[AMERICAN JOURNAL OF SCIENCE, VOL. 286, JUNE, 1986, P. 463-488]

SEDIMENTOLOGY AND SANDSTONE PETROGRAPHY OF THE UPPER KIRTLAND SHALE AND OJO ALAMO SANDSTONE, CRETACEOUS-TERTIARY BOUNDARY, WESTERN AND SOUTHERN SAN JUAN BASIN, NEW MEXICO

MARGARET A. KLUTE

Laboratory of Geotectonics, Department of Geosciences, University of Arizona, Tucson, Arizona 87521

ABSTRACT. Sedimentology and petrography of the upper Kirtland Shale and Ojo Alamo Sandstone imply strongly that sedimentation was essentially continuous across the Cretaceous-Tertiary boundary in the southern and western San Juan Basin, although palynological evidence is equivocal. The contact between the two formations records a fluvial facies change rather than a major regional unconformity.

Sandstone and finer grained lithofacies of the upper Kirtland Shale represent channel, point-bar, crevasse-splay, and floodplain environments within a sandy to muddy meandering fluvial system on an alluvial plain. Sandstone lithofacies within the Ojo Alamo Sandstone represent transverse bar, bar top, channel, vertical accretion, and flood deposits on a braidplain within sandy braided stream systems of combined South Saskatchewan and Platte types. The contact between the two formations is marked locally by deep scour, but gradational and intertonguing relationships elsewhere preclude the possibility that the contact is a major regional unconformity. Multiple scour surfaces within and at the base of the Ojo Alamo Sandstone are interpreted as minor breaks in sedimentation.

Sandstones in both formations are feldspathic and lithic arenites containing the same types of detrital grains. Detrital modes indicate that upper Kirtland Shale sandstones contain slightly more plagioclase and volcanic lithic fragments than Ojo Alamo Sandstone samples, which in turn are slightly more enriched in potassium feldspar and polycrystalline quartz.

A sediment source lying to the north or northwest, and containing volcanic rocks, is inferred from paleocurrents and sandstone compositions. Southeastward thinning of the Fruitland-Kirtland interval suggests increased subsidence in the northern San Juan Basin during latest Cretaceous time. Unroofing of uplifted Precambrian basement rocks in the San Juan Mountains probably triggered the transitional change from meandering to braided fluvial style.

INTRODUCTION

In the San Juan Basin of northwestern New Mexico (fig. 1), the Cretaceous-Tertiary boundary is located within a thick sequence of nonmarine rocks (fig. 2). Vertebrate fauna restrict the position of the boundary to the stratigraphic interval including the upper part of the Kirtland Shale and the overlying Ojo Alamo Sandstone (fig. 3) (Lindsay, Butler, and Johnson, 1981). Attempts to resolve the position of the boundary more precisely based on biostratigraphy, magnetostratigraphy, and radio-

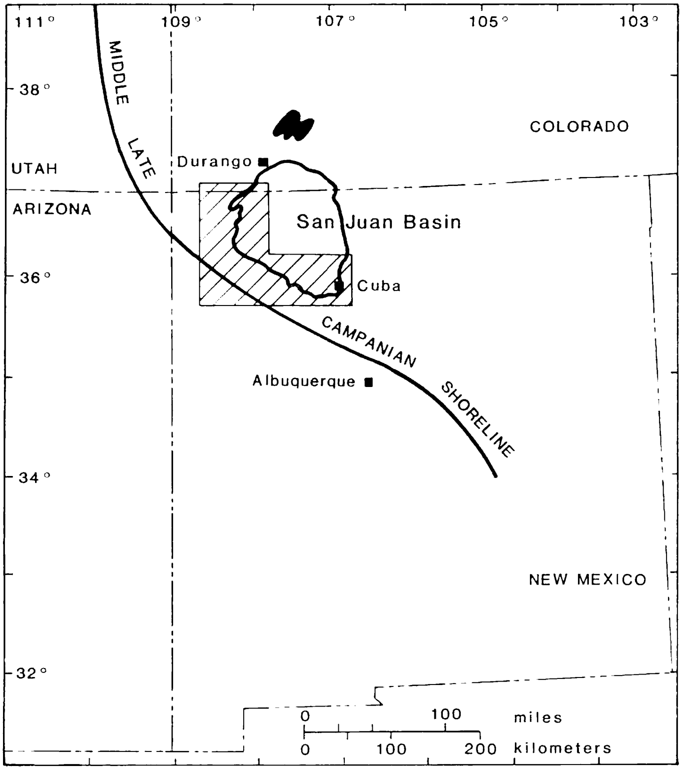

Fig. 1. Map showing location of the San Juan Basin and the study area (diagonal lines). San Juan Basin delineated by the upper contact of the Kirtland Shale. Also shown are the position of the Middle Late Campanian shoreline at time of maximum transgression (Molenaar, 1983) and the location of present outcrops of Precambrian basement rocks in the San Juan Mountains (shaded area) (McGookey, 1972).

metric dating have resulted in conflicting interpretations due to disagreement about the completeness of the Kirtland-Ojo Alamo interval. While some investigators consider this section to be relatively complete (Dane, 1936; Klute, 1983; Lindsay, Butler, and Johnson, 1981), others have placed a major regional unconformity at or near the base of the Ojo Alamo Sandstone (Reeside, 1924; Baltz, Ash, and Anderson, 1966; Fassett and Hinds, 1971; Fassett, 1982, 1985). The presence or absence of a major unconformity and hiatus within this section affects biostratigraphic and magnetostratigraphic correlations and influences models for deposition in the basin. The purpose of this report is to describe the sedimentology, sandstone petrography, and contact relationships of the upper Kirtland Shale and Ojo Alamo Sandstone and to determine whether these parameters provide evidence for a major regional unconformity at or near the base of the Ojo Alamo Sandstone.

The global significance of the Cretaceous-Tertiary boundary has been the subject of many recent studies, sparked by the discovery of anomalously high concentrations of iridium coincident with the boundary at more than sixty localities (Alvarez and others, 1980, 1984). Alvarez and others (1980) suggest that the iridium was derived from a meteor impact event which caused globally synchronous end-Cretaceous extinctions. Magnetostratigraphy of Upper Cretaceous and Paleocene strata in the San Juan Basin initially conflicted with this hypothesis, because the Cretaceous-Tertiary boundary was interpreted to occur within a normal polarity zone correlated with chron 29N (Butler and others, 1977). However, Lowrie and Alvarez (1977) demonstrated that the Cretaceous-Tertiary boundary in Gubbio, Italy occurs in a reversed polarity zone correlated with chron 29R. These data jointly suggested nonsynchronous end-Cretaceous extinctions of marine and terrestrial fauna. Subsequent detailed rock-magnetism studies have resulted in identification of a remagnetized normal polarity zone just below the base of the Ojo Alamo Sandstone (Butler, 1984; Butler and Lindsay, 1985). Removal of this overprinted zone from the section has resulted in a revised San Juan Basin polarity zonation (fig. 3) in which the Cretaceous-Tertiary boundary occurs within a reversed polarity interval correlated with chron 29R, consistent with the location of the boundary in the Gubbio section. Thus, the presence of a major regional unconformity within the San Juan Basin section is

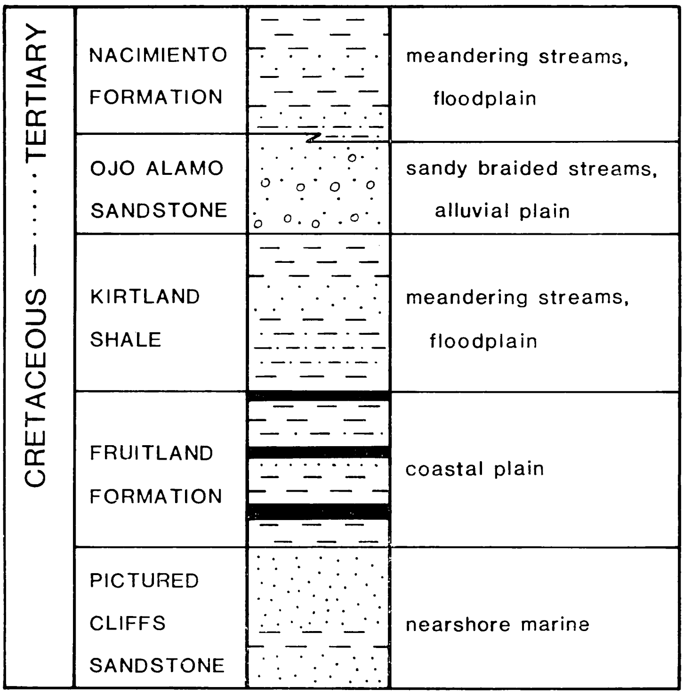

Fig. 2. Stratigraphic column and depositional environments of formations adjacent to the Cretaceous-Tertiary boundary in the San Juan Basin. Thickness not to scale.

