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Stratigraphy, paleontology and age of the Fruitland and Kirtland Formations (Upper Cretaceous), San Juan Basin, New Mexico

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STRATIGRAPHY, PALEONTOLOGY AND AGE OF THE FRUITLAND AND KIRTLAND FORMATIONS (UPPER CRETACEOUS), SAN JUAN BASIN, NEW MEXICO

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Abstract—Campanian-Maastrichtian nonmarine strata of the San Juan Basin pertain to the Fruitland Formation and the Kirtland Formation. The Kirtland consists, in ascending order, of the Bisti, Hunter Wash, Farmington, De-na-zin and Naashoibito Members. The Fruitland is dominantly of deltaic and paludal origin and the Kirtland is of broadly fluvial origin. The Bisti Member is a gas reservoir. The majority of fossil vertebrates are from an interval in the uppermost Fruitland and from the Naashoibito Member. Distinct vertebrate and invertebrate faunas and floras can be distinguished for the Fruitland, pre-Naashoibito Kirtland and Naashoibito. Diverse evidence indicates that the Fruitland is of Judithian (late Campanian) age, the pre-Naashoibito Kirtland is of Edmontonian (early Maastrichtian) age and the Naashoibito is of Lancian (late Maastrichtian) age. There is no large-scale angular unconformity at the base of the Ojo Alamo Sandstone.

INTRODUCTION

The Fruitland and Kirtland Formations are of great economic and paleontologic importance. The Fruitland is the source of the most important coal resources in New Mexico. Together, these two formations have yielded the largest and most diverse vertebrate faunas from Upper Cretaceous nonmarine strata in the southern Rocky Mountains (Fig. 1). The age of these units and their contained faunas has also been a prominent source of discussion in relation to studies of the Cretaceous/Tertiary boundary. Surprisingly, considering these factors, these formations are relatively poorly studied. Here we synthesize the existing literature on the stratigraphy, paleontology and age of these units and augment this synthesis with new data. Abbreviations are AMNH, American Museum of Natural History; KU, Kansas University; NMMNH, New Mexico Museum of Natural History; YPM, Yale Peabody Museum; USNM, United States National Museum.

STRATIGRAPHY

Fruitland Formation

Bauer (1916, p. 274) named the Fruitland Formation for outcrops around the settlement of Fruitland on the San Juan River. He described these strata as being of brackish and freshwater origin and as bearing coal. Bauer (1916, plate 44) mapped the Fruitland from the San Juan River to Ah-shi-sle-pah Wash (Meyers Creek). Subsequently, the Fruitland has been mapped around most of the perimeter of the San Juan Basin and has been extensively studied in the subsurface (e.g., Reeside, 1924; Fassett and Hinds, 1971).

Fruitland-Kirtland boundary

Bauer (1916, p. 274) noted that the Fruitland Formation merges into the Kirtland Formation "by a gradational zone containing in many places sandstone lenses that are apparently of fluviatile origin." From an accompanying plate, it is clear that Bauer (1916, plate 45) consistently placed the formational boundary at the top of a sandstone above the last persistent coal (Fig. 2). Reeside (1924, plate 2), who accompanied Bauer on his expedition and who later extended Bauer's stratigraphy into the remainder of the San Juan Basin, also used this boundary. Study of Bauer and Reeside's unpublished field notes (courtesy of J. H. Hartman) and relocation of their measured sections indicates that the formational contact they both used is the top of a unit recently termed the "Bisti member" of the Kirtland Formation (Fig. 3; Hunt, 1986; see below). This is a sequence of laterally extensive brown-capped sandstones that occur above the coal-bearing strata in the northwestern quadrant of the San Juan Basin. Subsequent workers have tended to draw the formational contact at the occurrence of the highest coal (e.g., Fassett and Hinds, 1971). This is an ambiguous contact and has led some authors (e.g., Lindsay et al., 1981) to overestimate greatly the thickness of the Fruitland because thin coals occur in what most authors consider to be strata of the lower shale member of the Kirtland Formation. We advocate use of the base of the brown sandstones as an unambiguous Fruitland-Kirtland formational contact in the northwestern portion of the basin. In the remainder of the basin, we place the formational contact at the top of the highest coal 1 m or more in thickness. We, thus, advocate inclusion of the Bisti Member within the Kirtland Formation because this fluvial unit is more closely related genetically to the strata of the Kirtland than to the paludal Fruitland Formation and because the Bisti Member always has an erosional contact with the underlying Fruitland and a conformable contact with the overlying Kirtland strata. However, the erosional base of the Bisti Member is not a major unconformity and merely represents the erosional scour that is present at the base of all channel-sandstone bodies. Indeed, paleontological data, summarized below, indicates that no significant period of time is represented by this erosional surface.

Kirtland Formation

Bauer (1916, p. 274) named the Kirtland Shale for "predominantly clayey" strata that conformably overlie the Fruitland Formation. The Kirtland is "composed mostly of gray shale, with some brown, bluish, greenish, and yellowish shales, easily weathering gray-white sandstone and the brown resistant sandstone of the Farmington member" (Bauer, 1916, p. 274). Lindsay et al. (1981) renamed the Kirtland Shale the Kirtland Formation because the dominant lithologies are siltstone and sandstone. We concur with this usage.

Bisti Member

Hunt (1986) first used the term "Bisti member" for a thin, but very continuous sequence of sandstones that occur at the base of the Kirtland Formation. These sandstones are tabular and are distinctly bicolored with a white lower portion and a dark brown, ferruginous upper portion (Fig. 3). As noted by Hutchinson (1981) and Hutchinson and Kues (1985), these sandstones are very conspicuous in the western and northwestern portion of the San Juan Basin. We formally propose adoption of the name Bisti Member for this stratigraphic unit. The type section is adjacent to the location of the site of the now defunct Hunter's Store (Fig. 3; SW¼ SW¼ sec. 29, T13W, R24N). The Bisti Member has a maximum thickness of 5 m in the Hunter Wash area. This unit is prominent in all surface exposures of the lower Kirtland from north of the San Juan River (San Juan mine lease) to Ah-shi-sle-pah Wash to the south. It is also present near Durango, Colorado.

The Bisti Member does not always consist of a single sandstone interval. In the Fossil Forest area, 27 km southeast of Bisti, the Bisti Member comprises two typical brown-capped sandstones separated by a sequence of 7.5 m of mudstone, siltstone and a thin coal (Hunt,

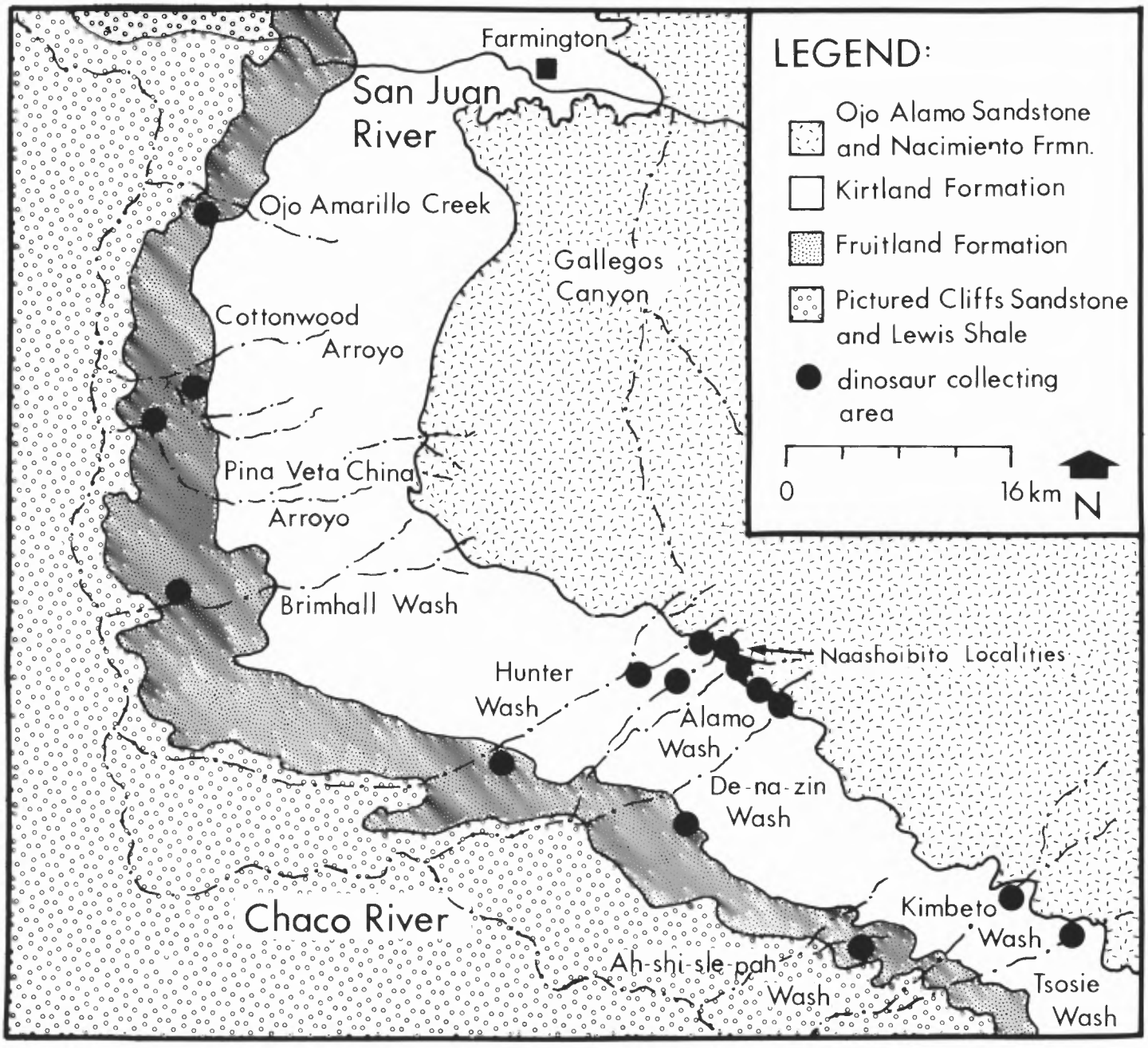

FIGURE 1. Distribution of the Fruitland and Kirtland Formations in northwestern New Mexico and location of some of the principal dinosaur collecting areas.

1984). Where only one sandstone is present, the Bisti extends from the base to the top of this unit. Where the Bisti Member is represented by a more complex sequence of strata, the base is at the bottom of the lowest brown-capped sandstone and its upper boundary is at the top of the highest such sandstone. Thus, all the finer grained strata between the sandstone are included in the Bisti Member.

Sandstones of the Bisti Member are more resistant to weathering than other sandstones in the upper Fruitland–lower Kirtland sequence and subsequently often cap ridges and pinnacles, for example in sec. 32, T24N, R13W. These pinnacles are frequently used as nesting sites, in Hunter Wash and the Fossil Forest area, by the ferruginous hawk, which is a candidate species for the federal threatened and endangered species list.

The Bisti Member is very conspicuous in geophysical logs (Fig. 4) as the only prominent sandstone between the Pictured Cliffs Sandstone and the Farmington Member of the Kirtland Formation. It is particularly prominent on Spontaneous Potential logs.

Hunter Wash Member

Reeside (1924) included all the fine-grained strata between the Fruitland Formation and the Farmington Sandstone Member of the Kirtland Formation in a unit informally termed the lower shale. He referred to this unit as the "lower shale member" of the Kirtland. This unit is readily mappable (e.g., O'Sullivan et al., 1979; Scott et al., 1979) and consists dominantly of green siltstone with minor white, lenticular sandstone, thin coal and rare volcanic ash beds.

