Stratigraphy, sediment dispersal and paleogeography of the lower Eocene San Jose Formation, San Juan Basin, New Mexico

Larry N. Smith

1992, pp. 297-309. https://doi.org/10.56577/FFC-43.297

in:

San Juan Basin IV, Lucas, S. G.; Kues, B. S.; Williamson, T. E.; Hunt, A. P.; [eds.], New Mexico Geological Society 43rd Annual Fall Field Conference Guidebook, 411 p. https://doi.org/10.56577/FFC-43

This page is intentionally left blank to maintain order of facing pages.

STRATIGRAPHY, SEDIMENT DISPERSAL AND PALEOGEOGRAPHY OF THE LOWER EOCENE SAN JOSE FORMATION, SAN JUAN BASIN, NEW MEXICO AND COLORADO

LARRY N. SMITH
Shell Western E&P Inc., P.O. Box 991, Houston, Texas 77001

Abstract—The fluvial lower Eocene San Jose Formation represents the last preserved period of deposition in the Laramide San Juan Basin. The basal Cuba Mesa Member of the formation is a nearly basinwide, coarse-grained sheet sandstone composed of multilateral and multistoried low-sinuosity fluvial channels. The Cuba Mesa is locally thickened where sheet sandstones are vertically amalgamated. The Cuba Mesa thins by intertonguing with mudrock and pinches out along the basin axis where the San Jose Formation conformably overlies the Paleocene Nacimiento and Animas Formations in northern New Mexico and Colorado. The Cuba Mesa Member unconformably overlies Paleocene and Mesozoic strata toward margins of the basin, with as much as 90° of angular discordance. Floodplain mudrock and disconnected sheet sandstones of the Regina Member were deposited laterally adjacent to and above the Cuba Mesa Member. Mudrock of the Regina Member also intertongues with the lobate, sandstone-dominated Ditch Canyon Member (named here) and Llaves Member. The Ditch Canyon Member represents southeast-directed fluvial deposition in the northwestern San Juan Basin from the Four Corners platform and southwestern San Juan uplift. The Llaves Member was deposited on the eastern side of the basin by west-southwest-flowing streams and is sedimentologically and stratigraphically similar to, but not continuous with, the Ditch Canyon Member. The Llaves Member is overlain by the siltstone-dominated Tapicitos Member. The Tapicitos was derived from uplifts east of the basin. Grain size in the Regina Member decreases toward the San Juan and Nacimiento uplifts, due to minimal erosion of coarse-grained sediment from these active, reverse-faulted monoclines. Small drainage basins along these active mountain fronts eroded mostly fine-grained sediment from Phanerozoic strata. Coarse-grained sediment of the Ditch Canyon and Llaves Members was deposited by fluvial systems that emanated from different paleo-drainage basins within structural reentrants between basin-marginal uplifts. The Cuba Mesa Member was deposited during late Paleocene through early Eocene subsidence in the center of the San Juan Basin with concurrent erosion and possibly slow sedimentation nearer basin margins. Synsedimentary angular unconformities within the Regina Member show that the Regina, Llaves and Ditch Canyon Members were deposited during episodic monoclinal folding near the Nacimiento fault.

INTRODUCTION

The lower Eocene San Jose Formation was deposited along high-energy, low-sinuosity streams and on extensive muddy floodplains that reflect the last preserved episode of sedimentation in the Laramide San Juan Basin of northwestern New Mexico and southwestern Colorado (Fig. 1; Smith et al., 1985; Smith, 1988). The San Jose is the most extensively preserved and exposed Eocene rock-stratigraphic unit in New Mexico and has yielded one of the largest and most diverse fossil vertebrate faunas of early Eocene age collected in North America (Lucas et al., 1981). The purposes of this study are to clarify the internal stratigraphy of the San Jose and the formation's contacts with subjacent Paleocene strata, document sediment dispersal in the basin, and summarize early Eocene paleogeography of the San Juan Basin and neighboring uplifts. A general model for accumulation of the San Jose Formation is presented. The Ditch Canyon Member, a fifth formal member of the San Jose Formation, is named for exposures in Ditch Canyon, near Cedar Hill, New Mexico (Fig. 1).

The physical stratigraphy of the San Jose is analyzed in measured sections, along continuous exposures, and from correlation of well logs chosen along or near cross sections (Fig. 2). Basinwide stratigraphic relations between the members of the San Jose and between the San Jose and subjacent formations has been unclear because of locally poor exposure, facies changes and similarity of lithology of subjacent formations. Stratigraphy, sediment dispersal and paleogeography of the basin indicate that primary influences on basin stratigraphy included synsedimentary tectonism and the positions of structural reentrants in uplifts neighboring the basin that controlled channel-belt locations.

PREVIOUS WORK

Stratigraphy

The San Jose Formation was named for mudrock and interbedded sandstones in the southeastern San Juan Basin (Simpson, 1948) that contain lower Eocene (Wasatchian, Lysite-equivalent) terrestrial fossils (Lucas et al., 1981, and references cited therein; Flanagan, 1986; Smith and Lucas, 1991). Baltz (1967) redefined the formation to include a basal, pervasive sandstone-dominated sequence (Cuba Mesa Member) that rests in slight to moderate angular unconformity on the Paleocene Nacimiento Formation in the southern San Juan Basin. Baltz (1967) mapped the San Jose in the southeastern part of the basin, defined four members, the Cuba Mesa (oldest), Regina, Llaves and Tapicitos (youngest) Members, and recognized an "unnamed member" in the east-central portion of the basin (Fig. 3A; Baltz, 1967, p. 56). Well-log correlations show that the San Jose reaches a maximum thickness of 630 m in subsurface.

Members of the San Jose were extended throughout the New Mexico portion of the San Juan Basin on small-scale maps of Mytton (1983) and Manley et al. (1987). The position of the basal San Jose contact on these maps corrects a mapping error on Dane and Bachman's (1957) map that was perpetuated by Dane and Bachman (1965), Fassett and Hinds (1971), and NMGS (1982) (see road logs for Day 2, Stop 1, this guidebook). Strata correlative to the San Jose in the northern and northeastern San Juan Basin, Colorado, were mapped as "Wasatch formation" (Reeside, 1924; Wood et al., 1948; Larsen and Cross, 1956), San Jose formation (Baltz, 1953), and undifferentiated Cretaceous and Tertiary strata (Barnes, 1953; Barnes et al., 1954) before the details of the stratigraphy of the San Jose were worked out to the south (Fig. 3).

The Nacimiento Formation (*sensu* Simpson, 1948) was named for a lower Paleocene (Danian equivalent) sequence of varicolored beds of fluvial and lacustrine sandstone and mudrock in the southern San Juan Basin (Lucas and Ingersoll, 1981) that attains a thickness of as much as 530 m (Baltz, 1967). A north-to-south decrease in grain size (Baltz, 1967, p. 38–39; Tsentas et al., 1981) and a few paleocurrent measurements in the Escavada Wash Member indicate north-to-south paleoflow. Arkosic sandstones near the top of the formation increase in thickness and prevalence northward, suggesting Paleocene erosion of Precambrian rocks north and northeast of the basin (Baltz, 1967).

The lower and upper Paleocene (Danian-to-Thanetian equivalent) informal upper member of the Animas Formation (*sensu* Barnes et al.,

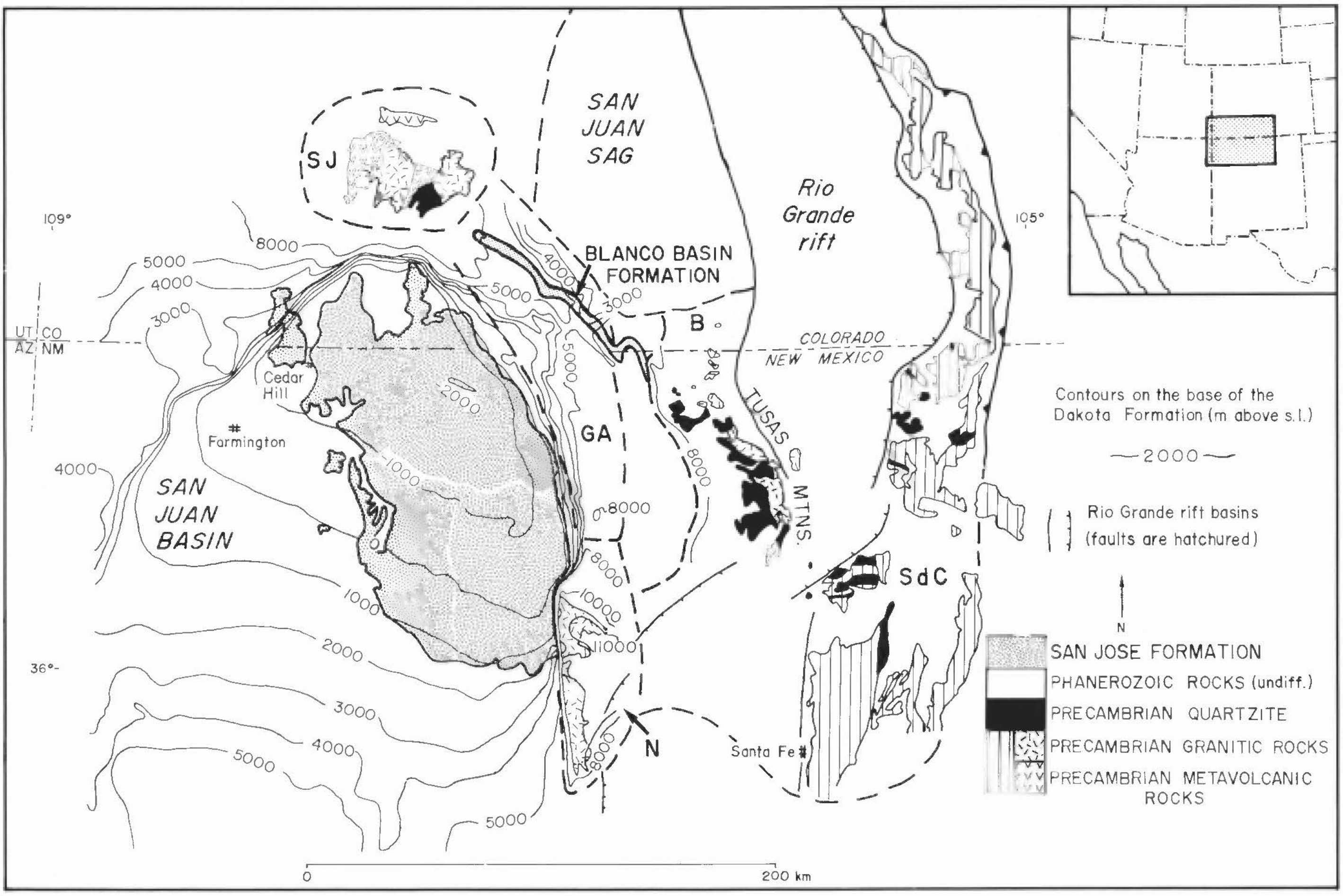


FIGURE 1. Location map of the San Jose Formation, Blanco Basin Formation, San Juan sag, and Precambrian outcrops. Locations, structure contours of the San Juan Basin, positions of uplifts (N = Nacimiento; B = Brazos; SdC = Sangre de Cristo; SJ = San Juan; GA = Gallina-Archuleta arch) are modified from Tweto (1979), Thaden and Zech (1984), and Gries (1985).

1954) was named for strata in the northern San Juan Basin that are in a stratigraphic position equivalent to the Nacimiento Formation (Granger, 1917; Simpson, 1935; in areas misidentified as "San Jose Formation" in Larsen and Cross (1956), Fassett and Hinds (1971), and Butler et al., (1981)). The uppermost Animas Formation (Tiffanian) in the northern part of the basin is younger than any Nacimiento strata (Torrejonian) and older than San Jose strata (Wasatchian) recognized in the southern San Juan Basin (Fig. 3). Animas strata comprise a generally fining-upward sequence of volcaniclastic conglomerates and sandstones, with arkosic conglomerates and sandstones near the top (Sikkink, 1987). The upper member of the Animas has been shown to intertongue with the Nacimiento in its eastern (Dane, 1946) and western (Barnes et al., 1954) outcrop belts.

The Blanco Basin Formation (Fig. 1; Cross and Larsen, 1935) is unfossiliferous, lithologically and stratigraphically equivalent to the San Jose Formation, and generally considered to have been deposited on a piedmont adjacent to the Eocene San Juan Basin (Baltz, 1953, 1967; Dunn, 1964a, b; Lucas, 1984; C. E. Chapin, personal comm. 1991; but see Brister, this volume). The Blanco Basin Formation contains as much as 120 m of stratified pebble conglomerate, coarse- to medium-grained sandstone, and red mudstone derived from Precambrian metamorphic and plutonic rocks and Phanerozoic sandstone and mudstone (Dunn, 1964a; Muehlberger, 1967).