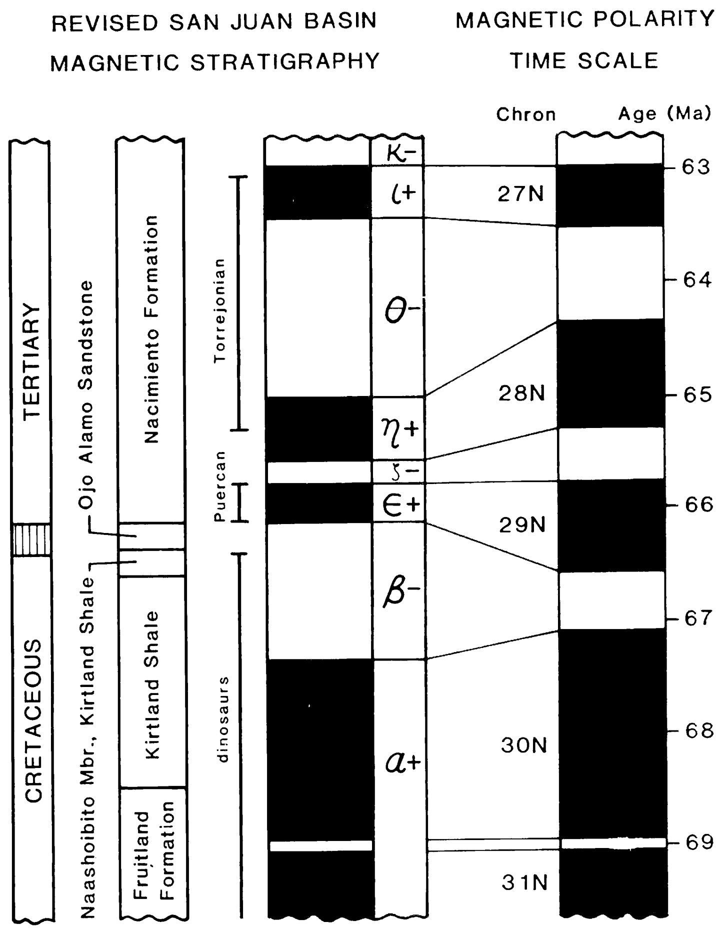

Fig. 3. Revised San Juan Basin magnetostratigraphy correlated with the magnetic polarity time scale of Ness, Levi, and Couch (1980). Normal polarity intervals are shaded. Biostratigraphic control for the position of the Cretaceous-Tertiary boundary in the San Juan Basin is also shown. From Butler and Lindsay (1985).

not required in order to establish a compatible correlation with the Gubbio section, as suggested by Alvarez and Vann (1979), Lucas and Schoch (1982), and Shoemaker and others (1984). However, it is necessary to assess independently the stratigraphic completeness of the section in order to establish correct magnetostratigraphic and biostratigraphic correlations and to resolve conflicting depositional models for the San Juan Basin at the beginning of Laramide time.

GEOLOGIC SETTING

The San Juan Basin is located in northwestern New Mexico and southwestern Colorado (fig. 1). During Late Cretaceous time, this region was on the western margin of the Western Interior seaway. As much as

1900 m of Upper Cretaceous strata accumulated in the area during three major transgressive-regressive episodes. Marginal marine deposits of the Pictured Cliffs Sandstone represent the final marine regression during the Campanian (Fassett and Hinds, 1971). Deposition in nonmarine environments continued through the remainder of the Cretaceous and the Paleocene, as recorded in the Fruitland Formation, Kirtland Shale, Ojo Alamo Sandstone, and Nacimiento Formation. The lithostratigraphy and depositional environments of these formations (fig. 2) are briefly described here.

The Fruitland Formation consists of as much as 150 m of interbedded sandstone, siltstone, shale, coal, and lignite and is interpreted as coastal plain deposits (Fassett and Hinds, 1971). The overlying Kirtland Shale is comprised of up to 600 m of shale, sandstone, siltstone, and claystone interbedded with minor amounts of coal, lignite, and conglomerate. The depositional environment of the Kirtland Shale has been interpreted as an alluvial plain with floodplain and channel subenvironments (Fassett and Hinds, 1971). Thicknesses of these formations are locally variable, but a regional northwest to southeast thinning of the Fruitland-Kirtland interval by as much as 640 m has been noted (Reeside, 1924; Dane, 1936; Fassett and Hinds, 1971) (fig. 4).

The Ojo Alamo Sandstone ranges in thickness from 6 to 120 m and consists of sandstone, pebbly sandstone, and local discontinuous lenses of conglomerate, siltstone, and claystone. Its lower contact with the Kirtland

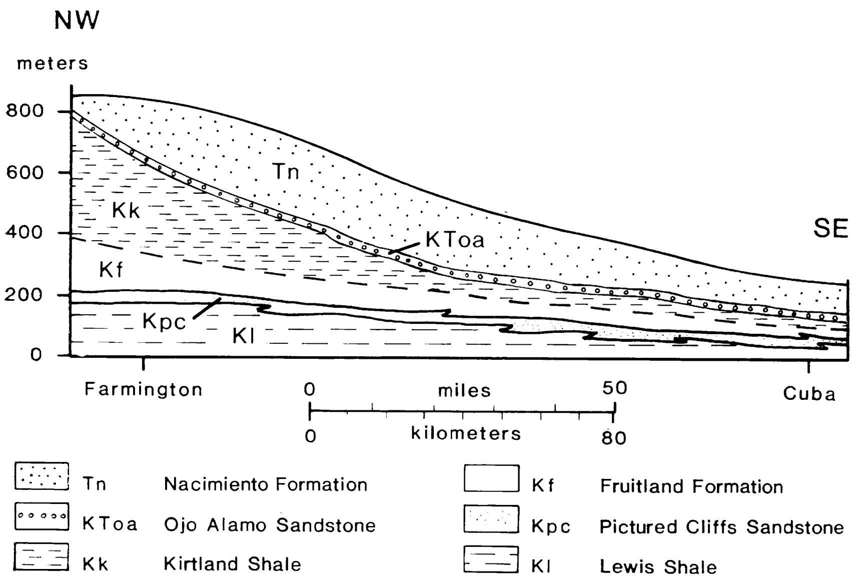

Fig. 4. Diagrammatic northwest-southeast cross section of Upper Cretaceous and Paleocene strata in the San Juan Basin, showing southeast thinning of the Fruitland-Kirtland interval. Basal datum is the Huerfanito Bentonite Bed. Modified from Fassett and Hinds (1971).

Shale is commonly marked by scour and channel-fill structures. The Ojo Alamo Sandstone is interpreted as a braided stream deposit (Fassett and Hinds, 1971).

The Nacimiento Formation gradationally overlies the Ojo Alamo Sandstone and is 150 to 460 m thick. It consists of siltstone, claystone, and interbedded discontinuous sandstone lenses and was deposited in channel, floodplain, alluvial fan, and lacustrine subenvironments of an alluvial plain (Baltz, 1967).

This sedimentary sequence documents a vertical transition in depositional environments from coastal plain to alluvial plain to braidplain and back to alluvial plain during the Campanian through Paleocene interval in the San Juan Basin (fig. 2). Uncertainty about the presence of an unconformity and hiatus at or near the base of the Ojo Alamo Sandstone leaves open the question of whether the transition from alluvial plain to braidplain was gradational or was preceded by a period of erosion. The sedimentological studies reported here attempt to answer this question.

STUDY SITES

Both structural and stratigraphic considerations influenced the selection of study sites. The San Juan Basin is a Laramide structural basin (Baltz, 1967) with an asymmetric geometry. Dips are gentle on the western and southern flanks but much steeper on the northern and eastern flanks (Fassett and Hinds, 1971). The Kirtland Shale crops out around most of the basin, but the Ojo Alamo Sandstone is absent in the north. Both formations are thin and poorly exposed along the steeply dipping eastern margin. These factors limited the study of the Ojo Alamo Sandstone to the western and southern margins of the basin in northwestern New Mexico, where excellent exposures of gently dipping strata are present in badlands and mesas. The study sites are south of exposures of the Animas and McDermott Formations which are not discussed in this report. Samples were collected from nine localities (fig. 5). Two of these (Ojo Alamo Arroyo, Barrel Springs Arroyo) are in the type region of the Ojo Alamo Sandstone. This is a portion of the outcrop belt that extends 35 km from Hunter Wash to Coal Creek and includes the type locality of the Ojo Alamo Sandstone at Ojo Alamo Arroyo (Baltz, Ash, and Anderson, 1966). Detailed stratigraphic sections were measured at five of the localities (figs. 6, 7). The magnetostratigraphy of three of the localities (Moncisco Mesa, Ojo Alamo Arroyo, Eagle Mesa) has been described (Lindsay, Butler, and Johnson, 1981; Butler and Lindsay, 1985).

NOMENCLATURE

The stratigraphic nomenclature used in this report is illustrated in figure 8. The term Ojo Alamo Sandstone is used in the restricted sense of Baltz, Ash, and Anderson (1966) rather than according to Bauer's original definition (1916), because the base of the Ojo Alamo Sandstone (restricted) is the only regionally mappable surface within the Kirtland-

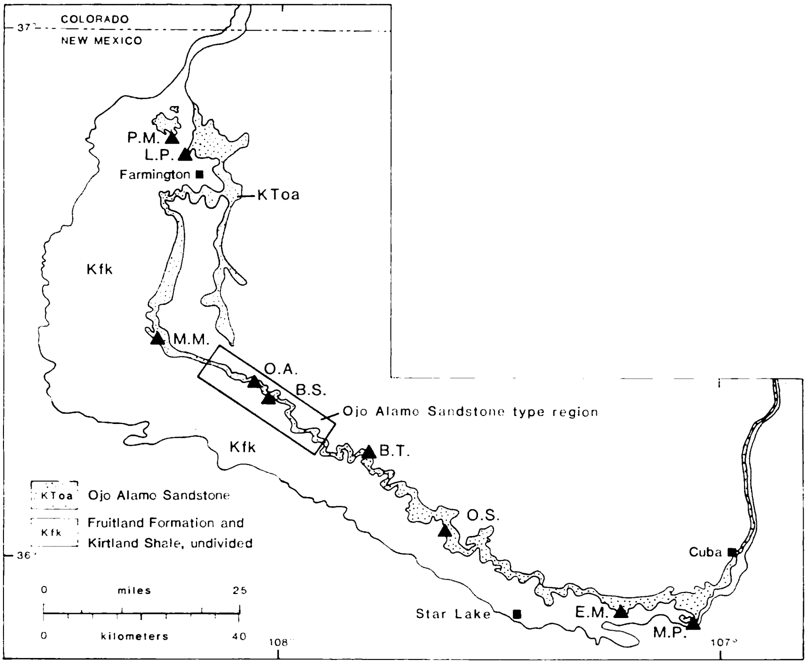

Fig. 5. Map showing the outcrop extent of the combined Fruitland Formation and Kirtland Shale (Kfk) and the Ojo Alamo Sandstone (KToa) on the southern and western margins of the San Juan Basin (from Fassett and Hinds, 1971). Study sites denoted by triangles: P.M., Piñon Mesa; L.P., La Plata; M.M., Moncisco Mesa; O.A., Ojo Alamo Arroyo; B.S., Barrel Springs Arroyo; B.T., Betonnie Tsosie Arroyo; O.S., Ojo Socorro; E.M., Eagle Mesa; M.P., Mesa Portales.

