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POLYPHASE LARAMIDE TECTONISM AND SEDIMENTATION IN THE SAN JUAN BASIN, NEW MEXICO

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Abstract.—Laramide tectonic subsidence in the San Juan Basin occurred in three discrete phases, and produced three episodes of sedimentation divided by basin-scale unconformities. Laramide deformation began 80–75 Ma as shown by thickness variations in the Lewis Shale and Pictured Cliffs Sandstone, and by apatite fission-track cooling data in adjacent Laramide uplifts. The first phase of rapid Laramide subsidence in the San Juan Basin culminated during late Campanian and early Maastrichtian time (~74–67 Ma) in the northwest part of the basin, and is represented stratigraphically by the Kirtland and Fruitland formations. Following a 6–8 My interval of basin-wide non-deposition or erosion, a second phase of subsidence occurred in late Maastrichtian to early late Paleocene time (~67–61 Ma), primarily in the northeast part of the basin. Resulting deposits consist of the Ojo Alamo Sandstone (Naashoibito and Kimbeto members) and the Nacimiento Formation. A second period of non-deposition or erosion, possibly basin-wide, ensued in the late Paleocene. The third phase of rapid subsidence and accommodation began in the early Eocene, also in the northeast part of the basin, and caused deposition of the San Jose Formation. Nearly one kilometer of post-San Jose deposits of middle Eocene–early Oligocene age were present in axial part of the the San Juan Basin, but were subsequently stripped.

INTRODUCTION

Of the basins of central and northern New Mexico, only the San Juan and Raton Basins (Fig. 1) contain a relatively complete succession of Laramide synorogenic deposits. The San Juan Basin is by far the better studied of the two because of many decades of academic interest and petroleum exploration. The San Juan Sag (Fig. 1; Kelley, 1955; Brister and Chapin, 1994), a northeastward extension of the San Juan Basin, has been relatively little studied because of cover by the mid-Tertiary San Juan volcanic field. Prior to the rise of the Archuleta Anticlinorium during the Paleogene, however, the San Juan Basin and the San Juan Sag were largely contiguous. Late Cretaceous–Paleogene sedimentation in the San Juan Basin and San Juan Sag occurred within a broad range of marine, marginal marine, coastal plain, and intermontane basin environments (Fig. 2). A detailed discussion of the stratigraphy in these areas, however, is beyond the scope of this report.

As will be described below, the Laramide stratigraphic succession in the San Juan Basin consists of three parts that are separated from one another by unconformities (Fig.3). These episodes of Laramide sedimentation are inferred to result mostly from tectonism because the duration of individual episodes is far longer than would be expected in Milankovitch-type climatic cycles, the thickness of resultant deposits greatly exceeds that which might result from eustatic base-level changes, and the basins show syntectonic relationships to adjacent uplifts.

Today, the San Juan Basin has the form of an asymmetrical syncline with an arcuate axis that is bowed to the north (Fig. 4). It has abrupt structural margins on the northwest (Hogback monocline), northeast (southwest limb of the Archuleta Anticlinorium) and east (Nacimiento Uplift). The southern part of the basin is a gentle north-dipping structural incline, the Chaco homocline (Chaco slope of previous workers). The Chaco homocline adjoins the north flank of the Zuni Uplift (Fig. 1), which bounds the basin on the south. The toe of the Chaco homocline is a faulted hingeline (Ayers et al., 1994) that separates the homocline from the gently folded, relatively flat-lying floor of the basin.

In this report, I limit the term Hogback to the monocline that forms the northwest boundary of the San Juan Basin (Figs. 1, 4). Many previous workers have also applied the name Hogback to the steep southwest limb of the Archuleta Anticlinorium that bounds the northeast side of the San Juan Basin. As will be shown below, the Archuleta Anticlinorium is mostly younger (Paleogene) and is nearly orthogonal to the trend of the Hogback monocline. Because of differences in the age and orientation of these structures, I reserve usage of the term Hogback monocline for the northwest basin-boundary structure. The Hogback monocline may continue on trend to the northeast to form the northwest boundary of the San Juan Sag (Fig. 1). Constraints in this latter region, however, are very poor due to limited drilling and cover by volcanic rocks of the San Juan field.

To illustrate the episodic nature of Laramide sedimentation, I use data from a well near the depositional axis of the San Juan Basin to calculate rates of stratal accumulation (Fig. 3). Note that these stratal accumulation rates reflect present stratal thicknesses and have not been corrected for compaction. Electric logs from the Aztec Oil and Gas Company Trail Canyon No. 1 well were examined by the writer and B. S. Brister (table 1; well 114 of Molenaar, 1983). Our picks are substantially the same as those of earlier researchers. To calculate stratal accumulation rates in this well, we identified geophysically distinct strata to which age determinations could be assigned (Table 1). Particularly useful were the $^{40}Ar/^{39}Ar$ age determinations for biozones in Upper Cretaceous marine strata by Obradovich (1993). Because high-precision dates from bentonites and dated biozones are available for Turonian through Campanian strata, stratal accumulation rates calculated for Upper Cretaceous units are generally better constrained than those for Paleogene continental successions.

INCEPTION AND EARLY PHASE OF SUBSIDENCE

From Turonian to early Campanian time (~95–80 Ma), the San Juan Basin occupied a small part of the Western Interior Basin, a broad foreland basin that, in part, subsided in response to the effects of tectonic loading in the Cordilleran thrust belt to the west (e.g., Lawton, 1988). During this time interval, stratal accumulation rates for the Mancos Shale, Point Lookout Sandstone, and Menefee Formation in the axial part of the San Juan Basin ranged

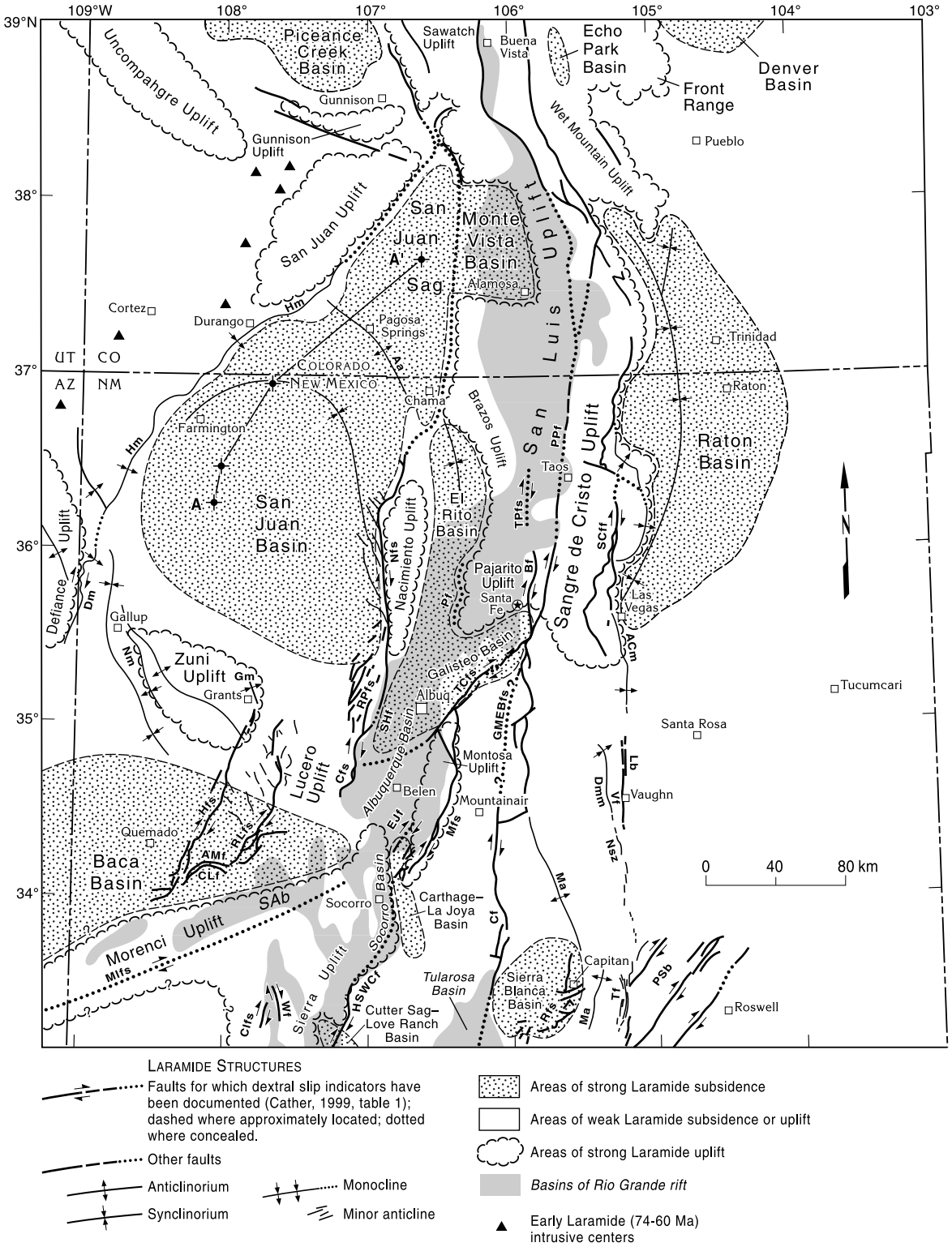

FIGURE 1. Map showing Laramide uplifts, basins, and selected structures, and Rio Grande Rift basins. Laramide structures are: Aa, Archuleta Anticlinorium; AMf, Alegres Mountain fault; ACm, Anton Chico monocline; Bf, Borrego fault; Clfs, Chloride fault system; Cf, Chupadera fault; Cfs, Comanche fault system; CLf, Cox Lake fault; Dm, Defiance monocline; Dmm, Derramadera monocline; EJf, East Joyita fault; GMEBfs, Glorieta Mesa-Estancia Basin fault system; Gm, Grants monocline; Hfs, Hickman fault system; Hm, Hogback monocline; HSWCf, Hot Springs-Walnut Canyon fault; Lb, Leon buckle; Ma, Mescalero arch; Mfs, Montosa fault system; Mlfs, Morenci lineament fault system; Nfs, Nacimiento fault system; Nsz, Nalda shear zone; Nm, Nutria monocline; Pf, Pajarito fault; PSb, Pecos Slope buckles; PPf, Picuris-Pecos fault; RLfs, Red Lake fault system; RPfs, Rio Puerco fault system; Rfs, Ruidoso fault system; SHf, Sand Hill fault; SCff, Sangre de Cristo frontal faults; TCfs, Tijeras-Cañoncito fault system; Tf, Tinnie fold belt; TPfs, Tusas-Picuris fault system; Vf, Vaughn fault; Wf, Winston fault. A–A′ is line of section for Figure 5. Sab, San Agustin Basin of Rio Grande Rift. Map has not been restored palinspastically. Evidence for oblique-slip on structures is summarized by Cather (1999, table 1).

