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STRATIGRAPHY AND DEPOSITIONAL HISTORY OF UPPER CRETACEOUS ROCKS OF THE SAN JUAN BASIN AREA, NEW MEXICO AND COLORADO, WITH A NOTE ON ECONOMIC RESOURCES

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INTRODUCTION

During Late Cretaceous time, the San Juan Basin was part of the large western interior geosyncline that transected much of North America. The San Juan Basin, which is a 100- to 150-mile (160- to 240-km)-wide, near-circular, early Tertiary structural basin, was superposed on a small part of this larger Cretaceous depositional basin, thus preserving an almost complete Upper Cretaceous section. These rocks, which contain large reserves of gas, oil and coal in or flanking the basin, crop out almost entirely around the basin. The many fine outcrops, the large quantity of subsurface well control (about 10,000 wells), and the simple structure within the basin make this area ideal for academic as well as economic studies of these rocks. Consequently, the literature abounds with many fine papers on different aspects of Upper Cretaceous rocks. A list of these papers probably would fill a good part of this volume.

Although the stratigraphy and depositional history of Upper Cretaceous rocks of the San Juan Basin have been covered in many different publications, it seems necessary to review them in a guidebook dealing with the San Juan Basin. Hopefully, this paper presents a balanced summary, based on the literature and many observations of the writer, with possibly a few new facts or ideas plus some stratigraphic trivia that may be of interest.

TIME-STRATIGRAPHIC ILLUSTRATION

A time-stratigraphic illustration portrays stratigraphy and depositional history in a time sense without the confinements of stratigraphic thicknesses. Using this method, units are placed in proper paleogeographic position in relation to other time-equivalent strata or events. Figure 1 is an Upper Cretaceous time-stratigraphic section across the San Juan Basin and extending southwest into the Zuni basin across the depositional strike. This section was constructed from both outcrop and well data and shows the generalized relationships of three major fields: marine shale or siltstone, marine and coastal-barrier sandstones and nonmarine deposits. These varying lithologies are the basis for differentiating most Upper Cretaceous formational units in this area. Because time, rather than thickness, is represented on the vertical scale, thickness can be shown only by notation; however, the interpretation of facies and formational relationships and of depositional history is more readily apparent using this type of illustration.

Many absolute time scales are available. Each has some limitation in fitting the stratigraphy (and paleontology) to absolute time. As more precise radiometric age dates are tied to paleontologic zonations, undoubtedly more accurate time scales will become available. The time scale used for Figure 1, right or wrong, seemed to be the best fit for the Upper Cretaceous of the San Juan Basin at the time (1972). However, problems still exist. For instance, (1) was Greenhorn time as long as that shown, and (2) was the rate of sedimentation of the Lewis Shale almost twice as fast as that of the upper Mancos Shale and six times that of the lower Mancos Shale, as depicted on the right side of Figure 1?

In constructing the cross section, some of the paleontological data were comprised in order to show the different time-stratigraphic units within the time scale that was used. This is especially true in the Mulatto Tongue through the lower part of the Point Lookout interval. More emphasis was placed on the physical relationships of the many marker beds, and a more-or-less uniform sedimentation rate was assumed within this interval. Recent fossil evidence indicates that the Mulatto and Satan tongues may be somewhat younger in their relation to the stages than is shown on the section. For a time correlation of the different units, strictly on the basis of the most recent macrofossil data, refer to the paper in this volume by Peterson and Kirk. Some of these data were unknown to this writer at the time of the construction of the time-stratigraphic section.

Needless to say, more refinements are necessary in tying paleontology to absolute time. However, the essence of a time-stratigraphic section is the portrayal of time-synchronous deposition (or erosion) and of how facies migrate through time—regardless of whether the time scale is absolutely correct.

DEPOSITIONAL SETTING

During Late Cretaceous time, the San Juan Basin area was a scene of interplay between a shallow seaway on the northeast and a clastic sediment supply coming across a low-relief area on the southwest. Or, as one geologist put it (Fassett, 1974), the area was *in the SCI-SWO ("sea came in, sea went out") zone.* Four or five major transgressions and regressions, as well as many minor ones, left a stratigraphic record similar to that shown in Figure 1. Most of the deposition took place during the regression, or when the shoreline was migrating seaward. During all this time, relative sea level was rising and/or the area was subsiding, at least episodically, so that at least 6,500 feet (2,000 m) of sedimentary rocks was deposited. Basin subsidence played a large part in this; during this same period of time, about half this thickness of strata was deposited in eastern Colorado and about twice as much was deposited in central Utah. Even within the San Juan Basin area, depositional thickening to the southwest can be demonstrated.

The regressive wedges consist of composited deltaic and interdeltaic deposits. The delta fronts and the strandlines of the interdeltaic areas were dominated by marine processes, dominantly longshore currents, which produced fairly straight shorelines and thick shoreface or coastal-barrier sands. The