Structure

The San Juan Basin is subcircular, with its structural axis near the northern and northeastern limbs of the basin, as defined by the elevation of the Cretaceous strata (Fassett and Hinds, 1971, fig. 15; Thaden and Zech, 1984). Structure defined on the base of Paleogene strata indicates a north-northwest-trending axis of the basin beneath the east-central portion of the San Jose Formation outcrop area (Smith and Lucas, 1991). Structure contours of the basin show greatest structural relief along the margins of the San Juan and Nacimiento uplifts (Fig. 1), although the amount of post–San Jose displacement across the basin margins is unknown. The histories and deep structural styles of the southern boundary of the San Juan uplift and the entire Gallina-Archuleta arch are poorly constrained (Kelley, 1955; Larsen and Cross, 1956; Gries, 1985). Surface exposures of the western boundary faults of the Nacimiento uplift indicate that near-surface, high-angle reverse faulting and monoclinal folding of Phanerozoic strata occurred prior to and during deposition of the San Jose Formation (Woodward, 1987; Smith, 1988). The deep structural style of the Nacimiento uplift has not been explored. Structural asymmetry of the basin suggests that tectonic loading of the northern, eastern and northeastern basin margins may be responsible for initiating subsidence, much like other Laramide, broken foreland basins in the west-central United States (Cross, 1986; Flemings et al., 1986). Deformation of Paleogene strata 2–4 km away from basin margins is slight, allowing straightforward surface and subsurface correlations.

STRATIGRAPHY

The San Jose Formation contains sandstone-dominated and mudrock-dominated lithofacies described in detail elsewhere (Smith, 1988; Smith and Lucas, 1991). The prevalent sandstone-dominated lithofacies of all members of the San Jose Formation is trough cross-stratified and horizontally stratified very coarse- to medium-grained quartzose-to-arkosic

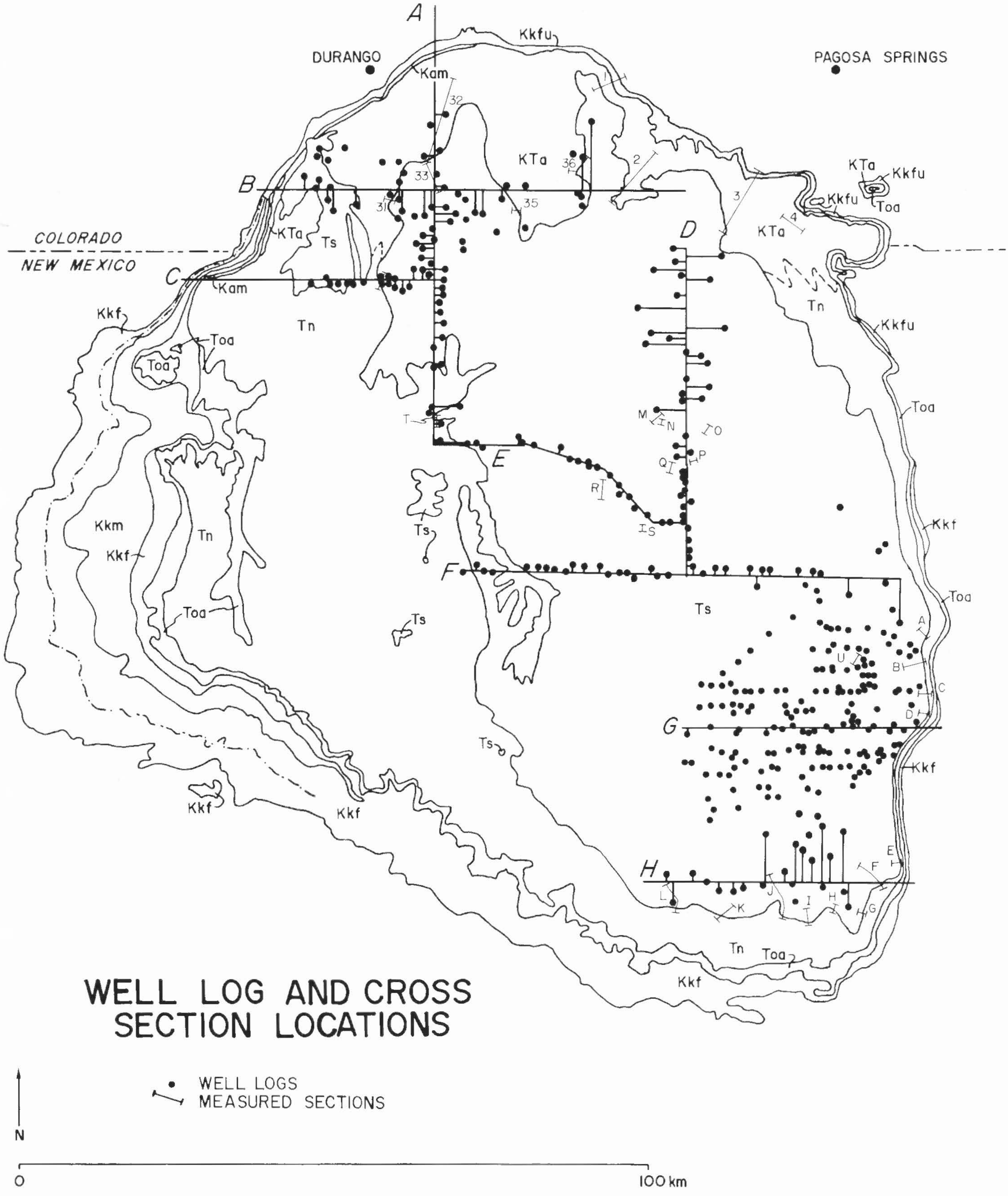


FIGURE 2. Geologic map of the San Juan Basin with locations of well logs, cross sections and measured sections. Kkf = Fruitland Formation and lower member and Naashoibito Member of Kirtland Shale; Kkm = Farmington Sandstone Member of Kirtland Shale; Kkfu = undifferentiated Kirtland and Fruitland Formations; KTa = Animas Formation; Kam = McDermott Member of Animas Formation; Toa = Paleocene Ojo Alamo Sandstone; Tn = Paleocene Nacimiento Formation; Ts = lower Eocene San Jose Formation. Modified from Reeside (1924), Barnes et al. (1954), Dane and Bachman (1965), Fassett and Hinds (1971), Mytton (1983), and Manley et al. (1987).

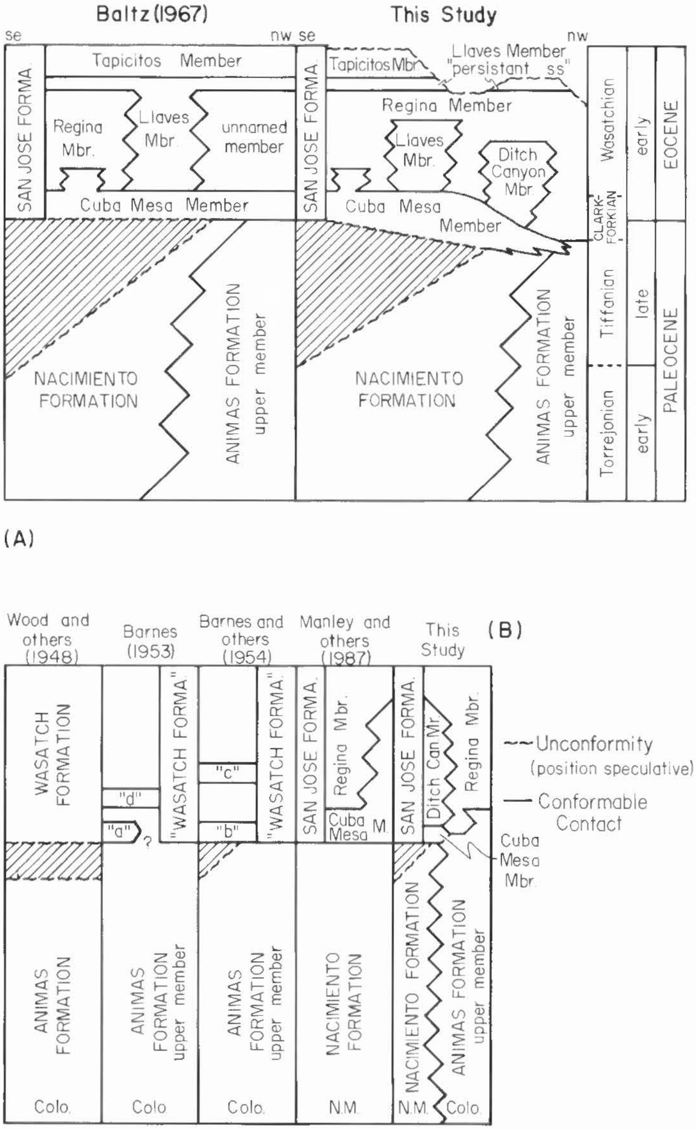


FIGURE 3. A. Stratigraphic chart of the San Jose Formation, comparing stratigraphy of this study to "probable correlations" of Baltz (1967, p. 86). The separation of the Llaves Member shown on the right is due to the placement of this cross section; the two bodies come into contact east of the cross section, as shown by correlations of Baltz in diagram. Time scale after Lucas and Ingersoll (1981). B. Stratigraphic chart depicting history of nomenclature for Paleogene strata in northwestern San Juan Basin, New Mexico (NM) and Colorado (CO).

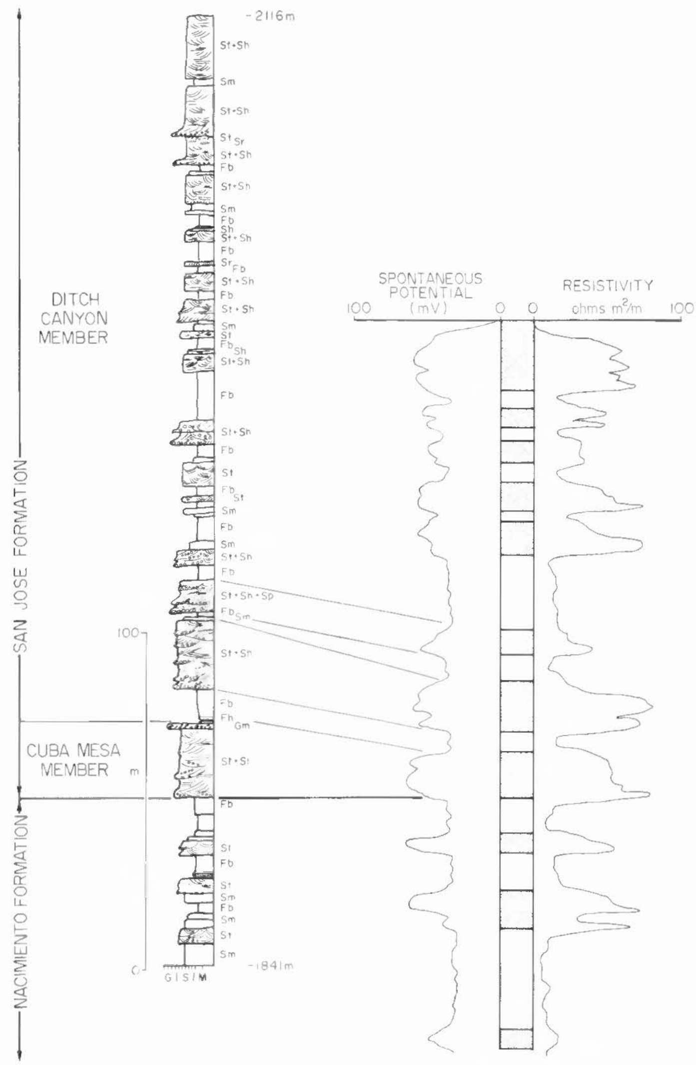


FIGURE 4. Correlation of type section of Ditch Canyon Member of the San Jose Formation to the upper part of well log (El Paso Natural Gas Co. San Juan 32-9 No. 81 (SW¼ sec. 26, T32N, R10W). The vertical scale of the section and the log is the same.

sandstone that contains local conglomerate (lithofacies St + Sh; Fig. 4). This lithofacies occurs in crosscutting channel scours that comprise sheet sandstone bodies with width-to-thickness ratios of 20 to 1000. Lithofacies St + Sh was deposited in high-energy, low-sinuosity stream channels that shifted across floodplains and abandoned channels, producing multistoried and multilateral sheet sandstone bodies. Less prevalent sandstone-dominated lithofacies include minor channel-lag conglomerates and cross-stratified and massive sandstones deposited by out-of-channel flow. Mudrock-dominated lithofacies include silt, clay and fine-grained sandstone in which most primary sedimentary structures were destroyed by bioturbation and pedogenesis on fluvial floodplains. Laminated shale deposited in anoxic shallow lakes on floodplains exist locally.