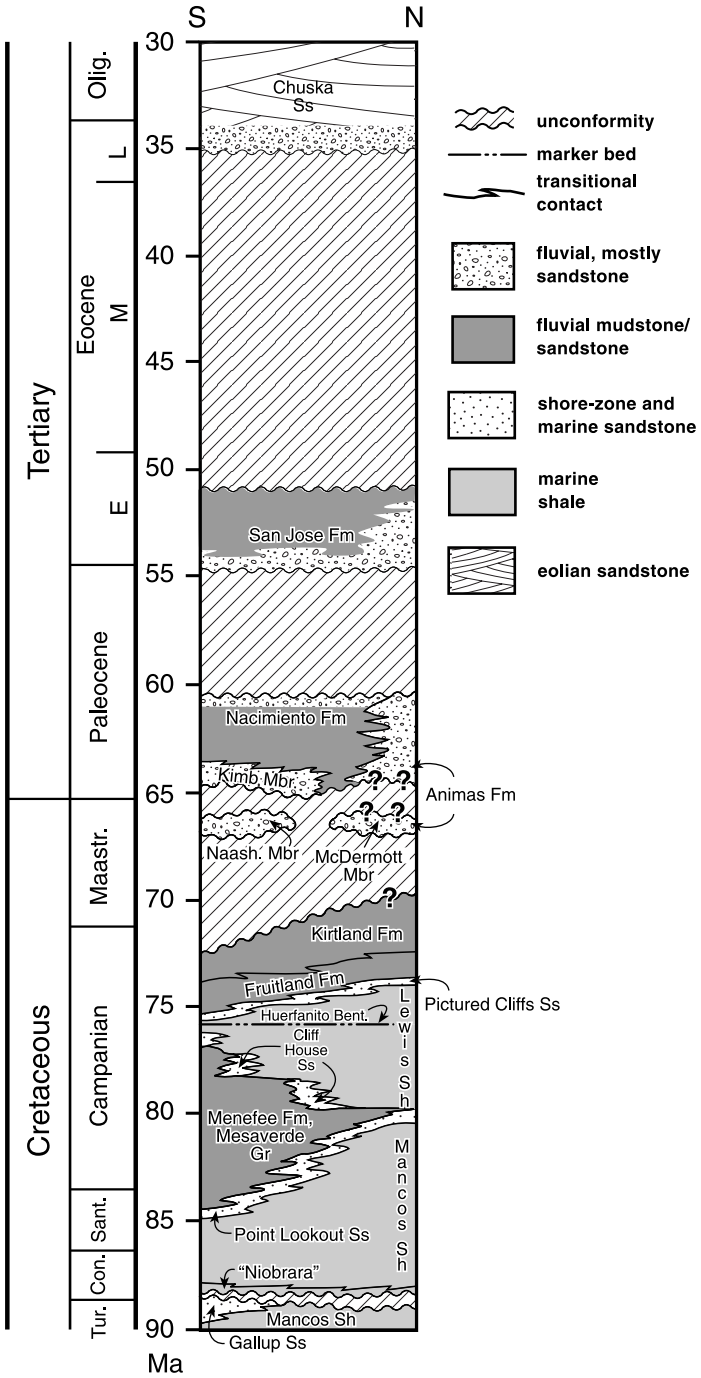

FIGURE 2. Stratigraphic column for the San Juan Basin for late Turonian–early Oligocene (90–30 Ma). Abbreviations are: Naash. Mbr, Naashoibito Member of Ojo Alamo Sandstone and equivalent units (Unit B of Baltz, 1967, and Smith, 1992a; pre-Ojo Alamo Sandstone of Ayers et al., 1994, fig. 2.4) (note that Fassett et al., 2002, consider this unit to be Paleocene); Kimb. Mbr, Kimbeto Member of Ojo Alamo Sandstone; Huerfanito Bent., Huerfanito Bentonite Member of Lewis Shale.

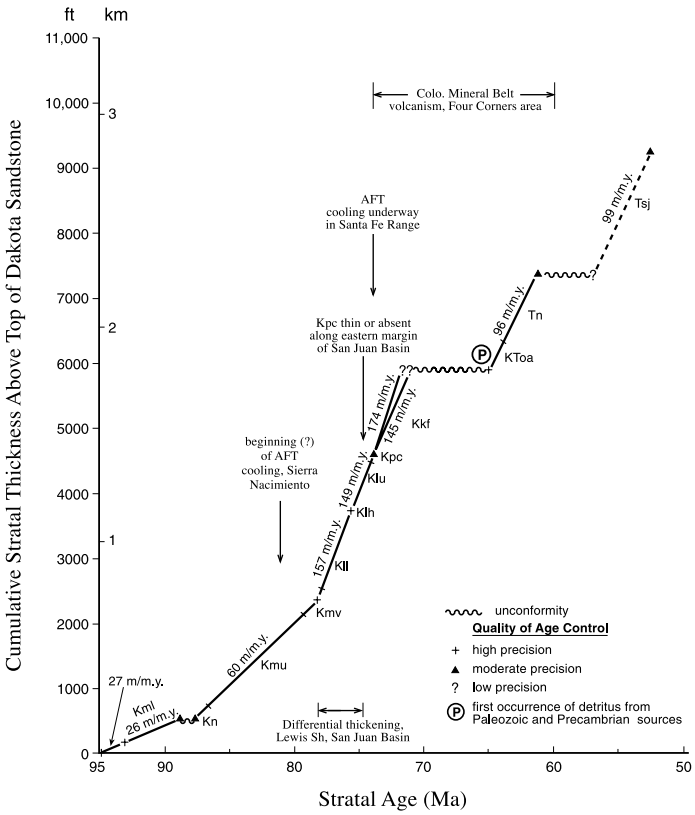

FIGURE 3. Graph of cumulative stratal thickness above top of Dakota Sandsone vs. stratal age for a well from the axial part of the San Juan Basin [Aztec Oil and Gas Company Trail Canyon No. 1; Table 1] showing stratal accumulation rates and unconformities. Note that thicknesses have not been decompacted. Units are: Kml, lower Mancos Shale; Kn, "Niobrara"; Kmu, upper Mancos Shale; Kmv, Mesaverde Group; Kll, lower Lewis Shale; Klh, Huerfanito Bentonite Bed; Klu, upper Lewis Shale; Kpc, Pictured Cliffs Sandstone; Kkf, Fruitland and Kirtland Formations; KToa, Ojo Alamo Sandstone; Tn, Nacimiento Formation; Tsj, San Jose Formation. Note that the well is collared in the lower part of the San Jose Formation (Table 1), and for that reason the stratal accumulation rate (dashed line) for the San Jose is derived from age-thickness relationships in the Tertiary depocentral area in the northeast part of the San Juan Basin (see text). Also shown are beginning of apatite fission-track (AFT) cooling in Nacimiento Uplift and Santa Fe Range (Kelley et al., 1992), timing of differential thickening of Lewis Shale (see text), timing of non-deposition or erosion of Pictured Cliffs Sandstone along evolving range-front of Nacimiento Uplift (Baltz, 1967; Fassett and Hinds, 1971), and age range of volcanism in Colorado Mineral Belt in the Four Corners area (Mutschler et al., 1987; Semken and McIntosh, 1997). Time scale after Obradovich (1993) and Woodburne and Swisher (1995).

from ~26–60 m/My (Fig. 3). The thickness of the Mancos Shale in the axial part of the San Juan Basin (643 m; Table 1) is similar to the Mancos thickness near Mesa Verde National Park (682 m; Leckie et al., 1997), nearby to the northwest of the basin (Fig. 4). These relationships indicate that differential subsidence had not begun in the San Juan Basin prior to ~80 Ma. In this paper, the onset of disruption of the foreland basin to form a mosaic of smaller intraforeland basins and uplifts is considered to define the beginning of the Laramide orogeny. As will be discussed below, initial Laramide deformation began in northern New Mexico and southern Colorado between about 80 and 75 Ma.