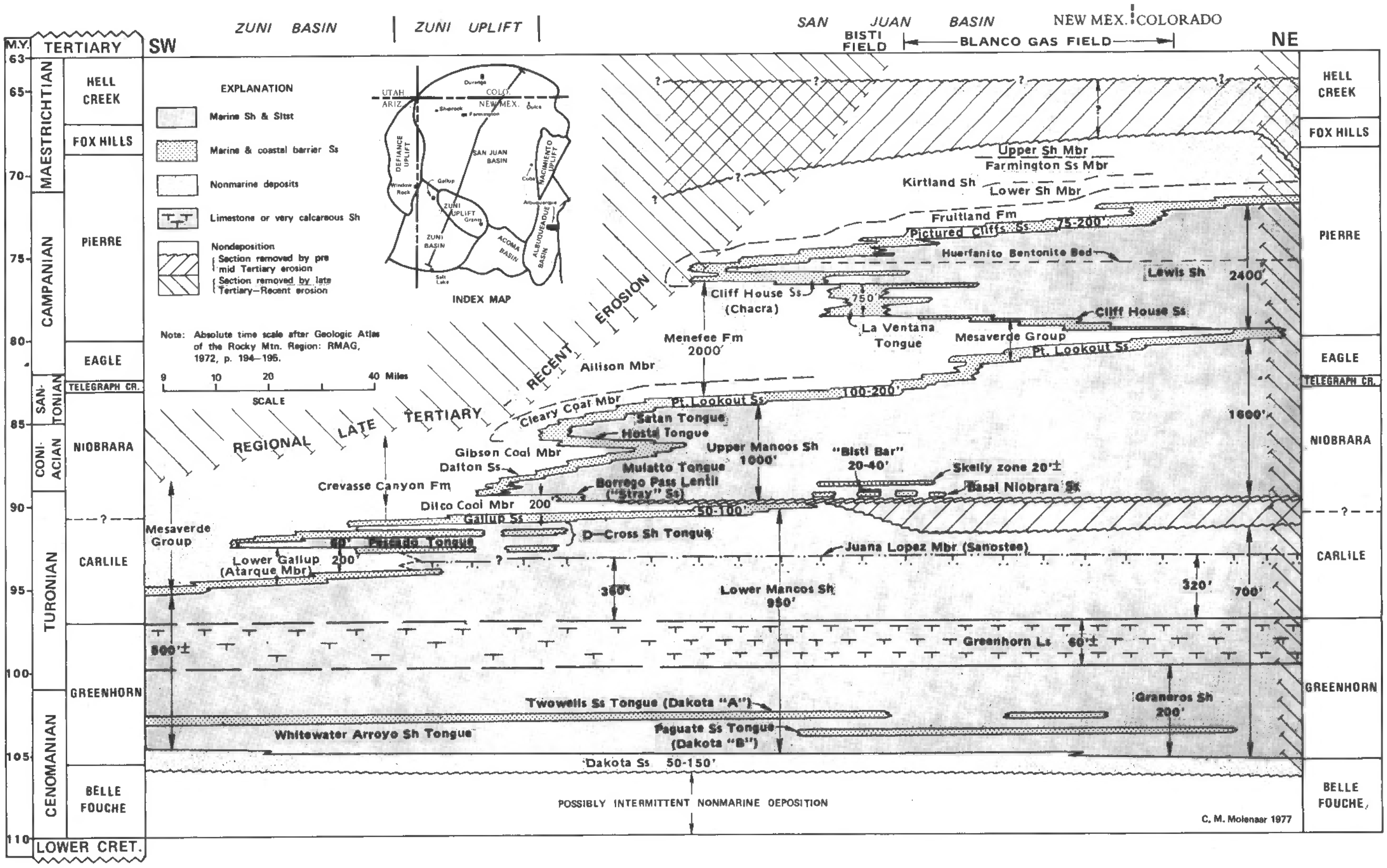

Figure 1. Upper Cretaceous time-stratigraphic section, Zuni basin-San Juan Basin, northwestern New Mexico and southwestern Colorado.

shoreface sands grade to sandy silts and muds moving seaward where deeper water and lower energy conditions prevailed.

In the discussion of the various coastal sandstone units, the writer uses the term coastal barrier as a general term to include all sandstone bodies that separate the open marine waters from the coastal-plain or brackish back-barrier environments. It includes both barrier islands and non-barrier-island shoreline sands.

The term "stratigraphic rise" is used to denote the vertical difference in stratigraphic position of a time-stratigraphic lithologic unit between two geographic points. Commonly the stratigraphic rise refers to the difference between the landward and seaward extents of a shoreline sandstone. This would essentially be a measure of basin subsidence or relative sea level rise. Because of the many good marker beds in the marine shales in the San Juan Basin and the close subsurface control, it is easy to measure on cross sections.

The nonmarine deposits can be divided into a lower delta or coastal-plain facies and an upper delta-plain or alluvial-plain facies. The lower delta or coastal-plain facies consists of paludal carbonaceous shale, coal, lacustrine sandstones and fluvial or distributary channel sandstones with associated levee and splay deposits. Where the coastline built up in one position owing to a still-stand of the shoreline, and where channel sands didn't interfere, thick coal deposits were produced. Farther landward on the upper delta or alluvial plain, carbonaceous shales and coal are less common and flood plain or interchannel shales and fluvial-channel sandstones predominate.

The coastal-barrier sandstones are generally well to very well sorted and range in texture from very fine grained (62-125 microns) at the base to fine grained (125-250 microns) in the upper part. The fluvial sandstones are moderately to well sorted and have a wide range in textures. Their coarser basal parts are generally coarser than the coastal-barrier sandstones. Conglomerates are rare in all of these facies.

Those readers interested only in general aspects of stratigraphy, depositional history and nomenclature need read no further. However, for those interested, additional details of the individual units will follow.

