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Dinosaurs, pollen, and the Cretaceous-Tertiary boundary in the San Juan Basin

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DINOSAURS, POLLEN, AND THE CRETACEOUS-TERTIARY BOUNDARY IN THE SAN JUAN BASIN, NEW MEXICO

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Abstract.— In the San Juan Basin, New Mexico, the Ojo Alamo Formation includes two members, the upper Kimbeto Member and the lower Naashoibito Member (previously assigned to the underlying Kirtland Formation). The Naashoibito Member produces dinosaur fossils, as does the De-na-zin Member of the Kirtland Formation, which lies unconformably beneath it. A lignite bed in the upper part of the De-na-zin Member has been identified as the horizon of a major unconformity and the source of some Paleocene palynomorphs. The overlying dinosaur remains in the Naashoibito Member thus have been assigned a Paleocene age, but new pollen data refute this interpretation. The dinosaurs from the Naashoibito Member are not well-known, but late Maastrichtian (Lancian) dinosaur taxa (*Torosaurus latus* and *Tyrannosaurus rex*), as well as the early Maastrichtian *Torosaurus utahensis*, are not demonstrably present in this unit, despite previous claims. Vertebrate biostratigraphy suggests an early Maastrichtian age for the Naashoibito Member of the Ojo Alamo Formation, and palynological analyses of this unit does not support a Paleocene age; thus there are no Paleocene (non-avian) dinosaurs in the San Juan Basin.

INTRODUCTION

The nature and stratigraphic position of the Cretaceous-Tertiary (K/T) boundary in the San Juan Basin, New Mexico (Fig. 1) has been the subject of discussion and controversy for much of the last century. By the late 1980's, a somewhat uncertain consensus had been reached: a substantial unconformity separates Paleocene strata, termed Ojo Alamo Sandstone by most workers, from underlying Upper Cretaceous strata of the Kirtland Formation. However, disagreements still remained over the most useful lithostratigraphic nomenclature, the precise age of the youngest dinosaur fossil assemblage in the section and the stratigraphic position of the highest autochthonous (not reworked) dinosaur fossils.

Recent work has re-ignited these disagreements and produced valuable new data to solve problems that were not resolvable as recently as the 1980's. Furthermore, new palynostratigraphic data, recently published, have been used to build a case for the presence of Paleocene dinosaurs in the San Juan Basin.

Here, we advocate a mappable lithostratigraphy of the K/T boundary interval in the San Juan Basin. We also clarify the stratigraphic distribution and precise ages of the youngest dinosaur assemblages in the basin, and refute the assertion that palynostratigraphy indicates the presence of Paleocene dinosaurs in the San Juan Basin. in this paper: NNMNH = New Mexico Museum of Natural History and Science, Albuquerque; SMP = The State Museum of Pennsylvania, Harrisburg, Pennsylvania; UNM = University of New Mexico, Department of Earth and Planetary Sciences, Albuquerque, New Mexico; and USNM = National Museum of Natural History, Smithsonian Institution, Washington, D. C.

LITHOSTRATIGRAPHY

Two somewhat different sets of lithostratigraphic nomenclature are applied to the strata that encompass the K/T boundary in the San Juan Basin (Fig. 2). The difference is in the application of the name Ojo Alamo Sandstone. Brown (1910) first used the term "Ojo Alamo beds" for strata that yield dinosaur fossils, but he provided no precise definition of its boundaries. Bauer (1916), mapping in the west-central San Juan Basin, defined the Ojo Alamo Sandstone as a tripartite unit-lower conglomerate, middle "shale" and upper conglomerate (Fig. 2). This usage was followed for about a half century, and the dinosaur (and other vertebrate) fossils from the middle "shale" came to be widely known as the "Ojo Alamo fauna" (e.g., Gilmore, 1916, 1919, 1922, 1935).

However, in 1966, Baltz et al. published a fundamental alteration in the lithostratigraphy of the Ojo Alamo Sandstone (Fig. 2). They restricted the name Ojo Alamo Sandstone to Bauer's "upper conglomerate" and reassigned the "lower conglomerate" plus middle "shale" to the Kirtland Formation as a new unit, the Naashoibito Member (Fig. 2). This lithostratigraphy was adopted by the U.S. Geological Survey, and has been widely used by subsequent workers, including ourselves (e.g., Lehman, 1981, 1985; Lucas, 1981; Lucas et al., 1987; Hunt and Lucas, 1992; Lucas and Sullivan, 2000a; Sullivan and Lucas, 2000a). A striking exception to this is Fassett, who has continued to consistently use Bauer's (1916) Ojo Alamo Sandstone (Fassett, 1973; 1987; Fassett et al., 1987, 2002).

Recent work by us (Lucas and Sullivan, 2000a) has convinced us that Bauer's (1916) definition of the Ojo Alamo Sandstone provides a more readily mappable, basin-wide unit of formational rank than does the Ojo Alamo Sandstone *sensu* Baltz et al. (1966). The easiest way to explain this is to understand that the Naashoibito Member of the Kirtland, which is only present in a limited portion of the west-central part of the San Juan Basin, where it was studied by Baltz et al. (1966), is laterally equivalent elsewhere to sandstone-dominated strata that have always been assigned to the Ojo Alamo Sandstone (Figs. 2, 3). This means that the Ojo Alamo Formation (it is more than a sandstone, lithologically) is a composite unit, both lithostratigraphically and chronostratigraphically. Locally, in the west-central San Juan Basin, the Ojo Alamo Formation consists of a basal, intermittent conglomerate or sandstone, a middle mudstone/siltstone unit and an upper conglomerate. In this part of the basin, Powell (1973) suggested