Approximately synchronous with the beginning of the final marine transgression (Cliff House Sandstone) in the San Juan Basin, stratal accumulation rates in the axial part of the basin more than doubled to ~150 m/My (Table 1, Fig. 3) during deposi-

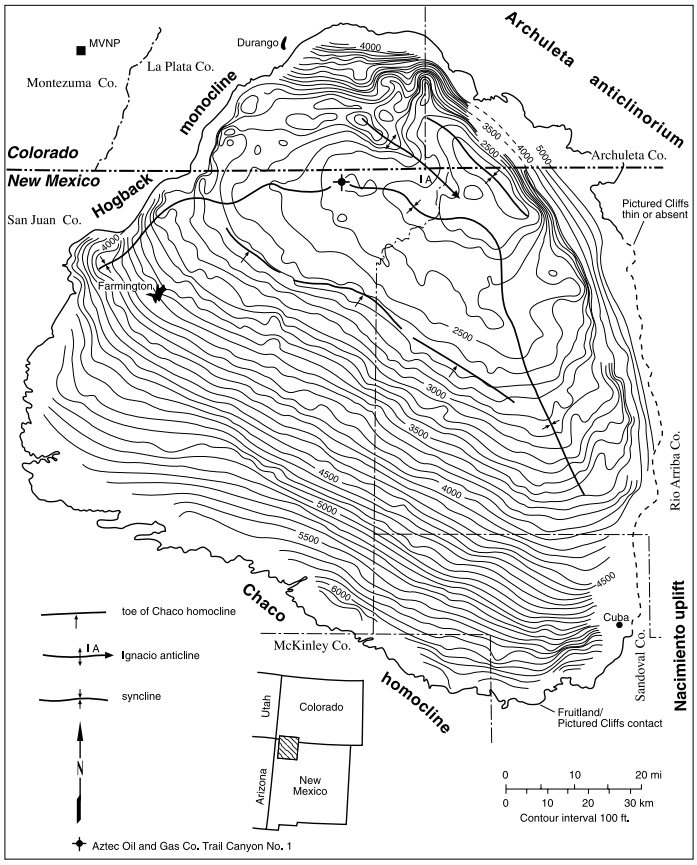

FIGURE 4. Structure-contour map of the San Juan Basin based on data from approximately 2500 well logs, contoured on the Huerfanito Bentonite Bed. Note location of Aztec Oil and Gas Co. Trail Canyon No. 1, utilized in Table 1 and Figure 3. IA, Ignacio anticline; MVNP, Mesa Verde National Park. Modified from Ayers et al. (1994, fig. 2.5)

tion of the Lewis Shale. The Lewis Shale attains its maximum thickness in the northern San Juan Basin and thins landward (southwest) to a pinchout in the southern part of the basin, as has been documented in the detailed regional cross-sections of Molenaar (1983). Recent drilling in the San Juan Sag (Gries et al., 1997), however, has demonstrated that the Lewis Shale also thins in the *seaward* direction (northeast) from its maximum thickness near the axis of the San Juan Basin (Fig. 5). Such seaward thinning is diametrically opposed to the expected seaward thickening that should result from the time-transgressive stratigraphic rise of the regressive Pictured Cliffs Sandstone that bounds the top of the Lewis Shale in both areas. The approximately two-fold thinning of the Lewis Shale between the axis of the San Juan Basin and the San Juan Sag is interpreted to reflect an early phase of differential subsidence in the San Juan Basin. This interpretation is supported by the subsidence-induced reorientation of upper Lewis-Pictured Cliffs shoreline as it prograded northeastward across the structural hingeline at the toe of the Chaco homocline (Ayers et al., 1994). The fact that differential thickening of the Lewis Shale also appears to occur below the intercalated 75.76 ± 0.45 Ma Huerfanito Bentonite Bed (Fassett and Steiner, 1997; Fig. 5) suggests that differential subsidence was underway by this time.

Differential thickening of the Lewis Shale is the earliest evidence of Laramide subsidence in the nascent San Juan Basin, and may have been related to an early phase of differential subsidence in the northeastern part of the basin (Ayers et al., 1994; note, however, that this conclusion was challenged by Fassett, 2000, who interpreted piston-like subsidence for the entire basin during Lewis and Pictured Cliffs deposition). The Archuleta Anticlinorium, which divides the San Juan Basin from the San Juan Sag, attained most of its structural relief in Paleogene time (see below), but may have been active also during Lewis time (middle to late Campanian) to account for the seaward thinning of the Lewis Shale. Late Campanian (~75 Ma) deformation also occurred along the eastern margin of the San Juan Basin, as is indicated by the thinness or local absence of the Pictured Cliffs Sandstone (Baltz, 1967; Fassett and Hinds, 1971; Woodward, 1987). Stratigraphic thinning or omission of the Pictured Cliffs is restricted to a narrow zone along the flank of the Nacimiento Uplift and the southern part of the Archuleta Anticlinorium, and is indicative of an early phase of activity on these structures.

The Pictured Cliffs Sandstone consists of shore-zone deposits related to the final (R-5) regression of the Late Cretaceous sea from northwestern New Mexico (Fassett and Hinds, 1971; Molenaar, 1983). The Pictured Cliffs shoreline prograded northeastward or north-northeastward. The shoreline was relatively linear, suggesting wave reworking and multiple deltaic sources of sediment (Flores and Erpenbeck, 1981; Ayers et al., 1994). The Pictured Cliffs regression occurred in response to increased sediment supply from volcanism and tectonism in southern Arizona (Cumella, 1983), and was markedly time-transgressive (Fassett, 2000, figs. 14, 18). Pronounced stratigraphic rise of the Pictured Cliffs Sandstone occurred near the synclinal axis of the San Juan Basin. This has been attributed to active basin subsidence (Ayers et al., 1994) or to decreased sediment supply (Fassett and Hinds, 1971).

Following the northeastward retreat of the Lewis sea and the regressive Pictured Cliffs shoreline, coal-bearing coastal plain deposits of the Fruitland Formation accumulated in the San Juan Basin and San Juan Sag. These deposits interfinger with the uppermost beds of the Pictured Cliffs Sandstone, and attain a maximum thickness of ~600 ft (183 m) in the northwestern San Juan Basin near Durango, Colorado (Ayers et al., 1991, fig. 14). Paleoflow was toward the northeast or north–northeast, as shown by sandstone isolith patterns in the Fruitland (Ayers et al., 1994). The thickness of the Fruitland Formation decreases to the southeast, at least in part due to syndepositional thinning (Hunt and Lucas, 1992).

The Kirtland Formation transitionally overlies the coal-bearing Fruitland Formation and was deposited in an alluvial plain environment. Depositional systems and direction of sediment transport for the Kirtland Formation, however, have only locally been adequately studied. Stratigraphic studies of the Kirtland Formation and the overlying Ojo Alamo Sandstone have led to varied stratigraphic nomenclature for these rocks (e.g., Bauer, 1916; Reeside, 1924; Baltz, 1967; Fassett and Hinds, 1971; Powell, 1973; Klute, 1986; Hunt and Lucas, 1992). In this study, I adopt the terminology of Hunt and Lucas (1992), although I herein regard the Naashoibito Member of Baltz et al. (1966) as

TABLE 1. Formation tops and selected age constraints for lithologic units in Aztec Oil and Gas Company Trail Canyon No. 1 (San Juan Basin, sec. 21, T32N, R8W).

UNIT	DEPTH (FT)	SELECTED AGE CONSTRAINTS
San Jose Fm	collar	Lower Eocene (Wasatchian, ~55–52 Ma)
unconformity		Lacuna of poorly constrained duration
Nacimiento Fm	830	Paleocene (~64.5–61 Ma)
Ojo Alamo Ss (Kimbeto Mbr)	1647	Lower Paleocene (~65–64.5 Ma)
unconformity		Lacuna ~6 my
Kirtland and Fruitland Fms	2110	Upper Campanian (~74 Ma to ~71.5 or 71 Ma, see text)
Pictured Cliffs Ss	3542	Contains zone of *Didymoceras cheyennese* [~74 Ma] near this well (Fassett, 2000, fig. 14).
Lewis Sh	3600	Contains Huerfanito Bentonite Bed (75.76 ± 0.34 Ma; Fassett et al., 1997) at 4404 ft.
Mesaverde Gr	5674	Contains 78.22 ± 0.26 Ma ash in upper part (Peters, 2001)
Point Lookout Ss	5938	
upper Mancos Sh	6060	
"Niobrara"	7380	
disconformity		Basal Niobrara disconformity (~89–88 Ma; Leckie et al., 1997, fig. 29)
lower Mancos Sh	7651	
Greenhorn Ls	8000	Contains zone of *Mammites nodosoides* [93 Ma]
lower Mancos Sh	8065	
Dakota Ss	8170	Contains zone of *Acanthoceras amphibolum* [94.93 ± 0.53 Ma] in upper part (Roberts and Kirschbaum, 1995)

Note: $^{40}Ar/^{39}Ar$ age constraints in brackets [ ] are from Obradovich (1993). Other age constraints are from Woodburne and Swisher (1995), Williamson and Lucas (1992),

the lower member of the Ojo Alamo Sandstone (e.g., Powell, 1973; Lucas and Sullivan, 2000, p. 100; Cather, in press).

Distinct thickening of the Kirtland-Fruitland interval (Fig. 6) suggests the existence of a Kirtland depocenter in the northwestern San Juan Basin, as was first noted by Caswell Silver (1950, 1951) and subsequently by other workers (Dilworth, 1960; Klute, 1986; Hunt and Lucas, 1992). Much of the northwestward thickening of the Kirtland-Fruitland interval may be due to syndepositional thickening of the Farmington Sandstone Member (Hunt and Lucas, 1992). As opposed to the relatively uniform northeastward paleoflow of the underlying Fruitland Formation, paleocurrent directions during deposition of the Farmington Sandstone Member (Fig. 6) were more variable (cf. Dilworth, 1960). Paleocurrents during Kirtland Formation deposition near De-nazin Wash in the southwestern San Juan Basin were northeastward, similar to those in the underlying Fruitland Formation (Fig. 6). In contrast, paleocurrents near the Kirtland depocentral area in the northwest part of the basin were easterly, nearly orthogonal to the adjoining Hogback monocline. These easterly paleocurrents imply a syntectonic relationship between the Kirtland depocenter and the Hogback monocline. An unresolved part of the southeastward thinning of the Kirtland, however, may be the result of latest Campanian–early Maastrichtian (~72–67 Ma) erosional beveling prior to deposition of the Naashoibito Member of Ojo Alamo Sandstone (Fig. 7b; Baltz et al., 1966; Fassett, 1985; Ayers et al., 1994).