Dakota Sandstone Interval

The Dakota transgression advanced generally from east to west or possibly east-southeast to west-northwest across the San Juan Basin. This was quite different from the southwesterly directed transgressions of later Cretaceous time. However, topographic relief in and around the San Juan Basin may have affected shoreline trends, especially in the lower part of the Dakota. On the southeast side of the basin, the Dakota interval is about 400 feet (122 m) thick and has been subdivided into four members or tongues separated by two tongues of Mancos Shale (Landis and others, 1973). A third tongue of Mancos is included in the lower Dakota member. In ascending order, the four Dakota members and two Mancos members are the Oak Canyon Member, Cubero Sandstone Tongue, Clay Mesa Shale Tongue of the Mancos, Paguate Sandstone Tongue, Whitewater Arroyo Shale Tongue of the Mancos and the Twowells Sandstone Tongue. **[Editor's note: see paper**

by Owen and Siemers elsewhere in this volume.] All are open marine deposits except possibly the lower half of the Oak Canyon Member, which may be of marginal-marine origin. The sandstone tongues are shallow-marine shelf sandstones extending into the seaway from their respective shorelines to the west. They are discontinuous in lateral distribution, especially the lower two, and are as much as 75 feet (23 m) in thickness. The Cubero and Paguate grades into nonmarine facies within the San Juan Basin, and the Twowells merges with the nonmarine Dakota farther west, north of Window Rock near the Arizona-New Mexico border. In the Four Corners area, the Dakota is all nonmarine, consisting of about 150 feet (46 m) of fluvial sandstone with carbonaceous paludal shale. The total stratigraphic rise of the base of the marine shale in transgressing across the San Juan Basin is about 350 feet (108 m).

The age of the lower part of the Dakota on the southeast side of the basin is early Cenomanian as indicated by marine fauna, and possibly Albian (Early Cretaceous) in the basal part on the basis of palynomorphs identified by R. H. Tschudy (Landis and others, 1973). The basal marine strata on the west side of the basin is late Cenomanian in age. Thus, if the time scale on the time-stratigraphic section is correct, it took 5 or 6 million years for the basal marine transgression to cross the San Juan Basin, or about that amount of time to deposit the upper 350 feet (108 m) of the Dakota on the southeast side of the basin. This time span shouldn't be taken as fact, inasmuch as the time scale is not necessarily that precise. It does point out the need for possible refinement though.

Oil company geologists have applied different informal terminology to some of the Dakota sandstones in the subsurface, such as Dakota A, Dakota B, etc. Also the name Tres Hermanos has been misapplied to the upper Dakota sandstones. The type Tres Hermanos Sandstone in the southern Acoma basin is early Carlile in age, much younger than the Dakota (Dane and others, 1971, p. B19). It probably is the basal sandstone of the Atarque Member of the lower Gallup.

Mancos Shale

The Mancos Shale comprises the bulk of marine deposits in the San Juan Basin. It represents deposition in deeper, quieter water in offshore areas where energy levels were lower and finer clastics could settle out. How deep the sea was in the more distal areas is speculative. It probably wasn't too deep, possibly 300 to 400 feet (91-122 m) at the most, as suggested by foraminiferal data and very low angle foresets (less than ½ degree) of time-marker beds.

In addition to shale and siltstone, the Mancos contains zones of calcareous concretions, a few thin limestone beds, many thin bentonite beds and a few offshore sandstone buildups. Some of these can be correlated for many miles on well logs in the subsurface. Some are prominent enough both in outcrops and subsurface to warrant member status. In addition the southwesterly extending tongues of Mancos Shale have been given names. These members and tongues are discussed separately.

Graneros Shale

The Graneros Shale, as used in the San Juan Basin, is that part of the Mancos Shale below the Greenhorn Limestone. Including the Dakota tongues, it ranges in thickness from about 350 feet (107 m) on the southeast side of the basin to about 60 feet (18 m) on the west side. The difference is due to transgressive onlap as explained in the section on the Dakota interval. On the eastern side of the basin, the Graneros is time-equivalent to the upper half of the type Graneros of eastern Colorado plus the Lincoln, Hartland and lower part of the Bridge Creek members of the Greenhorn Limestone of that same area. On the western side of the basin, the Graneros is time-equivalent to only the upper part of the Hartland and lower part of the Bridge Creek members.

Greenhorn Limestone

The Greenhorn Limestone Member of the Mancos Shale is an excellent electric log marker in the subsurface and probably represents a time line. It is composed of calcareous shale and thin beds of argillaceous limestone. The limestone beds pinch out in the southwestern part of the basin, but the calcareous shales are still recognizable, especially on electric logs. In surface outcrops, the Greenhorn can be recognized by the light-gray-weathering calcareous shale as constrasted to the darker gray normal Mancos Shale. It ranges in thickness from about 40 to 70 feet (12-21 m) in the subsurface, where the entire calcareous zone stands out on resistivity logs.

The Greenhorn Limestone of the San Juan Basin is time-equivalent to all but the lower part of the Bridge Creek Member; the upper member of the Greenhorn Limestone of the type area in eastern Colorado. It represents the time of maximum transgression into the Cenomanian-Turonian cycle. The shoreline was in the Cedar City, Utah, area about 280 miles (450 km) to the west, where over 400 feet (122 m) of shoreface sandstone containing the upper Greenhorn index fossil, *Inoceramus labiatus*, is present. The most shoreward outcrop of this interval in New Mexico is about 6 miles (10 km) north of Virden or 200 miles (322 km) south of Gallup. There the Greenhorn consists of sandy shale with limestone concretions. The original Greenhorn shoreline was still farther southwest of that point.