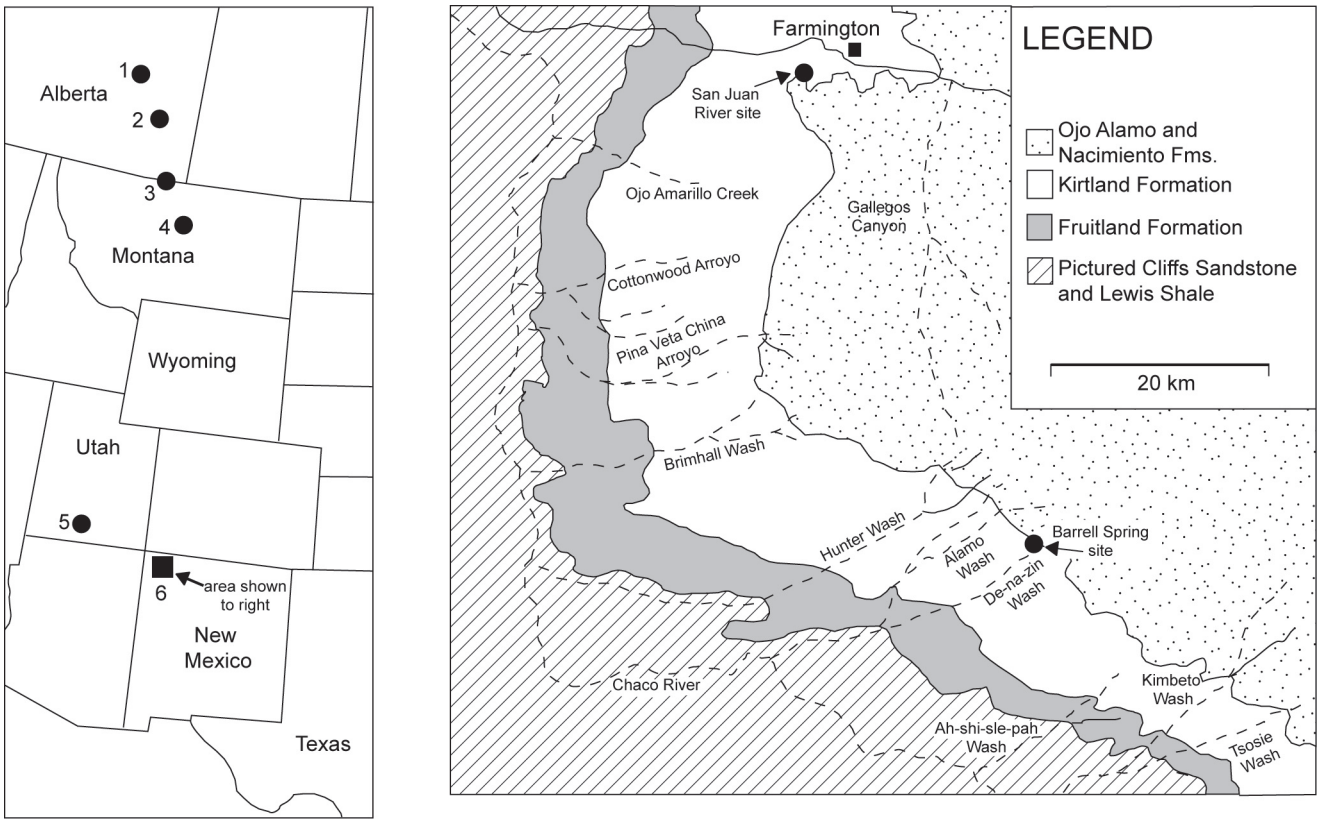


FIGURE 1. Map of the San Juan Basin, New Mexico showing the Upper Cretaceous-Paleocene strata. Ojo Alamo Formation includes the Naashoibito and Kimbeto members (modified from Sullivan and Lucas, 2003a). Locations (map on left) are: 1, Horseshoe Canyon and Bearpaw formations, Alberta; 2, Dinosaur Park and Oldman formations, Alberta; 3, Milk River Formation, Alberta; 4, Bearpaw, Two Medicine and Judith River formations, Montana; 5, Kaiparowits Formation, Utah; and 6, Fruitland, Kirtland and Ojo Alamo formations, New Mexico.

using the term Naashoibito Member for the lower conglomerate and middle mudstone, and he named the upper conglomerate the Kimbeto Member (Fig. 2). Elsewhere, the Ojo Alamo is a multistoried stack of sandstone and conglomerate (e.g., Baltz et al., 1966; Sikkink, 1987; Fassett et al., 1987). Following Sullivan et al. (2005), we continue to use the stratigraphic nomenclature of Powell (1973), thus removing the Naashoibito Member from the Kirtland Formation.

Locally, the lower part of the Ojo Alamo Formation (Naashoibito Member) yields dinosaur and other fossil vertebrates that indicate it is of Late Cretaceous age (see discussion below). However, palynomorphs indicate the Kimbeto Member, where it overlies the Naashoibito Member, is of Paleocene age (e.g., Baltz et al., 1966), as does its gradational and intertonguing upper contact with the overlying Paleocene Nacimiento Formation (Baltz et al., 1966; O'Sullivan et al., 1972; Lucas and Rigby, 1979; Rigby, 1981).

Two unconformities are associated with the Ojo Alamo Formation in the west-central San Juan Basin. The stratigraphically lower unconformity is at the base of the Naashoibito Member (lower conglomerate base). The stratigraphically higher unconformity is at the base of the Kimbeto Member (upper conglomerate base). Physical expressions of both unconformities are clear--both are stratigraphic breaks where coarser-grained, fluvial channel deposits scour and cut into underlying, finer-grained floodplain and associated deposits (e.g., Baltz et al., 1966; Rigby, 1981; Sikkink, 1987; Lucas and Sullivan, 2000a) (Fig. 4). However, the temporal value of both unconformities has been widely debated, and some authors have concluded the time involved is so short that these stratigraphic breaks should not be termed unconformities (Lindsay et al., 1981; Klute, 1986). Below, we address the time value of the unconformities associated with the Ojo Alamo Formation using a combination of data drawn from dinosaur biostratigraphy, palynology, lithostratigraphy, radioisotopic dates and magnetostratigraphic analysis.

DINOSAUR BIOSTRATIGRAPHY

Two, stratigraphically discrete dinosaur assemblages are relevant to the K/T boundary in the San Juan Basin. These are the assemblages from the De-na-zin Member of the Kirtland Formation and from the Naashoibito Member of the Ojo Alamo Formation. The third dinosaur assemblage, from the Kimbeto Member of the Ojo Alamo Formation, is not definitive.

De-na-zin Member (Kirtland Formation) Dinosaur Assemblage

Dinosaurs, and other fossil vertebrates, from the De-na-zin Member of the Kirtland Formation were first collected by George Pepper in 1902, Barnum Brown in 1904, James H. Gardner in 1908, Gardner and J. W. Gidley in 1909, and Walter Granger and William J. Sinclair in 1912 (Brown, 1910; Sinclair and Granger,

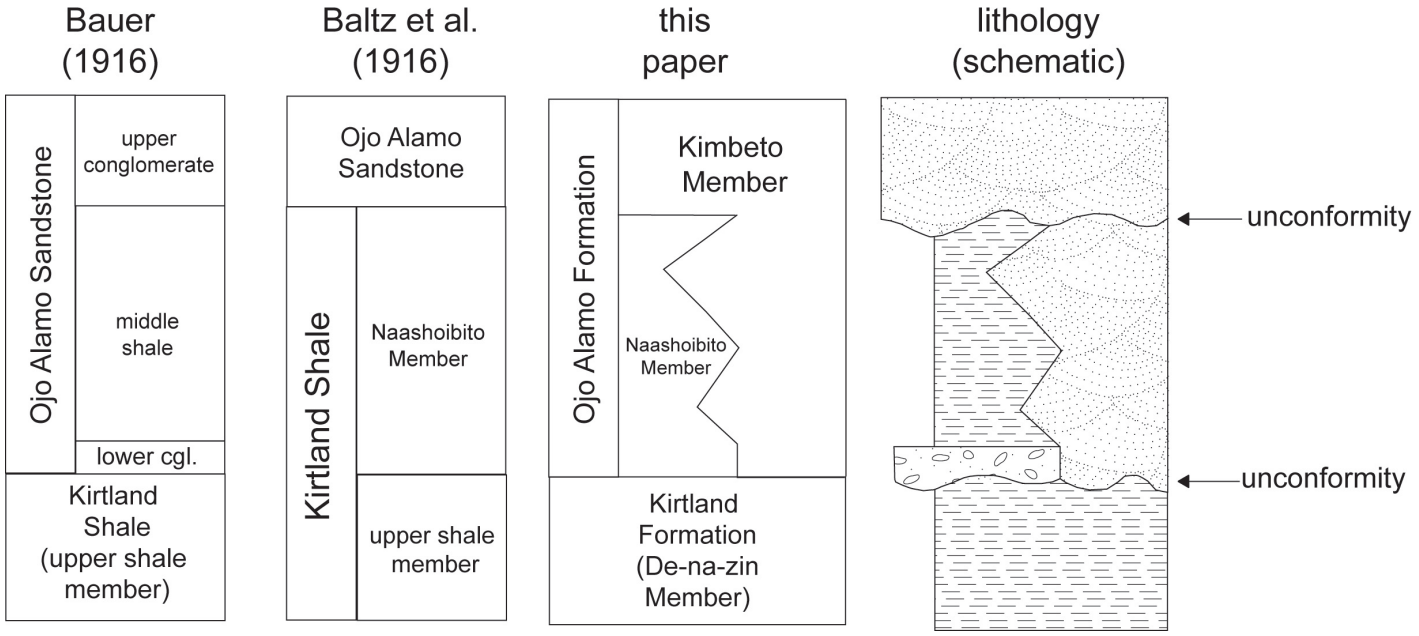


FIGURE 2. Comparative lithostatigraphic nomenclature of the Ojo Alamo Formation.

1914). Specimens collected during these expeditions included the holotype of the hadrosaurine dinosaur *Kritosaurus navajovius* Brown and numerous species of fossil turtles. These early expeditions were surpassed by that of C. Max Bauer and J. B. Reeside, Jr., who in 1915 amassed the largest collection up till that time of Late Cretaceous vertebrates from the San Juan Basin. Gilmore (1916) reported on these vertebrates from the Fruitland and Kirtland formations, together with those from the Ojo Alamo Formation (*sensu* Bauer, 1916). However, Gilmore (1916) was unable to establish the distinctiveness of the three dinosaur assemblages from these three stratigraphic units because of the then inadequate sample.