The thickening of the Kirtland and Fruitland Formations in the Farmington–Durango area suggests that the northwestern structural margin of the San Juan Basin (the Hogback monocline) was active during late Campanian–early Maastrichtian time. Thick coal deposits and northeast-trending net-coal isopach lines for the Fruitland Formation near the Hogback monocline (Fassett, 2000, fig. 28) may indicate that deformation on the monocline was initiated during Fruitland deposition. Adjacent to the Hogback monocline near Farmington, the Farmington Sandstone Member of the Kirtland Formation contains numerous 1–10 cm clasts of light-gray sandstone (Fig. 8). These clasts consist of sandstone that is better sorted and more quartzose than sandstone of the Kirtland Formation, and thus were not derived intraformationally. These clasts probably were derived from the texturally and mineralogically more mature Pictured Cliffs Sandstone. This, in turn, implies that the Pictured Cliffs Sandstone was exposed by uplift along the Hogback monocline during the late Campanian.

Stratal accumulation rates for the northwest-thickening Kirtland–Fruitland interval are not precisely constrained throughout most of the basin because of uncertainty about the effects of syndepositional differential subsidence versus post-Kirtland erosional bevelling. For this reason, a range of stratal accumulation rates (~145-174 m/My) is depicted in Figure 3. The lower rate is similar to the stratal accumulation rate that was determined for the Kirtland–Fruitland interval in the southwest part of the basin by Fassett (2000, fig. 17) and corresponds to the end-member case where basin-wide sedimentation rates were constant and all of the northwestward thickening resulted from subsequent bevelling (Fig. 7b; note that such post-depositional erosion predicts that the top of the Kirtland Formation is significantly younger to the northwest). The higher stratal accumulation rate assumes a constant time interval for Kirtland–Fruitland deposition (~2.5 My; Fassett, 2000, fig. 17) and represents the end-member case where northwestward thickening is entirely syndepositional and accumulation rates vary as a function of Kirtland–Fruitland thick-

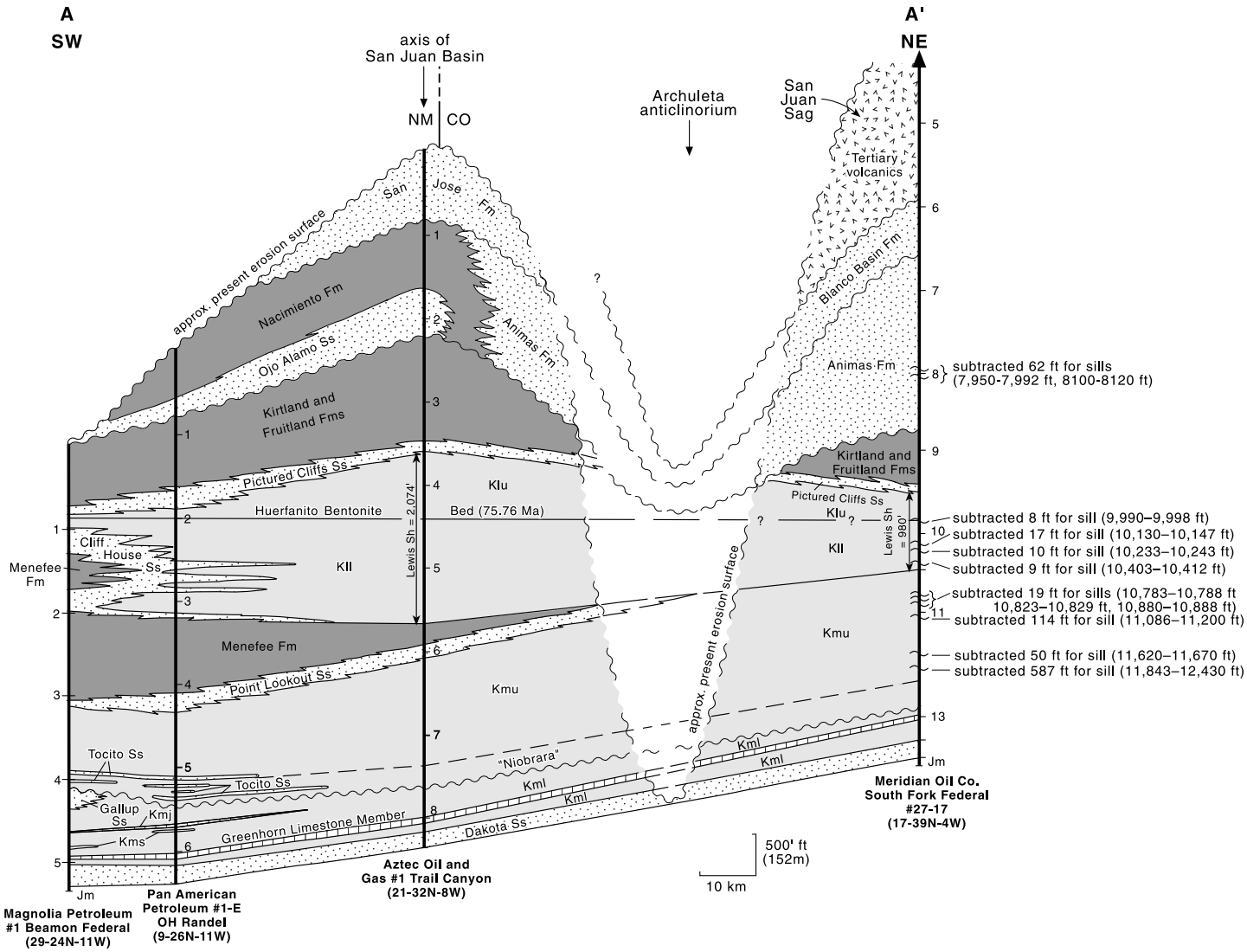

FIGURE 5. Cross section of Upper Cretaceous and Tertiary strata in San Juan Basin–Archuleta Anticlinorium–San Juan Sag area (line of section shown in Figure 1). Data for selected wells in San Juan Basin are modified slightly from Molenaar (1983, fig. 3, his wells 107, 109, and 114). Well in San Juan Sag is modified from Gries et al. (1997); note that thickness of Tertiary sills have been subtracted. Formation tops were picked by the writer and B. S. Brister. Datum is Huerfanito Bentonite Bed. Unit abbreviations are lower Mancos Shale (Kml), Semilla Sandstone Lentil (Kms), upper Mancos Shale (Kmu), lower Lewis Shale (Kll), upper Lewis Shale (Klu). Well near axis of San Juan Basin (Aztec Oil and Gas No. 1 Trail Canyon) is same as that utilized in Figure 3 and Table 1. Note approximate two-fold seaward thinning of Lewis Shale from axial part of San Juan Basin to the San Juan Sag.

ness (Fig. 7a; 174 m/My in the well depicted in Figure 3; note that the corresponding stratal accumulation rate in the northwestern depocenter would be ~243 m/My). The true value probably lies between these end-members.

Kirtland–Fruitland stratal accumulation rates equal or exceed those for continental deposits in other Laramide basins during Campanian–Eocene time in northern New Mexico (Cather, in press). The Kirtland Formation attains thicknesses of as much as 1500 ft (460 m) north of Farmington (Fassett and Hinds, 1971), and thus accounts for nearly half of the potential sedimentary accommodation related to the structural relief of the Hogback monocline in that area (~3500 ft [1070m]; Craigg et al., 1989). If decompacted using the parameters defined by Fassett (2000, fig. 7), the Kirtland may account for about three-quarters of this potential sedimentary accommodation. Although Kirtland/Fruitland strata are present in the San Juan Sag (Brister and Chapin, 1994; Gries et al., 1997), it is not known if they thicken toward the Hogback monocline as they do in the San Juan Basin.

Erslev (1997) and Ruf (2000) analyzed minor faults in the vicinity of Durango, Colorado, and argued for sequential northeast, northwest, and north-northeast σ_1 orientations during Tertiary time. The northwest σ_1 orientation is orthogonal to the trend of the Hogback monocline (Ruf, 2000, p. 94), and is interpreted here to be related to development of the monocline during late Campanian–early Maastrichtian time. This suggests that the age of the northwest σ_1 orientation of Erslev (1997) and Ruf (2000) is ~74–67 Ma, and not Paleogene as inferred by Ruf (2000, fig. 7.1). A pre-Tertiary age for most of the structural relief of the Hog-