Semilla Sandstone Member

The Semilla Sandstone Member of the Mancos Shale is a discontinuous offshore sandstone bar present in the southeastern San Juan Basin about 200 feet (61 m) above the Greenhorn Limestone. The best development of the unit is at the type section south of La Ventana, where it is 70 feet (21 m) thick (Dane and others, 1968). (An excellent roadcut exposure is along New Mexico Highway 44 about 22 miles [35 km] south of Cuba and 0.8 miles [1.3 km] south of the junction with the road to San Luis and Cabezon.) Where the sandstone bar isn't developed, it can be traced in the subsurface in the southeastern San Juan Basin as a thin silty or sandy "blip" on electric logs just below the base of the Juana Lopez Member (Molenaar, 1974, p. 254).

At most places the Semilla is very fine to fine grained, but in the type area the upper part becomes medium grained in texture. Northwest-dipping crossbeds in the upper part of the Semilla at the type area indicate northwesterly directed currents. This and the mineralogy of the sandstone have given rise to speculation regarding an igneous or metamorphic source area to the southeast (Dane and others, 1968, p. 13). Until such a source area can be better documented, the writer suggests that the northwesterly currents responsible for the northwest-dipping crossbeds were local and that the Semilla is an offshore equivalent of, and probably derived from, the lower regressive coastal-barrier sandstone of the lower Gallup or

Atarque Member (Molenaar, 1973, p. 94). This unit is present just south of the San Juan Basin (fig. 1), and its seaward pinchout, which trends northwest-southeast, is about 70 miles (113 km) southwest of the type section of the Semilla Sandstone. It is conceivable that sand anywhere along the trend of this shoreface could have been distributed by offshore currents to an area some distance from the shoreline.

The Semilla is also considered to be time-equivalent to, but separated from, the Codell Sandstone of the Raton basin of southeastern Colorado. The source for the Codell is also speculative. One suggestion is a source area immediately west of the Raton basin (Fassett, 1976, p. 186). This would be compatible with a local eastern source for the Semilla. It is evident that more work is necessary to resolve this problem.

Juana Lopez (Sanostee) Member

The Juana Lopez Member (also referred to as Sanostee by many workers) of the Mancos Shale is composed of thinly interbedded calcarenite, very fine grained arenaceous sandstone, and shale. The calcarenite is made up of fragmented fossil hash. The unit is 107 feet (33 m) thick at a reference section on the eastern side of the San Juan Basin and contains several species and genera of cephalopods and pelecypods, some of which are well-known index fossils used in zoning the thin unit (Dane and others, 1966). In the northwest corner of the basin, the upper half of the Juana Lopez has been truncated under the Niobrara unconformity. Thus it ranges in thickness from about 50 feet (15 m) to slightly over 100 feet (30 m).

The top of the Juana Lopez, which forms a small cuesta in outcrops, is a good electric-log marker in the San Juan Basin and probably represents a time line over much of the area. However, faunal zonation indicates that the top of the unit in outcrops in the southern part of the basin is time-equivalent to the middle part of the reference section. It has been suggested that the lithologic top of the Juana Lopez drops to a less-resistant calcarenite bed to the southwest. The Juana Lopez has also been shown to grade into nonmarine paludal shale to the southwest, without an intervening shoreface barrier (fig. 1). This is attributed to the depositional environment during Juana Lopez time, a widespread shallow sea at a time of little clastic influx. Thus offshore deposits would grade to a mudflat shoreline where wave energy and clastic supply were insufficient to build up a shoreface sand barrier (Molenaar, 1973, p. 94).

The Juana Lopez, or its equivalent lithology, extends well beyond the San Juan Basin. It is known in the Raton basin as the Juana Lopez; it has also been recognized in the northern Paradox basin in west-central Utah as the Ferron Sandstone, and as far as northwestern Colorado, where it is about 35 feet (11 m) above the upper Frontier Sandstone (Molenaar, 1975, p. 191).

D-Cross and Pescado Tongues

The D-Cross and Pescado tongues of the Mancos Shale represent a subregional transgression that separates the Gallup Sandstone into two parts in the area south of the San Juan Basin. The Pescado Tongue terminology was used in the area south of Gallup and the D-Cross Tongue name was used in the southern Acoma basin. Molenaar (1974, p. 257) has shown that the Pescado is equivalent to the lower half of the D-Cross Tongue; in the Gallup area a marine sandstone bar divides the D-Cross into two tongues. The total D-Cross interval ranges from 150 to 180 feet (46-55 m) in the Zuni and Acoma basin areas.

Gallup Sandstone and Basal Niobrara Sandstones

The Gallup Sandstone is the first major regressive wedge in the San Juan Basin. Just south of the basin, the D-Cross-Pescado transgression separates the main (or type) Gallup from a lower regressive wedge called the Atarque Member (of the Mesaverde), or lower Gallup. Figure 1 shows the relationships. The main or upper Gallup is unique to northwestern New Mexico and northeastern Arizona, in that it has no regressive equivalents in other parts of the western interior.

Because of space limitations, the time-stratigraphic section (fig. 1) erroneously shows the Dilco-Gallup contact to be at the top of the coastal-barrier sandstone. Actually, in that area, this contact, as originally defined, is placed at the top of a prominent fluvial sandstone (Torrivio Sandstone) which is about 50 to 100 feet (15-30 m) higher. Refer to Molenaar (1973) or the other paper by Molenaar in this volume, which show this relationship in the southwestern San Juan Basin. The Hospah sand, a local name for the main oil-producing sand at Hospah field in the southern San Juan Basin, is equivalent to this channel sandstone.

The stratigraphic rise at the top of the upper regressive Gallup Sandstone from its landward extent above the D-Cross Shale Tongue to its seaward pinchout (a distance of about 80 miles (129 km), is about 200 feet (61 m).