Ojo Alamo interval. The Naashoibito Member of the Kirtland Shale (Baltz, Ash, and Anderson, 1966) is recognized in the type region. The base of the Naashoibito Member is a pebbly sandstone containing siliceous pebbles similar to those in the Ojo Alamo Sandstone (fig. 7, Barrel Springs section). Since this unit is overlain by characteristic Kirtland Shale strata and does not contain sedimentary structures typical of the Ojo Alamo Sandstone, it is here considered part of the Kirtland Shale. Throughout this report, the term "upper Kirtland Shale" refers to a variable thickness (21-48 m) of strata immediately underlying the base of the Ojo Alamo Sandstone (restricted). It includes the Naashoibito Member of the Kirtland Shale in the type region and part of the Upper Shale Member of the Kirtland Shale (Bauer, 1916) at all other localities, except at Mesa Portales where the entire thickness of Kirtland Shale (48 m) was measured.

SEDIMENTOLOGY

Upper Kirtland Shale.—Two lithofacies are recognized within the upper Kirtland Shale: a fine-grained facies and a sandstone facies (figs. 6, 7). The fine-grained facies (F) is characterized by poorly sorted fine-grained

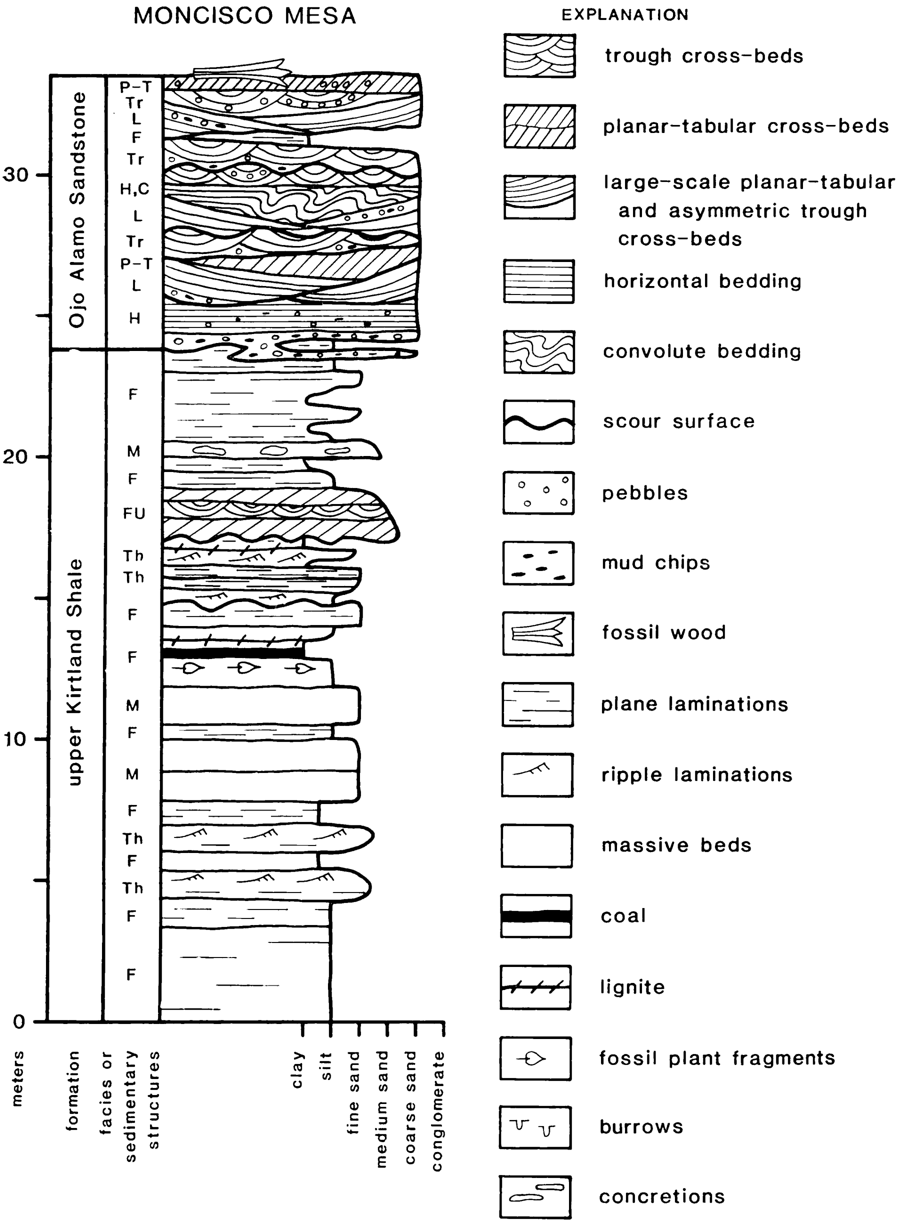

Fig. 6. Measured section from Moncisco Mesa showing sedimentary structures and textures and vertical distribution of lithofacies. Horizontal scale is grain size. Facies in upper Kirtland Shale: F, fine-grained facies; Th, thin cross-bedded sandstone subfacies; M, thick massive sandstone subfacies; FU, fining-upward sandstone subfacies. Sedimentary structures in Ojo Alamo Sandstone: H, horizontally bedded sandstone; L, large-scale planar-tabular and asymmetric trough cross-bedded sandstone; P-T, smaller scale planar-tabular cross-bedded sandstone; Tr, smaller scale trough cross-bedded sandstone; C, convolute bedded sandstone.

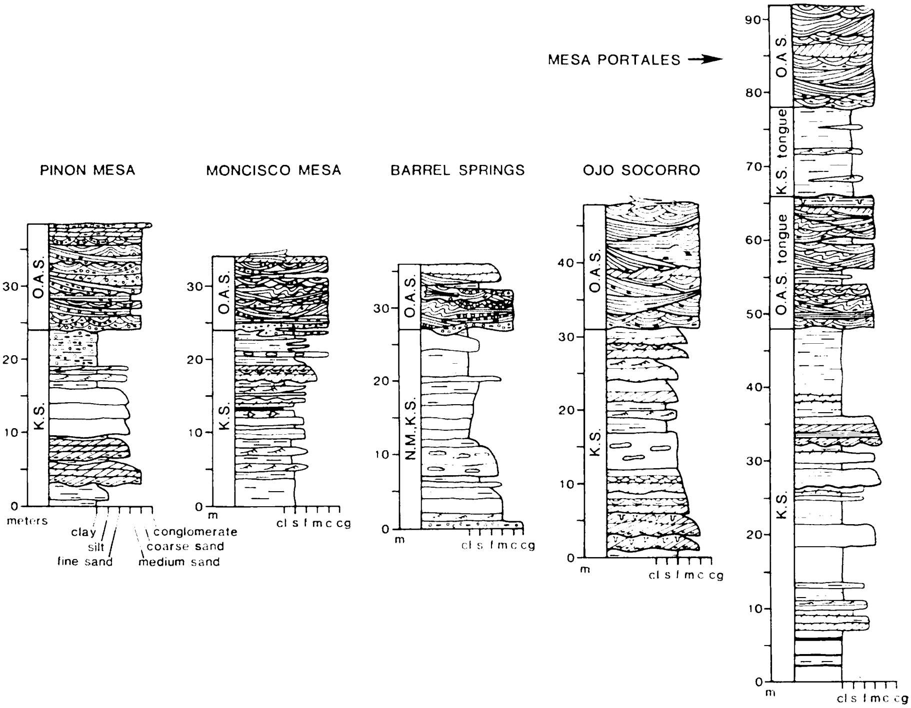

Fig. 7. Measured sections (see fig. 5 for localities) of Kirtland Shale and Ojo Alamo Sandstone showing regional distribution of lithofacies. Horizontal scale is grain size. See figure 6 for key to lithologic symbols. K.S., Kirtland Shale; N.M.,K.S., Naashoibito Member of Kirtland Shale; O.A.S., Ojo Alamo Sandstone.

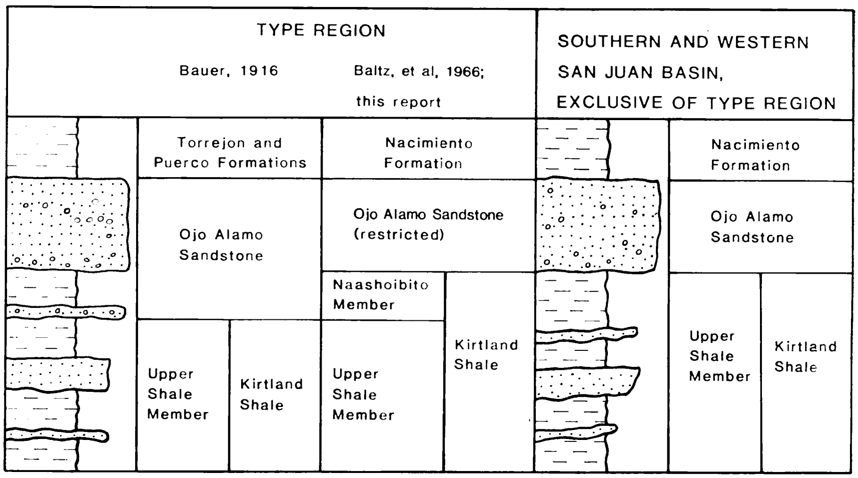

Fig. 8. Stratigraphic nomenclature for units adjacent to the Cretaceous-Tertiary boundary in the San Juan Basin.

strata, including sandy siltstone, silty fine-grained sandstone, and sandy to silty claystone. Better sorted claystones, siltstones, and shales are also present. Bedding ranges from massive to thinly laminated to ripple laminated. Most bedding is poorly defined, and vertical and lateral lithologic changes are commonly gradational. Discontinuous thin beds of coal, lignite, and carbonaceous siltstone containing plant fragments occur locally.