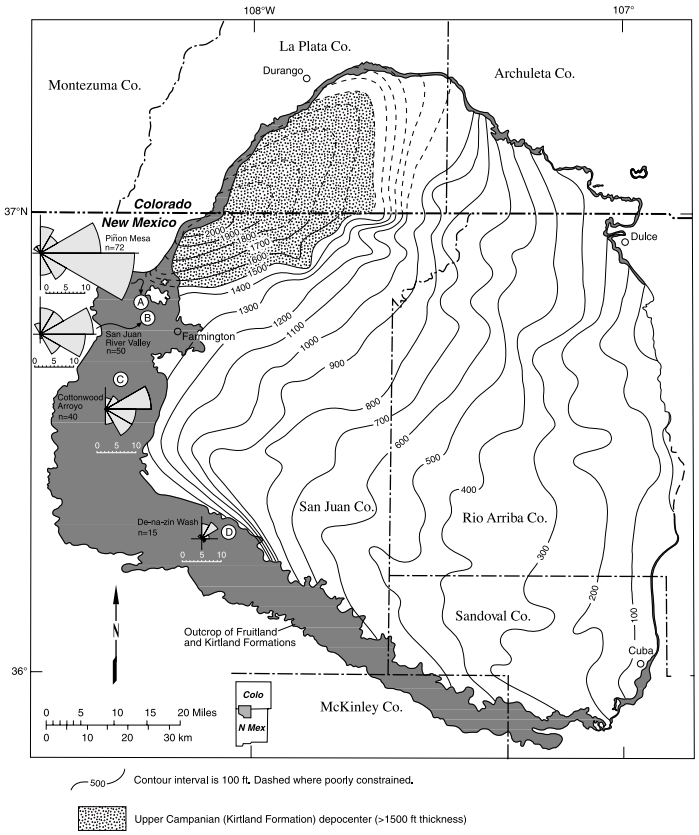

FIGURE 6. Isopach map of Fruitland and Kirtland Formations, San Juan Basin. Isopach contours are dashed where poorly constrained due to absence of overlying Ojo Alamo Sandstone. Paleocurrent data (based on cross bedding, parting lineation, and pebble imbrication) are for Farmington Sandstone Member of Kirtland Formation and were collected by the author. Scales show number of paleocurrent measurements. Paleocurrent localities are: A, Piñon Mesa; B, San Juan River Valley; C, Cottonwood Spring area; D, De-na-zin Wash. Base map modified from Fassett and Hinds (1971, fig. 11).

back monocline is also indicated by stratigraphic relationships in southwestern Colorado (Fig. 9; Baltz et al., 1966).

Dextral deformation also occurred on the southern extension of the Hogback system (the central Defiance monocline; Cather, this guidebook) as shown by a series of en echelon folds that modify the central Defiance monocline northwest of Gallup (Kelley, 1955). The timing of dextral deformation is poorly constrained, but may correspond to late Laramide (Eocene) wrench deformation in the southern Rocky Mountains (e.g., Chapin and Cather, 1981; 1983). Kelley (1967) estimated 13 km of dextral deformation on the Defiance monocline using offset of Jurassic stratigraphic features, but did not definitively document his estimate. Of published isopach maps that encompass the Defiance–Hogback system, the map of McKee et al. (1956, plate 7) contains the most numerous thickness data, and shows significant dextral deflections of isopachs across the monocline system. These, however, have not been shown to be tectonic in origin. Jurassic isopach maps by other workers (e.g., Craig et al., 1955; Harshberger et al., 1957) contain few thickness data near the Hogback–Defiance system and thus are ambiguous in their significance (cf. Lucas, this guidebook). More work is needed on this important problem.

MIDDLE PHASE OF SUBSIDENCE

The middle phase of tectonic subsidence and associated sedimentation in the San Juan Basin began in the latest Cretaceous with the deposition of the Animas Formation in the north and northwest part of the basin, and the Ojo Alamo Sandstone throughout the basin except in the northwest. The Animas Formation ranges from Late Cretaceous to Paleocene in age (Reeside, 1924; Lehman, 1985; Fassett and Hinds, 1971) and contains considerable andesitic detritus. The volcaniclastic McDermott Member constitutes the basal 100–300 ft (30–100 m) of the formation in the northwest part of the San Juan Basin, and is overlain with local unconformity by the drab beds of the Nacimiento Formation or the upper member of the Animas Formation (Reeside, 1924; Lehman, 1985, fig. 21). The McDermott Member may be a proximal equivalent of the Naashoibito Member of the Ojo Alamo Sandstone to the south (Reeside, 1924), although the two units are now disjunct because of incision prior to deposition of the Kimbeto Member of the Ojo Alamo Sandstone (Lehman, 1985).

A significant unconformity divides the Kirtland Formation from the overlying Naashoibito Member of the Ojo Alamo Sandstone in the southwestern San Juan Basin. The unconformity occurs 16 ft (4.9 m) above a volcanic ash bed in the upper part of the Kirtland Formation (De-na-zin Member of Hunt and Lucas, 1992) that has been dated at 73.04 ± 0.25 Ma by the $^{40}Ar/^{39}Ar$ technique (Fassett and Steiner, 1997). The upper constraint on the duration of the lacuna represented by the unconformity is given by probable late Maastrichtian (Lancian) dinosaur bones and fossil mammals from the Naashoibito Member (Lehman, 1985, Hunt and Lucas, 1992) which are approximately 67 Ma (S. G. Lucas, personal commun., 2001; note that Fassett et al., 2002, considered these dinosaur fossils to be Paleocene). These relations indicate a lacuna of at least ~6 My duration that encompassed at least latest Campanian and early Maastrichtian time in the southwestern San Juan Basin.

The Naashoibito Member is locally conglomeratic and is generally less than about 100 ft (30 m) thick. Paleocurrent directions in the Naashoibito have not been adequately studied. Powell (1972) reported south–southwest paleoflow for the unit, but did not present his data or describe the locations of his measurements. The Naashoibito Member is not everywhere present in the San Juan Basin; locally it was either not deposited, or it was erosionally removed prior to deposition of the Kimbeto Member of the Ojo Alamo Sandstone (Lehman, 1985; Smith, 1992a; Ayers et al., 1994). The overlying Kimbeto Member (also locally conglomeratic) is early Paleocene in age (~65 Ma; Fassett and Lucas, 2000) because of intertonguing with the overlying, fossiliferous Nacimiento Formation (Baltz et al., 1966). The unconformity between the Kimbeto Member and the Naashoibito Member may contain the Cretaceous–Tertiary boundary (Baltz et al., 1966; Hunt and Lucas, 1992; cf. Fassett et al., 2002) and encompasses no more than about 2–3 m.y. of missing stratigraphic record (Hunt and Lucas, 1992, p. 235; Lucas and Williamson, 1993a), perhaps far less. Where the Naas-

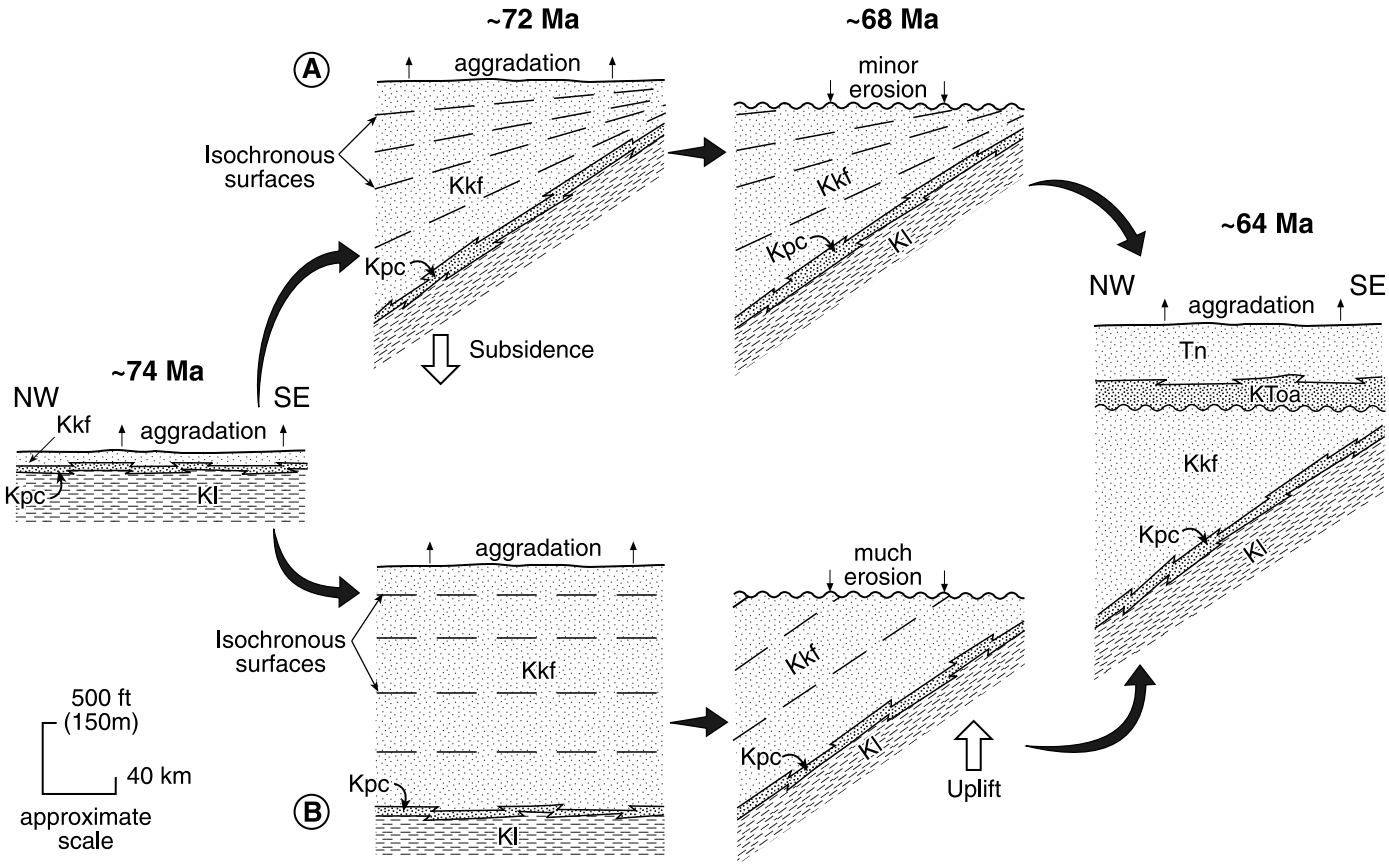

FIGURE 7. Schematic, northwest–southeast cross sections of San Juan Basin from 74 to 64 Ma showing contrasting models for development of northwest thickening of Kirtland and Fruitland formations (Kkf). Kl, Lewis Shale; Kpc, Pictured Cliffs Sandstone; KToa, Ojo Alamos Sandstone; Tn, Nacimiento Formation. (A) Thickening of the Kirtland–Fruitland interval is syndepositional. Minor erosion prior to deposition of the Ojo Alamo Sandstone gives rise to basin-scale angular unconformity at top of Kirtland Formation, as is evident in regional subsurface correlations (e.g., Ayers et al., 1994, fig. 2.3). (B) Kirtland and Fruitland formations are deposited as an isopachous succession. Post-depositional tilting and major erosion produces wedge-shaped geometry and regional angular unconformity. Note that in this model the age of the Kirtland beneath the superjacent unconformity is distinctly younger to the northwest.