Several elongate offshore bars occur above and seaward from the regressive Gallup. These sandstone bars are oil producers in the central San Juan Basin—the so-called Gallup oil fields or pools; and have been referred to as transgressive Gallup, Tocito, or basal Niobrara sandstones. In outcrops in the Boulder Lake area on the east side of the basin, Landis and Dane (1967) applied the name Cooper Arroyo Sandstone to a thin sandstone bed. This also is a basal Niobrara sandstone. These sandstones are much coarser than the regressive Gallup sandstones; they are coarse grained with occasional pebble zones as contrasted to the fine-grained regressive sandstones. **[Editor's note: see discussion at stop 1; first day in road log.]**

In areas seaward from the regressive Gallup, the basal Niobrara sandstones rest unconformably on the lower Mancos or are developed within a 150-foot (46-m) interval above the unconformity. In places, the unconformity cuts as far down section as the Juana Lopez. Campbell (1973) presented an interpretation in which there is no unconformity and the coarse sands were swept obliquely downslope seaward from the regressive fine-grained shoreface sands. This would necessitate these highly crossbedded, medium- to coarse-grained sands being deposited in 200 to 300 feet (61-91 m) of water. This interpretation was based on a number of core holes drilled by Humble (now Exxon) in the northwestern San Juan Basin. These logs have not been released as far as the writer knows.

Crevasse Canyon Formation

The Crevasse Canyon Formation is the catch-all for the predominantly nonmarine deposits between the Gallup Sandstone and the Point Lookout Sandstone in the southern San Juan Basin. Also, for some obscure reason, the Dalton Sandstone, a regressive coastal-barrier sandstone, is included in the Crevasse Canyon. In ascending order, the various members are

Dilco Coal Member, Dalton Sandstone Member, Bartlett Barren Member and the Gibson Coal Member. The Bartlett Barren Member is not snown on the time-stratigraphic section because of space limitations and also because it merges with the Gibson through facies change in the vicinity of the section. It was defined in the Gallup area as a non-coal-bearing zone below the Gibson and above the Dilco or Dalton Sandstone. It appears to be of only local significance.

In the area landward from the pinchout of the Point Lookout Sandstone, the Crevasse Canyon-Menefee contact is placed at the top of the coaly zone of the undivided Cleary and Gibson members. Farther south where the coaly zone is not present, everything is simply included in the Mesaverde Group (Beaumont and others, 1956).

Mulatto Tongue of the Mancos Shale

The Mulatto Tongue of the Mancos Shale represents a major transgressive event which has equivalents throughout the western interior. In the northern Rockies, this transgression advanced farther westward than the preceding Greenhorn transgression (Weimer, 1960, p. 15). Seaward from the northeastern extent of the underlying Gallup Sandstone, the transgressive deposits unconformably overlie the lower Mancos Shale as mentioned previously. It is speculative whether or not this unconformity is present farther southwest, where the Mulatto transgresses the nonmarine deposits of the Dilco.

Along the line of section, the Mulatto is about 500 feet (152 m) thick near the seaward pinchout of the overlying Dalton Sandstone. It is slightly thicker to the southeast and thinner to the northwest.

An interesting feature of the basal deposits of the Mulatto Tongue in the southern San Juan Basin is the thin layer of quartzite and chert pebbles and cobbles at the contact of marine shale and paludal shale. These pebbles are not a lag from the underlying Dilco, but were transported into the area during the transgression. They are thought to have been derived from Paleozoic rocks of the thrust belt of central Utah (Molenaar, 1973, p. 104). In areas where the offlapping Borrego Pass lentil ("stray sandstone") is present, the pebble layer is at the contact of the sandstone and overlying Mulatto Shale.

The Mulatto Tongue, as well as seaward equivalents in the upper Mancos Shale, is quite sandy. In detail it is composed of thinly interbedded shale, siltstone and very fine grained, ripple-bedded sandstone. Thin beds of sandstone may make up 50 percent of the unit and locally, either due to a slightly greater sand percentage or calcite cementation, make resistive beds in outcrops and electric logs. Some of these have been mistakenly reported as Gallup tops in the eastern San Juan Basin.

El Vado Sandstone Member of the Mancos Shale

The El Vado Sandstone Member of the Mancos Shale is a local sandstone buildup in the upper Mancos. It was named by Landis and Dane (1967) for a 100-foot (30-m)-thick, resistant sandy unit that occurs in outcrops in the El Vado-Boulder Lake areas on the northeastern side of the San Juan Basin. It consists of thinly interbedded siltstone and very fine grained sandstone and shale, and can be correlated into the subsurface in that part of the basin. The top ranges from 200 to 300 feet (61-91 m) above the basal Niobrara unconformity (Molenaar, 1974, p. 254). Stratigraphically it falls well below the seaward pinchout of the Dalton Sandstone 40 to 70 miles (65-113 m) to the southwest and, therefore, is not a seaward equivalent of the most regressive part of the Dalton. The El Vado can be correlated in the subsurface about 50 miles (80 km) southwest of the type area before it loses its resistive character on electric logs. Apparently it is just an offshore buildup of interbedded sandstone and shale within the upper Mancos, or perhaps it is merely the increase in calcium carbonate cement in the northeastern part of the basin that makes it recognizable on resistivity logs. King (1975, p. 59) however, suggested giving the El Vado Sandstone formational status and extending it to the south to encompass much of the Mulatto, Dalton and Hosta interval.