The sandstone-dominated Cuba Mesa and Llaves Members of the San Jose Formation include sandstone tongues that trace into or correlate with the main bodies of the units. Sandstones lithologically identical to the Cuba Mesa and Llaves Members, but surrounded by mudrock, are assigned to the mudrock-dominated, Regina or Tapicitos Members (Fig. 3). Most of the stratigraphy discussed in this study is based on new subsurface data that can be correlated directly with outcrops.

Sandstone beds were picked on 400 logs of natural gas and oil wells by deviation of resistivity- and SP-values from mudrock baselines (after Dresser Atlas, 1975). Beds as thin as 1.5 m were picked on working copies of the logs. Comparison of measured sections to electric logs in the San Jose indicates that sandstones recognized in the subsurface correspond to lithofacies St + Sh, whereas mudrock recognized in the subsurface corresponds to floodplain mudrock, splays and levees (Fig. 4; Smith and Lucas, 1991).

Stratigraphic unit boundaries in the subsurface were picked and correlated based on correlation with, and reinterpretation of, contacts mapped on the surface (Baltz, 1967; Mytton, 1983), and correlation with, and reinterpretation of, previous subsurface work in the region (Baltz, 1967; Fassett, 1968; Fassett and Hinds, 1971; Brimhall, 1973; Stone et al., 1983). These previous studies were not carried out with the intention of analyzing facies changes within members of the San Jose; the members were portrayed as continuous and consistent with the formal members, with only minor lateral changes in thickness.

Cuba Mesa Member

The Cuba Mesa Member of the San Jose Formation has been traced in outcrop (Baltz, 1967, plate 1; Mytton, 1983; Manley et al., 1987) and partly in subcrop (Baltz, 1967, plate 5) from its type locality near Cuba, New Mexico, into Colorado. The unit consists of white to yellow, thickly bedded, locally conglomeratic, very coarse- and coarse-grained arkosic and quartzose sandstone with minor mudrock lenses (Fig. 5A). The Nacimiento Formation beneath the Cuba Mesa Member locally contains arkosic sandstones that are similar in lithology to those of the Cuba Mesa (Baltz, 1967, p. 56). The base of the Cuba Mesa is at the base of a laterally continuous, thickly bedded arkosic sandstone that rests on an unconformity in the southern outcrop area. This contact is the base of the "Wasatch formation" of Reeside (1924, p. 40–41) in the formation's western outcrop area.

The Cuba Mesa Member in its type area contains a basal sheet sandstone and vertically stacked, amalgamated sheet sandstones that result in local thickening from 25 to 240 m (Figs. 5A, 6). The Cuba Mesa Member is a distinct 40- to 100-m-thick sheet sandstone in the west-central portion of the San Juan Basin. It thins toward the center of the basin by intertonguing with mudrock of the Regina Member and the upper Nacimiento Formation, and pinches out in subsurface where the Regina Member rests in apparent conformity on the Nacimiento Formation (Figs. 6–10; Smith and Lucas, 1991).

The nature of the contact between the Cuba Mesa Member and the Nacimiento Formation (and equivalent strata of previous workers) in outcrops north of latitude 36°45′ has been described as conformable toward the center of the basin (Stone et al., 1983, p. 25–26). In the San Jose's southern outcrop, at latitude 36°N, it unconformably overlies Paleocene, and locally Mesozoic strata, with 1–90° discordance (Baltz, 1967; Lucas et al., 1981).

The San Jose–Animas contact in the northernmost San Juan Basin ("Wasatch"-Animas contact of previous workers) has been described as both unconformable (Wood et al., 1948) and conformable (Barnes, 1953; Barnes et al., 1954) in the center of the basin, and as unconformable where it overlaps Paleocene and Mesozoic strata near the basin margin (Baltz, 1953; Barnes et al., 1954). The Cuba Mesa Member is traceable into the "a" sandstone of Barnes (1953), which is equivalent to the "b" sandstone of Barnes et al. (1954). This bed can be traced up the Animas River Canyon, to Bridgetimber Mountain, and in part, around the base of the Mesa Mountains (Barnes, 1953; Barnes et al., 1954) and in subsurface until it pinches out to the northeast (Figs. 6, 7).

The San Jose–Animas contact in the H-D Hills of southwestern Colorado is defined at the base of a persistent, ledge-forming sandstone ("Wasatch-Animas" of Wood et al., 1948; the "d" sandstone of Barnes, 1953; Tweto, 1979). Tiffanian strata of the Animas Formation (Granger, 1917; Simpson, 1935; Barnes et al., 1954; "Wasatch formation" in Reeside, 1924; "San Jose Formation" in Fassett and Hinds, 1971 and Butler et al., 1981) directly beneath the San Jose in the H-D Hills is laterally equivalent to strata of the Cuba Mesa and Regina Members in the Mesa Mountains (Figs. 3, 6, 7).

The "a" and "d" sandstones are discontinuous in the north-central San Juan Basin (Barnes, 1953) and indicate intertonguing between the San Jose and Animas Formations. Lack of continuity of any single sandstone at the base of the San Jose in this area has caused differences in the definition of the contact on the published maps cited above. These data indicate preservation of upper Paleocene strata in Colorado con-

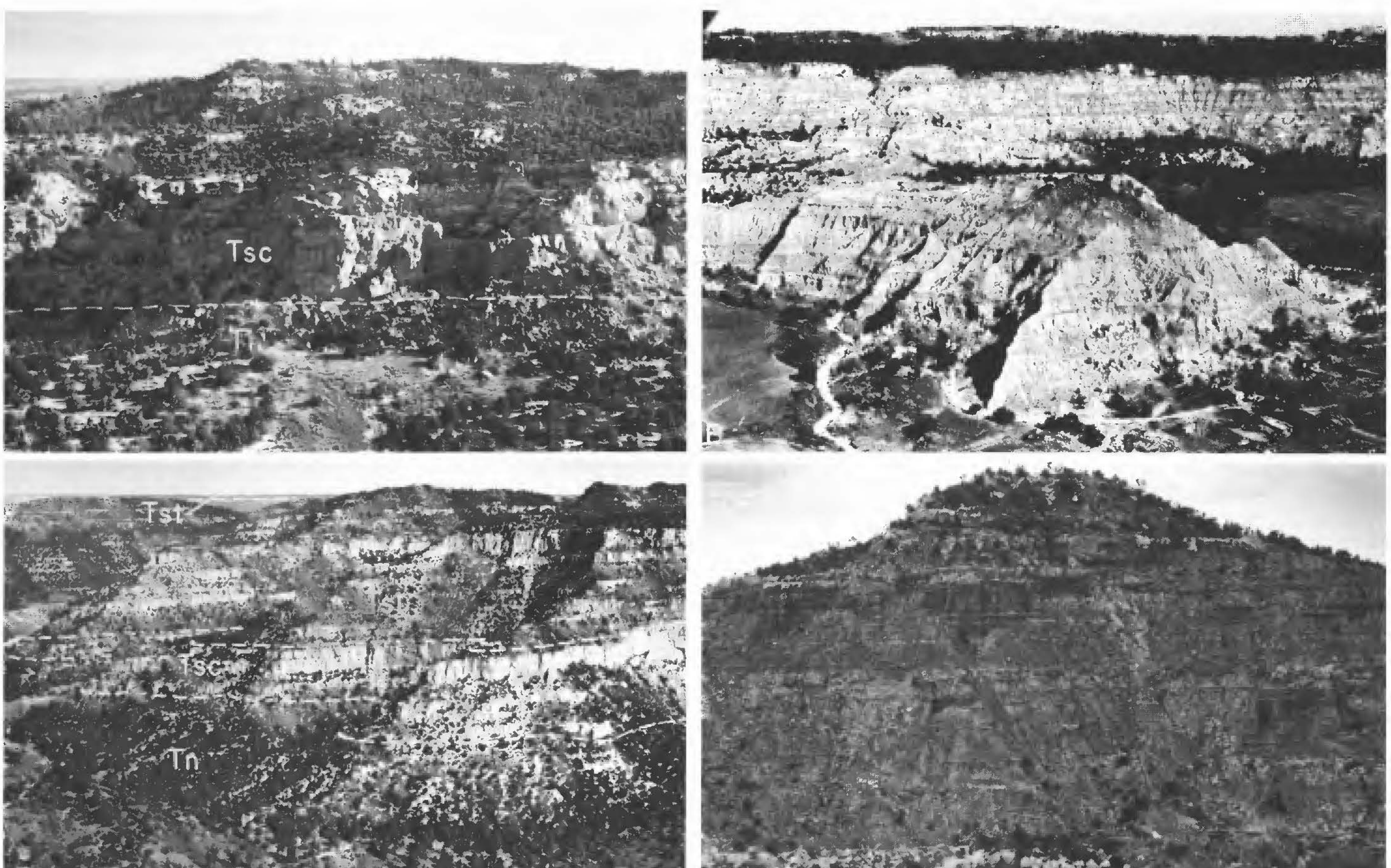


FIGURE 5. Members of the San Jose Formation. A. Cuba Mesa Member, view to north. Thick sandstone sequence on right half of photo splits and intertongues with mudrock of the Regina Member on the left half. Cliff in foreground is approximately 80 m high. Location: lat. 36°00′41″, long. 107°5′12″. B. Mudrock-dominated Regina Member, view to northwest. Location: lat. 36°15′00″, long. 106°57′00″. C. Sandstones and mudrocks of the Llaves Member overlying the Cuba Mesa Member, view to southwest. Ridge to the right of the main canyon is 250 m high. Location: lat. 36°24′17″, long. 106°52′21″. D. Tapicitos Member, view to north. Exposure is approximately 150 m high. Location: lat. 36°22′14″. Symbols: Tsc = Cuba Mesa Member; Tsr = Regina Member; Tsl = Llaves Member; Tst = Tapicitos Member.

formably below and adjacent to San Jose strata, whereas equivalent strata may either have been eroded (Baltz, 1967), not deposited, or are represented by unfossiliferous Cuba Mesa Member in the southern part of the basin (Fig. 3).

The pinchout boundary of the Cuba Mesa lies near the north-northwest-trending structural axis of the San Juan Basin. The presence of a sheet sandstone at the base of the San Jose along the formation's eastern, western, southern and some of the northern basin margins suggests that the Cuba Mesa pinches out centripetally toward the Paleogene basin axis.

Regina Member

The Regina Member of the San Jose Formation is composed of interbedded mudstone, fine- to very coarse-grained sandstone, minor shale, and a few conglomeratic sandstones (Fig. 5B; Table 1). Mudrock intervals in the Regina Member are dominated by lenticular to sheet-like varicolored bodies of claystone and siltstone that are commonly sandy. Sandstone beds are lenticular over scales ranging from a few meters to many kilometers. The Regina Member on the cross sections has few sandstones that are correlative between well logs (Figs. 7–9; Smith and Lucas, 1991). Lenticular conglomeratic sandstones in the northernmost outcrops of the member contain cobbles derived from Precambrian rocks common in the San Juan uplift north of the San Juan Basin.