We coin the name Hunter Wash Member for this stratigraphic unit. The type section is along Hunter Wash (Fig. 5) in secs. 23–26, 27–28, 33–34, T24N, R13W, and secs. 8–9, 16–20, T24N, R12W (Reeside, 1924, plate 2, section 15). The name Hunter Wash local fauna was

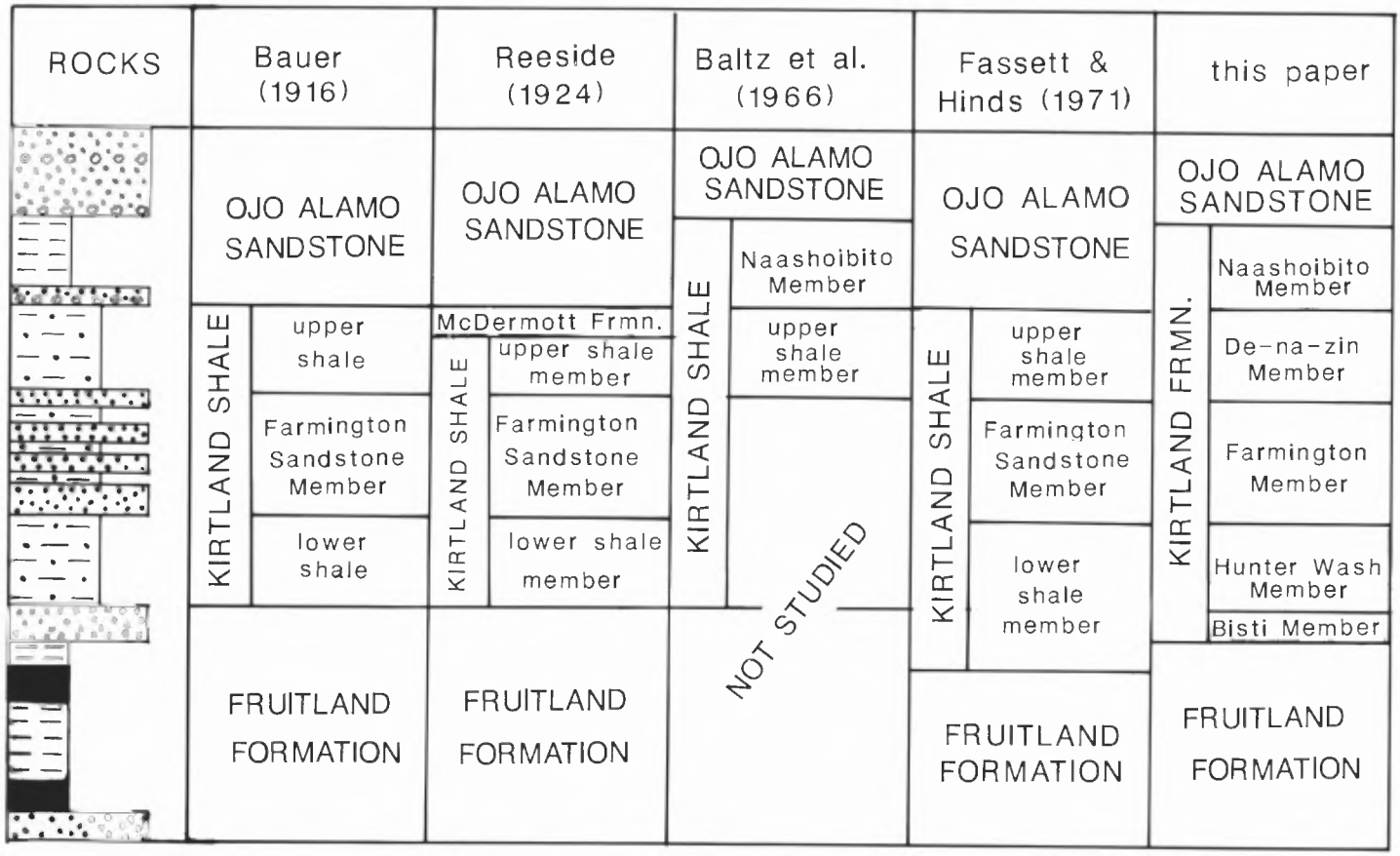

FIGURE 2. Changing nomenclature of the Fruitland and Kirtland Formations. Note that older authors placed the Naashoibito Member within the Ojo Alamo Sandstone and that the boundary between the Fruitland and Kirtland Formations has been placed at the top of the Bisti Member (Bauer, 1916; Reeside, 1924), at the top of the highest thick coal (Fassett and Hinds, 1971) and herein at the base of the Bisti Member.

proposed by Clemens (1973) and was subsequently used by Lehman (1981), Lucas (1981) and Kues and Lucas (1985), among others, to refer to the vertebrate fossil assemblages from the Fruitland and Kirtland Formation below the Naashoibito Member. This paleontological term is abandoned here and should not be confused with the rock-stratigraphic term Hunter Wash Member. The Hunter Wash Member is about 375 m thick in its type area and consists of green and gray siltstones and mudstones, minor thin (<1 m thick) carbonaceous mudstones and coals, white lenticular, crossbedded sandstone and rare, thin, air fall volcanic ashes.

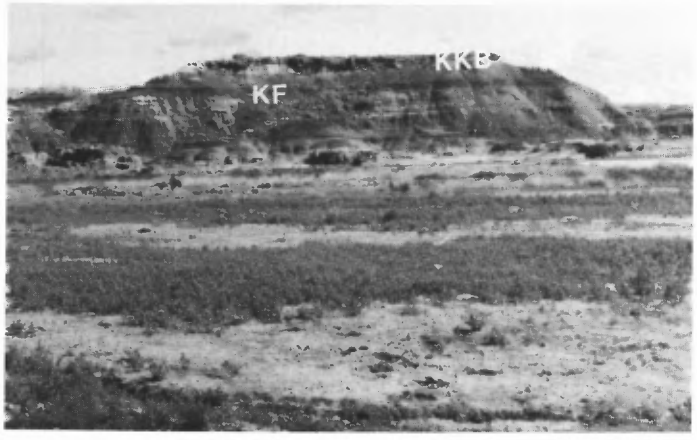

FIGURE 3. Type section of the Bisti Member of the Kirtland Formation. Abbreviations: KF, Fruitland Formation; KKB, Bisti Member of the Kirtland Formation.

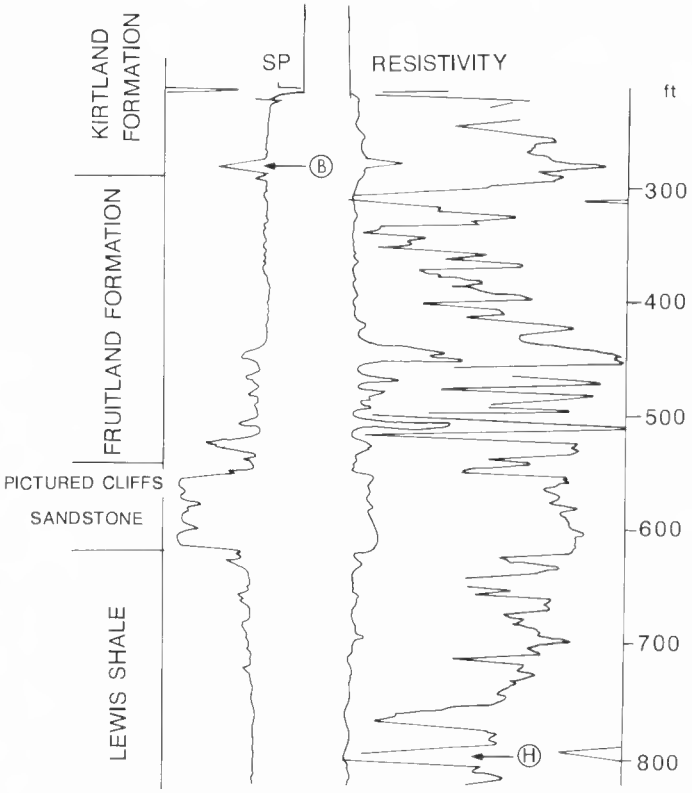

FIGURE 4. Geophysical log of Standard Oil of Texas Navajo Tribal 9-1 (sec. 9, R15W, T27N) showing prominence of Bisti Member of Kirtland Formation (indicated by B). Huerfanito Bentonite Bed is indicated by H.

FIGURE 5. Aerial view, looking approximately north, of outcrops of the Fruitland Formation (KF), The Bisti member of the Kirtland Formation (KKB), including its type section (KKB(T)) and a portion of the type section of the Hunter Wash Member of the Kirtland Formation (KKH), along Hunter Wash, San Juan County, New Mexico. The upper left of the photograph is in sec. 29, T24N, R13W and the lower right is in sec. 3, T23N, R13W. Dip is to the northeast. Photograph is copyrighted by Paul L. Sealey and is used with permission.

Farmington Member

The Farmington Sandstone Member was the only one of the four members of the Kirtland Formation named by Bauer (1916). Since the Farmington Sandstone Member also includes conglomerate, mudstone and siltstone, we refer to it as the Farmington Member. Farmington Member sandstones are typically tabular in geometry and consist of a lower friable yellowish unit overlain by a brown, ferruginous upper portion (Bauer, 1916, plate 68A). The type section of the Farmington is along the San Juan River (Bauer, 1916, plate 65, section A′), where the unit is 139 m thick (Bauer, 1916). The Farmington is a clastic wedge originating northwest of the present San Juan Basin (Reeside, 1924, plate 2). Individual sandstone lenses of the Farmington become thinner and less numerous to the southeast (Fassett and Hinds, 1971).

De-na-zin Member

Reeside (1924) applied the informal term "upper shale member" to a sequence of siltstone, mudstone and sandstone between the Farmington Member and the Ojo Alamo Sandstone, which included what is now termed the Naashoibito Member of the Kirtland Formation (Baltz et al., 1966). Bauer (1916) had referred to this unit as the upper shale. The "upper shale member" is a thin (usually less than 30 m) unit but it is pervasive and mappable (e.g., Baltz et al., 1966, fig. 3). We here name the upper shale member of Reeside (1924) the De-na-zin Member for outcrops in NW¼ sec. 19, T24N, R11W (Alamo Mesa East 7.5 minute quadrangle). The De-na-zin Member is about 30 m thick in its type area and consists of green mudstone, siltstone and minor sandstone. It forms a slope break between the Farmington Member and the lower conglomerate of the Naashoibito Member. The De-na-zin Member has been mapped by Brown (1982) in and around the type area.