Dalton Sandstone Member of the Crevasse Canyon Formation

The Dalton Sandstone Member of the Crevasse Canyon Formation overlies the Mulatto Tongue and, except for locally being coarser grained and containing scattered pebbles, is a typical regressive coastal-barrier sandstone. It rises stratigraphically about 500 feet (152 m) from southwest to northeast and has two lower tongues in the outcrop belt northeast of Gallup. The thinning of the upper tongue can be seen in outcrops north of Pinedale Trading Post. It is about 90 feet (27 m) thick at the west end of Ram Mesa and thins to a pinchout edge about 6 miles (10 km) to the east. (Refer to cross section in other paper by Molenaar in this volume.) The upper surface of this thinning wedge represents an oblique component of the original shoreface (less any compaction). This calculates to be about 16 feet (5 m) per mile. Assuming a shoreline trend of N. 60 W., true dip of the shoreface would be about 35 feet (11 m) per mile.

Hosta Tongue of the Point Lookout Sandstone

The Hosta Tongue of the Point Lookout Sandstone is a basal transgressive sandstone of the Satan transgression in the southern San Juan Basin. It attains a maximum thickness of about 130 feet (40 m) and is a fining-upward sequence representing deepening water (Sabins, 1964, p. 304). This character differentiates it from most transgressive Upper Cretaceous sandstones of the western interior, which are either very thin or are actually regressive offlap deposits in an overall transgression. The top of the Hosta Tongue rises stratigraphically about 100 to 150 feet (30 to 46 m) from northeast to southwest.

Satan Tongue of the Mancos Shale

The Satan Tongue of the Mancos Shale represents another transgression, probably of regional significance. It is equivalent to the unnamed shale tongue in the Kaiparowits area and to the "Masuk" Shale of the Wasatch plateau. It ranges in thickness from zero at its landward extent south of Crownpoint to about 300 feet (91 m) at the seaward pinchout of the underlying Hosta-Dalton sandstones. In the prominent outcrops just south of Crownpoint, it is about 100 feet (30 m) thick and consists of thinly interbedded, very fine grained sandstone and fissile, dark-gray shale. Rather than gradual thinning to the south between the Hosta and Point Lookout sandstones, the whole Satan interval becomes sandier and merges with the massive sandstone of the combined Hosta and Point Lookout. This can be seen on cliff faces near Satan Pass and Mariana Pass, south and southwest of Crownpoint respectively. Satan Pass, of course, is the type locality of the Satan Tongue.

Mesaverde Group

The Mesaverde Group of the type area at Mesa Verde National Park in southwestern Colorado is made up of, in ascending order, the Point Lookout Sandstone, Menefee Formation and the Cliff House Sandstone. Subsequent use of the term Mesaverde in other areas of the western interior has lost much of its meaning, except that it refers to the thick marine and nonmarine unit overlying the main thick Upper Cretaceous shale. In the southern San Juan Basin and areas farther south, the base of the Mesaverde is placed at the base of the Gallup, as shown on the time-stratigraphic section. The individual formations of the Mesaverde are considered separately. **[Editor's note: for a detailed electric log cross section of the subsurface Mesaverde Group see the paper by Fassett elsewhere in this volume.]**

Point Lookout Sandstone

The Point Lookout Sandstone is the most extensive regressive coastal-barrier sandstone in the San Juan Basin; it represents a regional regression throughout the western interior. Equivalent regressive sandstones are the upper part of the Yale Point Sandstone of the Black Mesa basin, the upper part of the John Henry Member of the Straight Cliffs Formation of the Kaiparowits plateau; the Star Point Sandstone of the Wasatch plateau; and at least part of the Blackhawk Formation of the Book Cliffs of Utah. In prograding across the San Juan Basin, a distance of about 130 miles (209 km), the Point Lookout rises stratigraphically about 1,200 feet (366 m). It merges with the Cliff House Sandstone on the north side of the basin; and, when "last seen" in outcrops west of Pagosa Springs, the combined unit consists of about 100-150 feet (30-45 m) of thin, fringy, marine sandstone beds. The total pinchout probably was not much farther northeast.

The landward pinchout of the Point Lookout Sandstone is shown in two places in the southwestern San Juan Basin on the "Geologic Map of New Mexico" (Dane and Bachman, 1965). The pinchout also occurs in the Cañoncito area 25 miles (40 km) west of Albuquerque. A line connecting these points trends about N. 60° W. The Point Lookout Sandstone is shown on the state geologic map in the Acoma basin or embayment about 50 miles (80 km) southwest of this line. The writer examined these outcrops and concluded that they are thick fluvial sandstones and are not related to the Point Lookout.

Menefee Formation

The Menefee Formation, the middle unit of the type Mesaverde, represents nonmarine-paludal to alluvial-plain deposition landward from the Point Lookout and Cliff House shorelines. It is composed of paludal carbonaceous shales and coals, fluvial sandstones and flood plain shales. The coals occur in proximity to the shorelines, where environmental conditions were more conducive to the formation of coal swamps.

The Menefee thickens from a pinchout edge on the north flank of the San Juan Basin to about 2,000 feet (610 m) in the area of the landward extent of the overlying Cliff House. Farther south the Menefee thins, owing to late Tertiary to Recent erosion. In the southern part of the San Juan Basin, the Menefee is divided into two members, the Cleary Coal Member at the base and the non-coal bearing Allison Member above. However, the upper part of the Allison is very carbonaceous and coaly, as coastal swamp conditions are again repeated behind the Cliff House shoreline. This zone is sometimes referred to as the upper coal-bearing unit of the Menefee.

Cliff House Sandstone

The Cliff House Sandstone is a fairly thick sandstone unit deposited in a transgressive cycle. Most transgressive sandstones in the western interior are very thin. However, even though the Cliff House is considered an overall transgressive sandstone, genetically the thick sandstone buildings are offlap or regressive deposits. They represent deposition during stillstands or regressions of the shoreline before being overridden by the overlying Lewis transgression. These buildups clearly intertongue with the marine Lewis Shale to the northeast and the nonmarine Menefee Formation to the southwest.

