-trending isoclinal folds. Hayes (1970) suggested that these compressive structures were likely the source area for the Gallup Sandstone. The coarse, feldspathic nature of the Torrivio does indeed suggest a tectonic event in the source area, whereas the composition of the lower marine sandstones does not demand tectonism in the source area. Thus it is only the uppermost part of the Gallup, the portion that is lithogenetically unrelated to the main Gallup, that suggests a tectonic–compressive event in the source area.

Numerous other localities throughout the Rocky Mountain foreland were structurally active at about 90 m.a. Merewether and Cobban (1985) have documented at least six of these in Colorado and in the Wyoming province. Their age data were determined biostratigraphically using W. A. Cobban's sequence of Late Cretaceous molluscan index fossils.

Named by Allen and Balk (1954) for exposures in the Tohatchi quadrangle 25 mi north of the Vanderwagen quadrangle, the Crevasse Canyon Formation (*Kcc*) overlies the Torrivio Member of the Gallup Sandstone. It is a mostly nonmarine unit (entirely nonmarine in the Zuni Basin) composed of shale, mudstone, lenticular fluvial-channel sandstones, carbonaceous mudstone, and minor coal. The distribution, morphology, and grain size of the sandstone bodies and the fact that they are enclosed in the fine-grained sediments of the flood basin or backswamp suggest that there was an abrupt return to a meandering fluvial system following deposition of the Torrivio braid plain.

A local structural strike of N40°W can be determined from the outcrop pattern of the Crevasse Canyon Formation across the quadrangle. Dips are gently northeastward, and, as a result, the unit is eroded off in the southwestern part of the quadrangle. It thickens from a feather edge in the central part of the quadrangle to perhaps as much as 800 ft in the subsurface at the northeast corner. Cross section A–A′ shows these structural and stratigraphic details.

Large sandstone concretions commonly weather out of the fluvial-sand units; the concretions generally have a darker color and show some hematitic oxidation. The bases of the sandstone units are generally not scoured surfaces, an observation that may suggest rather high rates of sedimentation. A preserved palm trunk was found within the lower 10 ft of the Crevasse Canyon in the NW1/4NW1/4 sec. 24, T13N, R19W, but petrified-wood fragments are not abundant.

At least two horizons are coal bearing, and these are in the Dilco-equivalent part of the section. Only the lower half of the Crevasse Canyon is exposed in the quadrangle, the upper half being hidden by a cover of Tertiary sediments throughout the northeast corner of the quadrangle. The upper half, however, is perhaps equivalent to the Bartlett Barren Member and is therefore unlikely to contain appreciable coal. The two coal horizons in the lower half of the section occur at approximately 45 ft and 300 ft above the base. The lower horizon has two widely spaced coal beds, one 1.0 ft thick and one 1.4 ft thick. Its stratigraphic position is very close to what Berge Exploration (1985) reported for the Dilco No. 2 coal bed in the adjacent Twin Buttes quadrangle. The upper horizon, for which the stratigraphic position is estimated only from projecting structural dips, is approximately 300 ft above the base, contains five coal or coaly, carbonaceous beds, and spans a vertical interval of 57 ft. Four of these beds are less than 0.8 ft thick and were not sampled; the thickest bed, the basal one, measures 2 ft in thickness. The zone may be seen in outcrop in the SE 1/4SE1/4 sec. 11, T13N, R19W along the north side of the local access road. Coal resources are discussed more fully in a following section.

Tertiary

An upper Tertiary sedimentary unit unconformably overlying the Crevasse Canyon Formation is preserved only on the higher surfaces in the central part of the Zuni Basin but becomes much more widespread westward into Arizona. Named the Bidahochi Formation (*Tbu*) for exposures near the village of the same name by Reagan (1924), it was subsequently subdivided into three members by Repenning and Irwin (1954). The three members were designated: (1) the lower member, dominated by mudstone and sandstone with some lacustrine facies, (2) the volcanic member composed of basalt and basaltic lapilli tuff ranging from 2 to 50 ft in thickness, and (3) the fluvially dominated upper member, approximately 270 ft thick. The Zuni Basin occurrences have been assigned to the upper member by most authors, including Repenning et al. (1958).