Fassett and Hinds (1971) included the De-na-zin Member in the Farmington Member. This stratigraphic nomenclature gives rise to a very misleading impression of basin evolution. Thus, in their cross sections (e.g., Fassett and Hinds, 1971, plate 2, cross section E–E′) it appears that the Ojo Alamo is truncating the Farmington (Fig. 6A) and De-na-zin Members. However, the Farmington Member actually is pinching out to the southeast (Baltz et al., 1966, fig. 3) so that the De-na-zin and Hunter Wash Member become inseparable (Fig. 6B). In this same cross section, application of the name Fruitland Formation to all strata in the Fruitland-Kirtland sequence in the Cuba area again suggests that the Kirtland has been removed from the southern part of the basin by a pervasive unconformity at the base of the Ojo Alamo. Again, it is the stratigraphic nomenclature that is misleading. In the Cuba area

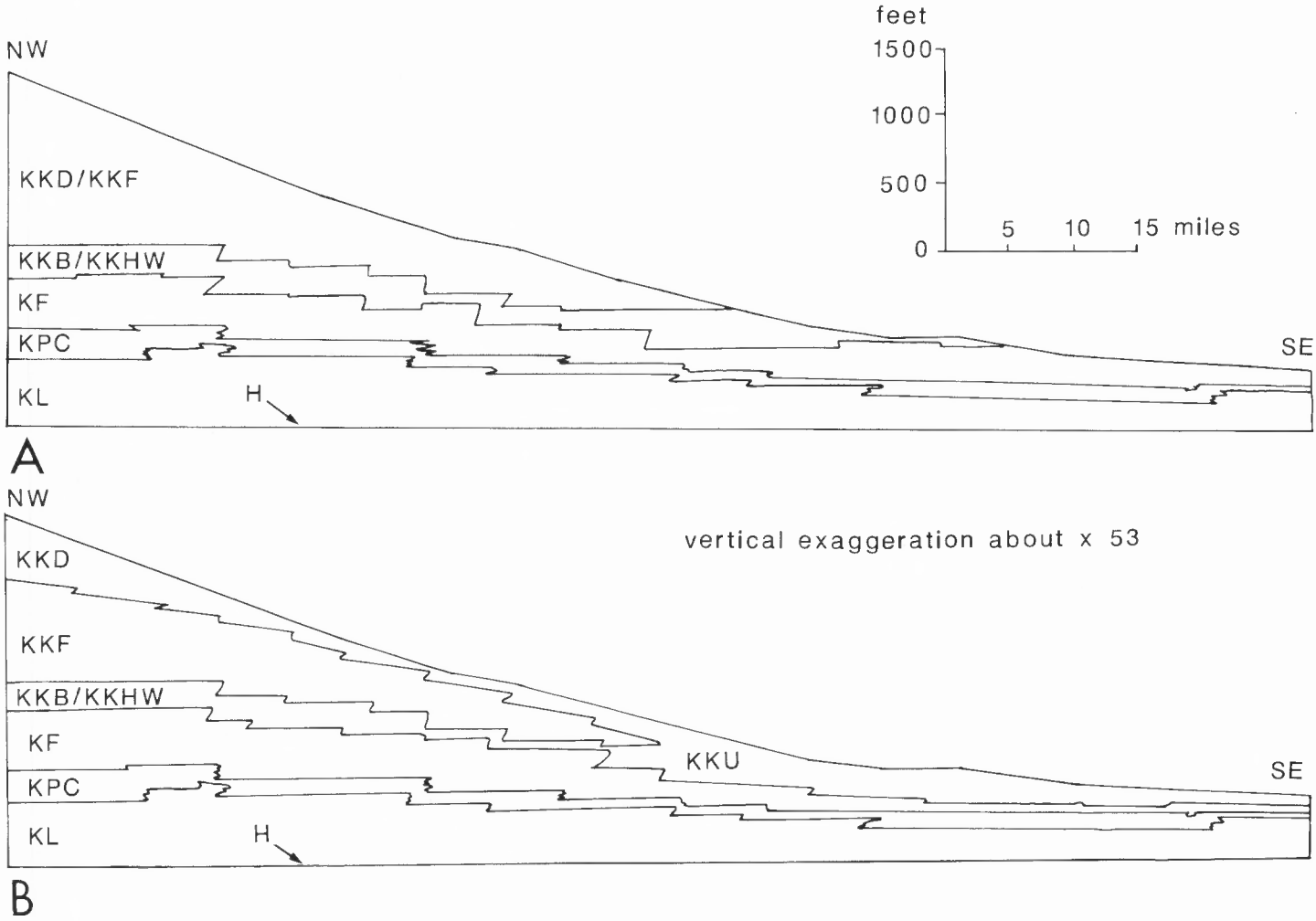

FIGURE 6. Cross sections across the San Juan Basin from northwest to southeast showing how differing use of nomenclature of Fruitland and Kirtland Formations affects ideas of a pervasive unconformity at the base of the Ojo Alamo sandstone (adapted from Fassett and Hinds, 1971, plate 2). A, Nomenclature of Fassett and Hinds (1971) suggesting angular unconformity at the base of the Ojo Alamo Sandstone because of progressive southwestward truncation of the Farmington and De-na-zin Members of the Kirtland Formation and the Kirtland Formation undivided. B, Nomenclature of this report, indicating that there is no angular unconformity at the base of the Ojo Alamo Sandstone because the Kirtland Formation is continuous across the basin and most depositional thinning is caused by the pinching out of the Farmington Member (after Hunt, 1984, plate 1). Abbreviations are: H, Huerfanito Bentonite Bed; KF, Fruitland Formation; KKB, Bisti Member of Kirtland Formation; KKD, De-na-zin Member of Kirtland Formation; KKF, Farmington Member of Kirtland Formation; KKHW, Hunter Wash member of Kirtland Formation; KKU, Kirtland Formation undivided; KPC, Pictured Cliffs Sandstone.

is a lower coal-bearing or carbonaceous-shale bearing unit (Fruitland Formation) overlain by a unit barren of coal (Kirtland Formation), as shown by Fassett and Hinds themselves (1971, figs. 10, 12). Obviously, if the Kirtland is present in the southeastern basin, where the Fruitland-Kirtland sequence is thin, there is a large component of depositional thinning from the northwest to the southeast and this thinning is not due to an angular unconformity at the base of the Ojo Alamo Sandstone (cf., Klute, 1986).

Naashoibito Member

Baltz et al. (1966) named the Naashoibito Member of the Fruitland Formation for strata that were generally included in the lower part of the Ojo Alamo Sandstone (e.g., Brown, 1910; Sinclair and Granger, 1914; Bauer, 1916; Powell, 1973). These strata are distinguished by the purple color of the mudstones, the presence of a lower conglomeratic sandstone and by a high percentage of channelform sandstones compared to the underlying De-na-zin Member. All rock types are rich in volcanic debris. The upper portion of the De-na-zin Member includes a few purple mudstones, which undoubtedly led Reeside (1924) to recognize the presence of the McDermott Formation below the Naashoibito. Powell (1973) included the Naashoibito Member in the Ojo Alamo Sandstone and named the overlying Ojo Alamo Sandstone restricted of Baltz et al. (1966) the Kimbetoh Member. We do not follow this usage as there is no lithostratigraphic (or paleontological or sequence stratigraphic) evidence for allying the Naashoibito Member with the "Kimbetoh Member."

Flynn (1986) suggested placing the lower contact of the Naashoibito Member below the lower conglomerate at the base of the purple mudstones in the upper De-na-zin Member of other authors. We dispute Flynn's claim that dinosaur fossils are common in the purple mudstones below the lower conglomerate. Further, we do not advocate adoption of his revised lower contact of the Naashoibito simply because this contaet is not mappable. As Flynn (1986, p. 6) himself noted, the purple mudstones below the lower conglomerate grade laterally into "typical" drab De-na-zin mudstones. The only mappable lower contact for the Naashoibito is at the base of the lower conglomerate.

SEDIMENTOLOGY

Fruitland Formation

The Fruitland Formation is the major coal-producing unit in New Mexico and is obviously of broadly paludal origin. Detailed sedimen-

tology has demonstrated that the Fruitland was deposited as landward facies of two types of shorelines, a deltaic complex to the northwest and a barrier shoreline to the southeast (Erpenbeck, 1979; Flores and Erpenbeck, 1982). Paleoflow was to the northeast at right angles to a shoreline that trended northwest-southeast (e.g., Hunt, 1984).

Kirtland Formation

The Bisti Member represents fluvial deposition by streams of lower sinuosity than those that characterized the upper Fruitland. Paleoflow in the southwestern portion of its outcrop was to the northeast, whereas flow from the San Juan River area was to the southeast. This suggests that drainage was at least partially concentric and that the paleoslope was no longer perpendicular to the former shoreline. The Bisti Member has an areal distribution that approximates that of the Farmington Member, which suggests that both were infilling a structural depression that represented increased downward flexing of the San Juan Basin (the Kirtland Basin of Silver, 1951). Thickness trends of the entire Fruitland-Kirtland sequence (Fassett and Hinds, 1971, fig. 11, plate 2, cross section E–E′) indicate that the northwestern quadrant of the basin subsided more rapidly than other segments during the late Campanian–late Maastrichtian.

The Hunter Wash Member represents deposition by high sinuosity streams in a subsiding basin as indicated by the presence of isolated, single-story channels surrounded by large volumes of overbank fine-grained sediments.

It is clear that the Farmington Member is of fluvial origin, not marine as suggested by Dilworth (1960) on the basis of reworked marine microfossils. This is indicated by paleogeography and the dominance in the Farmington of tabular, crossbedded sandstones with erosional bases (e.g., fluvial channels) and the abundance of nonmarine fossils (dinosaurs, plants). The Farmington Member is characterized by tabular sandstone bodies with relatively minor intervals of siltstone. This suggests that rates of deposition were close to rates of subsidence in the northwestern San Juan Basin during deposition of this unit.

The Naashoibito Member represents deposition by low-sinuosity meandering and braided streams with associated well-drained floodplains (Lehman, 1985). The Naashoibito Member represents the end of a trend through the Fruitland and Kirtland of increasingly well drained overbank conditions. It differs from underlying units, except locally in the upper De-na-zin Member, by including a large proportion of intermediate volcanic detritus (Lehman, 1985).

ECONOMIC IMPORTANCE OF THE BISTI MEMBER OF THE KIRTLAND FORMATION

The Bisti Member of the Kirtland Formation is of economic importance, as it yields both gas and, potentially, uranium. Rich, but small scale, uranium deposits are locally present in the Bisti Member, as for example on the San Juan mine lease west of Farmington. The small size of these deposits and the depressed price of uranium means that these occurrences will probably not be mined in the near future.

In recent years the Fruitland Formation has been actively explored for natural gas development with the realization that coal seams can represent significant reservoirs. However, there have been several gas fields in the Fruitland-Kirtland sequence that are not associated with coal. Minor gas and oil fields have been associated with the Farmington Member (e.g., Wyper Farmington Field), which is a thick sequence of sandstone and therefore a good prospect for a reservoir. However, some fields have produced from lower intervals in the Kirtland and in the Fruitland, which are dominated by finer grained rock types that are not normally considered good reservoirs. This is somewhat surprising, as Fruitland "reservoirs tend to be limited in areal extent, discontinuous, and elusive. The sandstone bodies are traditionally so small that there is some difficulty in mapping most of them from section to section" (Riggs, 1983, p. 951).

Even from cursory examination of Fassett (1978, 1983), it is clear that there are two principal kinds of gas fields in the Fruitland–Hunter Wash Member sequence. The first have thick pay intervals in the lower Fruitland and have production histories that indicate increased rates of yield through time (e.g., Ignacio Blanco Fruitland–Pictured Cliffs and Los Pinos Fruitland North and South Fields). Increased production with time is typical of coal reservoirs, as gas yield rises with dewatering and these fields are undoubtedly producing from Fruitland coals (Aitken, 1983). The second group of fields are producing from laterally extensive sandstones, which many drillers have placed in the uppermost Fruitland (e.g., Flora Vista Fruitland, Gallegos Fruitland, Kutz Fruitland, Kutz Fruitland West Fields). These fields are producing from the Bisti Member of the Kirtland Formation.

TAPHONOMY

Fossil plants

Plant megafossils become increasingly rare up-section through the Fruitland and Kirtland Formations. They are very common in the carbonaceous strata of the Fruitland Formation and virtually all rock types contain disseminated plant debris. In finer grained rock types, well-preserved leaves are sometimes found (e.g., Robison et al., 1982). Plants are less common in the well-drained rocks of the lower Kirtland and are totally absent from the Naashoibito Member. Pollen also becomes increasingly uncommon up through the sequence and is again absent from the Naashoibito Member. This trend in plant preservation is due to the increased drainage and increased oxidation represented by environments from the Fruitland to the Naashoibito.