Greenish gray, yellow, brown, purple and red mudrocks and bioturbated sandstones of the Regina Member (Smith, this guidebook, Day 2 Road Log) were designated the Almagre facies by Simpson (1948) for outcrops in the southeastern part of the basin (Haskin, 1980). Red mudrock and sandstone of the Regina Member directly adjacent to and below the Llaves Member and the entire Tapicitos Member (Fig. 6)

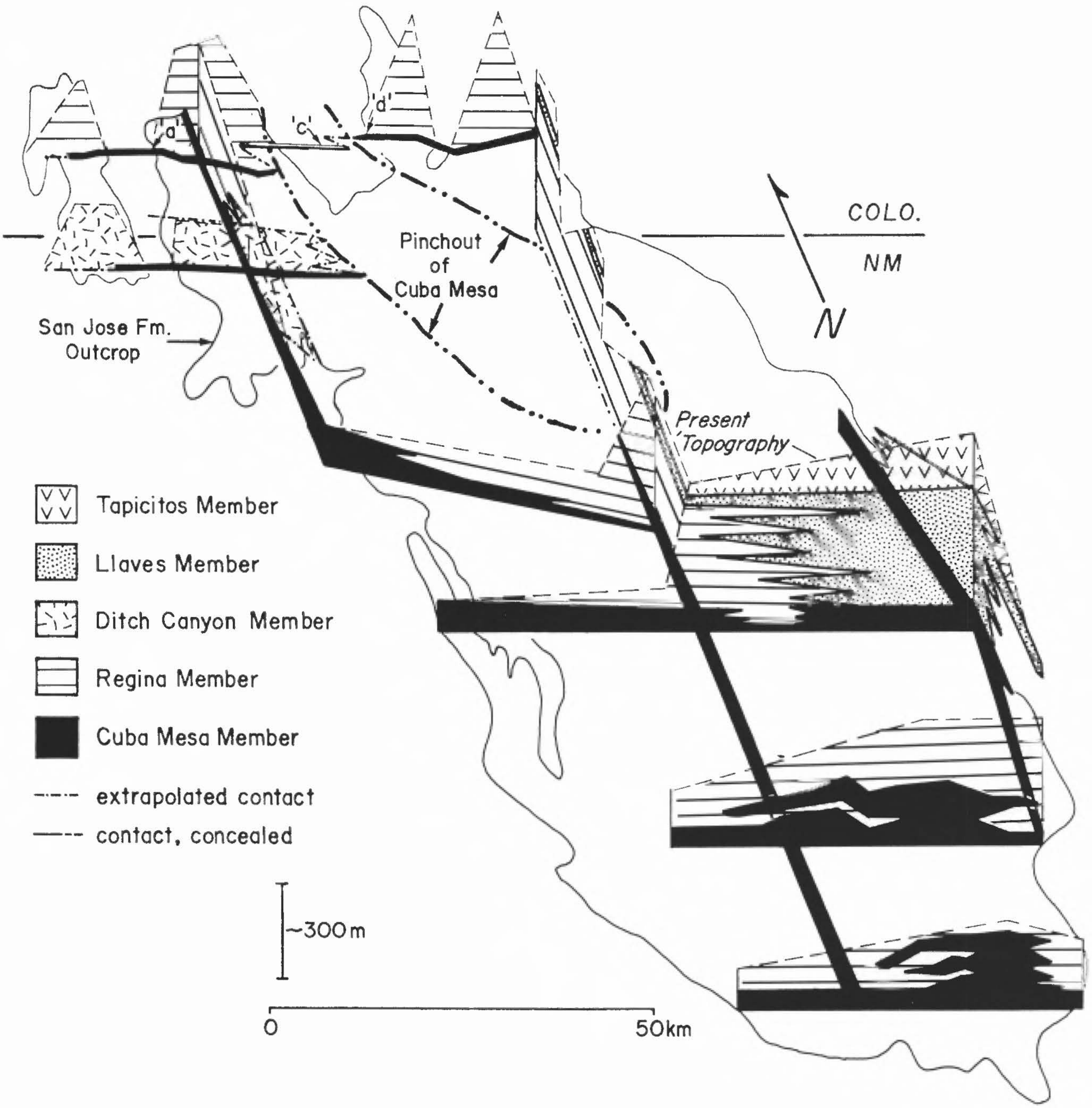


FIGURE 6. Fence diagram of the stratigraphy of the San Jose Formation. Cross sections A, B and C are after Figs. 7–9; D, E and F are after Smith and Lucas (1991); and G and H are after Smith (1988).

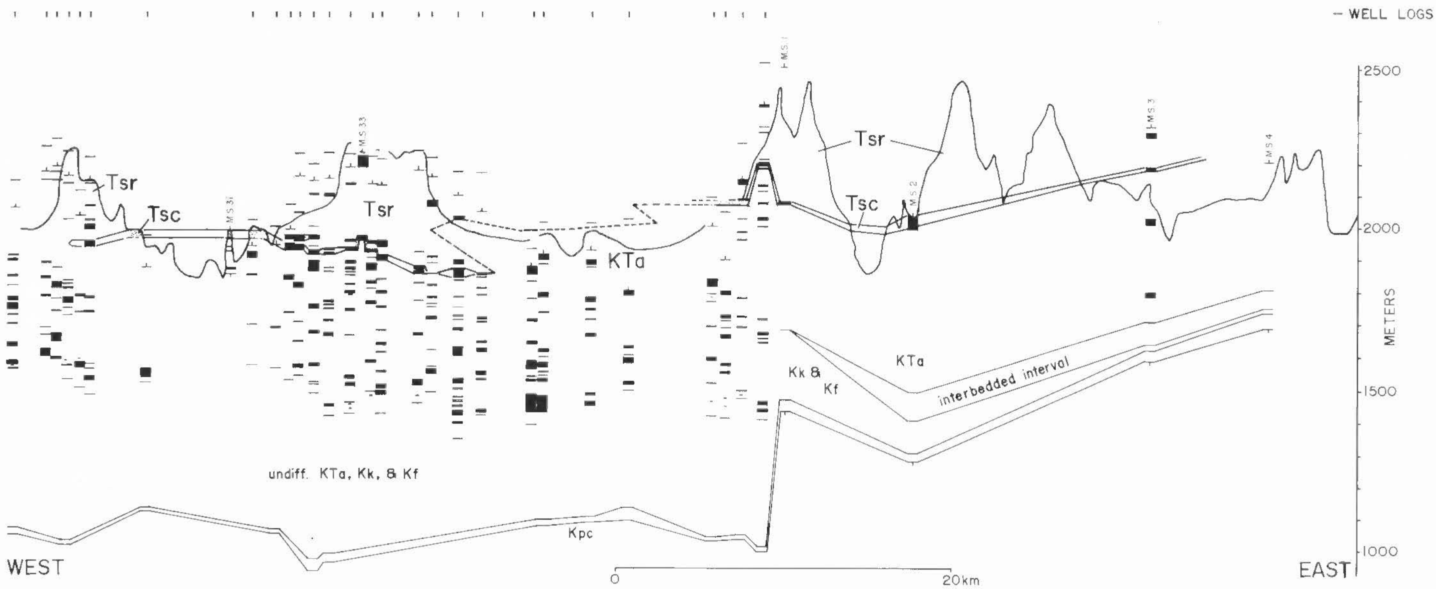


FIGURE 7. East-west cross section in Colorado (Section B, Fig. 2) of subsurface and surface data for stratigraphy of the northern San Juan Basin. Symbols are same as in Fig. 5.

were termed the Largo facies by Simpson (1948) and Haskin (1980). These changes in color reflect differences in average grain sizes of mudrock; the redder strata are generally coarser (Smith, 1988). The Almagre and Largo facies of the San Jose Formation are not mappable units, include portions of the Regina, Llaves and Tapicitos Members, and should not be used as stratigraphic terms for the formation (Baltz, 1967).

The lower contact of the Regina is conformable with the Cuba Mesa Member. Contacts between the Regina Member and the Llaves Member are conformable and intertonguing. Sandstone and mudrock percentages in well logs suggest a southward coarsening in the Regina Member (Table 1). The smallest percentage of sandstone in the Regina occurs in the northern part of the San Juan Basin, near its structural axis and the San Juan uplift. This fining trend of the Regina Member corresponds with the northeastward pinchout of the Cuba Mesa Member.

Baltz (1967, p. 56) inferred that the Regina Member tongues out to the northeast from the southeastern part of the San Juan Basin into sandstones equivalent to the Llaves Member in the area north of 36°30′, as he showed it does near Llaves, New Mexico (p. 50–51). The continuity of the Regina Member through this region (Fig. 6) shows that the Regina and "unnamed" members of Baltz (1967, p. 56) are equivalent (Fig. 3A). The mudrock-dominated strata "in the northern third of the central basin in New Mexico and Colorado . . ." (Baltz, 1967, p. 56) should be referred to as Regina Member.

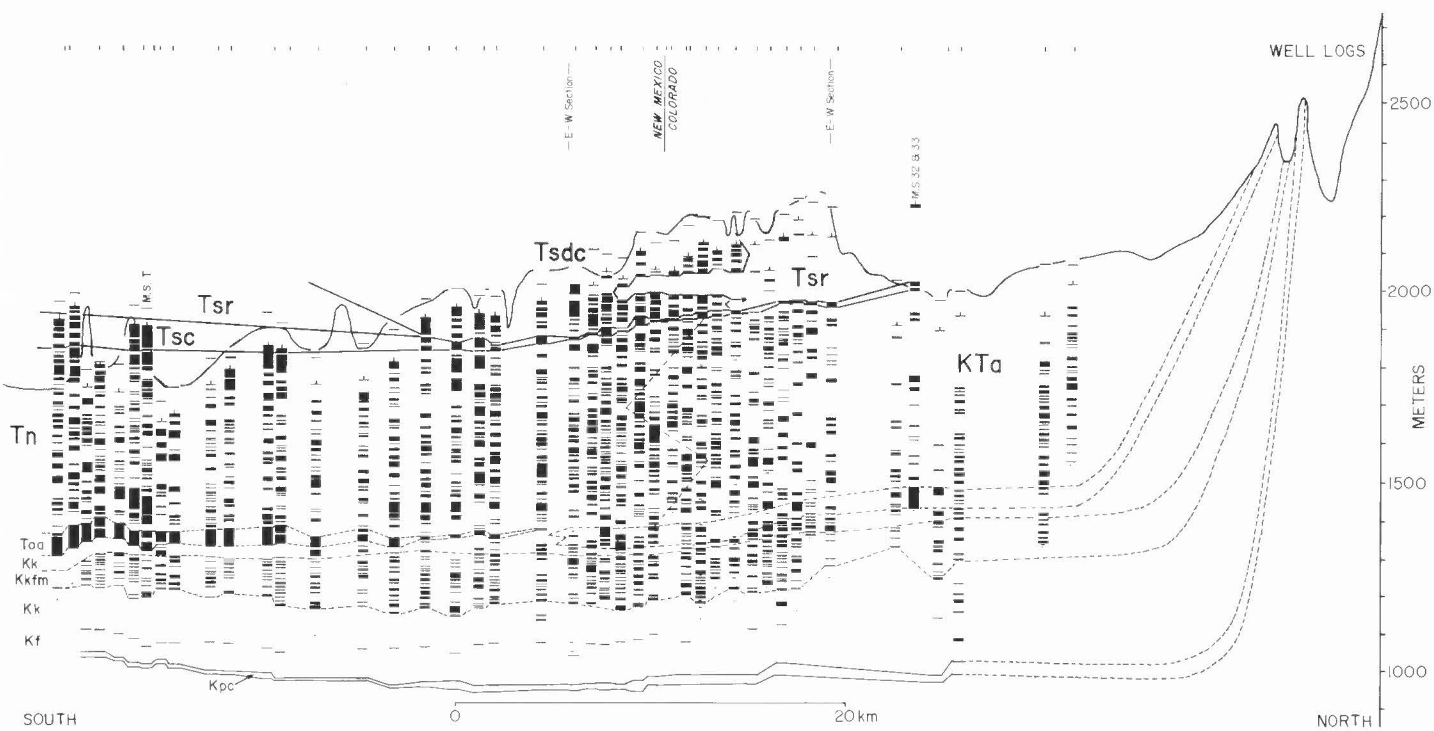


FIGURE 8. North-south cross sections in Colorado and northwestern New Mexico (Section A, Fig. 2) of subsurface and surface data for stratigraphy of the northern San Juan Basin. Symbols are same as in Fig. 5.