The Bidahochi Formation remnants in the Vanderwagen quadrangle consist of moderately reddish brown to light-brown argillaceous sandstone, some mudstone, and at least two white rhyolitic ash beds. The color, texture, and lithologies suggest that the major sources of these sediments were the Permian and Triassic rocks of the adjacent Zuni uplift with lesser amounts provided by the Jurassic and Cretaceous section. Reworked Cretaceous molluscs can be found locally in the Bidahochi, and confusion will result if the investigator or hobbyist is not familiar with the lithologies and weathering characteristics of the Cretaceous versus Tertiary sediments. Both *Pycnodonte kellumi* and *P. newberryi* with lesser amounts of *Exogyra levis* have been collected from the Bidahochi Formation; these were derived from the Twowells Tongue and the Bridge Creek Limestone part of the section.

Large-scale, intraformational slump and soft-sediment-deformation features are common in the Bidahochi of the area. These features, the lack of well-developed fluvial-channel sandstones, and the poor degree of sorting indicate deposition in an interstream (interfluve) area with a weak or poorly developed levee system and relatively high rates of sedimentation.

The surface upon which the Bidahochi rests slopes gently to the west and southwest. This surface was called the Zuni erosion surface by McCann (1938), who calculated a west–southwestward gradient of 29 ft per mile in this area. Recent calculations in the Vanderwagen area show a gradient of approximately 33 ft per mile from the northeast corner to the southwest corner of the quadrangle. As McCann (1938) stated, this would seem to be a very high gradient for deposition of the fine-grained sediment that characterizes the Bidahochi locally; consequently, some late Pliocene westward tilting of the Zuni surface and perhaps the entire Zuni uplift is indicated.

The base of the Bidahochi is commonly a grayish-red to moderately reddish brown mudstone containing sandy pedogenic carbonate beds or nodules. In other areas, such as in sec. 23, T13N, R19W, the base is friable sands, which do not offer good, reliable crossbed-dip directions.

Approximately 60 ft above the base a stark-white, rhyolitic ash bed is present. This bed varies in thickness from 12 inches (W1/2NW1/4 sec. 18, T13N, R18W) to 30 inches (N 1/2 sec. 11, T13N, R19W). A second bed can be seen at many localities approximately 11–12 ft above the first one; this upper bed does not exceed 8 inches in thickness. Total thickness of the residual Bidahochi reaches approximately 140 ft in the NE1/4 sec. 18, T13N, R18W; it may become appreciably thicker in sec. 9 at the northeast corner of the quadrangle if the northeastward dip of the pre-Tertiary rocks persists.

COAL RESOURCES

Coal occurs in three stratigraphic units in the Vanderwagen quadrangle. In ascending order they are: (1) the middle part of the main Gallup (*Kgmm*), (2) the Ramah unit (or coal-bearing part of the Gallup; *Kgr*), and (3) the Crevasse Canyon Formation (*Kcc*). Fig. 6 illustrates these three

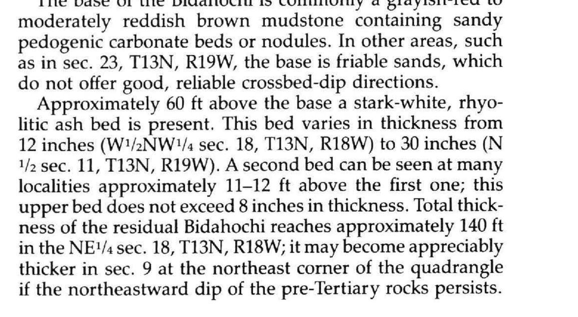

FIGURE 5—Late-middle and early-late Turonian shoreline reconstruction showing area of deposition of Tres Hermanos Formation and the pivotal point in the Gallup area. Line of section for Fig. 4 is marked by X's.