Invertebrate fossils

Invertebrate fossils have a distributon in the Fruitland and Kirtland Formations similar to that of plants. The majority of invertebrate fossils are unionid bivalves and nonmarine gastropods, and these are common in the Fruitland, fairly rare in the lower Kirtland and rare in the upper Kirtland. In the lowermost Fruitland there are banks of oysters, indicating brackish waters. In most of the remainder of the Fruitland, unionids and gastropods occur in fine-grained overbank environments. In the Hunter Wash and Bisti Members of the Kirtland, unionids and gastropods are mainly restricted to channel-lag accumulations. This trend again is related to the increased drainage represented by environments in the Kirtland. An upward trend can be discerned from brackish to more freshwater assemblages (Hartman, 1981).

Vertebrate fossils

Vertebrate fossils are nonrandomly distributed in the Fruitland and Kirtland Formations. The majority of fossils are from two stratigraphic intervals in the upper Fruitland Formation–Bisti Member of the Kirtland and in the Naashoibito Member of the Kirtland (Fig. 7). The upper Fruitland–Bisti Member sequence has yielded the majority of fossils from Hunter Wash, Ah-shi-sle-pah Wash and the Fossil Forest area, and these constitute virtually all the pre-Naashoibito fossil vertebrate specimens. This stratigraphic restriction was noted by Clemens (1973) and Hunt (1984, 1991).

In addition, the vast majority of upper Fruitland–Bisti vertebrate fossils have been collected from a restricted area within the outcrop belt of these units extending from Hunter Wash southeast to Ah-shi-sle-pah Wash. The Naashoibito fauna is geographically restricted because this stratigraphic unit only occurs in a limited geographic area and elsewhere is removed by pre–Ojo Alamo erosion. Part of the explanation for the areal restriction of the upper Fruitland–Bisti fossil collections is related to human geography. The Navajo Reservation encompasses most of the potentially fossiliferous interval in an area between Hunter Wash and the San Juan River, and these lands have always received much less attention than public lands to the southeast. In southern Colorado, vegetation and steeper dips prevent the formation of badlands in the Fruitland and Kirtland Formations, which severely limits the potential for finding fossils in these strata.

The geographic distribution of the upper Fruitland–Bisti Member fauna may be related to two factors: (1) fossils appear to be preserved in strata in the northwest deposited behind fluvially dominated deltas, whereas shorelines to the southeast represent barrier islands and few fossils are preserved in coastal deposits landward of them (Hunt and Lucas, 1983; Hunt, 1984, 1991); and (2) the area with the highest

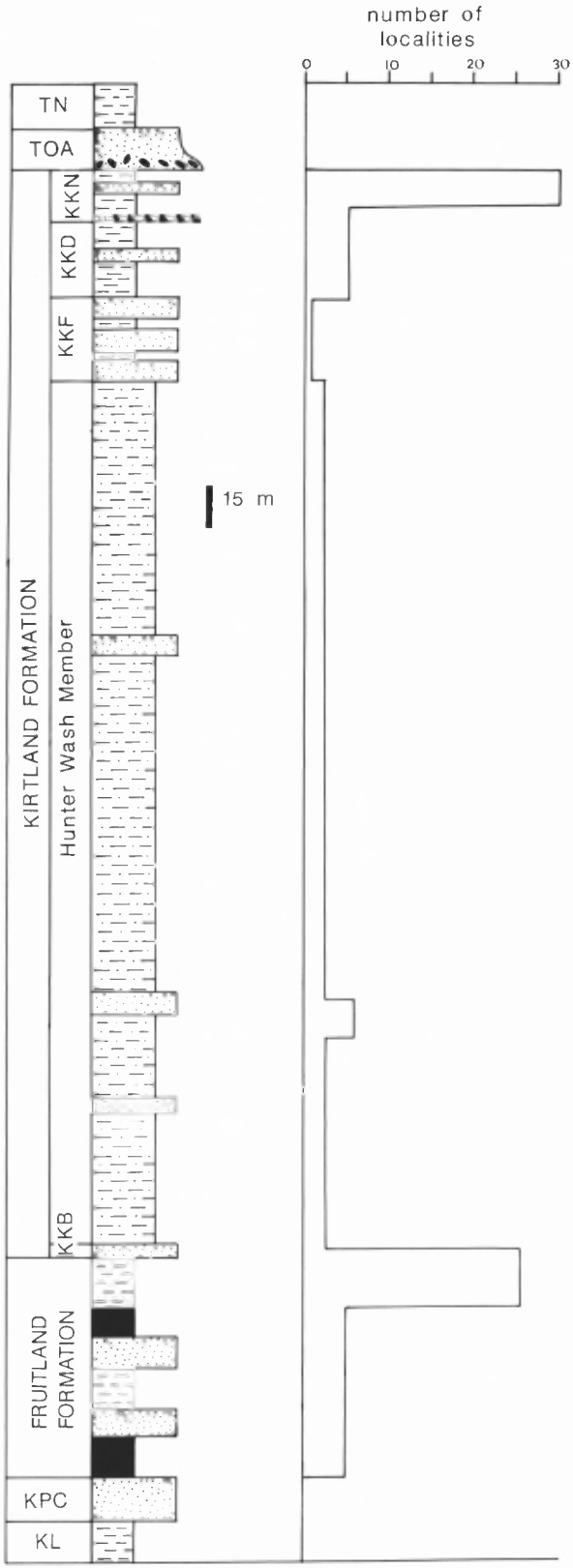

FIGURE 7. Semiquantitative diagram showing distribution of fossil vertebrate localities in the Fruitland and Kirtland Formations of the Hunter Wash/De-na-zin/Willow Wash drainage. Data from Kues et al. (1977), O'Sullivan et al. (1979), Scott et al. (1979), Brown (1982) and NMMNH locality files. Abbreviations are: KKB, Bisti Member of Kirtland Formation; KKD, De-na-zin Member of Kirtland Formation; KKF, Farmington Member of Kirtland Formation; KL, Lewis Shale; KPC, Pictured Cliffs Sandstone; TOA, Ojo Alamo Sandstone; TN, Nacimiento Formation.

concentration of fossils corresponds to the area in which the Bisti and Farmington Members crop out, and probably represents an area of the basin in which Upper Cretaceous deposition was subject to increased rates of subsidence (Hunt, 1984, 1991). Both factors may be related, as deltaic deposition in the northwestern part of the San Juan Basin may have resulted from a slightly steeper paleoslope in this area due to the increased subsidence.

In the upper Fruitland–Bisti sequence, vertebrate fossils are equally common in both channel and interchannel environments (Hunt, 1984, 1991), whereas in the Naashoibito Member well-preserved fossils are confined to meandering stream channels (Lehman, 1985). In many Upper Cretaceous stratigraphic units, vertebrate fossils are much more common in channel deposits (Hunt, 1984, 1991).

PALEONTOLOGY

Plants

The taxonomy of fossil plants from the Fruitland and Kirtland Formations is confused. Most work has been based on the taxonomy of F. H. Knowlton, a preeminent paleobotanist of the early twentieth century. However, Knowlton, as was customary in his time, placed many Cretaceous specimens in modern taxa on the basis of gross morphological similarities (e.g., *Ficus*, *Laurus*) and with no regard to variability of the foliage on one plant. Initial collections were made by Bauer and his party (Knowlton, 1916) and later, smaller samples were reported by other USGS geologists (Lee, 1917; O'Sullivan et al., 1972). Specimens were collected more recently by Kues et al. (1977), Tidwell et al. (1981) and Robison et al. (1982). Large undescribed collections, principally made by J. McClammer, are at NMMNH and YPM.

Most recent workers (e.g., Kues et al., 1977; Tidwell et al., 1981) considered the Fruitland and Kirtland floras as one entity. We present separate floral lists for both formations (Tables 1, 2) because they represent such different environmental settings and different ages. No megafossil plant specimens have been recovered from the Naashoibito Member of the Kirtland Formation. All early collections of plant fossils from the "Ojo Alamo Sandstone" of older usage were from the upper conglomerate or Ojo Alamo Sandstone of modern workers and not from the Naashoibito Member of the Kirtland, which earlier workers considered to be part of the "Ojo Alamo." Additional specimens reported by Lee (1917) are from an undivided Fruitland-Kirtland sequence ("Laramie") near Dulce, but it is clear that they are from the lower Fruitland Formation (Lee, 1917, plate 25A). It is not clear if other floras reported by Lee (1917), for example from near Durango, are from the Fruitland or Kirtland. O'Sullivan et al., (1972) listed specimens from an undivided Fruitland-Kirtland sequence, and these occurrences are not repeated in Table 1. Kues et al. (1977) and Tidwell et al. (1981) both reported new occurrences but did not report, with a few exceptions, which of the two formations their specimens came from. Taxa that could not be assigned to either formation were not included and this, unfortunately, includes most of the palm diversity.

There are no recent detailed studies of the floras of the Fruitland and Kirtland Formations. Therefore, interpretations of differences in diversity must be considered preliminary, but we think that such comparisons are of some utility. It is clear that although the floras of the Fruitland and Kirtland Formation are of about equal diversity, there are major differences between the two floras (Tables 1, 2). Ferns are more common in the Kirtland, which reflects the fact that modern ferns in the tropics are more common in upland and better drained areas (Berry, 1924). The genus *Anemia* has modern species that are restricted to swamps (Tidwell et al., 1981) and is restricted to the Fruitland. Conifers are more diverse in the Fruitland flora, and taxa that are important in swamp communities, such as *Brachyphyllum macrocarpum* and *Sequoia cuneata* (Parker, 1976; Tidwell et al., 1981) are restricted to the Fruitland.

The Kirtland flora (Table 2) contains fewer monocots, which are represented by several families not found in the Fruitland (e.g., Cyperaceae, Araceae, Cannaceae). Palms are only present in the Fruitland. The dicots form the majority of plant specimens in both the Fruitland and Kirtland floras (Tidwell et al., 1981). Dicots are more diverse at

TABLE 1. Flora of the Fruitland Formation, from Knowlton (1916), Kues et al. (1977) and Tidwell et al. (1981).

- Filicophyta
  - Scizaeaceae
    - *Anemia hesperia*
    - *Anemia* sp.
  - Polypodiaceae
    - *?Asplenium coloradense*
- Coniferophyta
  - Araucariaceae
    - *Araucaria* sp.
    - *Araucaria longifolia*
  - Cupressaceae
    - *Brachyphyllum macrocarpum*
  - Taxodiaceae
    - *Sequoia reichenbachii*
    - *Sequoia obovata?*
    - *Sequoia cuneata*
    - *Cunninghamites pulchellus*
- Anthophyta
  - Monocotyledonae
    - Palmae
      - *Sabalites imperialis*
      - *Sabalites montana*
      - *Sabalites* sp.
    - Pontederiaceae
      - *Heteranthera cretacea*
  - Dicotyledonae
    - Saliceae
      - *Salix baueri*
      - *Salix* sp.
    - Fagaceae
      - *Quercus baueri*
    - Moraceae
      - *Ficus squarrosa?*
      - *Ficus rhamnoides*
      - *Ficus planicostata*
      - *Ficus praetrinervis*
      - *Ficus starkvillensis?*
      - *Ficus praelatifolia*
      - *Ficus curta?*
      - *Ficus wardii*
      - *Ficus baueri*
      - *Ficus leei*
      - *Ficus* sp.
    - Nymphaeceae
      - *Nelumbo* sp.
    - Cercidiphylluaceae
      - *?Cercidiphyllum* sp.
    - Menispermaceae
      - *Menispermites* sp.
    - Magnoliacea
      - *Magnolia cordifolia*
    - Lauraceae
      - *Laurus baueri*
      - *Laurus coloradensis*
      - *Cinnamomum sezannense*
    - Saxifragaceae
      - *Ribes neomexicana*
    - Leguminosae
      - *?Leguminosites neomexicana*
    - Rhamnaceae
      - *Rhamnus goldianus*
      - *?Zizyphus* sp.
    - Myrtacea
      - *Myrtophyllum torreyi*
- Incertae sedis
  - *Phyllites neomexicanus*
  - *Phyllites petiolatus*
  - *Pterospermites undulatus*
  - *Pterospermites* sp.
  - *Carpites baueri*
  - *Carpites* sp.