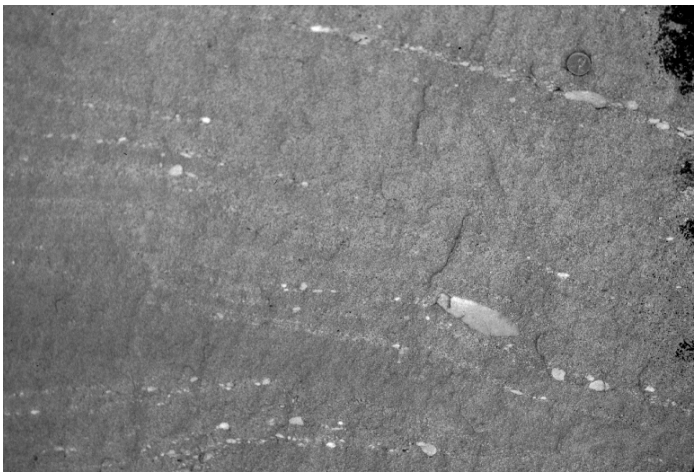

FIGURE 8. Light-colored clasts of well-sorted quartzose sandstone in the Farmington Sandstone Member of the Kirtland Formation at Twin Mounds, ~10 km west of Farmington, New Mexico. Penny for scale at upper right. Similar sandstone clasts 0.5–10 cm in length are locally abundant in the western exposures of the Farmington Sandstone Member, and are interpreted to have been derived from exposures of the Pictured Cliffs Sandstone along the Hogback monocline.

hoibito is not present, however, the basal Ojo Alamo unconformity may represent a lacuna of as much as 6–8 My.

Stratal accumulation rates in the southwestern San Juan Basin were very low during the time interval between the end of deposition of the Kirtland Formation (73.04 ± 0.25 Ma in the southwest part of the basin) and initial deposition of the Kimbeto Member of the Ojo Alamo Sandstone (~65 Ma). Most of this time interval is represented by unconformities or possibly cryptic condensed sections; only deposition of the thin Naashoibito Member locally interrupted this period of non-deposition or erosion. These low stratal accumulation rates (Fig. 3) mark the interval between the first and second phases of Laramide subsidence and sedimentation in the San Juan Basin.

The Ojo Alamo Sandstone exhibits paleocurrent and provenance evidence for derivation from source regions northwest of the basin (Powell, 1973; Lehman, 1985; Klute, 1986; S. M. Cather, unpubl.). Citing evidence for southeasterly paleoflow and the presence of clasts derived from Paleozoic, Precambrian and Laramide volcanic sources, some workers have interpreted the Ojo Alamo Sandstone as recording the local beginning of the Laramide orogeny during late Maastrichtian–early Paleocene

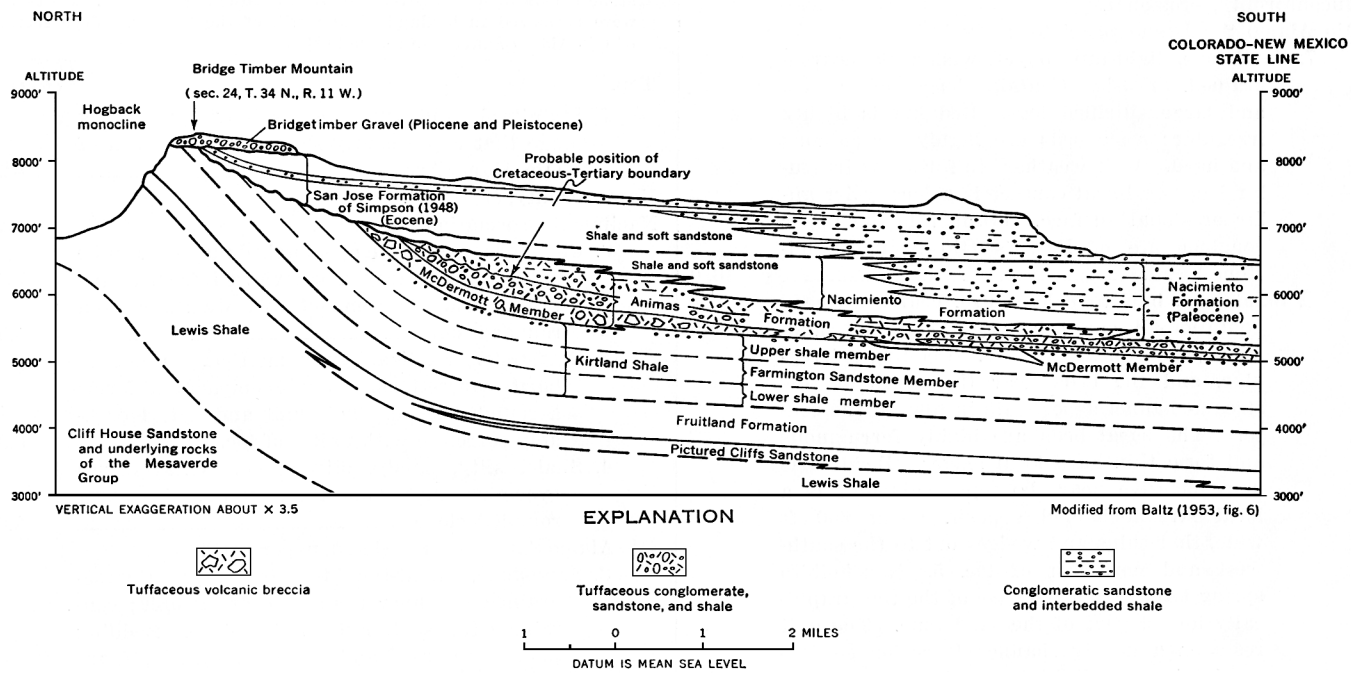

FIGURE 9. Diagrammatic cross section (Baltz et al., 1966), near Bridge Timber Mountain, ~17 km southwest of Durango, Colorado, showing relationship between Upper Cretaceous–Paleogene units and folding in the Hogback monocline. Bridge Timber Mountain is the only place along the monocline where a relatively complete Laramide stratigraphic succession is preserved. Note that most folding occurred prior to deposition of the Paleogene Nacimiento and San Jose formations.

time (e.g., Fassett, 1985; Lehman, 1985). The data presented above, however, support an entirely different scenario: the initiation of Laramide tectonism and rapid subsidence in the San Juan Basin preceded deposition of the conglomeratic sediments of the Ojo Alamo by approximately 10 My, and deposition of these coarse-grained units occurred during and immediately following a *lull* in subsidence and accommodation (Fig. 3). The association of the coarse-grained deposits of the Naashoibito and Kimbeto Members of the Ojo Alamo with an episode of low accommodation implies that these coarse-grained, sheet-like units were unable to spread southeastward until late Campanian–early Maastrichtian rapid basin subsidence had ceased. The existence of such "antitectonic" (Paola et al., 1992) conglomeratic sequences has been supported both by theory (Leeder and Gawthorpe, 1987; Blair and Bilodeau, 1988) and by stratigraphic analysis of other Laramide basins (Beck et al., 1988).

The second phase of Laramide subsidence and sedimentation in the San Juan Basin began with deposition of the Kimbeto Member of the Ojo Alamo Sandstone shortly after the Cretaceous–Tertiary boundary. The Kimbeto Member consists of sandstone, pebbly sandstone, and conglomerate that were deposited by generally southeast-flowing braided streams (Powell, 1973; Klute; 1986; S. M. Cather, unpubl.; cf. Sikkink, 1987, who interpreted generally southward paleoflow). The Kimbeto Member is as much as 400 ft (120 m) thick and is present throughout the basin, except in its northwest part where it grades laterally into fine-grained deposits of the Nacimiento Formation (Baltz et al., 1966; Lehman, 1985). Elsewhere in the basin, the Kimbeto Member grades upward into the Nacimiento Formation. Although the Kimbeto Member appears to be entirely of early Paleocene age, it contains dinosaur bones that have been variously interpreted to be reworked (Lucas and Williamson, 1993a) or to represent dinosaurs that survived the terminal K–T event (Fassett and Lucas, 2000).

The bulk of the medial Laramide phase of sedimentation in the San Juan Basin is represented by the Nacimiento Formation and its northern lateral equivalent, the upper member of the Animas Formation. The genetic stratigraphy and sediment-dispersal systems of these units have not yet been adequately studied. Consisting largely of mudstone and fine sandstone, the Nacimiento is as much as 1650 ft (500 m) thick and was deposited during the early to early late Paleocene in the southern and western parts of the basin (~64.5–61 Ma; Williamson and Lucas, 1992; Williamson, 1996). The age range of the upper member of the Animas Formation is imprecisely known, but includes beds of late Paleocene (Tiffanian) age (Simpson, 1935).