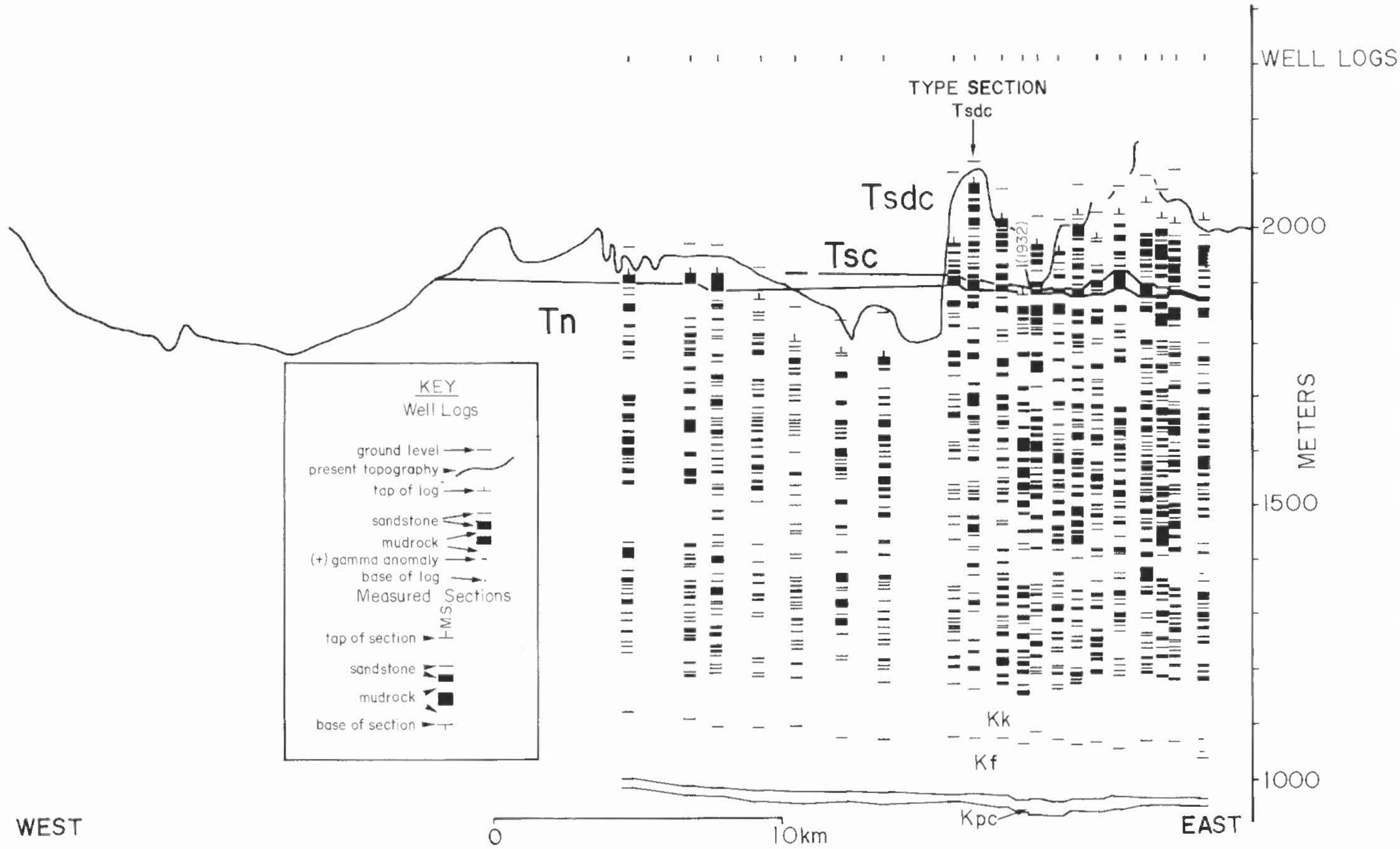


FIGURE 9. East-west cross section in New Mexico (Section C, Fig. 2) of subsurface and surface data for stratigraphy in the northern San Juan Basin. Symbols are same as in Fig. 5.

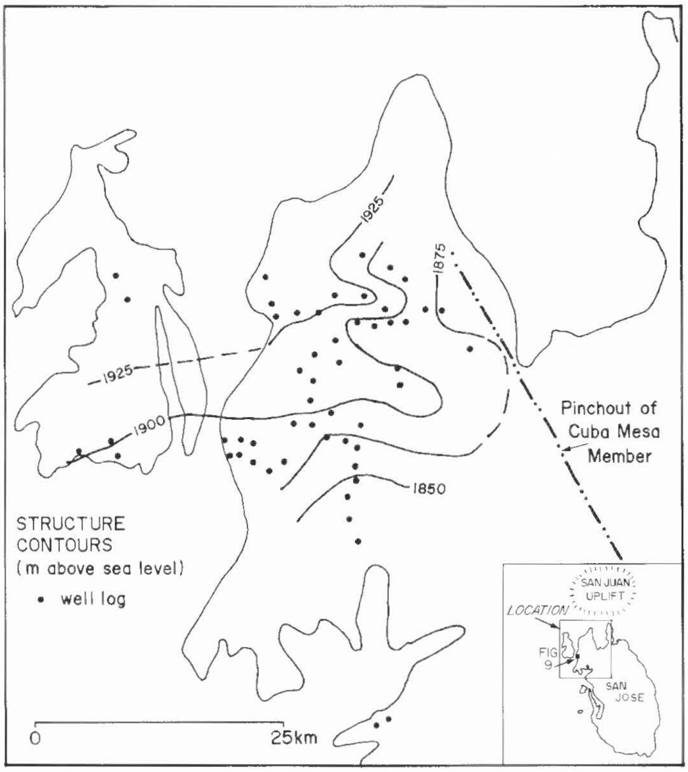


FIGURE 10. Map of structure contours on the Cuba Mesa Member in the northwestern San Juan Basin.

TABLE 1. Summary of facies in each member of the San Jose Formation, as compiled from well logs, including percentages of sandstone and mudrock in each member and in important different areas of Regina Member. A = Data from stratigraphic sections; B = relative amounts of sandstone and mudrock in the Regina Member in well logs. Letters in parentheses refer to cross sections from which data were obtained.

A	Percent of Section	Average bed thickness	Range in thickness	Number of beds
REGINA MEMBER				
Medium-Coarse Sandstone	38%	5.4 m	0.5-23 m	49
Fine Sandstone and Mudrock	62%	8.4 m	0.5-42 m	57
LLAVES AND TAPICITOS MEMBERS				
Medium-Coarse Sandstone	34%	6.2 m	1.5-10.5 m	17
Fine Sandstone and Mudrock	66%	9.6 m	1.75-47.25 m	14

B	Sandstone	Mudrock
Central basin (F, E)	38%	62%
Northeast basin (D)	35%	65%
Northwest basin	12%	88%

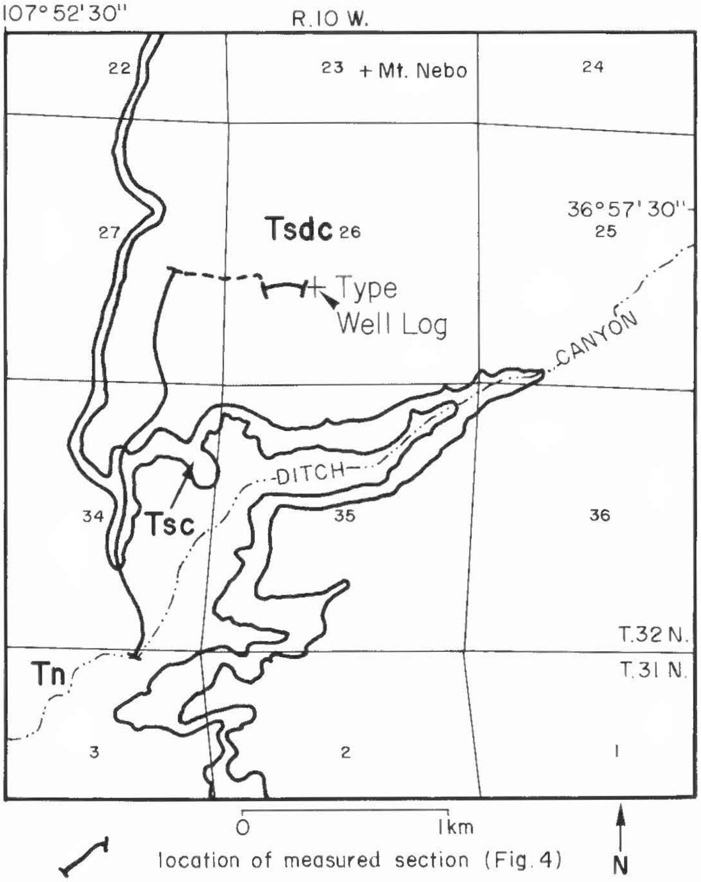


FIGURE 11. Geologic map of Ditch Canyon showing location of the type section of the Ditch Canyon Member of the San Jose Formation. Symbols as in Fig. 5.

Llaves and Tapicitos Members

The Llaves Member includes a lower sequence of sheet sandstones that intertongues with the Regina Member in the east-central portion of the San Juan Basin and an upper, laterally persistent sheet sandstone (Fig. 3A; Baltz, 1967). The arkosic to quartzose sandstones are red, yellow and gray, very coarse- to medium-grained, locally conglomerative and thickly bedded (Fig. 5C). The Tapicitos Member is a slope forming unit that is characterized by red mudrock and pink sandstone (Fig. 5D; Smith, this guidebook, Day 2 Road Log). The Tapicitos is similar in bed thickness and overall character to the Regina Member (Table 1). The Llaves and Tapicitos Members cap the high topography in the eastern and northeastern portions of the basin (Fig. 6). The upper, persistent sheet sandstone of the Llaves Member correlates across canyons in the northeastern outcrop area of the San Jose (Fig. 6). Dominance of mudrock in the Regina Member below the persistent sheet sandstone of the Llaves Member in the central and northeastern portions of the basin indicates that the main body of the Llaves tongues out to the north and west (Fig. 6), much as it does to the south (Baltz, 1967).

Ditch Canyon Member

The San Jose Formation in the northwestern portion of the San Juan Basin, between the Colorado–New Mexico border and the San Juan River, is composed mostly of very coarse- to medium-grained sheet sandstones and lesser quantities of mudrock that rest conformably on the Cuba Mesa Member. This sandstone dominated unit is here named the Ditch Canyon Member of the San Jose Formation for exposures in Ditch Canyon, New Mexico (Figs. 11, 12). The type section and type well log of the member are shown in Fig. 4 and located in Fig. 11. Correlation of this section and well log to nearby well logs is shown in Fig. 9. The type section of the Ditch Canyon Member is composed of 220 m of yellow, medium-, coarse- and very coarse-grained sandstone and conglomerates (66%) and gray, green and purple mudrock (34%). Sandstones are dominantly trough cross-stratified in large-scale sets with common granule- and pebble-sized quartzite conglomerate clasts along erosional scours.

The basal contact of the Ditch Canyon Member is chosen at the base of the first mudrock above the sandstone of the Cuba Mesa Member. The contact between the Ditch Canyon and Regina Members is defined along boundaries of sheet sandstones that can be traced laterally from the Ditch Canyon Member into the Regina Member (Figs. 6–9). Maps of percent sandstone and average sandstone thickness in the northwestern outcrop area of the San Jose Formation portray the northeastward pinchout of the Ditch Canyon Member into the Regina Member (Fig. 13). The Ditch Canyon Member thins from 220 m at the type section northward into two tongues that pinch out 5 km into southern Colorado (Fig. 7). The Ditch Canyon Member thins by intertonguing with the Regina Member near the San Juan River, approximately 30 km southeast of the type section.

In mapping the northwestern portion of the San Juan Basin in New Mexico, Manley et al. (1987) showed a thickening of the Cuba Mesa Member in the region between the San Juan River and Ditch Canyon to account for the increase in percentage of sandstone. Correlation of the entire sequence of sheet sandstones in Ditch Canyon with the Cuba Mesa Member is not tenable because the strata here named Ditch Canyon Member are stratigraphically above the Cuba Mesa Member and cannot be traced into sandstones of the Cuba Mesa. Separation of the

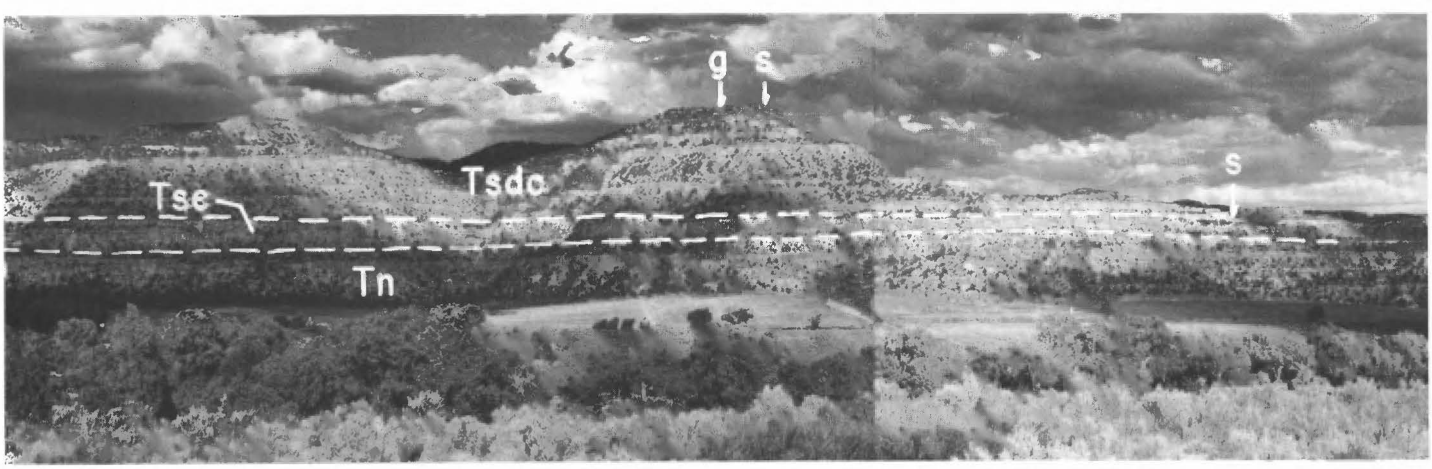


FIGURE 12. Photographic panorama looking east of the San Jose Formation and subjacent strata on Mount Nebo. Ta = Paleocene Animas Formation; Tsc = Cuba Mesa Member; Tsd = Ditch Canyon Member; arrows show approximate locations of the type section (s) and gas well (g) from which the type electric log of the Ditch Canyon Member was made (Fig. 4).