TABLE 2. Flora of the Kirtland Formation (below the Naashoibito Member) from Knowlton (1916), Lee (1917), O'Sullivan et al. (1972), Kues et al. (1977), Tidwell et al. (1981), Robison et al. (1982) and Hunt (1984).

- Filicophyta
  - *Asplenium neomexicana*
  - *Asplenium* sp.
  - *Onoclea neomexicana*
  - *Woodwarthia crenata*
  - Salvinaceae
    - *Salvinia* sp.
- Coniferophyta
  - Araucariaceae
    - *Araucaria* sp.
  - Taxodiaceae
    - *Sequoia cuneata*
- Anthophyta
  - Monocotyledonae
    - Cyperaceae
      - *Cyperacites* sp.
    - Araceae
      - *Pistia corrugata*
    - Cannaceae
      - *?Canna magnifolia*
    - Dicotyledonae
    - Salicaceae
      - *Salix lancensis*
    - Juglandaceae
      - *Carya antiquorum*
    - Fagaceae
      - *Dryophyllum subfalcatum*
    - Moraceae
      - *Ficus crossii*
      - *Ficus leei*
    - Menispermaceae
      - *Menispermites belli*
    - Magnoliacea
      - *Magnifolia berryi*
    - Lauraceae
      - *Laurus coloradensis*
      - *Laurophyllum salcifolium*
      - *Laurophyllum wardiana*
      - *Laurophyllum* sp.
    - Platanaceae
      - *Platanus nobilis*
      - *Platanus raynoldsi*
    - Leguminosae
      - *?Leguminosites neomexicana*
    - Rhamnaceae
      - *Rhamnus goldianus*
      - *Rhamnus minutus*
      - *?Zizyphus* sp.
    - Vitaceae
      - *Vitis lobata*
      - *Cissus marginata*
    - Dillenaceae
      - *Dillenites cleburni*
    - Myrtacea
      - *Myrtophyllum torreyi*
      - *Myrtophyllum neomexicanum*
    - Caprifoliaceeae
      - *Viburnum antiquum*
- Incertae sedis
  - *Pterospermites* sp.
  - *Carpites baueri*
  - *Carpites lancensis*
  - *Carpites* sp.
  - *?Ficus trineruis*
  - unidentified flowers and fruit

the family level in the Fruitland, being represented by 14 families as opposed to 12 in the Fruitland. However, the specific diversity is apparently greater in the Fruitland flora, particularly within the Moraceae (Table 1).

The floral evidence agrees with a general increase in drainage from the Fruitland to Kirtland. The abundance of medium-sized angiospermous leaves with entire or nearly entire margins and drip points suggests a warm-temperature to subtropical climate during deposition of both formations by analogy with modern floras (Lucas, 1981; Tidwell et al., 1981; Robison et al., 1982).

Invertebrates

Invertebrate fossils are relatively common in the Fruitland Formation but are rare in the Kirtland Formation and have only been reported from one locality in the Naashoibito Member (Tables 3, 4). The Naashoibito specimens are unstudied unionid bivalves (O'Neill, personal comm. 1992). The majority of specimens represent brackish-tolerant oysters in the lower Fruitland and freshwater unionid bivalves and gastropods in stratigraphically higher units. Stanton (1916) described the numerous specimens collected by Bauer and Reeside. Unfortunately, many of these taxa are represented in the USNM by only one specimen (Hartman, oral comm. 1985). Lee (1917) reported additional records of nonmarine invertebrates from the "Laramie" of southwestern Colorado but it is not clear if these specimens were from the Fruitland Formation or the Kirtland Formation. Subsequently, the only large collections have been made by Kues et al. (1977) and J. H. Hartman (North Dakota Mining and Mineral Resources Research Institute) during the past decade. Hartman is studying these collections and is currently revising the taxonomy of these molluscs. He has collected topotypes of Stanton's taxa and has sampled localities throughout the Fruitland-Kirtland sequence in New Mexico and Colorado. Kues (1983) reported the unusual occurrence of a crustacean and a bryozoan from the Fruitland Formation.

TABLE 3. Invertebrate fauna of the Fruitland Formation from Stanton (1916), Kues (1983) and Hutchinson and Kues (1985).

Bryozoa
?Conopeum sp.
Crustacea
?Xanthoidea sp.
Bivalvia
Ostrea glabra
Anomia gryphorhynchus
Anomia gryphaeiformis
Modiola latiscostata
Unio holmesianus
Unio amarillensis
Unio gardneri
Unio reesiderei
Unio brachypisthus
Unio neomexicanus
Unio brimhallensis
Unio cf. *Unio primaevus*
Corbicula cytheriformes
Corbula chacoensis
Panopaea simulatrix
Teredina neomexicana
Teredina sp.
Gastropoda
Neritina baueri
Neritina sp.
Campeloma amarillensis
Tulotoma thompsoni
Melania insculpta
?Goniobasis subtortuosa
Physa reesidei
Physa sp.
Planorbis chacoensis

The diverse bivalves and gastropods of the Fruitland may have biochronologic utility, but this will depend on revision of their taxonomy.

Vertebrates

Introduction

The vertebrate faunas of the Fruitland and Kirtland Formations represent the largest and most diverse Late Cretaceous faunas of the southern Western Interior and have a long history of collection and study (Hunt et al., 1992). Three vertebrate faunas can be discriminated within the Fruitland and Kirtland Formations: (1) Fruitland Formation (Table 5); (2) Hunter Wash Member, Farmington Member and De-na-zin members of the Kirtland Formation (Table 6); and (3) Naashoibito Member of the Kirtland Formation (Table 7). These faunas form a sequence of decreasing diversity. This is in part due to the fact that the majority of microvertebrate sites are in the Fruitland Formation. Microvertebrate localities account for all the mammalian and amphibian fossils from these strata. It is unfortunate that some recent authors (e.g., Weishampel, 1990) continue to list the fauna of the Kirtland as a whole despite the long realization that two faunas of demonstrably different ages are present in this formation (e.g., Lehman, 1981; Lucas, 1981; Lucas et al., 1987).

Microvertebrates

Virtually all fish, amphibian and reptiles, apart from turtles and dinosaurs, are represented by disarticulated microvertebrate specimens. The taxonomy of these specimens is, by necessity, largely typological, but they are comparable with contemporaneous faunas in the Western Interior (e.g., Estes, 1964; Sahni, 1972; Bryant, 1989).

Turtles

A large number of turtles are present in the Fruitland and Kirtland faunas (Tables 5–7). Unfortunately, as is true of most Mesozoic faunas, most turtles are represented solely by shells. There is some debate about the utility of shells in turtle taxonomy (e.g., Gaffney, 1972), and the diversity of turtle taxa listed here is probably inflated.

Dinosaurs

The dinosaur faunas of the Fruitland and Kirtland Formations were first described in detail by Gilmore (1916), who based his study on specimens collected by Bauer and Reeside. Subsequently, the collections of Charles Sternberg were described by Wiman (1930, 1931, 1932, 1933), Osborn (1923), Gilmore (1935) and Ostrom (1960, 1961). Kues et al. (1977), Lehman (1981), Rowe et al. (1981), Lucas et al. (1987) and others have described subsequent discoveries (Tables 5–7).

A large, undescribed collection from the upper Fruitland has been amassed by Wolberg and co-workers in the Fossil Forest area. These specimens are dominated by disarticulated material but include partial skeletons (Hunt, 1984, 1991). They are housed at the University of Kansas and are being described by J. P. Hall.

The dinosaur specimens from the Fruitland and Kirtland Formations largely consist of disarticulated and isolated bones. Partial skeletons and skulls are uncommon (e.g., Wiman, 1930; Ostrom, 1961).

The dinosaur faunas of the Fruitland and Kirtland Formations were recently reviewed by Lucas et al. (1987). However, in the last 5 years there has been a marked increase in the literature on dinosaur taxonomy

TABLE 4. Invertebrate fauna of the Kirtland Formation (pre-Naashoibito Member), from Stanton (1916) and Reeside (1924).

Bivalvia
?Unio pyramidatoides
Unio baueri
Unio sp.
Gastropoda
Viviparus sp.

TABLE 5. Vertebrate fauna of the Fruitland Formation, from Gilmore (1916, 1919, 1935), Osborn (1923), Wiman (1931, 1932, 1933), Ostrom (1961), Powell (1973), Clemens (1973), Kues et al. (1977, Armstrong-Ziegler (1978), Lucas (1981), Hutchinson and Kues (1985), Lucas et al. (1987), Flynn (1986), Bryant (1987), Hall and Wolberg (1989), Lehman and Carpenter (1990), Weishampel (1990), Lucas (1992), and this paper.

Chondrichthyes
Selachii
Hybodontidae
Lonchidion selachos
?*Lonchidion selachos*
Hybodus sp.
Isuridae
Isurus sp.
Orectolobidae
Squatirhina americana
Squatirhina sp.
Batoidea
Dasyatidae
Myledaphus bipartitus
Myledaphus sp.
Pristidae
Ischyrhiza avonicola
Ptychotrygon cf. *P. triangularis*
Squatirhina sp.
Osteichthyes
Acipenseriformes
Acipenser cruciferus
Polyodontidae
Paleopsephurus wilsoni
Amiiformes
Amiidae
Amia fragosa
Amia cf. *Amia uitaensis*
Amia sp.
?*Amia chauliodeia*
Melvius thomasi
Lepidosteiformes
Lepisosteidae
Atractasteus occidentalis
Atractasteus sp.
Elopiformes
Phyllodontidae
Paralbula casei
Paralbula cf. *P. casei*
cf. *Pseudoegertonia* sp.
Perciformes
Sciaenidae
Platacodon nanus
Amphibia
Anura
Discoglossidae
Scotiophryne pustulosa
Pelobatidae
?*Eopelobates* sp.
Urodela
Prosirenidae
Prodesmodon cf. *P. copei*
Batrachosauroididae
Opisthotriton kayi
?Urodela
Cuttysarkus mcnallyi
Reptilia
Testudines
Baenidae
"*Baena*" *nodosa*
Boremys pulchra
Compsemys sp.
Neurankylus eximius
Dermatemydidae
Adocus bossi
Adocus kirtlandius
Adocus sp.
?*Basilemys* sp.
Trionychidae
Aspideretes sp.
Trionyx sp.
indet
Sauria
Teiidae
Leptochamops denticulatus
Chamops segnis
Anguidae
cf. *Gerrhonotus* sp.
gen. et sp. indet.
Serpentes
Aniliidae
Coniopholis cosgriffi
Crocodilia
Crocodylidae
Brachychampsa sp.
?*Brachychampsa* sp.
Leidyosuchus sp.
?*Thoracosaurus* sp.
indet
Saurischia
Ornithomimidae
cf. *Ornithomimus* sp.
indet
Dromaeosauridae
indet
Troodontidae
indet
Tyrannosauridae
?*Albertosaurus libratus*
?*Albertosaurus* sp.
n. gen. et sp.
Ornithischia
Nodosauridae
indet
Ankylosauria
indet
Pachycephalosauridae
indet
Ceratopsidae
Pentaceratops sternbergii
indet
Hypsilophodontosauridae
?*Thescelosaurus* sp.
Hadrosauridae
Kritosaurus navajovius
Parasaurolophus cyrtocristatus
?*Corythosaurus* sp.
Reptilia incertae sedis
egg-shell fragments
Mammalia
Multituberculata
Neoplagiaulacidae
Mesodma sp.
?*Mesodma* sp.
?new genus and species
?Neoplagiaulacidae
Cimexomys cf. *C. judithae*
Ptilodontidae
Mesodma cf. *M. senecta*
cf. *Kimbetohia campi*
?Ptilodontidae
Mesodma n. sp. or *Cimexomys* cf. *C. antiquus*
Cimolodontidae
Cimolodon electus
Cimolodon n. sp. near *C. nitidus*
Cimolodon sp.
cf. *Cimolodon* sp.
Eucosmodontidae
new genus and species
cf. Eucosmodontidae
n. gen. et sp.
Cimolomyidae
Meniscoessus intermedius
cf. *Essonodon* n. sp.
?*Essonodon* sp.
Family incertae sedis
Paracimexomys judithae
Paracimexomys n. sp.
?*Essonodon* sp.
indet
Metatheria
Didelphidae
Alphadon halleyi
Alphadon parapraesagus
Alphadon cf. *A. wilsoni*
Alphadon cf *A. marshi*
Alphadon n. sp. A
Alphadon n. sp. B
cf. *Peradectes* sp.
Ectocentrocristus foxi
Pediomyidae
Pediomys fassetti
Pediomys cf. *P. cooki*
Aquiladelphis paraminor
Stagodontidae
cf. *Eodelphis* sp.
Eutheria
Leptictidae
?*Gypsonictops clemensi*
Gypsonictops cf. *G. lewisi*
Gypsonictops n. sp.
Palaeoryctidea
Cimolestes lucasi
cf. *Cimolestes* sp.
?Nyctitheriidae
Paranyctoides cf. *P. sternbergii*
Eutheria incertae sedis
indet