The sandstone lithofacies consists of fine- to coarse-grained sandstone subdivided into three subfacies: fining-upward sequences (FU), thin cross-bedded sandstones (Th), and thick massive sandstones (M). Fining-upward sequences range from 1 to 5 m thick. They characteristically have scoured bases overlain by cross-bedded sandstone containing pebble-sized mud clasts. Grain size decreases upward from medium- or coarse-grained sandstone at the base to fine-grained sandstone or siltstone at the top. Gradational upper contacts with fine-grained facies are common. Large-scale epsilon cross-beds or planar-tabular cross-beds up to 2 m thick occur at the bases of fining-upward sequences. These are typically overlain by smaller scale planar-tabular and trough cross-beds, which in turn grade upward to ripple laminations. Solitary burrow structures up to 1 cm in diam and 10 cm long occur at the tops of some sequences.

The thin cross-bedded sandstones are less than 1 m thick. They typically have scoured bases overlain by medium to fine-grained cross-bedded or thinly laminated sandstone. Sedimentary structures include small scale planar-tabular cross-beds, ripple laminations, and horizontal laminations.

Thick massive sandstones are up to 3 m thick and composed of medium- to fine-grained sandstone. These beds typically have no visible sedimentary structures, although in some cases, faint horizontal laminations are discernible. The weathered, poorly indurated condition of the rocks may obscure primary bedding.

Vertical and regional distributions of upper Kirtland Shale lithofacies are illustrated in figure 7. Both facies are present at all localities, although the fine-grained facies is most abundant. The southeasternmost section at Mesa Portales has relatively more fine-grained facies than other localities. Otherwise, neither vertical nor lateral trends in facies distribution were recognized on either local or regional scales.

Ojo Alamo Sandstone.—The Ojo Alamo Sandstone consists of a single lithofacies of medium to coarse-grained sandstone and pebbly sandstone containing local lenses of claystone and siltstone (figs. 6, 7). The sandstone occurs as large lenticular bodies up to 15 m thick that continue for a kilometer or more laterally. These bodies overlap one another and are in contact along scour surfaces or else are separated by thin siltstone and claystone interbeds. Multiple scour surfaces within the sandstone bodies subdivide them into depositional packages which contain a variety of sedimentary structures. These include large-scale planar-tabular and asymmetric trough cross-beds (L), smaller scale trough (Tr) and planar-tabular (P-T) cross-beds, horizontal beds (H), and convolute beds (C).

Mud intraclasts, siliceous pebbles and cobbles, and fossil logs are also incorporated into the sandstone bodies. Grain size usually remains constant, in the coarse- to medium-grained size range. Some fining upward trends from coarse- to medium-grained occur but are not common.

The most notable of the sedimentary structures within the sandstone bodies are large-scale planar-tabular and asymmetric trough cross-beds. Sets are up to 3 m thick and commonly extend tens of meters laterally. Asymmetric trough-shaped scours or low-angle truncation surfaces at the bases of the sets are overlain by cross-laminae which range in geometry from planar-tabular to asymmetric trough-shaped. Cross-laminae are 2 to 15 cm thick and dip less than 25 degrees. They are composed of medium- to coarse-grained sandstone and may have siliceous pebbles or mud clasts concentrated near basal scour surfaces or dispersed along cross-laminae. The sets are overlain by smaller-scale trough or planar-tabular cross-beds or else are truncated by scour surfaces at the bases of overlying large-scale cross-bed sets.

Smaller scale trough cross-beds, 20 cm to 5 m wide and 10 cm to 1 m deep, are also abundant in the Ojo Alamo Sandstone. They commonly occur in multiple sets with trough depths decreasing upward and are found either above the large-scale cross-bed sets or else immediately above scour surfaces.

Single and multiple sets of planar-tabular cross-beds up to 2 m thick are present within the upper parts of some of the sandstone bodies. Horizontally bedded sandstone is also present, ranging in scale from small localized lenses up to 50 cm thick and a few meters wide to large sheets up to 2 m thick and extending more than 10 m laterally. Individual beds within these units are 2 to 15 cm thick. Convolute bedding and fluid-escape structures are common within the horizontally bedded sandstone sheets and also occur within the large-scale planar-tabular and asymmetric trough cross-bed sets.

Scoured and channeled surfaces occur at the bases of and within the lenticular sandstone bodies. A single vertical section commonly contains several scour surfaces. Relief on these surfaces ranges from 1 to 3 m vertically over 30 m in lateral distance. Conglomeratic sandstones containing mud clasts and siliceous pebbles commonly occur immediately above scoured surfaces. Mud clasts are usually 1 to 3 cm long but may be a meter or more in length. Siliceous pebbles and mud clasts also occur as lag deposits in trough cross-beds and dispersed along cross-laminae in the large-scale cross-beds. Petrified fossil logs, up to 15 m long and 1 m in diam, are locally abundant in the Ojo Alamo Sandstone, particularly in the type area near Barrel Springs Arroyo.

Lenses of massive to thinly bedded siltstone and shale (F) up to 1 m thick are present between some of the sandstone bodies. These are slightly more common in the northwest but overall never comprise more than 5 percent of the total section. Basal contacts of these lenses are mostly conformable and gradational. Upper contacts are typically truncated by overlying scour surfaces.

Regional distribution of sedimentological features in the Ojo Alamo Sandstone is shown in figure 7. Pebbles are abundant in the northwest but are mostly absent south of the Betonnie Tsosie locality (fig. 5). Grain size decreases slightly from northwest to southeast. Powell (ms) documented this trend, reporting a gradual decrease in mean grain size from upper medium-grained (1.2 phi) to lower medium-grained (2.0 phi) sand. Thickness averages 15 to 46 m but ranges from less than 6 m to greater than 120 m, with a slight decrease in mean thickness to the southeast (Fassett and Hinds, 1971; Powell, ms). Other sedimentological features of the Ojo Alamo Sandstone, including the distinctive large-scale cross-beds, smaller scale planar-tabular and trough cross-beds, horizontal and convolute bedding, multiple scour surfaces, and abundant mud clasts, occur consistently throughout the study area.

DEPOSITIONAL ENVIRONMENTS

Miall (1981) has summarized facies models for both meandering and braided rivers. These models are the result of systematic study of both modern rivers and ancient fluvial deposits by many investigators. Sedimentological characteristics of the upper Kirtland Shale and Ojo Alamo Sandstone have been interpreted according to these facies models.

Upper Kirtland Shale.—The upper Kirtland Shale is most similar to muddy, fine-grained meandering river facies (Jackson, 1978), except that Kirtland strata are slightly more sandy. Lithofacies within the upper Kirtland Shale record deposition in different subenvironments of an alluvial plain drained by meandering rivers. The fine-grained facies represents deposition on floodplains by vertical accretion associated with overbank flow during flood events. Fining-upward sequences within the sandstone facies are interpreted as point bar deposits formed within active meandering channels. Thin cross-bedded sandstones are interpreted as crevasse-splay deposits which accumulated on the floodplain when channel levees were breached during flood events. Thick massive sandstones may represent channel fill, levee, or floodplain deposits, though the lack of preserved sedimentary structures in these rocks precludes specific interpretation. Coal, lignite, and carbonaceous siltstone were deposited in local reducing environments such as swamps, oxbow lakes, or abandoned chutes on the tops of point bars. Burrow structures indicate invertebrate activity on bar tops. The depositional environment for the entire Kirtland Shale has been similarly interpreted by Fassett and Hinds (1971).

Ojo Alamo Sandstone.—The Ojo Alamo Sandstone has been interpreted as a deposit of sandy braided streams on a broad alluvial plain (Fassett and Hinds, 1971; Powell, ms). Braided stream environments have been subdivided into six types (Miall, 1981). The Ojo Alamo Sandstone is interpreted here as a combination of the South Saskatchewan and Platte types. Transverse-bar, bar-top, channel, vertical accretion, and flood deposits are recognized.

The large-scale planar-tabular and asymmetric trough cross-bed sets are interpreted as transverse-bar deposits. In modern environments, transverse bars are wide, flat-topped tabular bodies deposited in shallow depressions in stream bottoms. They grow oblique to current direction by downcurrent migration of foresets resulting in large scale sets of planar-tabular cross-beds (Smith, 1971). Transverse-bar deposits usually have planar bases, but examples with inclined and asymmetric scoured bases similar to those in the Ojo Alamo Sandstone have been reported from the modern Lake Eyre basin in Australia (Williams, 1971), the Donjek River of Canada (Rust, 1972), and the Westwater Canyon Member of the Morrison Formation in New Mexico (Campbell, 1976).

Smaller scale trough and planar-tabular cross-beds that overlie the large-scale cross-bed sets are interpreted as bar-top deposits that formed as sediment was transported across the tops of active transverse bars in ripples or dunes (Smith, 1970). Smaller scale trough cross-beds that immediately overlie scour surfaces and occur in sets with depths decreasing upward are interpreted as channel deposits similar to those reported from the modern South Saskatchewan River (Cant and Walker, 1978) and the Devonian Battery Point Sandstone of Quebec (Cant, 1978).

Horizontally bedded sandstones are interpreted as upper flow regime flood deposits. Associated convolute bedding probably formed due to soft sediment deformation and fluid escape after rapid deposition. Similar horizontal bedding is abundant in modern flood deposits of Bijou Creek (Colorado), where convolute structures are attributed to deformation of thixotropic sand during waning flood conditions (McKee, Crosby, and Berryhill, 1967). Some of the horizontally bedded sandstone may have been deposited in shallow water on bar tops in lower flow regime conditions (Miall, 1977).

Scour surfaces are interpreted as channels incised into previously deposited sediments. Two processes that result in the cutting of large scour hollows are avulsion during high-discharge events and bar dissection during falling water stages (Miall, 1977). The major scours at the bases of some of the large-scale lenticular sandstone bodies are attributed to avulsion events, which result in a shift in position of the main active braided tract on the braidplain. Scour surfaces within the sandstone bodies are interpreted as channels cut into transverse bars.

Scour surfaces in the Ojo Alamo Sandstone are commonly overlain by siliceous-pebble and mud-clast conglomerates. The mud intraclasts were probably derived from local fine-grained deposits eroded away during channel shifting or flood events. Similar intraclast-strewn surfaces are known from both modern and ancient braided stream deposits (Cant and Walker, 1976, 1978; Smith, 1970).