After these initial forays, Charles H. Sternberg set out to collect Cretaceous vertebrates in the San Juan Basin, in the summer of 1921, where he met J. B. Reeside, who showed him some of the key collecting localities in the upper Kirtland Formation (De-na-zin Member) near the heads of Hunter and Ojo Alamo washes (Sternberg, 1932). It is here that Sternberg presumably collected the holotype of *Parasaurolophus tubicen,* among other dinosaurs (Mateer, 1981; Hunt et al., 1992; Sullivan and Williamson, 1999; Wiman, 1931) and probably collected the "mesosuchian" crocodilian *Denazinosuchus kirtlandicus* (Wiman, 1932; Hunt et al., 1992; Lucas and Sullivan, 2003). Approximately 17 km to the south, in the lower Kirtland Formation (Hunter Wash Member), Sternberg collected in the Fossil Forest (near Coal Creek), where he discovered another species of *Parasaurolophus*, *P. cyrtocristatus* and probably the holotype of *Pentaceratops sternbergii* (Osborn, 1923; Ostrom 1961, 1963; Sullivan and Williamson, 1999; Hunt and Lucas, 2003). At another locality (29 km to the southeast), in the region of Meyers Creek (now Ah-shi-sle-pah Wash), Sternberg recovered the holotype of *Pentaceratops fenestratus* (Wiman, 1930; Sternberg, 1932; Rowe et al., 1981).

Nearly 50 years passed before collecting resumed in the upper part of the Kirtland Formation (De-na-zin Member) and the lower part of the Ojo Alamo Formation (Naashoibito Member) as part of a paleontological survey to assess the significance of the paleontological (Cretaceous-Tertiary) resources in the San Juan Basin (Kues et al., 1977). This survey collected fossils from the De-na-zin Member and the overlying Naashoibito Member.

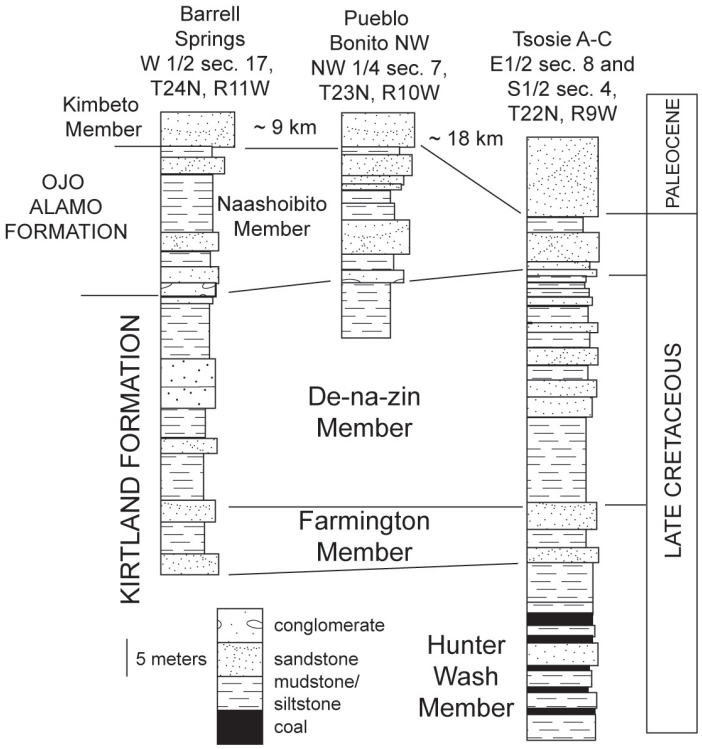


FIGURE 3. Correlation of upper Kirtland and Ojo Alamo formations between De-na-zin and Betonnie Tsosie arroyos, San Juan Basin, New Mexico (after Lucas and Sullivan, 2000a). Note how Naashoibito Member thins and becomes more sandy from north to south.

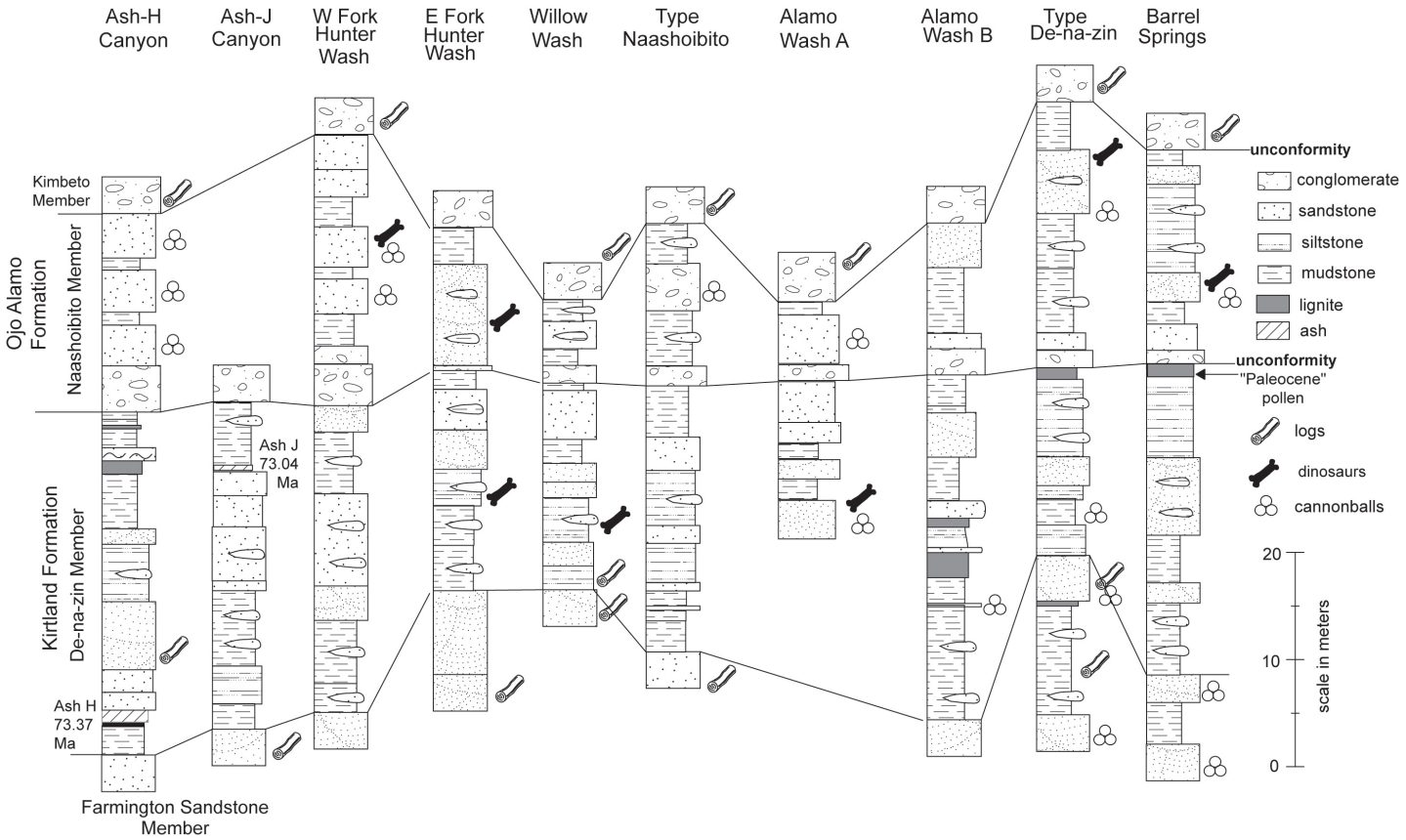


FIGURE 4. Selected measured stratigraphic sections of the upper Kirtland Formation and most of the Ojo Alamo Formation in the badlands from Hunter Wash to De-na-zin Wash (see Figure 1 and Lucas and Sullivan, 2000b for map coordinates of sections). Note stratigraphic relief at base of Kimbeto Member, locations of dated ashes H and J, and lignite from which Fassett et al. (2000) reported "Paleocene" pollen.