The stratal accumulation rate for the Nacimiento Formation near the basin axis is ~96 m/My (Fig. 3, Table 1). This is comparable to the range of stratal accumulation rates (63–116 m/My, not decompacted) estimated for the main body of the Nacimiento in the southern part of the basin (Williamson, 1996, fig. 16). The upper ~65–260 ft (20–80 m) of the Nacimiento Formation consists of the sandstone-dominated (locally pebbly) Escavada Member (Williamson and Lucas, 1992) that contains numerous silcretes and exhibits markedly lower stratal accumulation rates (11–25 m/My) than subjacent parts of the formation (Williamson, 1996).

LATE PHASE OF SUBSIDENCE

Throughout much of the periphery of the San Juan Basin, outcrops of the Paleocene Nacimiento Formation and correlative upper Animas Formation are overlain by pebbly sandstones of the Cuba Mesa Member of the Eocene San Jose Formation with disconformity or slight angular unconformity (Baltz et al., 1966; Baltz, 1967). The duration of the lacuna represented by this unconformity is imprecisely known because of poor biostratigraphic control in the Cuba Mesa Member. Smith and Lucas (1991) and Smith (1992b) argued that the unconformity beneath the Cuba Mesa Member gives way to a conformable sequence of fine-grained deposits toward the area of maximum Tertiary subsidence in the northeast part of the basin. In this area, the San Jose–Nacimiento contact was considered by them to be mudstone on mudstone. Such a scenario would suggest that unconformity development in peripheral areas occurred in response to increased tectonic subsidence and accommodation (relative to sediment supply) that temporarily focused sedimentation near the basin center (Smith, 1992b).

To further evaluate the nature of the San Jose–Nacimiento contact, electric logs for representative wells in two east–west transects, one in T32N and one in T30N, were examined by the writer and B. S. Brister. These transects encompassed the area within which the basal Cuba Mesa Member of the San Jose Formation was interpreted to be absent by Smith and Lucas (1991) and Smith (1992b). Our analysis indicates the presence of sandstone of the Cuba Mesa Member throughout this area. Furthermore, the San Jose–Nacimiento contact is sharp and resembles the electric-log response elsewhere in the southern part of the basin where the contact is known to be unconformable. Based on these observations, we infer that the San Jose–Nacimiento contact may be everywhere disconformable, and that the previous interpretation of a conformable contact relationship near the basin axis is possibly the result of miscorrelation.

Unconformity development as a result of *decreased* tectonic subsidence and resultant decreased accommodation, as proposed above for the unconformity beneath the Ojo Alamo Sandstone, is an alternative mechanism by which the San Jose–Nacimiento unconformity may have developed. If tectonic subsidence and accommodation peaked during deposition of the fine-grained deposits of the lower Nacimiento Formation and subsequently decreased to zero by the end of deposition of the Escavada Member, an explanation would be provided for the silcretes and diminished strata accumulation rates of the Escavada as well as for a possible basin-wide surface of non-deposition or erosion that caps it. More work on the nature of the San Jose–Nacimiento contact in the San Juan Basin is needed.

The San Jose Formation represents the final preserved episode of Laramide sedimentary aggradation in the San Juan Basin. The San Jose is as much as 1800 ft (550 m) thick and contains early Eocene (Wasatchian) fossil vertebrates in its middle and upper parts (Smith and Lucas, 1991; Smith, 1992b; Lucas and Williamson, 1993b). Stratal accumulation rates for the San Jose Formation, estimated from thicknesses and age relations in the Eocene depocenter in the northeast part of the San Juan Basin, are ~99 m/My (Fig. 3). Note, however, that these rates are imprecise because of age uncertainty for the Cuba Mesa Member, only the upper part of which has been dated by interfingering with the Wasatchian Regina Member of the San Jose Formation.

Largely fluvial in origin, the San Jose Formation shows evidence for southwesterly to southeasterly paleoflow (Smith and Lucas, 1991). A major belt of south-flowing channels developed parallel to, and west of, the rising Nacimiento Uplift (Smith, 1992b). The Blanco Basin Formation of the San Juan Sag is a piedmont deposit that may be equivalent to the San Jose Formation (Lucas, 1984; Brister, 1992), although poor age constraints and geographic isolation of the Blanco Basin Formation preclude precise correlation. Early Eocene fluvial systems exited the southeastern San Juan Basin and flowed east into the Galisteo Basin (Cather, 1992). As shown by stratigraphic relationships in the Chuska Mountains, nearly one kilometer of post-San Jose Formation sediments may have been deposited in the San Juan Basin during middle Eocene–early Oligocene time (e.g., Fassett, 1985; Cather et al., this guidebook). These sediments were subsequently stripped by erosion, mostly during the middle and late Tertiary.

DISCUSSION

Isopach patterns and structure contour maps document that the Laramide evolution of the San Juan Basin was complex. As described previously, late Campanian sedimentation was focused

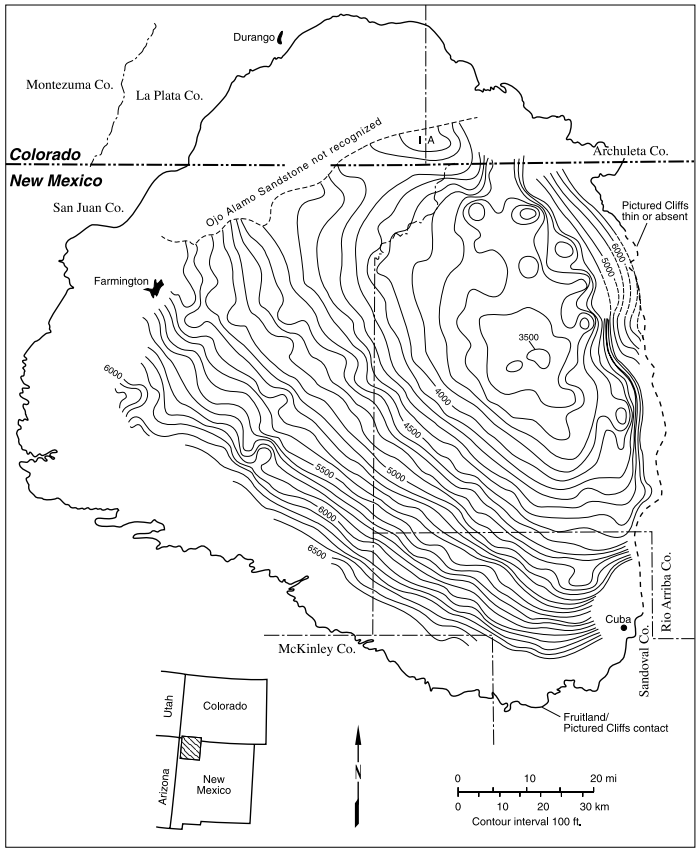

FIGURE 10. Structure contour map of base of the Tertiary (base of Kimbeto Member of the Ojo Alamo Sandstone), San Juan Basin. IA, Ignacio anticline. Modified from Ayers et al. (1991, fig. 7).

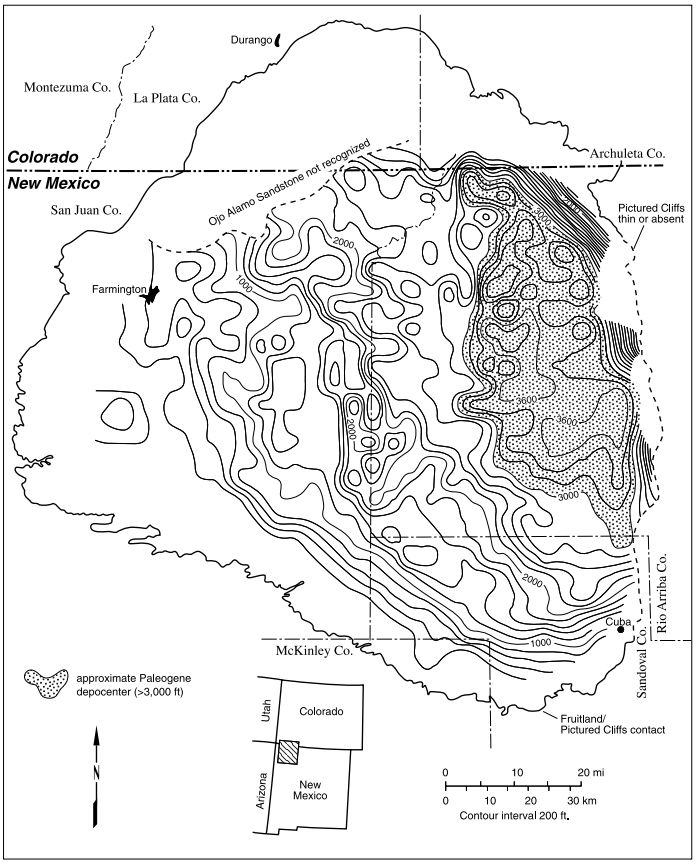

FIGURE 11. Isopach map of Tertiary strata (Kimbeto Member of the Ojo Alamo Sandstone, Nacimiento and San Jose Formations) in San Juan Basin. Note that upper surface of the isopach interval is modern topography. Modified from Ayers et al. (1991, fig. 18).