TABLE 6. Vertebrate fauna of the Kirtland Formation (pre-Naashoibito Member), from Gilmore (1916, 1919, 1935), Wiman (1930, 1931, 1932, 1933), Powell (1973), Clemens (1973), Kues et al. (1977), Armstrong-Ziegler (1978), Lucas (1981), Mateer (1981), Lucas et al. (1987), Flynn (1986), Bryant (1987), Hall and Wolberg (1989), Lehman and Carpenter (1990), and this paper.

- Chondrichthyes
  - Selachii
    - Squatirhinidae
      - indet
    - Batoidea
      - Dasyatidae
        - *Myledaphus* sp.
- Osteichthyes
  - Amiiformes
    - Amiidae
      - ?*Amia chauliodeia*
      - *Melvius thomasi*
  - Lepidosteiformes
    - Lepisosteidae
      - *Atractasteus occidentalis*
      - *Atractasteus* sp.
- Reptilia
  - Testudines
    - Baenidae
      - "*Baena*" *nodosa*
      - "*Baena*" *ornata*
      - "*Baena*" sp.
      - *Boremys pulchra*
      - *Neurankylus eximius*
      - *Thescelus insiliens*
    - Dermatemydidae
      - *Adocus bossi*
      - *Adocus kirtlandius*
      - *Basilemys nobilis*
    - Trionychidae
      - *Aspideretes ovatus*
      - *Aspideretes vorax*
      - *Plastomenus robustus*
      - *Plastomenus* sp.
      - *Platypeltis sternbergi*
  - Crocodilia
    - Goniopholidae
      - *Goniopholis kirtlandicus*
    - Crocodylidae
      - *Brachychampsa* sp.
      - *Leidyosuchus* sp.
      - ?*Thoracosaurus* sp.
  - Saurischia
    - Ornithomimidae
      - cf. *Struthiomimus* sp.
    - Dromaeosauridae
      - indet
    - Tyrannosauridae
      - *Albertosaurus* sp.
      - *Aublysodon* cf. *A. mirandus*
  - Ornithischia
    - Nodosauridae
      - ?*Euplocephalus* sp.
      - indet
    - Ankylosauria
      - indet
    - Ceratopsidae
      - cf. *Chasmosaurus* sp.
      - *Pentaceratops fenestratus*
    - Hadrosauridae
      - *Kritosaurus navajovius*
      - *Parasaurolophus* sp.
- Mammalia
  - Multituberculata
    - Neoplagiaulacidae
      - *Mesodma formosa*
    - Cimolomyidae
      - cf. *Meniscoessus* sp.
  - Metatheria
    - Didelphidae
      - *Alphadon marshi*

TABLE 7. Vertebrate fauna of the Naashoibito Member of the Kirtland Formation from Brown (1910), Hay (1908, 1910), Gilmore (1916, 1919, 1922), Wiman (1931, 1933), Mateer (1976), Kues et al. (1977), Lehman (1981, 1984, 1985), Lucas et al. (1987) and this paper.

- Osteichthyes
  - Lepisosteidae
    - *Atractasteus* sp.
  - Cyprinidae
    - indet
- Reptilia
  - Testudines
    - Baenidae
      - "*Baena*" *nodosa*
      - *Thescelius insiliens*
      - *Neurankylus eximius*
      - *Compsemys* sp.
    - Trionychidae
      - *Aspideretes vorax*
      - *Aspideretes fontanus*
      - *Aspideretes austerus*
    - Dermatemydidae
      - *Adocus vigoratus*
      - *Basilemys nobilis*
      - *Holplochelys* cf. *H. bicarinata*
  - Crocodilia
    - Goniopholididae
      - *Goniopholis* sp.
    - Crocodylidae
      - indet
  - Saurischia
    - Ornithomimidae
      - indet
    - Dromaeosauridae
      - indet
    - Tyrannosauridae
      - ?*Albertosaurus* sp.
      - cf. *Tyrannosaurus* sp.
    - Saurornithoididae
      - indet
  - Sauropodomorpha
    - Titanosauridae
      - *Alamosaurus sanjuanensis*
  - Ornithischia
    - Ankylosauridae
      - indet
    - Nodosauridae
      - ?*Panoplosaurus* sp.
      - indet
    - Ankylosauria
      - indet
    - Ceratopsidae
      - *Torosaurus* cf. *Torosaurus latus*
      - indet
    - Hadrosauridae
      - *Edmontosaurus saskatchewanensis*
      - *Parasaurolophus tubicen*
      - indet
- Mammalia
  - Multituberculata
    - Neoplagiaulacidae
      - *Mesodma formosa*
    - Cimolomyidae
      - *Essonodon browni*
      - cf. *Meniscoessus* sp.
  - Metatheria
    - Didelphidae
      - *Alphadon marshi*
      - *Alphadon* sp.

with the publication of two important books (Weishampel et al., 1990; Carpenter and Currie, 1990). Thus, we briefly review some aspects of the faunas and describe some recently collected specimens. Unfortunately, the recent literature lacks species-level revisions of some of the most important taxa, notably the Hadrosauridae, Ceratopsidae and Tyrannosauridae.

Carnosaurs—Carnosaur specimens are rare in the Fruitland and Kirtland Formations. Although generically indeterminate, one specimen worthy of note is NMMNH P-20879 (Fig. 8M), a pedal phalanx from the Kirtland Member. NMMNH P-20879 is comparable with phalanges of *Tarbosaurus* (Molnar et al., 1990, fig. 6.12E) and undoubtedly represents the third phalanx of the fourth digit of the right pes.

The record of tyrannosaurids in the San Juan Basin is poor, with only one partial skeleton (of *Aublysodon*) known from either the Fruitland or Kirtland Formations (Lehman and Carpenter, 1990). It is not even clear if this taxon is a tyrannosaur (Molnar et al., 1990). The only questionable record of *Tyrannosaurus* is based on an isolated tooth from the Naashoibito Member of the Kirtland Formation (Lucas et al., 1987). Tyrannosaurid taxonomy is in a state of flux, as is obvious if the recent classifications of Paul (1988), Molnar et al. (1990) and Carpenter (1990) are compared. Until the family is revised and the osteology of some important taxa (e.g., *Tyrannosaurus*) are described, it is difficult to identify fragmentary specimens.

Sauropods—The only described sauropod from the Fruitland or Kirtland is *Alamosaurus sanjuanensis* (Gilmore, 1922). Wolberg et al. (1988) listed a "new genus and species of titanosaurid" from the Fruitland Formation. However, lacking any documentation of this occurrence, we do not include it in our faunal lists.

Ankylosaurs—Several localities in the Fruitland and Kirtland yield nodosaurid scutes. Keeled scutes of nodosaurids can be distinguished from ankylosaurids in that ankylosaurid scutes are commonly excavated on their medial surface and thus are thin (Coombs and Maryanska, 1990). In contrast, nodosaurid scutes tend to be flat or only slightly cupped on their medial surface (Coombs and Maryanska, 1990). NMMNH P-20880 (Fig. 8K–L) represents the first specimens of a nodosaurid reported from the Fruitland Formation. These specimens are thick, keeled plates with only slightly concave medial surfaces. NMMNH P-1078 (Fig. 8I–J) is two large keeled plates of a nodosaur from the Naashoibito Member of the Kirtland Formation. These plates are similar to dorsal scutes of *Edmontia* (Coombs and Maryanska, 1990, fig. 22.13 upper).

Hadrosaurs—Several partial skeletons of hadrosaurs have recently been recovered from the Fruitland and Kirtland Formations. One such specimen from the Naashoibito Member was recently described by Hunt and Lucas (1991). A second partial skeleton is of an indeterminate hadrosaur from the upper Fruitland Formation of Ah-shi-sle-pah Wash (Fig. 8A–C, F–H). This specimen is interesting in that two ?successive ribs show healed fractures at about their midpoint (Fig. 8B–C).

A third hadrosaur skeleton from the Naashoibito Member of the Kirtland Formation includes much of a skull (Fig. 9) and associated postcranial elements (Fig. 8D–E). This specimen represents a hadrosaurine, as it possesses an anterodorsal process on the maxilla (Horner, 1990) and has a flat dorsal skull profile (skull roof not illustrated). The most diagnostic element is the jugal (Fig. 9A–D). The rounded lower margin of the lateral temporal fenestra, the narrow elongate postorbital process and the nearly right angle formed by the ventral margin below the lateral temporal fenestrae are of taxonomic value. In all these characters, NMMNH P-1041 differs from Judithian and Edmontonian taxa and from the Lancian hadrosaurines *Anatotitan* (Weishampel and Horner, 1990, fig. 26.5C), *Edmontosaurus regalis* (Lull and Wright, 1942, fig. 52) and *E. annectens* (Lull and Wright, 1942, fig. 53). However, the new specimen closely resembles the jugal of *Edmontosaurus saskatchewanensis* (Lull and Wright, 1942, fig. 56; Weishampel and Horner, 1990, fig. 26.5a) and we tentatively assign NMMNH P-1041 to this taxon.

Fruitland and Kirtland hadrosaurs have been most recently placed in three species, *Kritosaurus navajovius, Parasaurolophus tubicen* and *P. cyrtocristatus* (Lucas et al., 1987). Recently it has been suggested that *Kritosaurus* is either a junior subjective synonym of *Hadrosaurus* or *Gryposaurus* (e.g., Chapman and Brett-Surman, 1990) or that the genoholotype of *Kritosaurus* is indeterminate (Weishampel and Horner, 1990). The genoholotype of *Kritosaurus* (AMNH 5799) is a poorly preserved skull that is truncated at the anterior margin of the orbits. The entire lower jaw is preserved. We believe that this specimen can be distinguished from all other hadrosaur taxa and forms a basis for a distinct genus. Thus, *Kritosaurus* can be distinguished from most other hadrosaurine hadrosaurs (e.g., *Edmontosaurus, Anatitan, Maiasaura, Prosaurolophus, Saurolophus, Shantungosaurus*) by the high, short lateral profile of the skull. *Kritosaurus* is distinguished from *Brachylophosaurus* by the lack of a posterior extension of the nasals dorsal to the orbit, from *Aralosaurus* by the possession of much larger lateral temporal fenestrae and from *Hadrosaurus* by differences in the ilium (see below). We consider *Kritosaurus* to be a valid genus and a subjective senior synonym of *Gryposaurus*, contra Weishampel and Horner (1990).