Thin, localized, lenticular fine-grained deposits such as those in the Ojo Alamo Sandstone are also common in modern and ancient braided stream deposits. They are interpreted as slack water deposits in abandoned channels, low-water bar-top deposits, or overbank deposits (Smith, 1970; Rust, 1972; Cant and Walker, 1976, 1978).

The Ojo Alamo Sandstone contains some elements of both the South Saskatchewan and Platte facies models for sandy braided rivers (Miall,

1981) and so is interpreted here as a combination of the two. The South Saskatchewan model consists of fining-upward cycles separated by multiple scour surfaces. Trough cross-beds are abundant. The Platte model consists of noncyclic sequences of planar-tabular cross-beds without upward grain size change and with few trough cross-beds. The Ojo Alamo Sandstone has the lack of grain size change and abundant planar-tabular cross-beds of the Platte model but also has the multiple scour surfaces and abundant trough cross-beds of the South Saskatchewan model.

The Ojo Alamo Sandstone depositional environment consisted of coalescing braided streams on a broad braidplain. Within individual braid tracts, aggradation occurred mainly in transverse-bars which were subsequently dissected as channels shifted. Channels were floored by lag deposits of mud clasts and siliceous pebbles and by migrating dunes. Fine-grained sediments that accumulated locally in inactive areas on the braidplain were rarely preserved. These deposits were commonly reworked during channel shifting and flood events, providing a local source for mud intraclasts. Sheets of horizontally bedded sand deposited during flood events were internally deformed soon after deposition due to fluid escape. When aggradation reduced the local stream gradient, avulsion during floods resulted in shifting of active braided tracts to a part of the braidplain with a higher stream gradient. Channel complexes migrated over all parts of the braidplain by this mechanism.

CONTACT RELATIONSHIPS

The nature of the contact between the Kirtland Shale and the Ojo Alamo Sandstone varies along the southwest margin of the San Juan Basin. Erosional, gradational, and intertonguing relationships are all observed locally. The contact is placed at the base of the lowest sandstone containing the characteristic sedimentary structures and other features of the Ojo Alamo Sandstone. Most typically, the contact is a scoured surface at the base of a large-scale lenticular sandstone body consisting of conglomeratic sandstone (composed of mud clasts and/or siliceous pebbles) overlying fine-grained facies of the Kirtland Shale. Basal scour surfaces vary in magnitude at different localities. In the type region, prominent scour surfaces have as much as 7 m of relief. At most other localities (Piñon Mesa, La Plata, Moncisco Mesa, Betonnie Tsosie Arroyo, Ojo Socorro, Eagle Mesa), erosional relief along the basal contact is only 1 or 2 m. The magnitude of relief along the basal contact in these areas is no greater than the relief on intraformational scour surfaces within the lenticular sandstone bodies of the Ojo Alamo Sandstone. The intraformational scour surfaces have been interpreted here as channel scours which represent only minor breaks in sedimentation (Cant and Walker, 1976).

At three localities, scoured basal contacts could be traced laterally into sequences with gradational contacts. At Piñon Mesa (figs. 5, 7) characteristic Ojo Alamo Sandstone locally overlies 5 m of pebbly mudstone containing both mud clasts and siliceous pebbles. Siliceous pebble compositions are similar to those in the Ojo Alamo Sandstone. The pebbly mudstone has gradational contacts with both the underlying Kirtland Shale and the overlying Ojo Alamo Sandstone. At La Plata (fig. 5), a sequence of interbedded fine-grained and sandstone facies of the Kirtland Shale locally grades upward into characteristic Ojo Alamo Sandstone without a prominent basal scour surface. A similar relationship is observed locally at Moncisco Mesa (figs. 5, 6). These three examples demonstrate lateral variation in the nature of the contact.

Strata of the Kirtland Shale and Ojo Alamo Sandstone intertongue at Mesa Portales (figs. 5, 7), as previously described by Fassett and Hinds (1971). On the south face of Mesa Portales, two lenticular sandstone bodies are separated by thin cross-bedded sandstone and fine-grained facies of the Kirtland Shale. Both sandstone tongues contain sedimentary structures characteristic of the Ojo Alamo Sandstone, including multiple intraformational scour surfaces, and both have low relief basal scour surfaces. They are interpreted as fluvial channel deposits. The lower sandstone body pinches out eastward into strata of the Kirtland Shale. The lower sandstone body also contains a thin tongue of Kirtland Shale strata which pinches out laterally to the west. The underlying Kirtland Shale consists of interbedded fine-grained and sandstone facies which are conformable and gradational without any major intraformational scour surfaces or other lithologic evidence for an unconformity. Fassett and Hinds (1971) have suggested that an obscure unconformity may be present within this sequence of Kirtland Shale strata.

PALEOCURRENTS

Paleocurrent directions were determined for the Ojo Alamo Sandstone at six localities (fig. 9). These measurements indicate down-dip directions of axes of well exposed trough cross-beds which are interpreted as in-channel deposits. Trough cross-beds from in-channel environments are considered good indicators of regional paleoslope (Cant and Walker, 1976). Vector means for each locality range from 97 to 146 degrees, and the grand vector mean for the six localities is 120 degrees. These results are compatible with a more extensive paleocurrent study of the Ojo Alamo Sandstone which indicated a southeast paleoflow direction of 138 degrees (Powell, ms). Sikkink (1983) reports north-to-south paleocurrent flow for the Ojo Alamo Sandstone. All these studies suggest that the source area for the Ojo Alamo Sandstone lay northwest or north of the San Juan Basin.

Paleocurrent directions for the upper Kirtland Shale were not determined in this study. Powell (ms) reported an average dip direction of 210 degrees on "several hundred" cross-beds in the Naashoibito Member of the Kirtland Shale. Dilworth (ms) reported northeastward to eastward dip directions on 26 cross-beds in the Farmington Sandstone Member of the Kirtland Shale near Farmington. The Farmington Sandstone Member occurs in the northwestern San Juan Basin and is a south-thinning package of fluvial sandstones and shales which lies 20 to 40 m below the upper Kirtland Shale strata described in this report. These two data sets are not

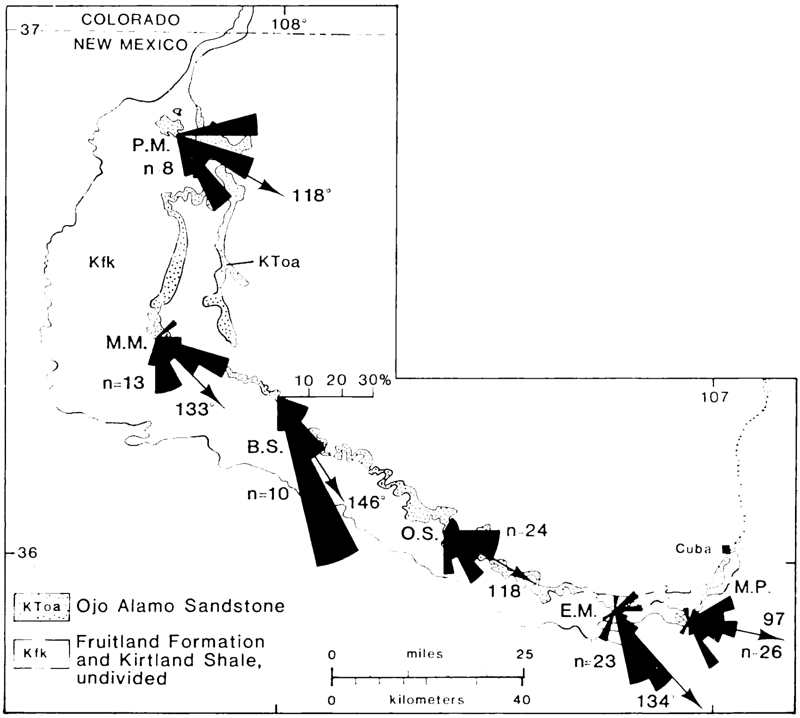

Fig. 9. Paleocurrent directions in the Ojo Alamo Sandstone determined from trough cross-bed axes. Vector mean direction and number of measurements (n) indicated for each site. See figure 5 for key to location abbreviations.

comprehensive or well documented, but they suggest there may have been a change in current flow direction from northeast and east to south during deposition of the Kirtland Shale.

SANDSTONE PETROGRAPHY

Detrital modes of sandstones from the upper Kirtland Shale and Ojo Alamo Sandstone were determined as a means of comparing their respective source terranes. Twenty five upper Kirtland Shale and 27 Ojo Alamo Sandstone samples collected from nine localities (fig. 5) were examined in thin section. Detrital modes were determined by point counting a minimum of 400 detrital grains per sample on thin sections stained for potassium feldspar. Detrital framework grains were identified and classified, and detrital modes were calculated and plotted on ternary diagrams, according to methods described by Dickinson (1970), Graham, Ingersoll, and Dickinson (1976), Dickinson, Helmhold, and Stein (1979), and Dickinson and Suczek (1979). Collection localities and detrital modes for individual samples are listed in table 1.

Sandstones from both formations are moderately to poorly sorted lithic and feldspathic arenites composed of subangular to subrounded, medium- to coarse-grained sand. Both formations contain the same types of detrital grains, although they are present in slightly different amounts. Grain types and categories for plotting on ternary diagrams are listed in figure 10.

Framework grain types include quartz (Q), feldspar (F), and lithic fragments (L). Monocrystalline quartz (Qm) is the most abundant quartz type in both formations. Polycrystalline quartz types (Qp) consist of multi-domain quartz, chert, and metachert. Potassium feldspars (K) include both orthoclase and microcline. Plagioclase feldspars (P) often show alteration to clay or sericite, and some have concentric zoning suggestive of volcanic origin. Volcanic lithic fragments (Lv) are the most abundant type of lithic fragment in both formations. Most of these are felsite grains composed of an aphanitic to microgranular groundmass which retains potassium feldspar stain. Some felsite grains contain plagioclase phenocrysts. Microlitic, microgranular-hypabyssal, and lathwork volcanic fragments are present in lesser amounts. No metavolcanic lithic fragments were observed. Sedimentary lithic fragments (Ls) are mostly siltstone and argillite but include a minor amount of fine-grained sandstone. Metasedimentary lithic fragments (Lm) occur in trace amounts and are included in the Ls category for detrital mode calculations. These include foliated quartz–mica tectonites and granular quartz–mica aggregates that rarely contain feldspar. Trace amounts of detrital biotite, white mica, and heavy minerals are present in both formations but are not included in calculated detrital modes.