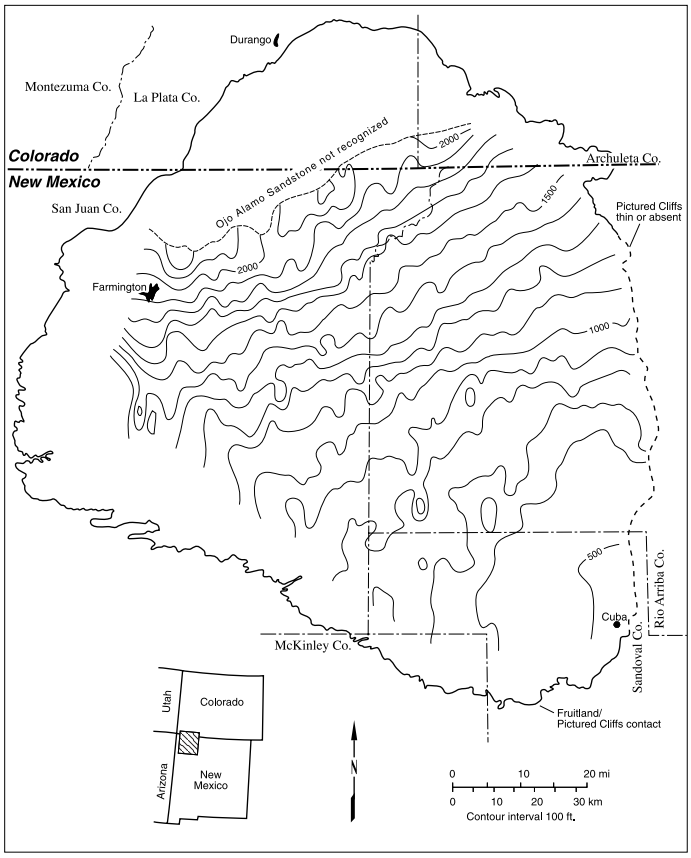

FIGURE 12. Isopach map of the stratigraphic interval between the Huerfanito Bentonite Bed and the base of the Paleocene Kimbeto Member of the Ojo Alamo Sandstone in the San Juan Basin. Note that if the slight southeastward depositional dip of the Kimbeto Member is neglected, this map approximates a structure contour map on the Huerfanito Bentonite Bed during earliest Tertiary time. Modified from Ayers et al. (1994, fig. 2.12).

in the northwest part of the basin (Fig. 6). By early Tertiary time, the depocenter had shifted to the northeast part of the basin. A structure contour map (Fig. 10) of the base of the Tertiary (base of the Kimbeto Member of the Ojo Alamo Sandstone) reveals a north–northwest trending asymmetrical syncline with about 3000 ft (900 m) of structural relief. The steep northeast limb of the syncline is contiguous with the southwest limb of the Archuleta Anticlinorium. The axial area of the syncline approximately corresponds to the area of greatest thickness of Tertiary sediments in the San Juan Basin (Fig. 11), although interpretation of this isopach map is complicated by the fact that the upper surface of the isopach interval is modern topography. The relative importance of Paleocene versus Eocene structural development in the northeast part of the basin is not yet well documented.

An isopach map of the stratigraphic interval between the Huerfanito Bentonite Bed and the base of the Kimbeto Member of the Ojo Alamo Sandstone (Fig. 12) provides an interesting comparison with Figure 10. If one makes the simplifying assumption that the base of the Kimbeto Member was horizontal instead of dipping gently to the southeast as shown by paleocurrent analysis (Powell, 1973; Klute, 1986), then Figure 11 may be viewed as an approximate paleo-structure contour map on the Huerfanito Bentonite Bed at the beginning of Tertiary time. Note that the contours in Figures 10 and 12 are mutually nearly orthogonal, and imply that the San Juan Basin subsided in an oblique, seesaw fashion.

The northwest thickening of the Huerfanito–Kimbeto isopach interval depicted in Figure 12 represents the combined effects of at least three processes: (1) northward or northeastward (basinward) thickening of the Pictured Cliffs Sandstone (Fassett and Hinds, 1971; Ayers et al., 1991) and the upper Lewis Shale; (2) northwest syndepositional thickening during late Campanian time of the Kirtland Formation (Silver, 1951; Dilworth, 1960; Hunt and Lucas, 1992); and (3) possible southeastward erosional beveling during Maastrichtian time of the Kirtland and Fruitland Formations prior to deposition of the Ojo Alamo Sandstone (Fassett and Hinds, 1971; Smith, 1992a; Ayers et al., 1994). The latter two processes probably accompanied shortening of the Hogback monocline, as would be implied by the isostatic constraints of paired uplift and subsidence. By similar reasoning, subsequent major Paleogene subsidence in the northeast part of the basin was probably driven by shortening and tectonic loading in the Archuleta Anticlinorium, which, in turn, implies that the anticlinorium formed largely during Paleocene and Eocene time. Initial structural development of the anticlinorium, however, occurred earlier, during deposition of the

Lewis Shale and Pictured Cliffs Sandstone.

A Paleogene age is also indicated for the Ignacio anticline (Fig. 4), a major, southeast-plunging anticline in the northern part of the basin that is subparallel with, and probably related to, the nearby Archuleta Anticlinorium. The Ignacio anticline is not manifested by stratal thinning on the Huerfanito–Ojo Alamo isopach map (Fig. 12), but is visible on the Ojo Alamo structure contour map (Fig. 10).

SUMMARY

In Late Cretaceous time prior to about 80 Ma, stratal accumulation rates (not decompacted) in what was to become the axial part of the San Juan Basin were relatively low (26–60 m/My), and there is little evidence for differential, Laramide-style uplift and subsidence. Primarily because of the scarcity of control points on the early and middle Campanian parts of stratal accumulation-rate curve (Fig. 3) and because of the relatively imprecise nature of apatite fission-track cooling (AFT) data from adjacent uplifts, it is difficult to state precisely when the Laramide orogeny began in northern New Mexico. Several lines of evidence converge to suggest it began sometime between about 80 to 75 Ma: (1) Initial Laramide AFT cooling in the Nacimiento Uplift occurred 80.8 ± 7.5 Ma (two-sigma error), and cooling was underway in the southern San Luis Uplift (Santa Fe Range) at least by about 74 Ma (Kelley et al., 1992; Kelley and Chapin, 1995); (2) stratal accumulation rates increased greatly in both the Raton Basin (Cather, in press) and the San Juan Basin in the middle Campanian (80–75 Ma); (3) non-deposition or erosion of the Pictured Cliffs Sandstone (~75 Ma) occurred in the southeastern San Juan Basin in the eastern limb of the evolving range–margin syncline adjacent to the Nacimiento Uplift and to parts of the Archuleta Anticlinorium; and (4) a two-fold seaward thinning of the middle to late Campanian Lewis Shale between the axial part of the San Juan Basin and the San Juan Sag documents an early episode of northward or northeastward tilting and subsidence in the San Juan Basin that began prior to deposition of the Huerfanito Bentonite Bed (75.76 ± 0.34 Ma; Fassett et al., 1997; Fig. 5).

In the San Juan Basin, Laramide sedimentation consisted of three distinct phases that were divided by probable basin-wide unconformities. Episodes of rapid subsidence and sedimentation were characterized by underfilled, mudstone-dominated successions, whereas intervening episodes of decreased accommodation and overfilling produced basin-scale unconformities and associated sandstone- and conglomerate-dominated sedimentary deposits.

The early phase of Laramide subsidence in the San Juan Basin culminated in the late Campanian to early Maastrichtian, and was recorded by marine, marginal marine, and coastal plain sedimentation. Northwest tilting of the San Juan Basin occurred ~74–67 Ma and created a depocenter in the northwest part of the basin adjacent to the Hogback monocline. This depocenter may have extended northeastward along the Hogback monocline into the San Juan Sag, which was only weakly differentiated from the San Juan Basin at this time. During deposition of the Kirtland and Fruitland Formations, stratal accumulation rates equaled or exceeded those for continental deposits of any basin in northern New Mexico or southern Colorado during the Late Cretaceous through Eocene (Cather, in press). Cessation of subsidence and accommodation in the middle to late Maastrichtian produced a basin-wide unconformity in the San Juan Basin that marked the end of the early phase of Laramide subsidence.

The medial phase of Laramide subsidence and accommodation in the San Juan Basin began in the latest Maastrichtian to early Paleocene and continued until early late Paleocene (Ojo Alamo Sandstone and Nacimiento Formation). Sediments, now entirely non-marine, accumulated in a Paleocene depocenter that developed in the northeast part of the basin adjacent to the rising Archuleta Anticlinorium. Paleozoic and Precambrian detritus first appeared in late Maastrichtian–early Paleocene Ojo Alamo Sandstone. During the late Paleocene and earliest Eocene a period of decreased subsidence and accommodation may have produced a second episode of basin-wide non-deposition or erosion that marked the end of the medial phase of sedimentary accumulation in the San Juan Basin.

The final, late Laramide (Eocene) phase of tectonism caused renewed subsidence and sediment accumulation in the San Juan Basin, and saw the creation of numerous new basins in the Laramide foreland (Chapin and Cather, 1981, 1983). In the San Juan Basin, late Laramide fluvial sedimentation continued to be focused in the northeast part of the basin adjacent to the rising Archuleta Anticlinorium. The lower Eocene San Jose Formation is the youngest Laramide unit preserved in the basin. It is probable that nearly one kilometer of additional basin-fill, subsequently stripped, was present in the basin prior to the onset of mid-Tertiary erosion (Cather et al., this guidebook).

The end of Laramide subsidence in the San Juan Basin occurred prior to deposition of the Chuska Sandstone in the southwest part of the basin. The base of the Chuska Sandstone overlies a low-relief erosion surface that beveled tilted Mesozoic strata along the East Defiance monocline (Wright, 1956). The lower, fluvial part of the Chuska Sandstone contains an ash that has been dated at 34.75 ± 0.20 Ma (late Eocene; Cather et al., this guidebook). These fluvial beds consist mostly of distal piedmont deposits that prograded south–southwestward from the San Juan uplift following the cessation of Laramide subsidence in the San Juan Basin (Cather et al., this guidebook).

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