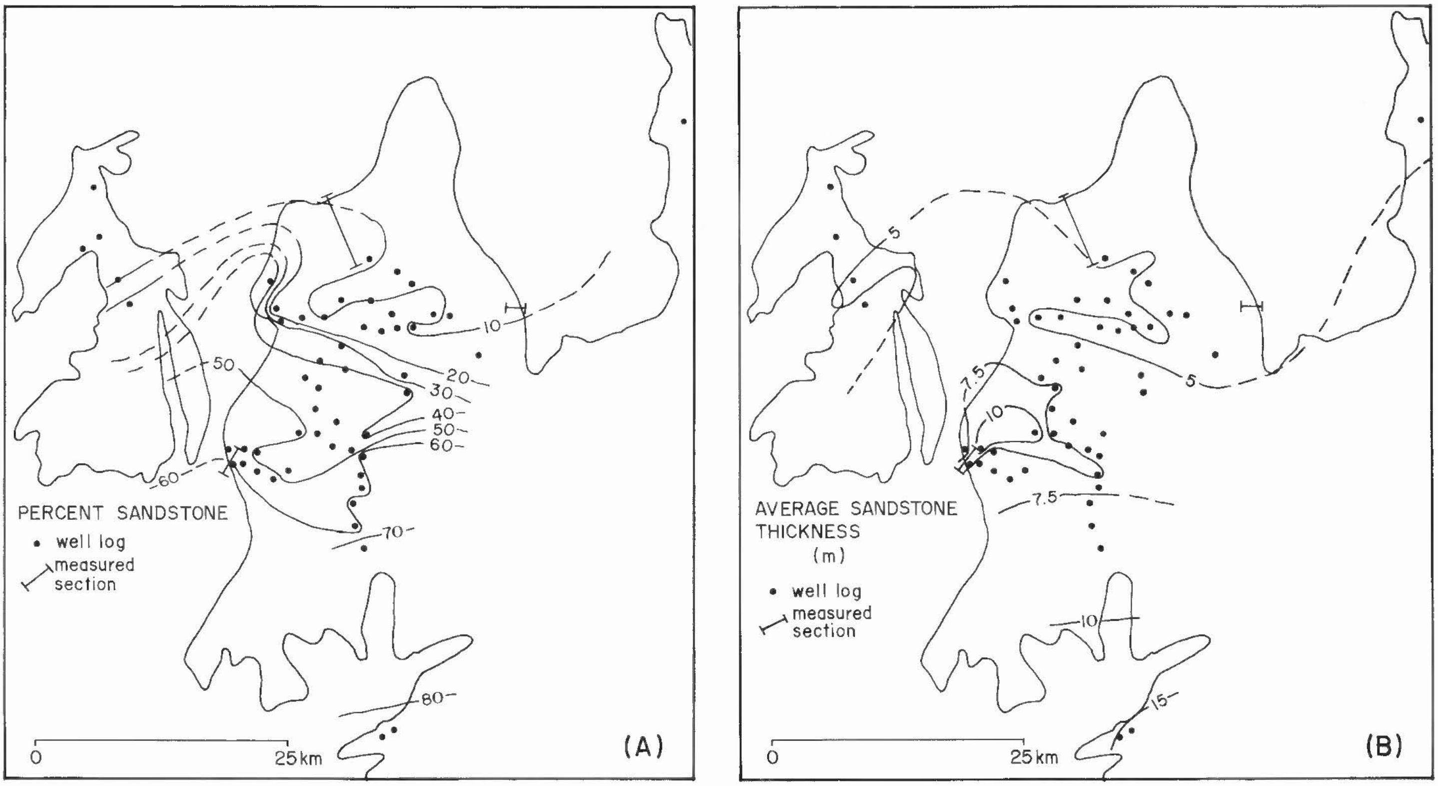


FIGURE 13. Maps of percent sandstone (A) and average sandstone thicknesses (B) in the San Jose Formation in the northwestern portion of the San Juan Basin. Location as in Fig. 10.

Ditch Canyon Member from the Regina Member is justified by the fact that laterally restricted sequences of strata with high percentages (>40%) of sandstone occur only in two places in the basin. These stratal sequences, the Llaves and Ditch Canyon Members, are located near basin margins and represent locally high concentrations of channel sandstones adjacent to otherwise mudrock-dominated Regina Member strata. The Llaves and Ditch Canyon Members are at equivalent stratigraphic positions in the basin but are not connected and were deposited by separate fluvial systems that entered the basin from different directions (Fig. 6).

No fossils have yet been found in the Ditch Canyon Member. The member is laterally equivalent to strata in the central and southeastern San Juan Basin, in which early Eocene vertebrate fossils are found (Lucas et al., 1981; Smith and Lucas, 1991). Based on this correlation, the member is considered early Eocene in age (Wasatchian land mammal "age" of Wood et al., 1941).

SEDIMENT DISPERSAL

Paleocurrent measurements on sedimentary structures in sheet sandstones were made at 105 stations, each including either a single sheet sandstone or a sequence of sandstones in an area less than 1 km^2. An average of 20 paleocurrent indicators were measured at each station; the indicators include (in order of decreasing abundance) axes of large-scale trough cross-strata, maximum dip directions of large-scale trough cross-strata, and clast imbrications. Measurements of paleocurrent indicators of a variety of scales (Miall, 1974) were made in order to understand small- and large-scale flow patterns in channels in the San Jose Formation (Smith, 1988). For the purpose of analyzing regional sediment dispersal, only data from sedimentary structures that represent relatively high-energy fluid flow are included here. Vector means calculated from data from each station press are presented in Fig. 14.

Paleocurrent show that streams flowed generally toward the south (Fig. 14). In detail, paleoflow was west-southwest along the eastern outcrop belt and from the northwest, northeast and north in the northern part of the basin. The more western paleocurrent direction of the Llaves and Tapicitos Members, compared to the Cuba Mesa and Regina Members in the eastern part of the study area is significant at the 95% confidence level.

Paleocurrents from the Cuba Mesa and Regina Members of the San Jose Formation in the southern San Juan Basin indicate paleoslope directions similar to those during deposition of subjacent Paleocene strata (Klute, 1986; Sikkink, 1987). In detail, the data indicate that streams depositing the Cuba Mesa Member flowed in a southwest to south direction around the position of the Nacimiento uplift. Data from elsewhere in the formation indicate paleoflow southwest, southeast and south toward the southern and southeastern margins of the basin, exiting the basin to the south to an as yet unknown baselevel. Regional paleocurrent directions for the San Jose data show an eastward component of paleoflow in the northwestern San Juan Basin, whereas most Paleocene paleocurrents are directed more due south. West-southwest paleoflow of the Llaves Member into the basin is consistent with cobble lithologies (Baltz, 1967) and petrographic and geochemical data (Chamberlin, 1987, unpubl. data) that indicate Precambrian quartzites of the Tusas Mountains (Williams, 1987) were important sources for its sediment (Fig. 1). Paleocurrents from the Blanco Basin Formation reported here (Fig. 14) agree with previous measurements (Dunn, 1964a), support correlation of this unit with Eocene sediments of the San Juan Basin, and indicate a northeastern source for sediment (Smith et al., 1985, and references therein).

PALEOGEOGRAPHY

Channel belts in the Eocene San Juan Basin

The three-dimensional arrangement of sandstone-dominated members of the San Jose Formation (Fig. 6) suggests three major channel-belt systems that entered the basin (Fig. 15). Channel sandstones within the Regina and Tapicitos, outside of indicated channel belts, indicate that major streams in the basin were not restricted to the major channel belts but preferentially occupied the three positions. Arkosic sandstone, metamorphic rock fragments, geochemical data and heavy minerals from the San Jose Formation suggest that Eocene streams tapped the

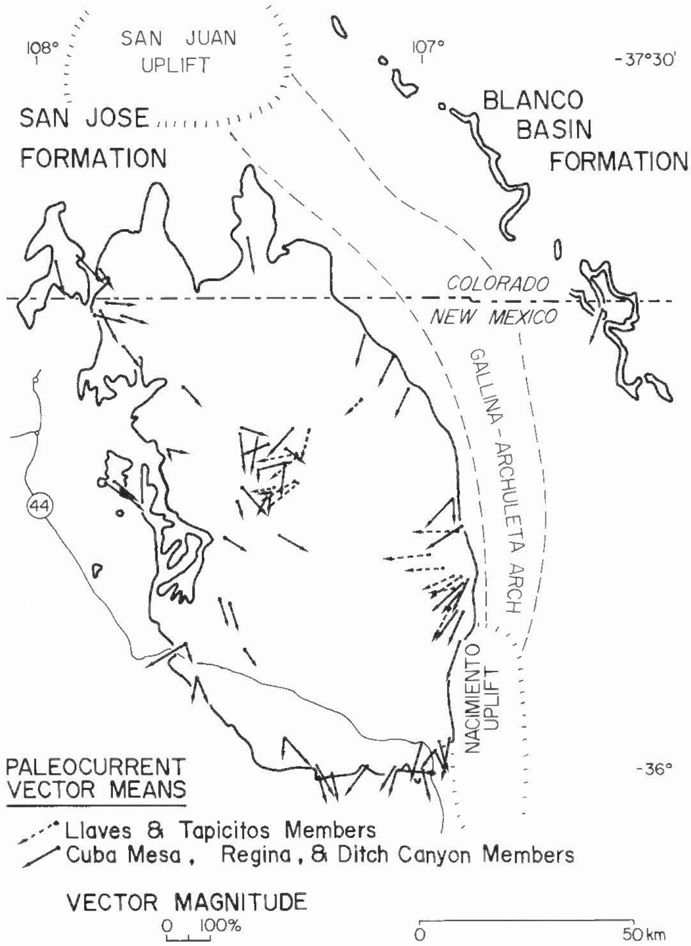


FIGURE 14. Map of paleocurrent vector means in the San Jose Formation and Blanco Basin Formation. Locations, statistics and values are in Smith (1988).

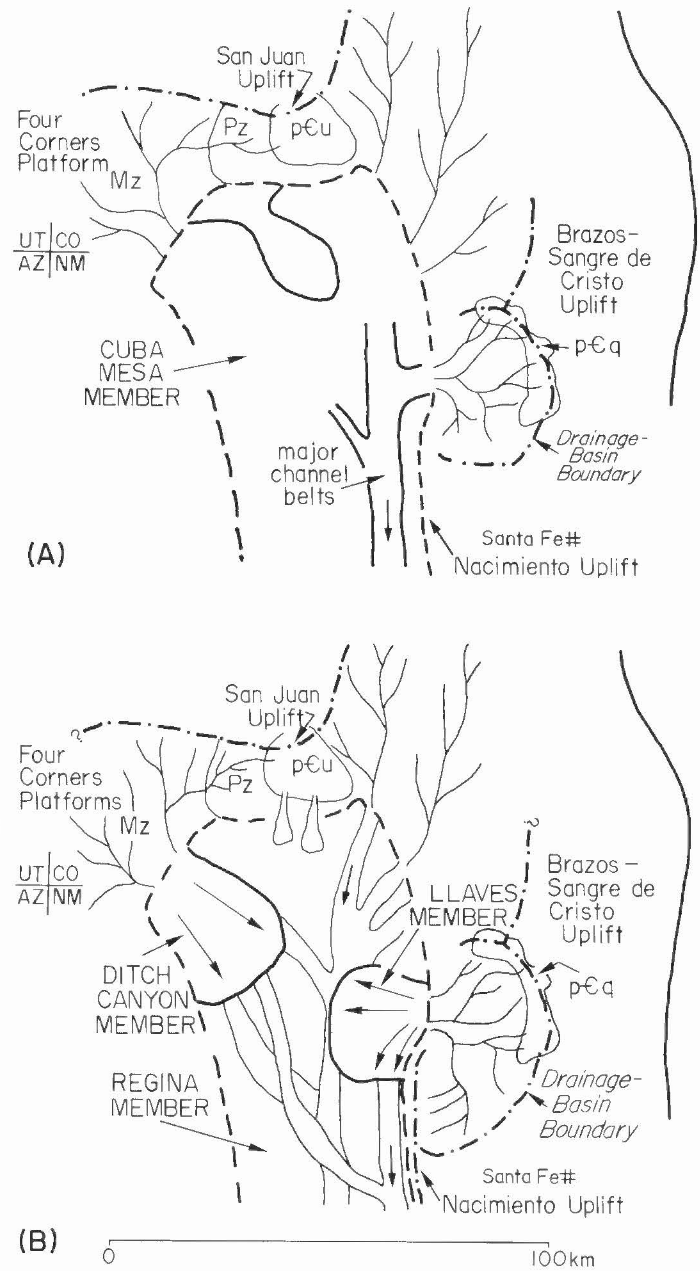


FIGURE 15. Maps of channel belts in San Jose Formation and possible drainage basins. A. Channel belts and paleogeography during deposition of the Cuba Mesa Member. B. Channel belts and paleogeography during deposition of the Regina, Ditch Canyon and Llaves Members.

core of the San Juan and Brazos uplifts (Chamberlin, 1987, unpubl. data). Clasts in Paleocene strata indicate Paleocene or earlier unroofing of Precambrian rocks in the San Juan and Brazos uplifts (Fig. 1; Klute, 1986; Sikkink, 1987). The availability of sediment derived from Precambrian basement prior to, and throughout, the early Eocene suggests that major changes in sediment types cannot necessarily explain the distribution of sandstones interpreted to represent channel belts of the San Jose.