Detrital modes of the two formations are compared on three ternary diagrams (fig. 10). The Q–F–L diagram emphasizes the strong similarity in composition of the two formations. Ojo Alamo Sandstone samples plot in a restricted field completely overlapped by the more scattered Kirtland Shale compositional field. Average detrital modes indicate that Kirtland sandstones contain slightly more lithic fragments than Ojo Alamo sandstones.

The greatest compositional difference between the two formations is their feldspar compositions. This is shown on the Qm–P–K diagram, which compares monocrystalline framework grains. Plagioclase abundance ranges from 9 to 59 percent in Kirtland sandstones but generally is greater than 25 percent. By contrast, most Ojo Alamo sandstones contain less than 30 percent plagioclase. Potassium feldspar abundances are mostly less than 25 percent in Kirtland sandstones but mostly greater than 20 percent in Ojo Alamo sandstones. On average, there is thus a consistently greater amount of potassium feldspar in the Ojo Alamo Sandstone than in the Kirtland Shale (fig. 10).

Comparison of amounts of unstable lithic and polycrystalline grain types on the Qp–Lv–Ls diagram indicates that the two formations overlap considerably in relative abundance of these components. In general, Kirtland sandstones tend to be more enriched in volcanic lithic fragments, and Ojo Alamo sandstones tend to contain more polycrystalline quartz.

TABLE 1

Upper Kirtland Shale

Locality	Sample number	Q-F-L %	Qm-P-K %	Qp-Lv-Ls %	Distance below Ojo Alamo Sandstone contact, meters
Pinon Mesa	1	53-21-26	64-19-17	36-46-19	18
	2	28-11-61	65-11-24	12-85- 3	5
	3	57-24-19	65-14-21	39-49-12	4
	4	42-17-41	65- 9-26	21-67-12	1
Moncisco Mesa	1	44-33-23	50-30-20	30-58-12	37
	2	38-39-23	47-29-24	16-67-17	10
	3	41-36-23	45-31-24	32-56-12	6
Ojo Alamo Arroyo	1	33-47-20	33-54-13	34-55-11	30
	2	45-35-20	54-29-17	17-72-11	5
	3	49-36-15	52-26-22	38-58- 4	3
Barrel Springs Arroyo	1	63-27-10	67-18-15	47-43-10	22
	2	36-48-16	58- 9-33	43-55- 2	17
	3	65-26- 9	70-16-14	37-63- 0	2
Ojo Socorro	1	20-32-48	34-59- 7	6-87- 7	30
	2	37-40-23	40-48-12	32-53-15	24
	3	34-36-30	43-40-17	21-72- 7	20
	4	44-37-19	48-38-14	33-61- 6	11
	5	39-39-22	47-36-17	18-67-15	2
Eagle Mesa	1	36-34-30	44-44-12	25-62-13	20
Mesa Portales	1	34-27-39	52-32-16	10-80-10	40
	2	22-26-52	37-49-14	12-70-18	39
	3	33-35-32	44-37-19	15-70-15	37
	4	43-43-14	47-39-14	28-65- 7	20
	5	44-35-21	51-34-15	26-58-16	17
	6	38-40-22	45-38-17	20-76- 4	4

Cobble and pebble compositions in the Ojo Alamo Sandstone (Reeside, 1924; Baltz, Ash, and Anderson, 1966; Powell, ms) reflect the composition of sandstone framework grains. Siliceous pebbles, especially chert, are most abundant. Other siliceous pebble types include vein quartz, quartzite, and sandstone. Volcanic pebble types are mostly rhyolitic but also include andesite, basalt, and dacite. Subordinate amounts of granite, gneiss, and schist are also present.

The identity of grain types present in the two formations and the similarity of their detrital modes suggest they were derived, at least in part, from the same sources. Volcanic fragments in both formations indicate the presence of volcanic rocks in the source area. Increased amounts of potassium feldspar and polycrystalline quartz in the Ojo Alamo Sandstone suggest an addition of basement-derived detritus to the sediment load. This may be attributed to dispersal of basement detritus into the basin from a new provenance, or alternately, to initial unroofing of basement rocks by erosion of volcanic cover in the same source area from which the Kirtland Shale sediment was derived.

Sandstone detrital modes

Ojo Alamo Sandstone					
Locality	Sample number	Q-F-L %	Qm-P-K %	Qp-Lv-Ls %	Distance above Kirtland Shale contact, meters
Pinon Mesa	5	36-42-22	37-18-44	34-50-16	1
	6	39-44-18	37-43-20	43-42-16	5
	7	54-26-20	58-12-30	49-45- 6	12
La Plata	1	54-38- 8	52-13-35	63-24-13	1
	2	45-40-15	45-20-36	46-43-11	1
	3	40-40-20	41-21-38	36-56- 8	1
Moncisco Mesa	4	46-32-22	60-13-27	37-42-21	1
	5	38-41-21	35-27-38	44-46-10	2
	6	39-38-23	44-25-31	29-62- 9	2
Ojo Alamo Arroyo	4	47-39-14	42-25-33	56-32-12	1
Barrel Springs Arroyo	4	40-42-18	40-34-26	40-21-39	4
	5	40-32-28	46-24-30	31-54-15	5
Betonnie Tsosie Arroyo	1	45-41-13	41-25-34	55-37- 8	1
	2	57-33-10	62-14-24	29-64- 7	6
Ojo Socorro	6	47-31-22	50-19-31	41-45-14	2
	7	39-43-18	36-24-40	45-48- 7	14
Eagle Mesa	2	46-36-18	49-27-24	39-55- 6	1
	3	39-40-21	42-38-30	32-66- 2	2
	4	58-34- 8	44-26-30	79-14- 7	10
Mesa Portales	7	41-37-22	49-15-36	19-71-10	1
	8	43-35-21	40-17-43	48-46- 6	1
	9	32-32-36	43-30-27	18-75- 7	2
	10	44-41-15	45-21-34	42-57- 1	9
	11	40-33-27	52-26-23	13-67-20	16
	12	44-42-14	41-24-35	52-10-38	29
	13	40-43-17	40-20-40	41-36-22	34
	14	45-38-17	43-15-42	47-45- 8	42

DISCUSSION

The data presented in this report lead to two major conclusions about depositional conditions of the upper Kirtland Shale and Ojo Alamo Sandstone on the southern and western margins of the San Juan Basin. The first is that the contact between the two formations is not a regionally continuous erosion surface. Instead, the contact varies laterally from erosional to gradational to intertonguing and represents a transitional change in fluvial style from meandering to braided. Secondly, detrital modes indicate that the source terrane for both formations contained similar felsitic volcanic rocks and that an additional source of basement-derived detritus was added to the Ojo Alamo Sandstone fluvial system.

These conclusions have implications for Late Cretaceous and Early Tertiary depositional models for the San Juan Basin. The Kirtland Shale

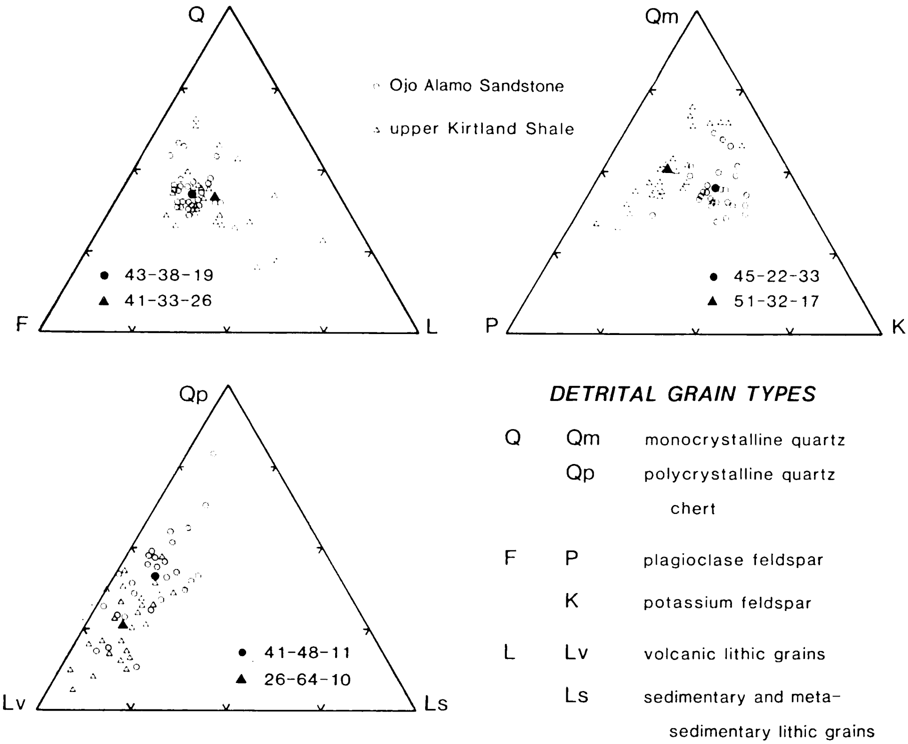

Fig. 10. Ternary diagrams comparing detrital modes of 25 upper Kirtland Shale and 27 Ojo Alamo Sandstone sandstone samples. Closed symbols indicate average detrital mode for each formation.

and Ojo Alamo Sandstone depositional environments represent two different types of fluvial systems which formed in response to specific environmental controls. Meandering systems characteristically have gentle slopes, predominance of suspended sediment load, and cohesive banks which confine flow to channels. In contrast, braided systems are characterized by steep slopes, predominance of coarse bed load, highly variable discharge, and easily eroded banks (Miall, 1981). The Kirtland Shale-Ojo Alamo Sandstone contact reflects an increase in slope and an influx of coarse sediment load to the basin. Gradational and intertonguing contact relationships indicate that this change was transitional on a basin-wide scale, although local deep scour occurred in some areas. These relationships were summarized succinctly by Dane (1936). He concluded that "there is no unimpeachable stratigraphic evidence of an important hiatus between the Kirtland and Ojo Alamo, and in view of evidence of transitional relations between the two formations it seems likely that deposition was essentially continuous in most localities, and that the southeast thinning of the Kirtland is not due to erosional truncation by the Ojo Alamo.