As an outgrowth of this survey, a book (Lucas et al., 1981) was published, containing an important article by Lehman (1981) on the fossil vertebrates of the Naashoibito Member ("Alamo Wash local fauna").

Lehman (1981) listed several dinosaur taxa that supposedly characterized the Alamo Wash local fauna, which he interpreted as derived from the Naashoibito Member. However, a careful re-evaluation of the stratigraphic position of specimens Lehman (1981) described as well as intense and stratigraphically precise collecting of the De-na-zin Member have shown that some of the dinosaur taxa previously attributed to the Naashoibito Member by Lehman (1981, 1985) are in fact are from the De-na-zin Member (Williamson and Sullivan, 1998; Sullivan and Williamson, 1999; Sullivan et al., 2005).

Lucas et al. (1987, p. 45) concluded that, "the dinosaur fauna of the Kirtland Shale, below the Naashoibito Member, is virtually identical to that of the (upper) Fruitland Formation." Lucas et al. (2000) thus listed a combined dinosaur fauna of the Kirtland Formation (Hunter Wash [which now includes the Bisti Member as the Bisti Bed], Farmington, and De-na-zin members) and noted that most of the taxa are known from the De-na-zin Member, which now is recognized to have the most diverse dinosaur fauna in the San Juan Basin Upper Cretaceous section. However, we note that this apparent diversity may be, in part, directly related to the fact that this interval has been preferentially collected and studied, in contrast to the other two stratigraphic intervals of the Kirtland Formation (Hunter Wash and Farmington members).

The dinosaur assemblage from the De-na-zin Member consists of *Ornithomimus antiquus* and *Saurornitholestes langstoni* as well as indeterminate ornithomimosaurids and dromaeosaurids (Lucas et al., 1987; Sullivan, 1997; Sullivan and Lucas, 2000b), the tyrannosaurids *Gorgosaurus* (=*Albertosaurus*, in part) and/or *Daspletosaurus* (Lucas et al., 1987; Carr and Williamson, 2000) (now considered to represent a new species of *Daspletosaurus* [Williamson and Carr, 2003b; Carr et al., 2005]), the sauropod *Alamosaurus sanjuanensis* (Sullivan and Lucas, 2000a), the ankylosaurid *Nodocephalosaurus kirtlandensis* (Sullivan, 1999), an indeterminate nodosaurid, the pachycephalosaur *Prenocephale* (= *Sphaerotholus*) *goodwini* (Williamson, 1999; Sullivan, 2000, 2003; Williamson and Carr, 2002, 2003a, 2005), a centrosaurine ceratopsian, the chasmosaurine ceratopsid *Pentaceratops sternbergii* (Wiman, 1930; Lucas et al., 1987) and other indeterminate chasmosaurines (Sullivan et al., 2005), and the hadrosaurs *Naashoibitosaurus ostromi*, *Kritosaurus navajovius* and *Parasaurolophus tubicen* (Hunt and Lucas, 1992, 1993; Sullivan and Williamson, 1999; Williamson, 2000). Other vertebrate taxa from the De-na-zin Member include amiid and lepisosteid fishes, turtles and the crocodilians *Denazinosuchus* and *Brachychampsa* (Lucas, 1992; Lucas and Sullivan, 2003; Sullivan and Lucas, 2003b). Williamson and Sullivan (1998) viewed this vertebrate

assemblage as biostratigraphically distinctive and referred to it as the Willow Wash local fauna (Fig. 5).

The dinosaur fauna of the De-na-zin Member shares some key generic level taxa with the fossil assemblage of the upper Fruitland Formation and lower Kirtland Formation (the "Hunter Wash local fauna" of Clemens, 1973). These include the genera *Gorgosaurus* or *Albertosaurus* and/or *Daspletosaurus*, *Pentaceratops*, *Kritosaurus* and *Parasaurolophus*. Accordingly, Sullivan and Lucas (2003a) recognized that the two local faunas represent a single biostratigraphic assemblage. It is characteristic of a faunachron (land-vertebrate "age") that encompasses nearly 3 million years of Campanian time and fills a long-standing biochronological gap between the Judithian and Edmontonian, recently named the Kirtlandian (Sullivan and Lucas, 2003a). The Kirtlandian is largely equivalent to "Bearpaw time," 72.8-74.2 Ma (revised isotopic dates for the Bearpaw provided by D. Eberth, pers. commun., 2005).

The biostratigraphic ranges of the tyrannosaurid taxa *Albertosaurus*, *Gorgosaurus*, *Daspletosaurus* and the lambeosaurine hadrosaur *Parasaurolophus* are all pre-Lancian (pre-late Maastrichtian), spanning the late Judithian (upper Campanian) through the early Edmontonian (lower Maastrichtian), approximately 75-70.3 Ma (Sullivan and Williamson, 1999; Carr and Williamson, 2000, 2004; Eberth et al., 2001; Currie, 2003; Eberth pers. commun., 2005). Specifically, *Daspletosaurus* is known from the Oldman, Dinosaur Park, Horseshoe Canyon and Kirtland formations and is known by multiple species from a wide geographic area (Currie, 2003). *Albertosaurus sarcophagus* is restricted to the Horseshoe Canyon Formation (early Edmontonian); *Gorgosaurus* (= *Albertosaurus* [in part]) *libratus* is restricted to the Dinosaur Park Formation (late Judithian) and possibly occurs in the Oldman Formation (also late Judithian) (Eberth et al., 2001; Currie, 2003). We note here that Carr and Williamson (2000, 2002, 2003b) recognized only one tyrannosaurid genus (*Daspletosaurus*) from the Kirtland Formation and concluded that all other tyrannosaurid fossils collected from the Fruitland and Kirtland formations are indeterminate to genus and species. The problematic carnosaur genus *Aublysodon* was considered a *nomen dubium* (Carr and Williamson, 2000), but was later synonymized with *Tyrannosaurus rex* (Carr and Williamson, 2004). Currie (2003) suggested that it may represent another undescribed species of *Daspletosaurus*.

Parasaurolophus tubicen is known only from the De-na-zin Member with certainty, whereas *Parasaurolophus cyrtocristatus* is known from both the Hunter Wash Member (Kirtland Formation) and the Kaiparowits Formation of Utah (Sullivan and Williamson, 1999; Sullivan and Lucas, 2003a). We regard these two species as distinct (*contra* Williamson, 2000), and both species are restricted to the Kirtlandian (Sullivan and Lucas, 2003a). *Parasaurolophus walkeri* is restricted to the Dinosaur Park Formation (Sullivan and Williamson, 1999; Eberth et al., 2001; Horner et al., 2004) and is of late Judithian age.

Naashoibito Member (Ojo Alamo Formation) Dinosaur Assemblage

The dinosaur (and other vertebrate) fossil assemblage from the Naashoibito Member has been termed the Alamo Wash local fauna (Lehman, 1981). As previously noted, from its inception, confusion regarding the constituent taxa of the Alamo Wash local fauna was introduced by Lehman (1981), who erroneously assigned some dinosaur localities to the Naashoibito Member that were actually in the De-na-zin Member. Lucas et al. (1987) and Hunt and Lucas (1992, 1993) repeated Lehman's assignments and made additional errors, so that several taxa, including *Pentaceratops*, *Parasaurolophus* and *Kritosaurus*, that Hunt and Lucas listed from the Naashoibito Member, actually are from the De-na-zin Member. A second problem with the dinosaur assemblage of the Naashoibito Member was the identification of incomplete specimens as *Torosaurus* and *Tyrannosaurus* by Lehman (1981), Lucas et al. (1987) and Carr and Williamson (2000).