Hadrosaurus foulkii is based on a partial postcranial skeleton and fragments of a skull (Lull and Wright, 1942, figs. 45–50). Only the postcranial specimens are complete enough for comparison with material of *Kritosaurus* (Lull and Wright, 1942; Pinna, 1979). The ilium is the most distinct of the elements represented in the skeleton of *Hadrosaurus*. Comparison of the ilia of *Hadrosaurus foulkii* (Leidy, 1856; Lull and Wright, 1942) and *Kritosaurus navajovius* (Parks, 1920) indicates that there are significant differences between the two taxa (Fig. 10). The ilium of *Hadrosaurus* is distinguished principally by having a deeper and more abruptly tapering anterior process (Fig. 10). Davies (1983) noted the following other differences between the ilia of *Hadrosaurus* and *Kritosaurus:* (1) the antitrochanter is weak with little or no ventral deflection in *Hadrosaurus*, whereas in *Kritosaurus* the antitrochanter is robust with a strong ventral deflection; (2) the ridge extending anteriorly on the dorsal margin is weak with a short, straight extension onto the posterior process in *Hadrosaurus*, but in *Kritosaurus* the ridge is well developed and extends anteriorly on the dorsal margin; (3) in *Hadrosaurus*, posterior end of the antitrochanter is midway down onto the body of the ilium with a faint ridge extending dorsocaudally onto the posterior process; and (4) the ratio of acetabular length/height is less in *Hadrosaurus* (0.82) than *Kritosaurus* (0.92). These differences are consistent with the variation between genera rather than within genera (cf. Brett-Surman, 1975). We conclude that *Kritosaurus* is not a junior subjective synonym of *Hadrosaurus*.

We consider that there are no significant differences between *Kritosaurus navajovius* and *Kritosaurus notabilis* and that they are synonyms. *Kritosaurus breviceps* (based on a partial dentary) and *Kritosaurus marginatus* (based on fragmentary postcrania) were assigned to the genus by Lull and Wright (1942) but we consider them nomina dubia. *Kritosaurus incurvimanus* is based on the posterior part of a skull and lower jaws and exhibits no differences from *K. navajovius*. Thus, we consider *Kritosaurus* to be a monospecific genus consisting only of *K. navajovius*.

Brown (in Sinclair and Granger, 1914) identified a maxilla and incomplete dentary (AMNH 5797) from the Naashoibito Member of the Kirtland Formation as belonging to *Kritosaurus*. However, these elements are not diagnostic at the generic level. Lucas et al. (1987) identified a right lower jaw of a hadrosaur from the Naashoibito Member as *Kritosaurus* (Lucas et al., 1987). This specimen is also generically indeterminate. Thus, there is no evidence for the presence of the hadrosaurine *Kritosaurus* in the Naashoibito Member of the Kirtland Formation.

Two of the three species of *Parasaurolophus, P. tubicen* and *P. cyrtocristatus*, have been named for specimens from the Fruitland and Kirtland Formations. It is significant that the only three good skulls of *Parasaurolophus* were all named as different species (cf. Lucas, 1991). However, pending a revision of this genus, we consider both the San Juan Basin species to be valid. Hopson (1975) and Weishampel (1981) considered that the long crested *P. walkeri* and *P. tubicen* represent males and the short crested *P. cyrtocristatus* a female. Given that *Parasaurolophus* is rare in all faunas in which it occurs, is only known

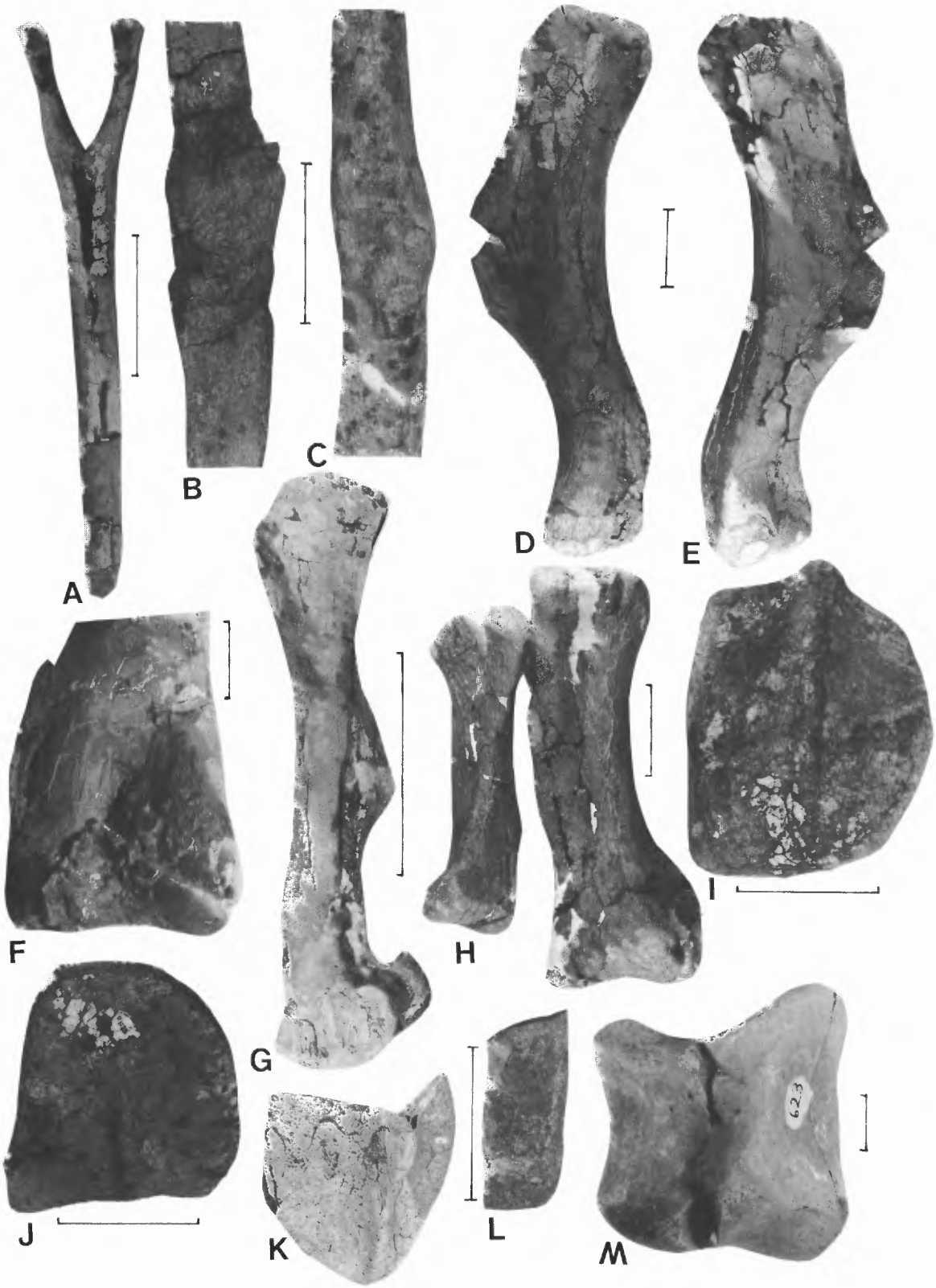

FIGURE 8. Dinosaur bones from the Fruitland and Kirtland Formations. A, Chevron of indeterminate hadrosaur (NMMNH P-1043) from the upper Fruitland Formation in posterior view. B–C, Ribs of indeterminate hadrosaur (NMMNH P-1043) from the upper Fruitland Formation in medial view with healed fractures. D–E, *Edmontosaurus saskatchewanensis*, right humerus (NMMNH P-1041) from the Naashoibito Member of the Kirtland Formation in posterior (D) and anterior (E) views. F, Posterior left tibia and astragalus of indeterminate hadrosaur (NMMNH P-1043) from the upper Fruitland Formation in posterior view. G, Left femur of indeterminate hadrosaur (NMMNH P-1043) from the upper Fruitland Formation in posterior view. H, Articulated left metatarsals 2 and 3 of an indeterminate hadrosaur (NMMNH P-1043) from the upper Fruitland Formation in anterior view. I–J, Indeterminate nodosaurid osteoscutes (NMMNH P-1078) from the Naashoibito Member of the Kirtland Formation in dorsal view. K–L, Indeterminate nodosaurid osteoscutes (NMMNH P-20880) from the upper Fruitland Formation in dorsal view. M, Third phalanx of fourth digit of pes of a tyrannosaurid (NMMNH P-20879) from the Naashoibito Member of the Kirtland Formation. Scale bars are 10 cm except for G (50 cm) and I (1 cm).

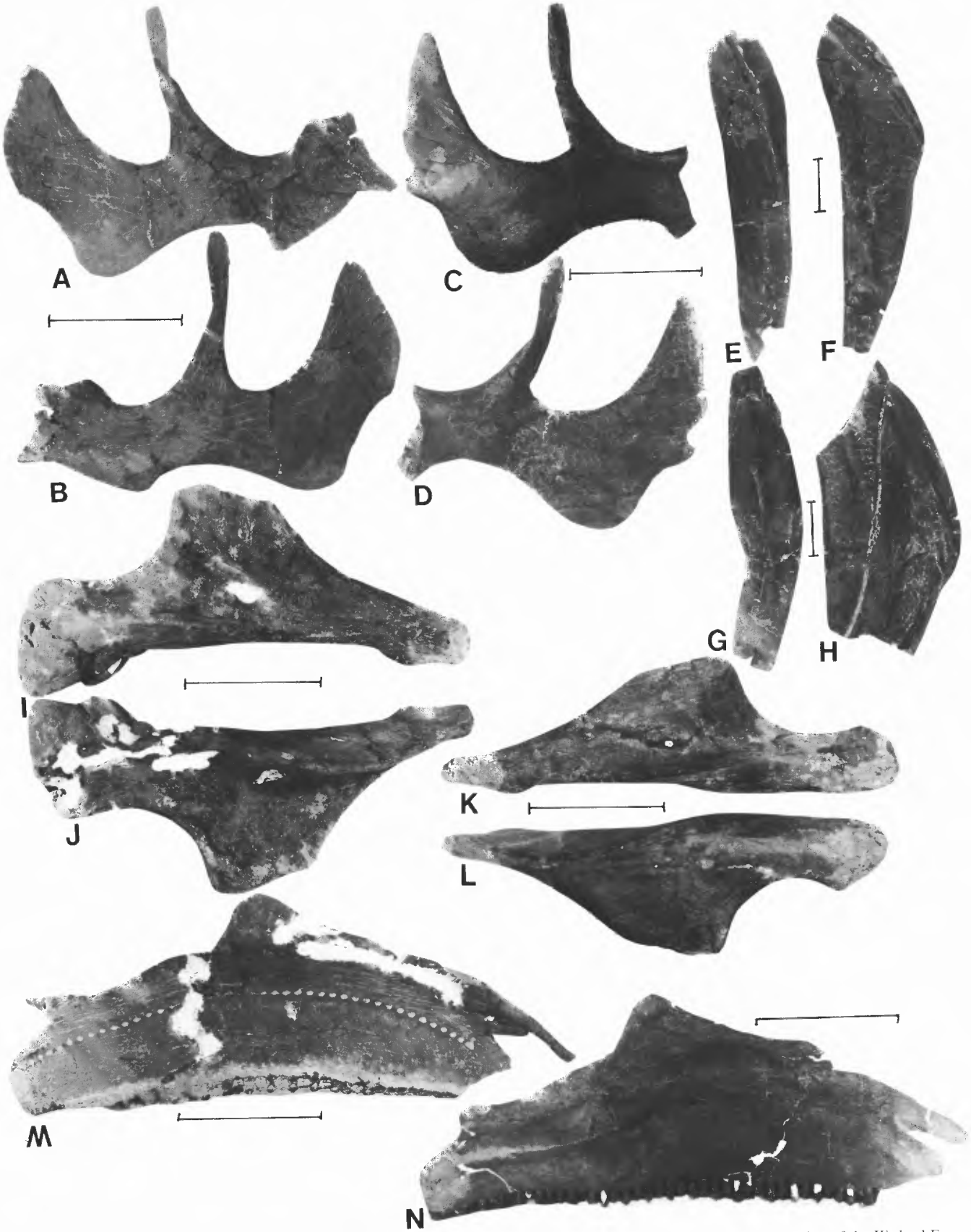

FIGURE 9. Cranial elements of the hadrosaurid *Edmontosaurus saskatchewanensis* (NMMNH P-1041) from the Naashoibito Member of the Kirtland Formation. A–B, Left jugal in medial (A) and lateral (B) views. C–D, Right jugal in lateral (C) and medial (D) views. E–F, Dentary tooth with terminal wear facet in occlusal (E) and mesial views. G–H, Dentary tooth and attached fragment of dentary in occlusal (G) and mesial (H) views. I–J, Right jugal in posteromedial (I) and anterolateral (J) view. K–L, Left quadrate in posteromedial (K) and anterolateral (L) views. M, Left maxilla in medial view. N, Right maxilla in lateral view. Scale bars are 10 cm except E–H (1 cm).