Nevertheless, there must have been a relatively sudden change in conditions of sedimentation to cause the deposition of the larger quantities of coarser clastic material of the Ojo Alamo over the area of the present San Juan Basin."

Influx of coarse detritus to the basin changed the base level of Kirtland streams. They were choked with coarse bed load and responded by widening and scouring into adjacent alluvial plain deposits, with eventual evolution into a system of coalescing braided streams. The multiple scour surfaces formed by channel cutting or avulsion. They represent local brief gaps in deposition, but aggradation was probably occurring somewhere on the braidplain at any given time. Fluvial processes varied on proximal and distal parts of the braidplain. Thicker, coarser deposits in the north suggest rapid aggradation proximally. Decrease in sand grain size and lack of pebbles to the south indicate decreasing energy distally. Preservation of floodplain deposits in the southeast at Mesa Portales suggests a transition to a meandering style of deposition distally.

Detrital modes of Kirtland Shale and Ojo Alamo Sandstone samples provide additional information about the causes of the change in depositional style. Both fluvial systems were supplied with sediment from a source terrane containing volcanic rocks. Volcanic detritus in older formations in the San Juan Basin, including the Pictured Cliffs Sandstone, was probably derived from southeastern Arizona (Cumella, 1983). Commencement of igneous activity in the Four Corners area during Late Cretaceous time may have caused a change in source area from the southwest to the north, northwest, or west for the uppermost Kirtland Shale (Molenaar, 1977). The increase in potassium feldspar and polycrystalline quartz in the Ojo Alamo Sandstone suggests a basement source, and southeastern paleocurrent directions indicate that the source was to the northwest. Uplifted Precambrian rocks on the west side of the San Juan Mountains in southwestern Colorado (fig. 3) are the inferred source for this detritus (Powell, ms).

Fassett and Hinds (1971) and Fassett (1985) have proposed a model for sedimentation in the San Juan Basin during Late Cretaceous through Early Tertiary time that requires a regional erosional unconformity in the sequence. They interpret the southeastward thinning of the Fruitland-Kirtland interval to be due to erosional removal of as much as 640 m of strata in the southeastern part of the basin. According to this model, a nearly uniform thickness of Fruitland-Kirtland strata was deposited from a southwestern source after retreat of the Pictured Cliffs sea to the northeast in the Campanian. Uplift in the southeast resulted in erosional beveling of these strata to their present southeast-thinning wedge shape. The Ojo Alamo Sandstone was then deposited on the beveled surface, separated from the underlying Kirtland Shale by an angular unconformity. They acknowledge the unconformity to be obscure on outcrop and suggest that it is located in shales below the contact in areas where gradational and intertonguing relationships are observed.

The transitional sedimentary relationships reported here between the upper Kirtland Shale and Ojo Alamo Sandstone conflict with the depositional model of Fassett and Hinds. Magnetostratigraphy for the Fruitland through Nacimiento interval in the San Juan Basin (Lindsay, Butler, and Johnson, 1981) also suggests that there is no significant hiatus within the section. An alternative model for deposition has been suggested by Lindsay and others (1983). According to this model, the Kirtland Shale thins to the southeast due to depositional thinning, as first suggested by Dane (1936), rather than to erosional truncation. Thinning of magnetozones from north to south provides additional support for this model (Butler and Lindsay, 1985).

Depositional thinning of the Kirtland Shale could be a result, in part, of differential subsidence between the northern and southern parts of the basin. Laramide uplift probably began in the San Juan Mountains in the Campanian (Tweto, 1975), as did Laramide igneous activity (Dickinson, Leopold, and Marvin, 1968; Armstrong, 1969). If initiation of sedimentation from the north began at about the same time, then the northern part of the basin probably underwent greater subsidence due to greater sediment loading. The shift in sediment source from southwest to northwest was probably a gradual process but was essentially complete by the time the upper Kirtland Shale was deposited. Continued uplift in the source area unroofed Precambrian basement rocks, resulting in an influx of coarse debris that caused the change from meandering to braided fluvial style.

Evidence for the age of the Kirtland Shale-Ojo Alamo Sandstone transition consists of sparse vertebrate and pollen fossil collections that give conflicting placement of the Cretaceous-Tertiary boundary in the western and southern San Juan Basin. This problem is discussed at length elsewhere (Baltz, Ash, and Anderson, 1966; Clemens, 1973; Tschudy, 1973; Fassett, 1982) and will be briefly summarized here. Dinosaur fossils are well known from the upper Kirtland Shale (Brown, 1910; Clemens, 1973) and are also reported from within the Ojo Alamo Sandstone near Star Lake (fig. 5) (Fassett, 1982). Thus, the Cretaceous-Tertiary boundary should be placed within or at the top of the Ojo Alamo Sandstone. However, palynological studies reveal a change between Cretaceous and Tertiary pollen forms below the Ojo Alamo Sandstone. This change occurs within the upper Kirtland Shale at Mesa Portales (Fassett and Hinds, 1971; Newman, 1985) and at the Kirtland Shale-Ojo Alamo contact at localities near Farmington and Star Lake (Newman, 1985). These conflicting age criteria suggest that the change between Cretaceous and Tertiary pollen forms in the San Juan Basin may not be regionally synchronous and may not be coincident with the Cretaceous-Tertiary boundary as defined by the last appearance of dinosaur fossils. Low abundance and poor preservation of pollen from these rocks (Anderson, 1960; Tschudy, 1973) may be a contributing factor to the equivocal palynological results. These unresolved problems with the pollen stratigraphy cast doubt on using palynology for the placement of the Cretaceous-Tertiary boundary in the San Juan Basin.

A palynologic hiatus within the Gasbuggy core from the east-central San Juan Basin (Tschudy, 1973) may be subject to these same problems, or it may reflect different conditions of deposition of the Ojo Alamo Sandstone on the east side of the basin, as described by Sikkink (1983). It is possible that the pollen data may be documenting an eastward time-transgressive aspect to the change from meandering to braided fluvial deposition, as suggested by Fassett (1982) and Newman (1985). However, the sedimentology and sandstone petrography indicate that this change was transitional on the south and west margins of the basin, rather than following a regional-scale hiatus.

The sedimentology and sandstone petrography reported in this paper suggest that there is not a significant regional unconformity between the upper Kirtland Shale and Ojo Alamo Sandstone. These data agree better with the alternate model of depositional thinning of Kirtland Shale from northwest to southeast and imply that sedimentation was nearly continuous across the Cretaceous-Tertiary boundary in concordance with the magnetostratigraphic record. The boundary is probably located within the Ojo Alamo Sandstone, but its exact position is enigmatic due to sparse and equivocal biostratigraphic evidence. Fassett (1982, 1985) and Shoemaker and others (1984) suggest that there was a hiatus in Kirtland Shale deposition corresponding to a palynological change. If this is true, the hiatus must have occurred prior to deposition of the strata studied here. Sedimentologic and petrographic data indicate only a transitional change in depositional style between the upper Kirtland Shale and Ojo Alamo Sandstone around the southwest margin of the San Juan Basin during Late Cretaceous to Paleocene time.

ACKNOWLEDGMENTS

I would like to thank William R. Dickinson, Everett H. Lindsay, Susan M. Kidwell, and Robert F. Butler for helpful discussions and manuscript review. In addition, E. H. Baltz, R. V. Ingersoll, C. M. Molenaar, N. D. Smith, and R. Wright made useful comments on preliminary drafts of the manuscript. Daniel J. Highkin, Kerry F. Inman, Joy E. McKinney, and W. D. Darton assisted with field work. I also benefitted from discussions with Kathryn M. Flanagan, Paul L. Heller, Timothy F. Lawton, and Steven R. May. Financial support from the Laboratory of Geotectonics in the Department of Geosciences at the University of Arizona and from National Science Foundation Grant EAR 8206262 awarded to E. H. Lindsay and R. F. Butler is gratefully acknowledged.

REFERENCES

Alvarez, L. W., Alvarez, W., Asaro, F., and Michel, H. V., 1980, Extraterrestrial cause for the Cretaceous-Tertiary extinction: Science, v. 208, p. 1095-1108.

Alvarez, W., Kauffman, E. G., Surlyk, F., Alvarez, L. W., Asaro, F., and Michel, H. V., 1984, Impact theory of mass extinctions and the invertebrate fossil record: Science, v. 223, p. 1135-1141.

Alvarez, W., and Vann, D. W., 1979, Comment on "Biostratigraphy and magnetostratigraphy of Paleocene terrestrial deposits, San Juan Basin, New Mexico": Geology, v. 7, p. 66-69.

Anderson, R. Y., 1960, Cretaceous-Tertiary palynology, eastern side of the San Juan Basin, New Mexico: New Mexico Bur. Mines and Mineral Resources Mem. 6, 58 p.

Armstrong, R. L., 1969, K-Ar dating of laccolith centers of the Colorado Plateau and vicinity: Geol. Soc. America Bull., v. 80, p. 2081-2086.

Baltz, E. H., 1967, Stratigraphy and regional tectonic implications of part of Upper Cretaceous and Tertiary rocks, east-central San Juan Basin, New Mexico: U.S. Geol. Survey Prof. Paper 552, 101 p.

Baltz, E. H., Ash, S. R., and Anderson, R. Y., 1966, History of nomenclature and stratigraphy of rocks adjacent to the Cretaceous-Tertiary boundary, western San Juan Basin, New Mexico: U.S. Geol. Survey Prof. Paper 524-D, 23 p.

Bauer, C. M., 1916, Stratigraphy of a part of the Chaco River Valley: U.S. Geol. Survey Prof. Paper 98P, p. 271-278.