Most of these problems have now been resolved by careful restudy in the field of the stratigraphic position of the dinosaur localities and by broader and more detailed morphological comparisons of the fragmentary dinosaur fossils from the Naashoibito Member (Williamson, 1998, 2000; Williamson and Sullivan, 1998; Sullivan and Williamson, 1999; Carr and Williamson, 2000; Sullivan, 1999; Lucas and Sullivan, 2000a, b; Farke, 2002; Sullivan et al., 2005). The result is that, save for one form taxon, *Alamosaurus sanjuanensis*, the dinosaur assemblage of the Naas-

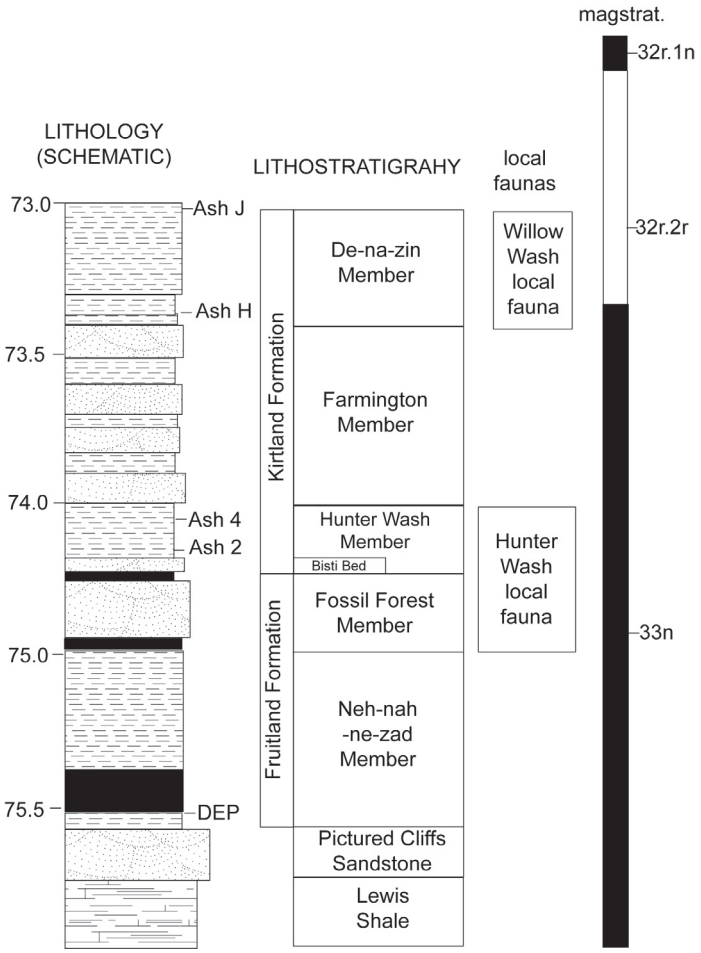


FIGURE 5. Composite lithostratigraphy of the Fruitland and Kirtland formations and their respective members and contained local faunas (modified from Sullivan and Lucas, 2003a).

hoibito Member, at present, consists solely of indeterminate ornithomimids, dromaeosaurids, saurornithoidids, tyrannosaurids, ankylosaurids, nodosaurids, ceratopsids, and hadrosaurines (Carr and Williamson, 2000; Lucas and Sullivan, 2000b; Sullivan and Lucas, 2003a; Sullivan et al., 2005). Some recently reported taxa, such as long ranging *Richardoestesia* and indeterminate Troodontidae, reported in an abstract by Weil and Williamson (2000), have not been documented and have limited biostratigraphic utility. The teiid lizard *Peneteius*, recently reported from the Naashoibito Member by Williamson and Weil (2004) and Weil et al. (2004), also has limited biostratigraphic utility, as it is known from both the Campanian and Maastrichtian (Nydam et al., 2000).

The multituberculate mammal *Essonodon browni* was first reported in the Naashoibito Member by Lehman (1984), based on a single left m1. Lehman (1984) noted that the specimen (UNM FKK-020) differed from other specimens of the species (presumably bona fide Lancian specimens) in being smaller in size and having a notched posterior margin. The genus been recently cited as an index taxon for the Lancian (Weil and Williamson, 2000), but it is *E. browni* that is the index taxon, not the genus. The presence of *Tyrannosaurus rex* and *Torosaurus utahensis* in the Naashoibito Member is no longer accepted (Sullivan et al., 2005). As a consequence, the distinctiveness of the Alamo Wash local fauna is now problematic. A brief discussion of material previously attributed to *Tyrannosaurus rex* and *Torosaurus utahensis* is critical to understanding the biostratigraphic position of this dinosaur fauna.

Lucas et al. (1987, p. 39, fig. 3E, G) described and illustrated a single tooth (Fig. 6), NMMNH P-13000 (formerly UNM FKK-076), from the Naashoibito Member and identified it as cf. *Tyrannosaurus rex*. Carr and Williamson (2000) also identified it as cf. *T. rex*, and furthermore suggested that some tooth fragments (NMMNH P-7199) from the Naashoibito Member may also pertain to *T. rex*. Both Lucas et al. (1987) and Carr and Williamson (2000) based their identifications on denticle densities. However, denticle densities are not reliable taxonomic identifiers for assigning isolated tyrannosaurid teeth to genus or species, nor is tooth size. The tooth (NMMNH P-7199) thus is best regarded as Tyrannosauridae indeterminate (Fig. 6), as serration size follows tooth size in tyrannosaurids, as noted by Farlow et al. (1991) and Carr and Williamson (2004). Another tyrannosaurid tooth from the Naashoibito Member (SMP VP-1574) shows variation in the number of denticles along the same carina: 13 denticles/cm at the apical end; 21 denticles/cm at the basal end, with a progressive decrease in size of each denticle toward the base.

In addition to the tyrannosaurid teeth, Lucas and Sullivan (2000a, fig. 5k) noted previously the occurrence of a badly weathered tyrannosaurid right femur (SMP VP-1113) from the Naashoibito Member, which we here identify as a femur of cf. *Daspletosaurus* sp., based on comparison with USNM 10754, a right femur of either *Gorgosaurus* or *Daspletosaurus* sp. (labelled as *Albertosaurus* sp.) collected by George F. Sternberg from the Dinosaur Park Formation, west branch of Little Sandhill Creek, Red Deer River, Alberta, Canada. Despite its poor preservation, the size and morphology of SMP VP-1113 closely resembles that of USNM 10754, which has a femoral length of 100 cm and shaft width of 12 cm, proximal width of 25 cm and distal width of 21 cm, suggesting that the two specimens are congeneric. Moreover, a left femur of a subadult *Tyrannosaurus rex* from the Lance Formation at Alkali Creek, Niobrara, Co., Wyoming (USNM 6183), also 100 cm in length, has a much wider shaft (15 cm) and much wider proximal (29 cm) and distal (27 cm) ends. Both *Gorgosaurus* and *Daspletosaurus* are restricted to sub-Lancian Maastrichtian strata (Eberth et al., 2001; Currie, 2003). Thus, the presence of *Gorgosaurus* or *Daspletosaurus* in the Naashoibito Member is consistent with, and reinforces, a pre-Lancian age for this member of the Ojo Alamo Formation.

Although the Maastrichtian cannot be formally subdivided (Odin et al., 2004), following D. Eberth (pers. commun., 2005), we consider the Lancian vertebrate faunachron to be 1 Ma in duration with its base coincident with the top of the Horseshoe Canyon in Alberta, its base coinciding with the Fox Hills Sandstone/Hell Creek contact (in Montana), and with the Fox Hills Sandstone/Lance Formation contact in Colorado. This puts the base of the Lancian within chron 30n.