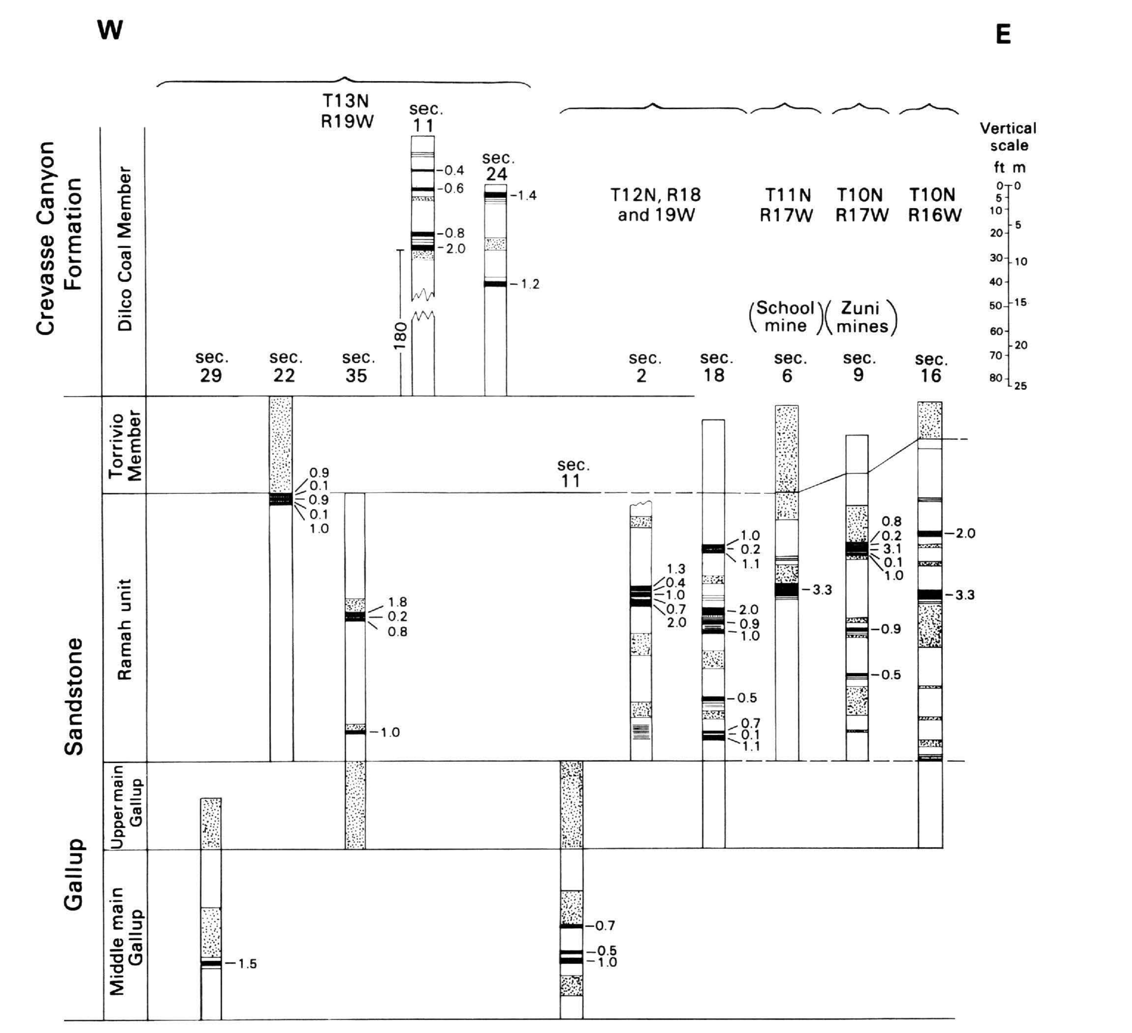

FIGURE 6—Coal sections in the central part of the Zuni Basin. Coal thicknesses in feet.

TABLE 1—Proximate analyses (in %) of coal samples from outcrop in central part of Gallup–Zuni coal field. Forms of analysis: A—as received and B—moisture free. Data for coals from Horsehead Canyon area provided by the U.S. Geological Survey.

Location	Geologic unit	Form of analysis	Volatile matter	Fixed carbon	Moisture	Ash	Sulfur	BTU/lb
Vanderwagen quad.								
Sec. 2, T12N, R19W	Kgr	A	42.47	43.85	2.9	7.85		9,170
		B	38.16	41.85	2.2	16.00		8,700
Sec. 3, T12N, R19W	Kgmm	A B	35.30	36.34	9.22	19.20	0.442	8,254
Sec. 14, T12N, R19W	Kgmm	A B	36.75	45.25	7.04	10.05	0.706	10,320
T13N, R19W	Kgr (lower part)	A B	36.50	45.60	10.25	7.15	0.530	9,026
T13N, R18W	Kgr (lower part)	A B	38.90	43.45	10.08	7.72	0.404	9.327
Horsehead Canyon area, School mine zone								
T12N, R18W	Kgr	A B	39.30	38.90	10.70	10.19	0.514	8,629
T12N, R18W	Kgr	A B	32.70	39.30	8.67	19.20	0.432	7,809
T10N, R17W and T11N, R17W	Kgr	A B	31.8–37.6	38.7–42.4	4.4–10.6	8.8–36.0	0.6–1.5	10,470+

units and compares the Vanderwagen area with coal occurrences 12 mi to the southeast in the Horsehead Canyon area where the Zuni mines and School mine were located.