Brown, B., 1910, The Cretaceous Ojo Alamo Beds of New Mexico with description of the new dinosaur genus Kritosaurus: Am. Mus. Nat. History Bull., v. 28, p. 267-274.

Butler, R. F., 1984, Paleomagnetism and rock-magnetism of continental deposits, San Juan Basin, New Mexico [abs.]: Geol. Soc. America Abs. with Programs, v. 16, p. 217.

Butler, R. F., and Lindsay, E. H., 1985, Mineralogy of magnetic minerals and revised magnetic polarity stratigraphy of continental sediments, San Juan Basin, New Mexico: Jour. Geology, v. 93, p. 535-554.

Butler, R. F., Lindsay, E. H., Jacobs, L. L., and Johnson, N. M., 1977, Magnetostratigraphy of the Cretaceous-Tertiary boundary in the San Juan Basin, New Mexico: Nature, v. 267, p. 318-323.

Campbell, C. V., 1976, Reservoir geometry of a fluvial sheet sandstone: Am. Assoc. Petroleum Geologists Bull., v. 60, p. 1009-1020.

Cant, D. J., 1978, Development of a facies model for sandy braided river sedimentation: comparison of the South Saskatchewan River and the Battery Point Formation, *in* Miall, A. D., ed., Fluvial Sedimentology: Canadian Assoc. Petroleum Geologists Mem. 5, p. 627-639.

Cant, D. J., and Walker, R. G., 1976, Development of a braided-fluvial facies model for the Devonian Battery Point Sandstone, Quebec: Canadian Jour. Earth Sci., v. 13, p. 102-119.

——— 1978, Fluvial processes and facies sequences in the sandy braided South Saskatchewan River, Canada: Sedimentology, v. 25, p. 625-648.

Clemens, W. A., 1973, The roles of fossil vertebrates in interpretation of Late Cretaceous stratigraphy of the San Juan Basin, New Mexico, *in* Fassett, J. E., ed., Cretaceous and Tertiary rocks of the southern Colorado Plateau: Four Corners Geol. Soc. Mem., p. 154-167.

Cumella, S. P., 1983, Relation of Upper Cretaceous regressive sandstone units of the San Juan Basin to source area tectonics, *in* Reynolds, M. W., and Dolly, E. D., eds., Mesozoic paleogeography of west-central United States: Soc. Econ. Paleontologists Mineralogists, Rocky Mountain Sec., Rocky Mountain Paleogeography Symposium II, p. 189-199.

Dane, C. H., 1936, The La Ventana-Chacra Mesa coal field, part 3 of Geology and fuel resources of the southern part of the San Juan Basin, New Mexico: U.S. Geol. Survey Bull. 860-C, p. 81-161.

Dickinson, R. G., Leopold, E. B., and Marvin, R. F., 1968, Late Cretaceous uplift and volcanism on the north flank of the San Juan Mountains, Colorado: Colorado School of Mines Quart., v. 63, p. 125-148.

Dickinson, W. R., 1970, Interpreting detrital modes of greywacke and arkose: Jour. Sed. Petrology, v. 40, p. 695-707.

Dickinson, W. R., Helmhold, K. P., and Stein, J. A., 1979, Mesozoic lithic sandstones in central Oregon: Jour. Sed. Petrology, v. 49, p. 501-516.

Dickinson, W. R., and Suczek, C. A., 1979, Plate tectonics and sandstone composition: Am. Assoc. Petroleum Geologists Bull., v. 63, p. 2164-2182.

Dilworth, L. O., ms, 1960, Upper Cretaceous Farmington Sandstone of northeastern San Juan County, New Mexico: M.S. thesis, Univ. New Mexico, 96 p.

Fassett, J. E., 1982, Dinosaurs in the San Juan Basin, New Mexico, may have survived the event that resulted in creation of an iridium-enriched zone near the Cretaceous-Tertiary boundary: Geol. Soc. America Spec. Paper 190, p. 435-447.

——— 1985, Early Tertiary paleogeography and paleotectonics of the San Juan Basin area, New Mexico and Colorado, *in* Kaplan, S. S., and Flores, R. M., eds., Cenozoic paleogeography of the west-central United States: Soc. Econ. Paleontologists and Mineralogists, Rocky Mountain Sec., Rocky Mountain Paleogeography Symposium III, p. 317-334.

Fassett, J. E., and Hinds, J. S., 1971, Geology and fuel resources of the Fruitland Formation and Kirtland Shale of the San Juan Basin, New Mexico and Colorado: U.S. Geol. Survey Prof. Paper 676, 76 p.

Graham, S. A., Ingersoll, R. V., and Dickinson, W. R., 1976, Common provenance for lithic grains in carboniferous sandstones from Ouachita Mountains and Black Warrior Basin: Jour. Sed. Pet., v. 46, p. 620-632.

Jackson, R. G., II, 1978, Preliminary evaluation of lithofacies models for meandering alluvial streams, *in* Miall, A. D., ed., Fluvial Sedimentology: Canadian Soc. Petroleum Geologists Mem. 5, p. 543-576.

Klute, M. A., 1983, Sedimentation across the Cretaceous-Tertiary boundary in the San Juan Basin, New Mexico [abs.]: Geol. Soc. America Abs. with Programs, v. 15, p. 291.

Lindsay, E. H., Butler, R. F., and Johnson, N. M., 1981, Magnetic polarity of Late Cretaceous and Paleocene continental deposits, San Juan Basin, New Mexico: Am. Jour. Sci., v. 281, p. 390-435.

Lindsay, E. H., Butler, R. F., Johnson, N. M., Klute, M. A., and Zeitler, P. K., 1983, Deposition across the Cretaceous-Tertiary boundary in the San Juan Basin, New Mexico [abs.]: Geol. Soc. America Abs. with Programs, v. 15, p. 308.

Lowrie, W., and Alvarez, W., 1977, Upper Cretaceous-Paleocene magnetic stratigraphy at Gubbio, Italy, III. Upper Cretaceous magnetic stratigraphy: Geol. Soc. America Bull., v. 88, p. 374-377.

Lucas, S. G., and Schoch, R. M., 1982, Discussion of 'Magnetic polarity zonation and biostratigraphy of late Cretaceous and Paleocene continental deposits, San Juan Basin, New Mexico': Am. Jour. Sci., v. 282, p. 920-927.

McGookey, D. P., 1972, Cretaceous system, *in* Geologic Atlas of the Rocky Mountain Region: Rocky Mountain Assoc. Geologists, p. 111-127.

McKee, E. D., Crosby, E. J., and Berryhill, H. L., 1967, Flood deposits, Bijou Creek, Colorado, June 1965: Jour. Sed. Pet., v. 37, p. 829-851.

Miall, A. D., 1977, A review of the braided river depositional environment: Earth Sci. Rev., v. 13, p. 1-62.

——— 1981, Analysis of fluvial depositional systems: Am. Assoc. Petroleum Geologists Education Note Ser., no. 20, 75 p.

Molenaar, C. M., 1977, Stratigraphy and depositional history of Upper Cretaceous rocks of the San Juan Basin area, New Mexico and Colorado, with a note on economic resources, *in* Fassett, J. E., ed., Guidebook of the San Juan Basin III, northwestern New Mexico: New Mexico Geol. Soc., Field Conf., 28th, Guidebook, p. 159-178.

——— 1983, Major depositional cycles and regional correlations of Upper Cretaceous rocks, southern Colorado Plateau and adjacent areas, *in* Reynolds, M. W., and Dolly, E. D., eds., Mesozoic Paleogeography of west-central United States: Soc. Econ. Paleontologists and Mineralogists, Rocky Mountain Sec., Rocky Mountain Paleogeography Symposium II, p. 201-224.

Ness, G., Levi, S., and Couch, R., 1980, Marine magnetic anomaly time-scales for the Cenozoic and Late Cretaceous: a precis, critique and synthesis: Rev. Geophysics and Space Physics, v. 18, p. 753-770.

Newman, K. R., 1985, Stratigraphic implications of palynomorphs from Kirtland and Ojo Alamo Formations (Cretaceous and Paleocene), San Juan Basin, New Mexico [abs.]: Geol. Soc. America Abs. with Programs, v. 17, p. 258.

Powell, J. S., ms, 1972, The Gallegos Sandstone (formerly Ojo Alamo Sandstone) of the San Juan Basin, New Mexico: M.S. thesis, Univ. Arizona, 131 p.

Reeside, J. B., Jr., 1924, Upper Cretaceous and Tertiary formations of the western part of the San Juan Basin, Colorado and New Mexico: U.S. Geol. Survey Prof. Paper 134, 117 p.

Rust, B. R., 1972, Structure and process in a braided river: Sedimentology, v. 18, p. 221-245.

Shoemaker, E. M., Steiner, M., Fassett, J. E., and Tschudy, R. H., 1984, Magnetostratigraphy of Upper Cretaceous rocks at Mesa Portales, New Mexico: Geol. Soc. America Abs. with Programs, v. 16, p. 255.

Sikkink, P. G. L., 1983, Depositional environment of the Tertiary Ojo Alamo Sandstone, San Juan Basin, New Mexico [abs.]: Geol. Soc. America Abs. with Programs, v. 15, p. 308.

Smith, N. D., 1970, The braided stream depositional environment: comparison of the Platte River with some Silurian clastic rocks, north-central Appalachians: Geol. Soc. America Bull., v. 81, p. 2993-3014.

——— 1971, Transverse bars and braiding in the lower Platte River, Nebraska: Geol. Soc. America Bull., v. 82, p. 3407-3420.

Tschudy, R. H., 1973, The Gasbuggy core — a palynological appraisal, *in* Fassett, J. E., ed., Cretaceous and Tertiary rocks of the southern Colorado Plateau: Four Corners Geol. Soc. Mem., p. 131-141.

Tweto, O., 1975, Laramide (Late Cretaceous-Early Tertiary) orogeny in the southern Rocky Mountains: Geol. Soc. America Mem. 144, p. 1-44.

Williams, G. E., 1971, Flood deposits of the sand-bed ephemeral streams of central Australia: Sedimentology, v. 17, p. 1-40.