Several ceratopsid fossils from the Naashoibito Member clearly do not pertain to *Pentaceratops*, the best known ceratopsid from the underlying upper Fruitland and Kirtland formations. These fossils are fragmentary cranial material consisting of isolated and/or fragmentary horn cores, squamosals and parietals. Lehman (1981, 1985) and Lucas et al. (1987) assigned these specimens to *Torosaurus*, generally as *Torosaurus* cf. *T. utahensis*. However, Sullivan et al. (2005) recently reassessed these identifications and have determined that these specimens are too incomplete to positively refer them to a genus and/or species (also see Farke, 2002). Moreover, we concluded that *Torosaurus utahensis* is a pre-Lancian ceratopsid, which is distinct from, and antedates, *Torosaurus latus*, the Lancian taxon. Thus, elimination



FIGURE 6. Three views of large, indeterminate tyrannosaurid tooth (NMMNH P-13000) from the Naashoibito Member of the Ojo Alamo Formation. Scale bar = 4 cm.

of *Tyrannosaurus* rex and *Torosaurus utahensis* (and *T. latus*) from the list of Naashoibito Member dinosaurs removes a long cited basis for assigning the unit a Lancian age (Hunt and Lucas, 1992, 1993; Lehman, 1981, 1985, 1996; Lucas et al., 1987; Carr and Williamson, 2000).

Sullivan and Lucas (2003a) previously placed the Naashoibito Member at about 70-71 Ma, correlative to the lower part of the North Horn Formation of Utah (thus early Maastrichtian, *contra* Cifelli et al., 1999; Loewen at al., 2001) and middle part of the Javelina Formation of the Big Bend region of Texas. All three units contain fossils of the titanosaurid sauropod *Alamosaurus sanjuanensis*. Parenthetically, titanosaurid sauropod remains, including *Alamosaurus sanjuanensis*, have recently been reported in upper Campanian strata (McCord, 1997; Lucas and Sullivan, 2000b; Heckert et al., 2003). McDowell et al. (2004) reported a date of 69 ± 1.0 Ma for strata containing *Alamosaurus sanjuanensis* in the Javelina Formation of Texas. We have used this date as a datum for *Alamosaurus sanjuanensis* in the San Juan Basin (Sullivan et al., 2005), which occurs in the basal part of the Naashoibito Member. Moreover, none of the vertebrates from the Javelina Formation point to a Lancian age (Sullivan et al., 2005). If this correlation is correct, then there is a hiatus of about 4 million years between the Kirtland Formation (based on Ash J dated at 73.04 Ma) and the base of the Naashoibito Member (69 Ma). Thus, the age of the Naashoibito is younger than Campanian/Maastrichtian boundary, which in land-vertebrate "age" terms is equivalent to late Edmontonian and thus is pre-Lancian. A distinct break marks a hiatus between the top of the Naashoibito Member and base of the lower Paleocene Kimbeto Member, a gap that may represent up to 3.5 million years (from 68 to 65.5 Ma), spanning the latter part of Edmontonian through Lancian time (= most of the Maastrichtian) (Sullivan and Lucas, 2003a) (Fig. 7).

Kimbeto Member (Ojo Alamo Formation) Dinosaur Assemblage

Several records of fragmentary and/or isolated dinosaur bones are known from the Kimbeto Member of the Ojo Alamo Formation (Fassett et al., 1987; Fassett and Lucas, 2000; Fassett et al., 2002). Powell (1973) cited the occurrence of numerous undiagnostic, water-worn, dinosaur bone fragments 1.8 to 3 meters above the base of the Kimbeto Member in the NW1/4 of the N1/2 of sec. 32, T25N, R12W, which he dubbed the "Monisco local fauna." However, Lucas (1981) and Fassett et al. (1987) reviewed these records in detail and concluded that most are of bones clearly reworked from underlying Upper Cretaceous strata, thus invalidating the distinct nature of this "local fauna." Palynomorphs recovered from the Kimbeto Member in the west-central San Juan Basin are of Paleocene age (e.g., Anderson, 1960; Baltz et al., 1966), so claims of the co-occurrence of these palynomorphs with autochthonous dinosaur bone are questionable. Furthermore, the Kimbeto Member grades upward into and intertongues with the lower Paleocene Nacimiento Formation, further supporting a Paleocene age of the Kimbeto Member (Baltz et al. 1966; O'Sullivan et al., 1972; Rigby, 1981).

Along the San Juan River near Farmington, at a location dubbed the San Juan River site (Fig. 1), an essentially complete, and well-preserved, hadrosaur femur was recovered from the Kimbeto Member of the Ojo Alamo Formation (Fassett et al., 1987). The occurrence of Paleocene palynomorphs stratigraphically below this femur has continued to be a problem in interpreting the age of the rocks and has added fuel to the notion that some dinosaurs survived the K/T extinction event (Fassett et al., 1987, 2000, 2002; Fassett and Lucas, 2000). However, despite the bone's near-pristine appearance, we argue here, largely based on parsimony, that the bone has been reworked, and not transported any significant distance, thereby preserving the integrity of the bone's outer surface. We note countless examples where reworked specimens, such as upper Paleozoic brachiopods, found among the pebbles of the Ojo Alamo Formation, preserve the shell in great detail. We note, too, that no other dinosaur bones have been discovered in this part of the section.

Fassett et al. (2002) further claimed that Paleocene pollen is present in the uppermost bed of the De-na-zin Member, and thus stratigraphically below the entire dinosaur fauna of the Naashoibito Member of the Ojo Alamo Formation (Fig. 4). We present data below that call into question this report of Paleocene palynomorphs stratigraphically below dinosaur fossils (also see Sullivan et al., 2002, 2003).

PALYNOLOGY

Palynology of the strata that encompass the K/T boundary in the San Juan Basin began with the work of Anderson (1960). Baltz et al. (1966), working in the west-central basin, used palynomorphs to place the K/T boundary at the base of the Kimbeto Member of the Ojo Alamo Formation. Subsequent palynostratigraphic work (e.g., Tschudy, 1973; Newman, 1987) in the west-central San Juan Basin supported this placement. But, work by Tschudy (in Fassett and Hinds, 1971) in the southern San Juan Basin placed the palynostratigraphic K/T boundary in the upper Kirtland Formation. More recent work in the west-central and northern basin reported by Fassett et al. (2000, 2002) and Fassett and Lucas (2000) also places a palynostratigraphic K/T boundary in the uppermost Kirtland Formation. Particularly significant is pollen from the uppermost De-na-zin Member of the Kirtland Formation at Barrel Springs (De-na-zin Wash: Fig. 1) in the west-central basin (sec. 17, T24N, R11W; UTM: 767,780.71 M.E.; 4,002,752.10 M. N., Z 12, NAD 27) that Fassett et al. (2002) claim indicates a Paleocene age for the uppermost De-na-zin Member.

However, the palynomorphs we obtained from this same lignite bed (Table 1) are an assemblage mostly made up of species that span the K/T boundary such as *Arecipites reticulates*, *Cycadopites fragilis*, *Dyadonapites reticulates*, *Pandaniidites typicus*, *Pityosporites constrictus*, *Schizosporis parvus*, *Taxodiaceaepollenites hiatus*, *Tricolpites reticulates*, and *Ulmoideipites krempi*. Exceptions are *Proteacidites retusus* and *P. thalmanni*, two species thought to have become extinct at the boundary (Nichols et al., 1990, 1992; Nichols, 1994). These species are found in Campanian and Maastrichtian strata, but the presence