The largest buildup, which attains a maximum thickness of about 800 feet (244 m), is known as the La Ventana Tongue of the Cliff House. It crops out just west of La Ventana on the east side of the basin and can be traced in the subsurface across the basin to outcrops of the Cliff House buildup on Hogback Mountain southwest of Farmington. The intertonguing of the La Ventana with the Lewis Shale is well displayed in outcrops just north of La Ventana.

A smaller but significant buildup to the southwest was originally called the "Chacra" sandstone, but is now regarded by most geologists as part of the Cliff House. **[Editor's note: This is the Tsaya Canyon sandstone member of the Cliff House Sandstone of this guidebook.]** It ranges from 150 to 300 feet (46-92 m) in thickness and forms the prominent outcrop belt on the southwest between Chacra Mesa and the area east of Newcomb. Stoney Buttes are isolated remnants of Cliff House and are probably not far from the original southwestern extent of the unit. The gas-producing sandstones in the central basin that have been referred to as "Chacra" sandstone are actually northeasterly extending tongues or offshore-bar equivalents to the upper part of the La Ventana (see paper by Fassett, elsewhere in this volume).

Several smaller buildings or steps are present to the northwest, in the deeper part of the basin, where they are gas productive. They aggregate about 300 feet (91 m) of stratigraphic rise (Hollenshead and Pritchard, 1961). The total stratigraphic rise of the Cliff House (or basal Lewis) from northeast to southwest in about 100 miles (161 km) is about 1,300 feet (396 m).

Lewis Shale

The Lewis Shale represents another significant transgressive episode that has equivalents in other parts of the western interior. However, it should not be confused with the "Lewis" shale of Wyoming and northwest Colorado, which is a later transgression that isn't represented in the San Juan Basin. Apparently the Lewis terminology was carried from the type area in the northwestern San Juan Basin to Wyoming and northwest Colorado before the miscorrelation was recognized. Therefore, the "Lewis" of that northern area is usually denoted by quotes.

Like the Mancos Shale, the Lewis contains many thin bentonite beds that serve as good time marker beds for subsurface correlation. One of the thickest of these has been named the Huerfanito Bentonite Bed (Fassett and Hinds, 1971, p. 6). It is several feet thick and can be correlated throughout the basin on resistivity, conductivity, and transittime logs. It is an excellent time surface to which stratigraphy of underlying and overlying formations may be related.

Pictured Cliffs Sandstone

The Pictured Cliffs Sandstone is a regressive coastal-barrier sandstone that represents the final retreat of the western interior sea from the San Juan Basin area. The continued regression to the northeast is represented by the slightly younger Trinidad Sandstone of the Raton basin. Like the Point Lookout, the Pictured Cliffs prograded at different rates; and, as a result of still-stands or small transgressions and subsequent regressions, greater thicknesses were built up. Locally, it is as much as 400 feet (122 m) thick, but the average thickness is much less. On the southeast side of the basin, the Pictured Cliffs is very thin; it is absent for a considerable distance along the outcrop belt on the east side. This is due to removal by pre Ojo Alamo (Paleocene) erosion in the northeastern part, but in the southeast part, the Fruitland Formation directly overlies the Lewis Shale. Fassett and Hinds (1971, p. 12) suggested that either concomitant uplift in the area caused rapid retreat of the sea and prevented development of strandline sands (Pictured Cliffs) or uplift resulted in erosion of the sands prior to Fruitland deposition.

The total stratigraphic rise of the Pictured Cliffs Sandstone across the San Juan Basin from outcrops on the southwest to outcrops on the northeast, a distance of about 80 miles (129 km), is about 1,100 feet (355 m) (Fassett and Hinds, 1971).

Fruitland Formation

The Fruitland Formation represents nonmarine, lower coastal-plain deposition behind the Pictured Cliffs shoreline. It consists of paludal carbonaceous shale and coal interbedded with siltstone and sandstone. It forms subdued topography, and the best outcrops usually are found in roadcuts. However, good outcrops of the Fruitland occur in the Bisti badlands just south of Bisti Trading Post on the Farmington-Crownpoint road. Some of the thickest coal beds in the basin occur in the Fruitland.

The upper contact of the Fruitland with the overlying Kirtland Shale is placed at the highest coal or carbonaceous shale bed. This is somewhat arbitrary, because different geologists may pick the contact very differently. The Fruitland ranges in thickness from zero on the east side of the basin, owing to truncation prior to Ojo Alamo (Paleocene) deposition (Fassett and Hinds, 1971), to about 500 feet (152 m), but averages about 300-350 feet (91-107 m).

Kirtland Shale

The Kirtland Shale conformably overlies the Fruitland Formation and represents upper coastal- or alluvial-plain deposition landward from the Fruitland coal swamps. It has been divided into three units called, in ascending order, the lower shale member, Farmington Sandstone Member, and upper shale member. The lower shale member is composed predominantly of gray shale containing a few thin interbeds of sandstone and siltstone. The Farmington Sandstone is composed of a number of fluvial sandstone beds interbedded with shale. The upper shale member also consists of sandstone and shale. The Farmington Sandstone and upper shale members are difficult to separate consistently, because of the presence of sandstone beds similar to the Farmington Sandstone throughout the upper shale member (Fassett and Hinds, 1971, p. 23). The lower shale member ranges in thickness from zero on the east, owing to truncation prior to Ojo Alamo deposition, to about 450 feet (137 m) and averages about 200-250 feet (61-76 m). The undivided Farmington Sandstone and upper shale member ranges in thickness from zero on the east to about 1,500 feet (457 m) in the northwest part of the basin.