Paleocurrents from the Cuba Mesa Member indicate that paleoflow from a variety of directions distributed sediment across much of the basin (Fig. 14). The vertical stacking of channel sandstones in the southeastern part of the Cuba Mesa outcrop is evidence for areally restricted trunk and tributary south-flowing channel belts along major and minor synclinal axes in the basin (Figs. 6 and 15A). Paleoflow toward this channel belt may have been along structurally controlled paleoslopes oriented toward the main basin axis.

Paleocurrents (Fig. 14), sandstone petrography (Dunn, 1964a, b; Chamberlin, unpubl. data) and geochemical data (Chamberlin, 1987) from the Blanco Basin and San Jose Formations indicate that sediment was derived from Precambrian and Phanerozoic rocks of the San Juan and Brazos–Sangre de Cristo uplifts north-northeast of the San Juan Basin (Fig. 15A). The structure of the region suggests sediment was delivered to the basin from one or more drainage basin(s) that emanated from a structural reentrant between the uplifts. Streams flowed across the position of the Gallina-Archuleta arch (Figs. 1 and 15A), suggesting this structure had little effect on drainage development.

Drainage that entered the basin from the northwest near the present New Mexico–Colorado border was shed directly from the Four Corners platform (Kelley, 1955). Paleocurrents and the geometry of the Ditch Canyon Member indicate that the transport route for most sandy sediment was southeastward along a channel belt into the basin (Fig. 15B).

The stratigraphy, paleocurrents and quartzite lithology of the Llaves Member (Baltz, 1967; Chamberlin, 1987) suggest that a paleodrainage basin, headed in the Ortega Quartzite of the Brazos uplift, eroded Precambrian quartzite units and discharged into the eastern San Juan Basin (Fig. 15B). A southwest-trending channel belt in the Cuba Mesa Member and paleocurrents in the southeastern portion of the San Jose Formation indicate that this paleodrainage basin supplied sediment to the basin during accumulation of the entire San Jose (Fig. 15; this guidebook, Day 1, Stop 3). The Ditch Canyon and Llaves Members represent separate loci of dispersed fluvial channel sedimentation.

The position of inferred fluvial channel belts near structural reentrants between major Laramide uplifts surrounding the San Juan Basin shows that extra-basinal paleogeography and tectonics imparted a significant control on stratigraphy. Grain size and source-area data for Paleocene strata beneath the San Jose in the northern part of the basin suggest similar northeastern and northwestern source areas (Reeside, 1924; Sikkink, 1987). The paleodrainage basins may have been initiated and maintained throughout the Laramide orogeny.

Stratigraphic model for San Jose Formation

Unconformities at the base of the Cuba Mesa Member along the northwestern, southern and eastern margins of the outcrop area indicate local basinward tilting and erosion of Paleocene and older strata during the late Paleocene and/or early Eocene (Baltz, 1953, 1967). Preservation of upper Paleocene strata conformably below San Jose strata in the northern San Juan Basin, and erosion or nondeposition of correlative strata elsewhere suggests subsidence may have been continuous across the Paleocene/Eocene boundary near the center of the basin. Accumulation of the basal sheet sandstone of the Cuba Mesa Member across basin-margin unconformities suggests preferential preservation of sandstone and lateral amalgamation of channel sands in these areas that underwent less continuous subsidence than near the basin center. Pinchout of the main Cuba Mesa sheet sandstone toward the basin center suggests that increasing subsidence rates led to thinner and ultimately disconnected channel bodies surrounded by floodplain mudrock in the center of the basin (after the model of Bridge and Leeder, 1979).

Intraformational angular unconformities and high-angle reverse faults in the Regina Member indicate that syndepositional early Eocene uplift and monoclinal folding occurred along the Nacimiento uplift. Stratigraphic relations show that this tectonism occurred after deposition of the basal sheet sandstone of the Cuba Mesa Member and was coincident with deposition of the mudrock-dominated Regina. The south-flowing channel belt parallel to the Nacimiento uplift represents vertical stacking of channel sandstones along a synclinal axis during subsidence related to basin-margin tectonism. Structural and stratigraphic relations along the southeastern basin margin support the assertion that accumulation of the basal sheet sandstone of the Cuba Mesa Member occurred during a period of relatively quiescent tectonism compared to the time of Regina Member deposition.

The Llaves and Ditch Canyon Members and the laterally equivalent Regina Member represent regions dominated by channel belt and floodplain sedimentation, respectively. Channel sedimentation occurred preferentially at the mouths of two structural reentrants between basin-margin uplifts (Fig. 15B). The position of fine-grained facies of the Regina Member directly adjacent to the San Juan and Nacimiento uplifts and paleocurrent patterns show that major bedload-dominated streams did not flow directly into the basin from active uplift fronts. Erosion of monoclinally folded Mesozoic and Paleozoic sedimentary strata along the active fronts may explain the rarity of coarse sediment in the adjacent basin. However, laterally restricted conglomeratic sandstones within mudrock-dominated sequences clearly show that some drainage basins, probably of small size, headed in Precambrian rocks along the active front of the San Juan uplift. Major drainage basins formed within structural reentrants between uplifts bordering the San Juan Basin provided arkosic, metavolcanic and quartzitic sediment to upper Paleocene and lower Eocene strata in the northwest, northeast and east-central margins of the basin.

The Tapicitos Member was dispersed west-southwestward into the basin from a direction similar to that of the subjacent Llaves Member. The Tapicitos represents the last preserved phase of sedimentation in the Laramide San Juan Basin. The coarse-grained nature of this siltstone-dominated red-bed unit suggests erosion of a source area more coarsely grained than that of the similar, but older, Regina Member. The coarsening-upward sequence of the Regina to Tapicitos Members may be due to a greater percentage of exposed basement rocks during the later phase of San Jose deposition.

CONCLUSIONS

1. The basal Cuba Mesa Member of the lower Eocene San Jose Formation unconformably overlies Paleocene strata of the Nacimiento and Animas Formations in the northwestern, southern and eastern parts of the San Juan Basin. The Cuba Mesa Member pinches out toward the structurally lowest part of the basin. The pinchout results in conformable contacts between the upper Paleocene Animas Formation and the Regina Member of the San Jose in southwestern Colorado, and between the Paleocene Nacimiento Formation and San Jose Formation in the New Mexico subsurface.

2. The mudrock-dominated Regina Member overlies and intertongues with the Cuba Mesa Member away from the center of the San Juan Basin. The Regina Member overlies the Nacimiento Formation in the New Mexico portion of the basin axis and overlies and intertongues with upper Paleocene strata of the Animas Formation in the northern part of the basin, in Colorado.

3. Sediment dispersal of the Cuba Mesa and Regina Members indicates streams entered the basin from the northwest, north-northeast and east, and exited to the south toward an as yet unknown baselevel.

4. The Llaves Member of the San Jose Formation is a lobate body of sheet sandstone and subordinate mudrock that emanated west-southwestward from a paleodrainage basin between the Nacimiento uplift and Precambrian quartzites of the Brazos uplift, east of the San Juan Basin. The Gallina-Archuleta arch was apparently not an impediment to sediment dispersal throughout deposition of the San Jose.

5. The Ditch Canyon Member of the San Jose Formation is named here for a lobate body of sheet sandstone and subordinate mudrock that was dispersed southeastward into the San Juan Basin from the Four Corners platform and western San Juan uplift. The Ditch Canyon Member intertongues with the Regina Member and is stratigraphically equivalent to, but not traceable into, the Llaves Member.

6. The Tapicitos Member represents the last preserved phase of sedimentation in the Laramide San Juan Basin. This mudrock-dominated red-bed unit was dispersed west-southwestward into the basin from source areas more coarsely grained than those of the similar, but older Regina Member.

7. Basal and intraformational unconformities and the three-dimensional distribution of channel and floodplain lithologies in the San Jose Formation indicate the rate of tectonic subsidence was a major factor in controlling basin stratigraphy. Deposition of the Cuba Mesa Member basal sheet sandstone occurred during erosion and onlapping of basin-margin areas and lateral amalgamation of channel sandstones. Synsedimentary subsidence along the basin axis, major paleodrainage basins within structural reentrants, and shedding of fine-grained sediment from small drainage basins along active uplift fronts controlled the positions of vertically stacked bodies of channel and floodplain sediments during syntectonic sedimentation of the Regina, Llaves, Ditch Canyon and Tapicitos Members.

ACKNOWLEDGMENTS

The clarity of this manuscript has benefited from criticism by Drs. Robyn Wright and Spencer Lucas. The Southern Ute Tribe and Jicarilla Apache Tribe are thanked for allowing access to their lands for collection of data. The Southern Ute Tribe and Mr. Brad Boyce were very helpful and gracious in making copies of well logs available. Drs. Spencer Lucas, Glenn Scott and Elmer Baltz provided valuable information concerning the stratigraphy of the San Juan Basin. Dr. Chris Condit's piloting of his airplane was essential for obtaining aerial photographs. Funding received from New Mexico Bureau of Mines and Mineral Resources, New Mexico Geological Society, Geological Society of America, Donald L. Smith Research Fund of the Rocky Mountain Section of SEPM, UNM Graduate Students Research Allocations Committee, and the Alumni Fund at UNM Department of Geology aided the completion of this study. Photographic and computer support from Shell Western E&P Inc. is gratefully acknowledged.

REFERENCES

Baltz, E. H., 1953, Stratigraphic relationships of Cretaceous and early Tertiary rocks of a part of northwestern San Juan Basin [M.S. thesis]: Albuquerque, University of New Mexico, 101 p.

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. Geological Survey, Professional Paper 552, 101 p.

Barnes, H., 1953, Geology of the Ignacio area, Ignacio and Pagosa Springs quadrangles, La Plata and Archuleta Counties, Colorado: U.S. Geological Survey, Oil and Gas Investigations Map OM-138, scale 1:63,360.

Barnes, H., Baltz, E. H. and Hayes, P. T., 1954, Geology and fuel resources of the Red Mesa area, La Plata and Montezuma Counties, Colorado: U.S. Geological Survey, Oil and Gas Investigations Map OM-149, scale 1:62,500.

Bridge, J. S. and Leeder, M. R., 1979, A simulation model of alluvial stratigraphy: Sedimentology, v. 26, p. 617–644.

Brimhall, R. M., 1973, Ground water hydrology of Tertiary rocks of the San Juan Basin, New Mexico; *in* Fassett, J. E., ed., Cretaceous and Tertiary rocks of the southern Colorado Plateau: Four Corners Geological Society Memoir, p. 197–207.

Butler, R. F., Gingerich, P. D. and Lindsay, E. H., 1981, Magnetic polarity stratigraphy and biostratigraphy of Paleocene and lower Eocene continental deposits, Clark's Fork Basin, Wyoming: Journal of Geology, v. 89, p. 299–316.