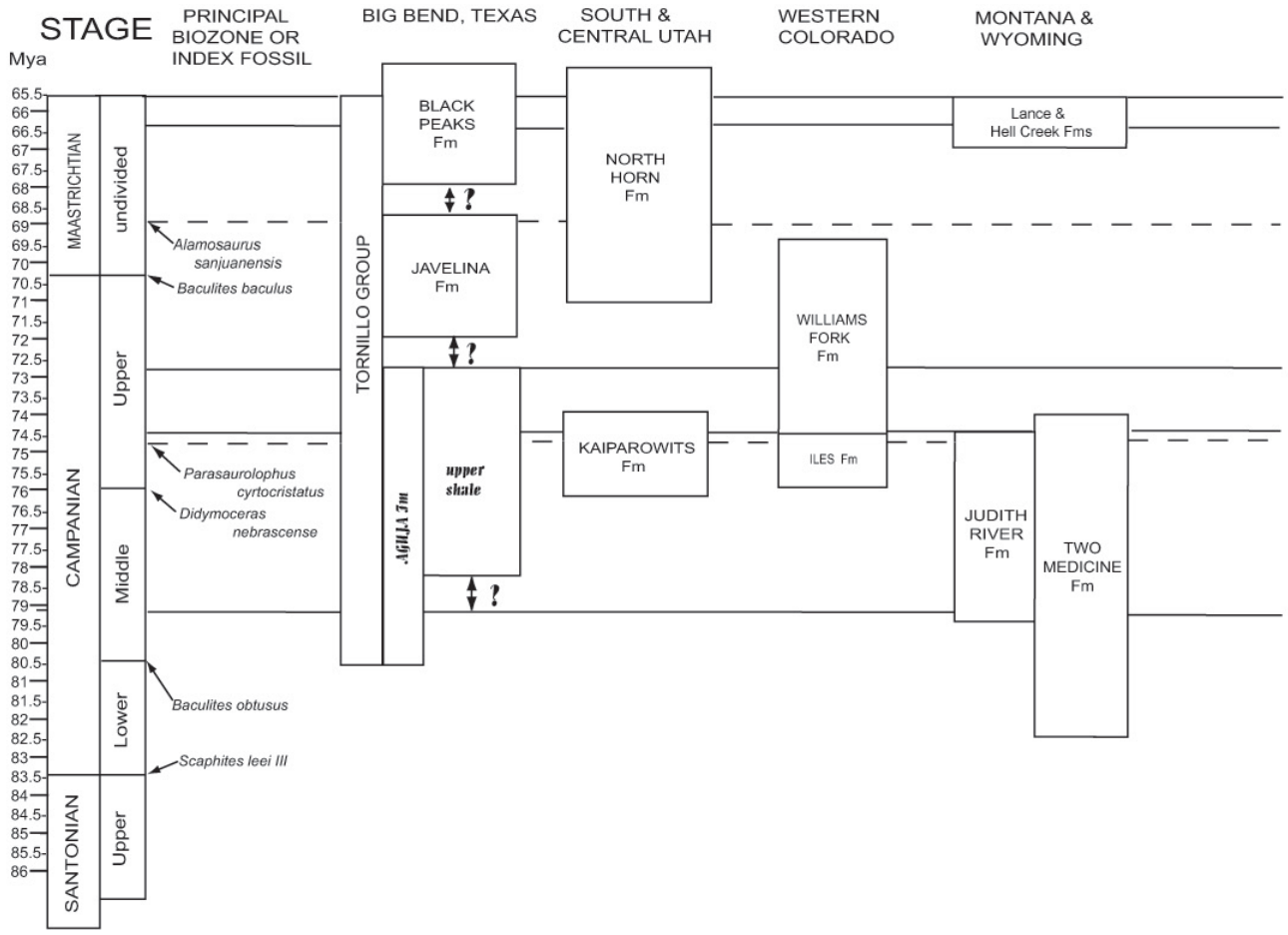


FIGURE 7. Correlation of Upper Cretaceous rocks of the San Juan Basin, New Mexico (modified from Sullivan and Lucas, 2003a; additional data, in part, from Odin et al., 2004; Lerbekmo and Braman, 2002; Gradstein and Ogg, 2004; Ogg, 2004; and D. Eberth pers. commun., 2005).

in the assemblage of *Pandaniidites typicus* and *Ulmoideipites krempi* suggests a Maastrichtian age.

After reporting these results to Fassett, he suggested (written commun., 2001) that we had actually not sampled the Paleocene pollen bed, which according to him, is slightly higher (~ 1m) in the same lignite bed. Accordingly, we undertook such sampling, but processing of several samples yielded no identifiable palynomorphs. Furthermore, there is no physical evidence of an unconformity in the lignite bed, or the overlying mudstone, although Fassett et al. (2002) claim that Paleocene strata rest directly on Campanian strata in this lignite bed, an unconformity of at least 7.5 million years. Thus, we are unable to replicate the palynological results of Fassett et al. (2002) through repeated sampling, so we consider them invalid.

Fassett et al. (2002, p. 319) reported a late Campanian to early Maastrichtian assemblage of palynomorphs from the lower part of the lignite bed (their sample # 04302000: Fassett et al., 2002, table 2), an assemblage that is essentially identical to our sample. Also, they could not, in 2000, extract diagnostic palynomorphs from eight samples collected stratigraphically higher in the lignite, an experience duplicated by us.

Nevertheless, Fassett et al. (2002) attached great significance to a 1985 sample (their sample 24-5: Fassett et al., 2002, table 2), which they concluded indicates a Paleocene age for this lignite bed in the uppermost part of the Kirtland Formation. They stated (Fassett et al., 2002, p. 318) that "this pollen assemblage is undoubtedly Paleocene" and that "the *Proteacidites* specimens in this assemblage must be reworked from the underlying Cretaceous strata." Fassett et al. (2002) then concluded that there must be an unconformity within the lignite bed of the uppermost Kirtland Formation with a hiatus of about eight million years.

We question the conclusions of Fassett et al. (2002) regarding the position of the K-T boundary and an eight-million-year hiatus at Barrel Springs (De-na-zin Wash) for the following reasons:

1. The age of the entire De-na-zin Member is late Campanian, about 73 Ma, as demonstrated by radioisotopic dates, which are consistent with magnetostratigraphy, vertebrate biostratigraphy and palynostratigraphy (Fig. 4).

2.There is no evidence of a physical break in the lignite bed high in the De-na-zin Member. This unit can be traced laterally over an area of approximately 62 km^2, and is shown in measured sections by Bauer (1916), Baltz et al. (1966), Lehman (1985) and