The total Kirtland Shale thins from northwest to southeast across the San Juan Basin owing to truncation prior to Ojo Alamo deposition. How much Upper Cretaceous strata have been removed is speculative, but certainly a considerable amount has been removed on the east side of the basin.

McDermott Member of the Animas Formation

The McDermott Member of the Animas Formation is a local unit present in outcrops along the northwest side of the San Juan Basin, primarily in the Colorado portion. It is composed of purple to brown nonmarine sandstone, conglomerate and shale of andesitic composition and is about 300 feet (91 m) thick in the Durango area. On the basis of dinosaur bones reported by Reeside (1924), the McDermott has been considered Late Cretaceous in age. It is now mapped as a basal member of the Animas Formation, which is considered Paleocene in age (Fassett and Hinds, 1971, p. 33). The McDermott (and the Animas) is thought to unconformably overlie the Kirtland.

The McDermott and probably the uppermost part of the Kirtland Shale represent a change in provenance from the distant southwesterly source for other Upper Cretaceous formations to a local north, northwest, or possibly even western source as igneous activity commenced in the Rico, La Plata, Ute and Carizzo Mountain areas. Late Cretaceous to earliest Tertiary radiometric age dates have been determined for intrusive rocks in those areas (Armstrong, 1969). Extrusive equivalents of intrusives could well have been the source for the volcanic detritus found in these uppermost Cretaceous units in the northwestern corner of the San Juan Basin.

ECONOMIC RESOURCES

The purpose of this paper has been to summarize the Upper Cretaceous stratigraphy and depositional history. However, because the San Juan Basin contains the third largest gas field (Prudhoe Bay is considered second) and one of the largest coal mines in the country; and both are from Upper Cretaceous rocks, it seems fitting to briefly mention the economic resources of the Upper Cretaceous rocks and the respective formations in which they occur. Much of the statistical data on the oil and gas are from the 1975 International Oil and Gas Development Yearbook of the International Oil Scouts Association.

Oil and Gas

The Blanco gas field covers about 1,340,000 acres of the central San Juan Basin. The field is unique because the accumulation largely is hydrodynamically controlled in the structurally low part of the basin. The major production is from the Dakota, Point Lookout, Cliff House and Pictured Cliffs sandstones, with minor production from the Fruitland Formation and Farmington Sandstone. The ultimate recovery is estimated to be about 23 trillion cubic feet of gas, plus significant amounts of condensate (Pritchard, 1972, p. 284). Total gas production in 1974 was about 556 billion cubic feet, and the cumulative production in 1974 was about 8½ trillion cubic feet.

Besides the gas and condensate production in the central San Juan Basin, the Dakota produces oil in several small, structurally controlled fields on the flanks of the basin, such as Hogback and Table Mesa fields and on the southern flank of the Chaco slope. Most of these fields are small. The two largest, Hogback and Rattlesnake fields, are in the 5-7 million barrel range, which is much larger than most of the others.

Most of the oil in the basin (excluding condensate) comes from stratigraphic traps in the transgressive Gallup or basal Niobrara sandstones. There are about 2 dozen fields or pools as large as 40 million barrels in size, with a total estimated ultimate recovery of about 150 million barrels. In addition there are a few fractured shale reservoirs in the lower part of the Niobrara part of the Mancos Shale. The only production from the regressive Gallup Sandstone is at Hospah field in the southern San Juan Basin. This field is structurally controlled and through 1974 had produced about 11½ million barrels of oil.

Channel sandstones in the Menefee Formation produce a small amount of oil in stratigraphic-structural traps at two or three small fields in the southern San Juan Basin.

Coal

The Fruitland Formation contains by far the largest minable coal reserves in the San Juan Basin area. The Navajo mine, which supplies coal for the Four Corners power plant southwest of Farmington, is one of the largest coal mines in the country. **[Editor's note: for a description of this mine see paper by Karna elsewhere in this volume.]** Many areas in which the Fruitland is at or near the surface contain large, strippable coal reserves.

The Menefee contains much smaller, but still significant, reserves of minable coal. These occur in the Cleary Coal Member at the base and in the upper coal member near the top. Because of steep dips in some of the areas of Menefee outcrops, some of the coal is not amenable to strip mining methods.

The Gallup Sandstone and the Dilco and Gibson members of the Crevasse Canyon Formation have been mined underground for coal since the 1880's in the southwestern San Juan Basin. Few if any are active today, except for the McKinley mine northwest of Gallup, which is a strip mine in the undivided Cleary and Gibson members. **[Editor's note: see Wilson, this volume.]**

Other Resources

Besides oil, gas and coal, which are the significant economic resources of the Upper Cretaceous rocks of the San Juan Basin area, uranium and humate are locally important. The major reserves and production of uranium occur primarily in Jurassic rocks in the southern San Juan Basin. However, some uranium ore has been mined in the Dakota in the Church Rock and Nutria monocline areas in the southwestern part of the basin.

Humate is a relative newcomer on the list of economic resources. Lithologically, humate is described as a humic-rich carbonaceous shale and is used principally as a soil conditioner. The San Juan Basin contains vast amounts of this material in the nonmarine, paludal deposits of the Crevasse Canyon, Menefee and Fruitland formations. Currently it is being strip-mined from the Menefee in the La Ventana-San Ysidro areas on the southeast side of the basin. The amount of production will probably be dependent on development of the market.

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