Chamberlin, R. M., 1987, Compositionally distinct Eocene fluvial systems in the San Juan Basin (NM-CO): a preliminary interpretation of "NURE" stream-sediment geochemical data: Geological Society of America, Abstracts with Programs, v. 19, p. 265

Cross, T. A., 1986, Tectonic controls of foreland basin subsidence and Laramide style deformation, western United States; *in* Allen, P. and Homewood, P., eds., Foreland basins: International Association of Sedimentologists, Special Publication 8, p. 15–39.

Cross, W. and Larsen, E. S., 1935, A brief review of the geology of the San Juan region of southwestern Colorado: U.S. Geological Survey, Bulletin 843, 138 p.

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

Dane, C. H., 1946, Stratigraphic relations of Eocene, Paleocene, and latest Cretaceous formations of eastern side of San Juan Basin, New Mexico: U.S. Geological Survey, Oil and Gas Investigations, Preliminary Chart 24, scale 1:63,360.

Dane, C. H. and Bachman, G. O., 1957, Preliminary geologic map of the northwestern part of New Mexico: U.S. Geological Survey, Miscellaneous Geological Investigations Map I-224, scale 1:380,160.

Dane, C. H. and Bachman, G. O., 1965, Geologic map of New Mexico: U.S. Geological Survey, scale 1:500,000.

Dresser Atlas, 1975, Log interpretation fundamentals: Dresser Industries, Inc., Houston, Texas.

Dunn, D. E., 1964a, Evolution of the Chama basin and Archuleta anticlinorium, eastern Archuleta County, Colorado [Ph.D. dissertation]: Austin, University of Texas, 114 p.

Dunn, D. E., 1964b, Tectonic significance of the Blanco Basin Formation: Geological Society of America, Special Paper 76, p. 271.

Fassett, J. E., 1968, Summary of geologic data obtained from borehole GB-1, Project Gasbuggy: New Mexico Geological Society, Guidebook 19, p. 24–27.

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 Colroado: U.S. Geological Survey, Professional Paper 676, 76 p.

Flanagan, K. M., 1986, Early Eocene rodents from the San Jose Formation, San Juan Basin, New Mexico: University of Wyoming, Contributions to Geology, Special Paper 3, p. 197–220.

Flemings, P. B., Jordan, T. E. and Reynolds, S. A., 1986, Flexural analysis of two broken foreland basins: the late Cenozoic Bermejo Basin and the early Cenozoic Green River Basin: American Association of Petroleum Geologists Bulletin, v. 70, p. 591.

Friend, P. F., Slater, M. J. and Williams, R. C., 1979, Vertical and lateral buildings of river sandstone bodies, Ebro Basin, Spain: Journal of the Geological Society of London, v. 136, p. 39–46.

Granger, W., 1917, Notes on Paleocene and lower Eocene mammal horizons of northern New Mexico and southern Colorado: American Museum of Natural History Bulletin, v. 37, p. 821–830.

Gries, R. R., 1985, San Juan sag: Cretaceous rocks in a volcanic-covered basin, southern Colorado: Mountain Geologist, v. 22, p. 167–179.

Haskin, R. A., 1980, Magnetic polarity stratigraphy and fossil Mammalia of the San Jose Formation, Eocene, New Mexico [M.S. thesis]: Tucson, University of Arizona.

Kelley, V. C., 1955, Regional tectonics of the Colorado Plateau and relationship to the origin and distribution of uranium: University of New Mexico Publications in Geology No. 5, 120 p.

Klute, M. A., 1986, Sedimentology and sandstone petrography of the upper Kirtland Shale and Ojo Alamo Sandstone, Cretaceous-Tertiary boundary, western and southern San Juan Basin, New Mexico: American Journal of Science, v. 286, p. 463–488.

Larsen, E. S. and Cross, W., 1956, Geology and petrology of the San Juan region, southwestern Colorado: U.S. Geological Survey, Professional Paper 258, 303 p.

Lucas, S. G., 1984, Correlation of Eocene rocks of the northern Rio Grande rift and adjacent areas: implications for Laramide tectonics: New Mexico Geological Society, Guidebook 35, p. 123–128.

Lucas, S. G. and Ingersoll, R. V., 1981, Cenozoic continental deposits of New Mexico: an overview: Geological Society of America Bulletin, Part I, v. 92, p. 917–932.

Lucas, S. G., Schoch, R. M., Manning, E. and Tsentas, C., 1981, The Eocene biostratigraphy of New Mexico: Geological Society of America Bulletin, v. 92, p. 951–967.

Manley, K., Scott, G. R. and Wobus, R. A., 1987, Geologic map of the Aztec $1° \times 2°$ quadrangle, northwestern New Mexico and southern Colorado: U.S. Geological Survey, Miscellaneous Investigations Map I-1730, scale 1:250,000.

Miall, A. D., 1974, Paleocurrent analysis of alluvial sediments: a discussion of directional variance and vector magnitude: Journal of Sedimentary Petrology, v. 44, p. 1174–1185.

Mytton, J. W., 1983, Geologic map of Chaco Canyon $30' \times 60'$ quadrangle, showing coal zones of Fruitland Formation, San Juan, Rio Arriba, and Sandoval counties, New Mexico: U.S. Geological Survey, Coal Investigations Map C-92A, scale 1:100,000.

New Mexico Geological Society, 1982, New Mexico highway geologic map: New Mexico Geological Society, scale 1:1,000,000.

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. Geological Survey, Professional Paper 134, p. 1–70.

Sikkink, P. G. L., 1987, Lithofacies relationships and depositional environment of the Tertiary Ojo Alamo Sandstone and related strata, San Juan Basin, New Mexico and Colorado: Geological Society of America, Special Paper 209, p. 81–104.

Simpson, G. G., 1935a, The Tiffany fauna, upper Paleocene, 1. Multituberculata, Marsupialia, Insectivora, and ?Chiroptera: American Museum Novitates, no. 796, 19 p.

Simpson, G. G., 1935b, The Tiffany fauna, upper Paleocene, 2. Structure and relationships of *Plesiadapis:* American Museum Novitates, no. 816, 30 p.

Simpson, G. G., 1935c, The Tiffany fauna, upper Paleocene, 3. Primates, Carnivora, Condylarthra, and Amblypoda: American Museum Novitates, no. 817, 28 p.

Simpson, G. G., 1948, The Eocene of the San Juan Basin, New Mexico: American Journal of Science, v. 246, pt. 1, p. 275–282; pt. 2, p. 363–385.

Smith, L. N., 1988, Basin analysis of the lower Eocene San Jose Formation, San Juan Basin, New Mexico and Colorado [Ph.D. dissertation]: Albuquerque, University of New Mexico, 166 p.

Smith, L. N. and Lucas, S. G., 1991, Stratigraphy, sedimentology, and paleontology of the San Jose Formation in the central San Juan Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 126, 44 p.

Smith, L. N., Lucas, S. G. and Elston, W. E., 1985, Paleogene stratigraphy, sedimentation, and volcanism of New Mexico; *in* Flores, R. M. and Kaplan, S. S., eds., Cenozoic paleogeography of west-central United States: Rocky Mountain Section of the Society of Economic Paleontologists and Mineralogists, Denver, p. 293–315.

Stone, W. J., Lyford, F. P., Frenzel, P. F., Mizell, N. H. and Padgett, E. T., 1983, Hydrogeology and water resources of San Juan Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Hydrological Report 6, 70 p.

Thaden, R. E. and Zech, R. S., 1984, Preliminary structure contour map on the base of the Cretaceous Dakota Sandstone in the San Juan Basin and vicinity, New Mexico, Arizona, Colorado, and Utah: U.S. Geological Survey, Miscellaneous Field Studies Map MF-1673, scale 1:500,000.

Tsentas, C., Lucas, S. G., and Schoch, R. M., 1981, Lithofacies of the upper part of the Nacimiento Formation, San Juan Basin, New Mexico: Geological Society of America, Abstracts with Programs, v. 13, p. 229.

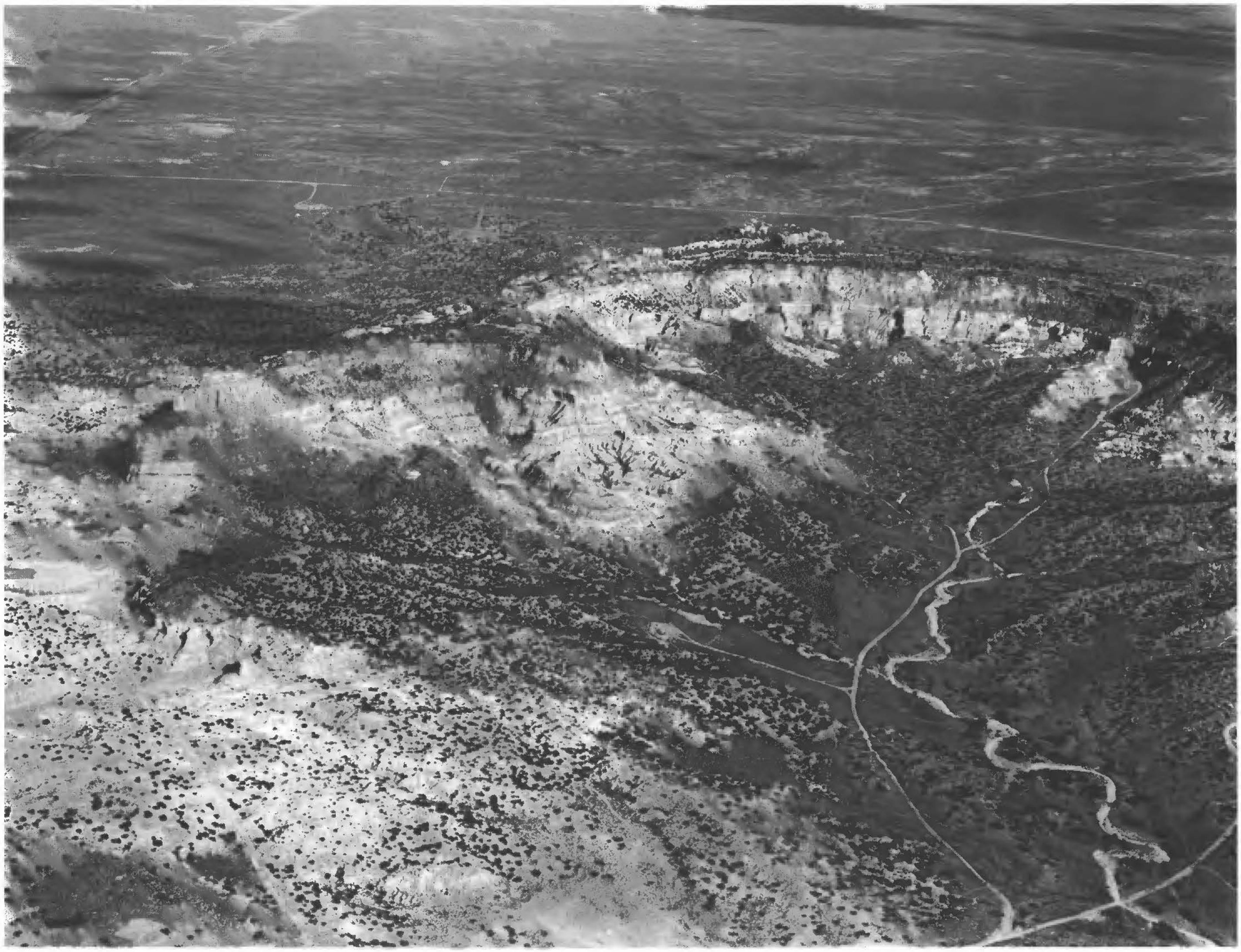
Tweto, O., 1979, Geologic map of Colorado: U.S. Geological Survey, scale 1:500,000.

Williams, M. L., 1987, Stratigraphic, structural, and metamorphic relationships in Proterozoic rocks of northern New Mexico [Ph.D. dissertation]: Albuquerque, University of New Mexico, 138 p.

Wood, G. H. Jr., Kelley, V. C. and MacAlpin, A. J., 1948, Geology of the southern part of Archuleta County, Colorado: U.S. Geological Survey, Oil and Gas Investigations Preliminary Map 81, scale 1:63,360.

Wood, H. E., Chaney, R. W., Clark, J., Colbert, E. H., Jepsen, G. L., Reeside, J. B. Jr. and Stock, C., 1941, Nomenclature and correlation of the North American continental Tertiary: Geological Society of America Bulletin, v. 52, p. 1–48.

Woodward, L. A., 1987, Geology and mineral resources of Sierra Nacimiento and vicinity, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 42, 84 p.



Aerial view of part of El Huerfano Mesa. Slopes and cliffs of the Paleocene Nacimiento Formation are capped by Cuba Mesa Member of San Jose Formation. Photograph taken the morning of 13 April 1992. Copyright © Paul L. Sealey, 1992.