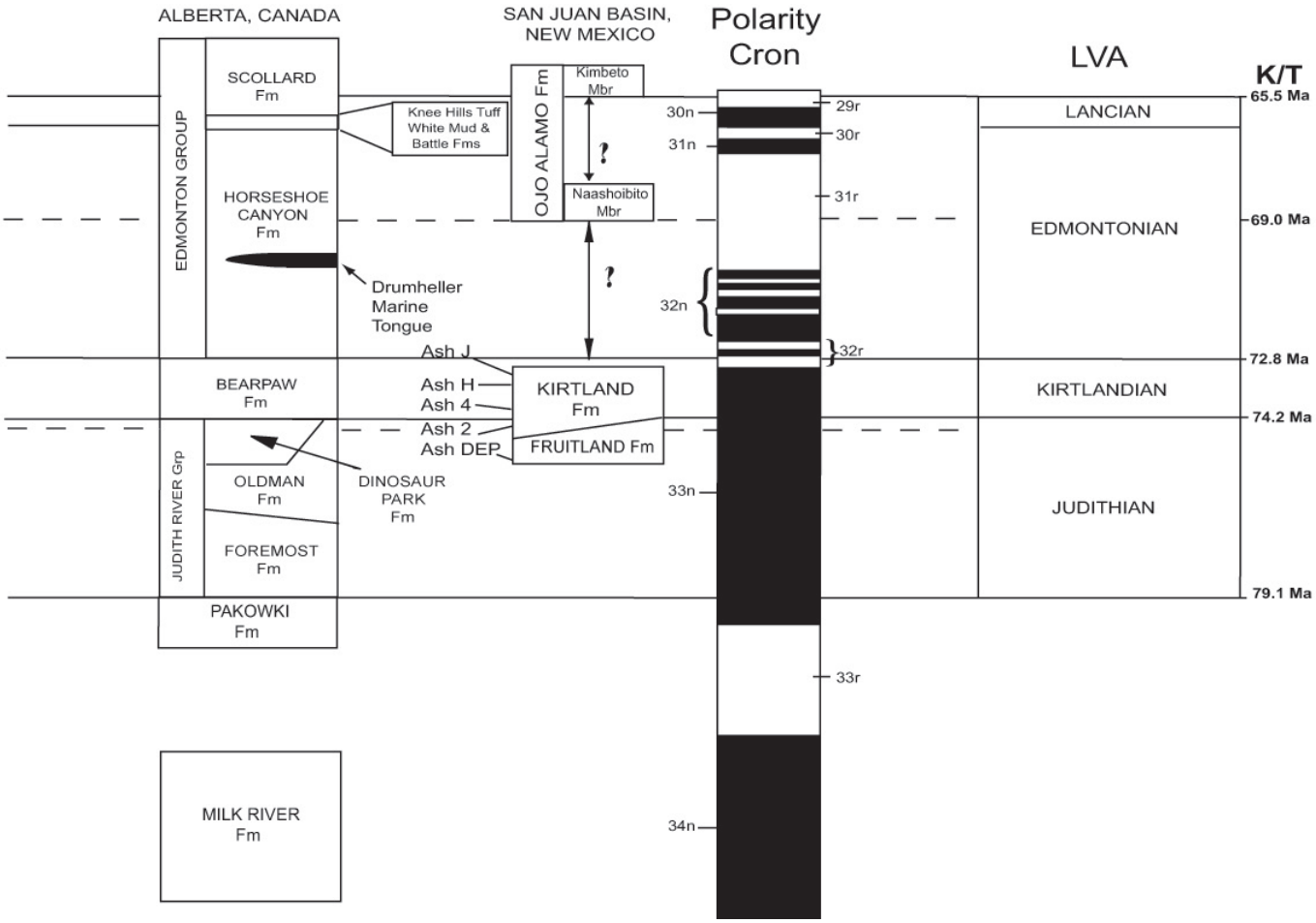


FIGURE 7. Continued.

Lucas and Sullivan (2000a) (also see Fig. 4). Throughout this area it is a consistent, ~ 1m thick bed of lignitic clay to lignite, and lacks clay, ash (tonstein) or sand partings. It thus represents a homogenous lithotype with no physical evidence within the lignite bed of an unconformity.

3. The palynomorphs from sample 24-5 of Fassett et al. (2002) suggest a Paleocene age for the sample based on the presence of *Momipites* spp. Like the sample from the San Juan River site (Fassett et al., 2000, 2002; Fassett and Lucas, 2000), sample 24-5 has a mixture of forms that are either known only from the Cretaceous or only from the Paleocene. *Proteacidites thalmannii* is a strictly Cretaceous form, and Fassett et al. (2002) conclude it is reworked based on the presence of *Momipites* spp. and the proposed Paleocene age of the sample.

4. The fact that extensive sampling by Fassett and ourselves in 2000-2001 could not replicate the species recovered in 1985 from sample 24-5 is troubling. Fassett et al. (2002, fig. 15) published a photograph of the exact location where sample 24-5 was recovered, and it is below a cliff of Paleocene Kimbeto Member of the Ojo Alamo Formation. This suggests the possibility that sample 24-5 was contaminated, or a slipped piece of Kimbeto Member, especially as neither Fassett nor us can now obtain Paleocene palynomorphs from this bed.

5. Above this bed, the Naashoibito Member of the Ojo Alamo Formation yields dinosaur and other vertebrate fossils from numerous locations (e.g., Gilmore 1919, 1922, 1935; Lehman, 1981, 1985; Lucas et al., 1987; Hunt and Lucas, 1992). Fassett et al. (2002) are correct to conclude that these fossils are autochthonous to the Naashoibito Member, not reworked from underlying Upper Cretaceous strata. However, the dinosaurs as well as some of the other vertebrate taxa (mammals, turtles) from the Naashoibito Member are known only from Cretaceous strata outside the San Juan Basin, including localities both north (Utah, Wyoming Montana and Alberta) and south (central New Mexico, west Texas) of the San Juan Basin.

Based on a single, non-replicatable record of *Momipites tenuipolis*, Fassett et al. (2002) concluded the entire vertebrate fossil assemblage of the Naashoibito Member is Paleocene. We regard it as Cretaceous, as have all previous workers. Its base is probably 69 Ma, based on the *Alamosaurus* datum; the upper Naashoibito Member/Kimbeto Member boundary is probably no younger that 68 Ma. The Naashoibito Member is a very thin unit relative to

the underlying and overlying De-na-zin and Kimbeto members, respectively (Lucas and Sullivan, 2000).

MAGNETOSTRATIGRAPHY AND GEOCHRONOLOGY

Fassett and Steiner (1997) published a series of Ar^{40}/Ar^{39} ages of ash beds from the Fruitland through De-na-zin Members that indicate they span a time interval from 74.11 ± 0.62 Ma to 73.04 ± 0.25 Ma (Fig. 5). Note that Ash 2, reported by Fassett and Steiner (1997) as in the upper Fruitland Formation is actually in the Hunter Wash Member of the Kirtland Formation (Fig. 5). Ash 4 is somewhat higher in the Hunter Wash Member. The stratigraphically highest ash bed (Ash J = 73.04 Ma) is in the upper De-na-zin Member, about 5 m below its contact with the overlying Naashoibito Member of the Ojo Alamo Formation (Figs. 4-5). A stratigraphically lower ash (Ash H = 73.37 Ma) is near the base of the De-na-zin Member, less than 5 m above its contact with the underlying Farmington Member (Fig. 4). This means the age of the De-na-zin Member is no younger than 73 Ma, or late Campanian.

Radioisotopic ages and biostratigraphy fix the Fruitland-Kirtland interval in the Campanian, so Maastrichtian age assignments based on magnetic-polarity stratigraphy (e.g., Butler et al., 1977; Lindsay et al., 1981; Butler and Lindsay, 1985) are no longer accepted (Lucas and Schoch, 1982; Sullivan and Lucas, 2003a). As Sullivan and Lucas (2003a) recently concluded, most of the Fruitland and lower Kirtland formations are of normal polarity, a long normal chron assigned to chron 33n by Fassett and Steiner (1997). The remaining reversed polarity zone of the upper Kirtland Formation is correctly assigned to chron 32r (Fassett and Steiner, 1997; Lerbekmo and Braman, 2002).

CONCLUSIONS

Based on the above data and discussion, we offer the following conclusions:

1. A mappable Ojo Alamo Formation includes two members. A lower Naashoibito Member, only recognizable in the west central part of the San Juan Basin, has a basal conglomerate overlain by sandstone with (locally) substantial interbeds of mudstone and siltstone. The upper Kimbeto Member (= Ojo Alamo Sandstone of Baltz et al., 1966) is sandstone, conglomeratic sandstone and conglomerate. Where the Naashoibito Member cannot be recognized, the entire Ojo Alamo Formation is the Kimbeto Member, although in such locations the lower part of the Ojo Alamo Formation may be sandstone-dominated strata laterally equivalent to the Naashoibito Member of Late Cretaceous age.

2. The Ojo Alamo Formation is a single lithostratigraphic unit (formation) but encompasses strata of very different ages. The Naashoibito Member is of Late Cretaceous (early Maastrichtian) age. Where the Kimbeto Member overlies the Naashoibito Member, the Kimbeto Member is of Paleocene age. Elsewhere, the Kimbeto Member may include strata of both Paleocene and Late Cretaceous age.

3. Two unconformities are associated with the Ojo Alamo Formation. The base of the Naashoibito Member (base of the lower conglomerate, in most places) is an unconformity between upper Campanian (De-na-zin Member of the Kirtland Formation) and early Maastrichtian (Naashoibito Member of the Ojo Alamo Formation) strata. The Paleocene Kimbeto Member unconformably overlies the early Maastrichtian Naashoibito Member in the west-central San Juan Basin.

4. Radioisotopic ages, magnetostratigraphy, vertebrate biostratigraphy and palynostratigraphy indicate the De-na-zin Member of the Kirtland Formation is late Campanian (~ 73 Ma).

5. Vertebrate biostratigraphy, based on the occurrence of *Alamosaurus sanjuanensis* as a datum (in the Javelina Formation), suggests that the Naashoibito Member is of early Maastrichtian age (Sullivan et al., 2005). Because the unit is relative thin, it probably represents no more that 1 million years of deposition (69-68 Ma).

6. Palynostratigraphy does not support assignment of a Paleocene age to any dinosaur fossils in the San Juan Basin.

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