All the coals tend to be thin and discontinuous, a finding also reported by Berge Exploration (1985) for the Twin Buttes quadrangle, which is adjacent on the north. One exception is the 5.4-ft-thick coal bed that occurs in the Ramah unit. This bed, the thickest in the quadrangle, is exposed in the abandoned workings in the SE1/4SE1/4 sec. 2, T12N, R19W (Fig. 7). It has a shale parting and a tonstein that reduce the net coal thickness to 4.3 ft. In-house analysis of weathered samples from this exposure yielded as-received BTU values ranging from 8700 to 9170. Ash content varies from 8% to 15%. An unweathered sample on a moist, mineral-matter-free basis would test out in the 10,500 BTU range or higher, and thus the coal can be considered to be of high-volatile C bituminous rank. Unfortunately, the bed cannot be traced laterally in outcrop to the west or east and is probably nonpersistent. Drilling in adjacent secs. 1 and 12 would provide important information on the downdip extent of this zone.

Coal-quality data for this coal and for coal from four other sampling localities throughout the quadrangle and three localities in the Horsehead Canyon area 12 mi to the southeast are given in Table 1.

TABLE 2—Coal resources by section and township and range for Vanderwagen quadrangle, in millions of tons. From outcrop data only.

Location of measured outcrop	Geologic unit	Measured	Indicated	Total rounded
Sec. 18, T12N, R18W	Kgr	.43	3.60	4.0
Sec. 2, T12N, R19W	Kgr	.45	3.75	4.2
Sec. 11, T13N, R19W	Kcc	.20	1.75	1.9
Sec. 22, T13N, R19W	Kgr	<.10	2.00	2.1
Sec. 35, T13N, R19W	Kgr	.20	1.50	1.7
Totals		1.40	12.60	13.9

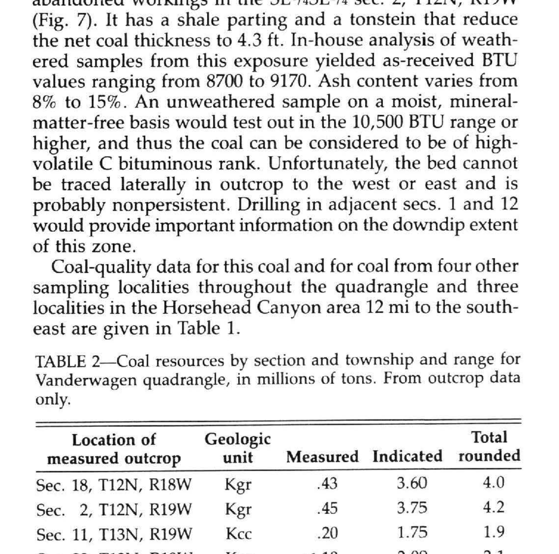

FIGURE 7—Coal section exposed at small abandoned workings in SE1/4SE1/4 sec. 2, T12N, R19W.

Coal resources were calculated from five outcrop localities (Table 2). The data were calculated in accordance with the procedures set forth by Wood et al. (1983) except that the minimum thickness used in the determinations was 2 ft, rather than the 14-inch minimum thickness suggested (Wood et al., 1983). The factor of 1740 tons per acre ft was used throughout. The measured category is the calculated coal resources in a circular area 0.25 mi in radius about the measured outcrop. The indicated category includes those resources in the doughnut-shaped area that extends from a radius of 0.25 mi out to a radius of 0.75 mi. Total coal resources for the quadrangle were calculated to be 13.9 million tons, essentially all of which are in the depth category of 0–150 ft. However, there is a good possibility that a small portion (10%) of these coal resources are in the 150–250-ft depth category.

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