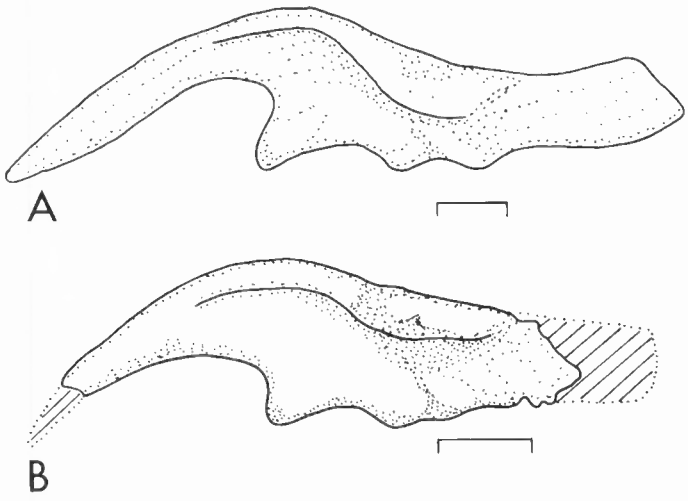

FIGURE 10. Comparison of the left ilia of (A) *Kritosaurus navajovius* (reversed from Parks, 1920) and (B) *Hadrosaurus foulki* (from Lull and Wright, 1942), illustrating the distinctly different morphology of this element in the two genera.

from three good skulls from three different stratigraphic units and that none of the three species co-occur, we consider speculations about sexual dimorphism in this genus to be unwarranted.

Ceratopsians—Four taxa of ceratopsians are currently recognized from the Fruitland and Kirtland Formations. Cf. *Chasmosaurus* is based on a horn core that can be reasonably assigned to this taxon (Gilmore, 1935; Lucas et al., 1987). *Pentaceratops* is represented by two putative species. Having examined all the skulls of these species, we conclude that only *P. sternbergii* is valid. *Pentaceratops fenestratus* is based on a skull distinguished only by an accessory "foramen" on one side of the frill (Wiman, 1930). Since this "foramen" is only present on one side of one frill (Mateer, 1981, pl. 3.1), it is probably a pathology. The skeleton described by Wiman (1930) as *Pentaceratops* was found without a skull and its affinities are presently unknown.

Dodson and Currie (1990) suggested that *Pentaceratops* might be a subjective junior synonym of *Chasmosaurus*. These genera are similar, but we believe that relative elongation of the frill in *Pentaceratops* is a diagnostic difference. However, we urge further study of the various skulls of *Pentaceratops* to gauge variation in this genus.

The presence of *Pentaceratops* in the Naashoibito Member of the Kirtland Formation is based on three specimens (Lucas et al., 1987). Lucas et al. (1987, fig. 5F) illustrated an indeterminate partial frill and postcranial elements. This specimen represents a small ceratopsian with well-developed epoccipitals that is distinct from *Torosaurus*, the other Naashoibito ceratopsian. Similarly, USNM 12741 is an indeterminate partial skull of a small ceratopsian. OSM 40-IX-1-41 through 40-IX-44-41 is a skull and postcranial skeleton of *Pentaceratops sternbergii*. However, this specimen is not from the Naashoibito Member as stated by Lucas et al. (1987). This specimen was found "in highly carbonaceous flaky shale containing plant fragments & much fossil resin" (Langston in Kues et al., 1977, p. 377). Since no megafossil plant remains have ever been found in the Naashoibito Member, it is certain that the Oklahoma specimen came from lower in the Fruitland-Kirtland sequence. The presence of abundant plant debris, fissile carbonaceous shale and amber strongly suggests that this specimen derives from the Fruitland Formation. In summary, no diagnostic specimens of *Pentaceratops* have been recovered from the Naashoibito Member of the Kirtland Formation and it is likely that the small identified ceratopsian represents the same taxon as is found in other Lancian localities in the southern Western Interior (Lehman, 1987).

Torosaurus specimens from the Naashoibito were previously assigned to the species *T. utahensis*, but this is now considered a junior subjective synonym of *T. latus* (Dodson and Currie, 1990). We strongly doubt that *T. latus* is a male *Triceratops*, as suggested by Ostrom and Wellnofer (1990). *Triceratops* is unknown in the southern Rocky Mountains where *Torosaurus* occurs, although these taxa co-occur in the northern Western Interior. More strikingly, the number of known individuals of *Triceratops* compared to the number of individuals of *Torosaurus* is more than 50:1. Given this ratio and their geographic disparity it is unlikely that these taxa are sexual dimorphs, ignoring morphological details.

Mammals

Mammalian fossils were first recovered from the Fruitland Formation by W. A. Clemens in the 1960s (Clemens, 1973). From the mid-1970s to the mid-1980s large-scale screenwashing was carried out by E. H. Lindsay (University of Arizona), D. L. Wolberg (New Mexico Bureau of Mines and Mineral Resources) and J. K. Rigby Jr. (formerly of the U.S. Bureau of Land Management and now at Notre Dame University). The majority of these collections have not been described, notably the University of Kansas specimens collected by Clemens and the nontherians from the Fossil Forest area under study by Wolberg and Rigby. Flynn (1986) described the more limited collections from the University of Arizona, and Rigby and Wolberg (1987) studied the therian mammals from the Fossil Forest area.

Faunal comparisons

The faunas of the Fruitland, pre-Naashoibito Kirtland and Naashoibito differ in a number of ways (Tables 5–7). The Fruitland Formation has a much greater diversity of fish, amphibians and lizards (Table 5). In part this is due to the fact that all these taxa are only found at microvertebrate localities that are more common in the Fruitland. However, the sedimentology of the Fruitland indicates high water tables and a prevalence of poorly drained environments, which would obviously favor a large fauna of fish and amphibians in contrast to the better drained conditions evident in strata of the Kirtland. The large diversity of mammals in the Fruitland is, however, evidently an artifact of the number of microvertebrate localities in this formation. The pre-Naashoibito and Naashoibito faunas of the Kirtland are depauperate in fish, amphibians, lizards and mammals.

The pre-Naashoibito Kirtland fauna (Table 6) is characterized by a diverse turtle fauna, with 14 taxa compared to only nine in the Fruitland. This diversity may be inflated by the confused taxonomy of these Cretaceous turtles. The lower Kirtland dinosaur faunas are relatively poorly known, but occurrences of cf. *Chasmosaurus* and *?Euoplocephalus* suggest that this fauna differs from that of the Fruitland Formation. However, the pre-Naashoibito fauna shares *Pentaceratops*, *Parasaurolophus* and *Kritosaurus* with the underlying fauna.

The Naashoibito fauna consists essentially only of turtles and dinosaurs (Table 7). This is in part due to the scarcity of screenwashing sites in the Naashoibito. The Naashoibito dinosaur fauna differs in possessing the theropod cf. *Tyrannosaurus*, the sauropod *Alamosaurus*, the nodosaur *?Panoplosaurus*, the hadrosaur *Edmontosaurus* and the ceratopsian *Torosaurus* cf. *T. latus*. Contrary to previous published reports, the Naashoibito fauna lacks *Pentaceratops* and *Kritosaurus*. Faunal differences between the Naashoibito and contemporary faunas in the northern Western Interior, notably the lack of *Triceratops* and *Leptoceratops* and the presence of *Alamosaurus*, are due to biogeographic factors (Lucas, 1981; Lehman, 1987).

THE AGE OF THE FRUITLAND AND KIRTLAND FORMATIONS

The age of the Fruitland and Kirtland Formations has long been a topic of debate (e.g., Lucas et al., 1987 and references therein) because of its bearing on problems of the Cretaceous/Tertiary boundary. However, there have always been a number of problems in determining the age of these units: (1) vertebrate fossils are not as common as in some other Late Cretaceous units in western North America and this is compounded by a relative lack of collecting; (2) these vertebrate faunas contain endemic taxa (*Pentaceratops*) and taxa that apparently have longer chronological ranges than in other regions (*Parasaurolophus*); (3) most workers agree that part of the sequence is of Edmontonian age, which has been considered difficult to distinguish from the Judithian and Lancian on the basis of vertebrate faunas (Lillegraven and

McKenna, 1986); (4) marine invertebrate faunas are poorly known from the immediately underlying Lewis Shale and Pictured Cliffs Sandstone in the area of the San Juan Basin where vertebrate fossils are common; (5) some palynological age data directly contradicts vertebrate age data; (6) radiometric ages have only been obtained from the uppermost Fruitland Formation and Hunter Wash Member of the Kirtland Formation (Brookins and Rigby, 1987); and (7) magnetostratigraphic correlations are at odds with other means of correlation. The literature relevant to the age of the formations is very large and confusing. Thus, we will limit our discussion to some of the main lines of evidence and their problems and possible resolutions. We only cite the more important papers.

Vertebrate fossils

Russell (1964, 1975) proposed a workable vertebrate zonation of the later part (Campanian-Maastrichtian) of the Cretaceous. Originally this zonation was based on dinosaurs and invertebrates, but more recently mammalian paleontologists (e.g., Lillegraven and McKenna, 1986) have very unfortunately ignored these elements of the faunas and have established a zonation that utilizes Russell's names but which relies totally on mammalian fossils. Russell's (1964) names, which he called stages, Lillegraven and McKenna termed (1986) "ages" and should more properly be called biochrons (Lucas, 1990, 1991). For the Campanian-Maastrichtian they are (in ascending order): Aquilan, Judithian, Edmontonian and Lancian. These biochrons are respectively of early Campanian, late Campanian, early Maastrictian and late Maastrichtian age (Eaton, 1987; contra Lillegraven and McKenna, 1986).

We consider it a retrograde step to define these biochrons simply on mammalian fossils for a number of reasons: (1) for taphonomic reasons, large dinosaur bones will always be more common than microvertebrate (mammal-bearing) localities; (2) there is more than 100 years of literature describing dinosaur, and other large vertebrate remains, from the Campanian-Maastrichtian of the Western Interior of the United States and but 30 years of publishing on mammalian fossils of this age; thus our understanding of the geographic and stratigraphic distribution of Cretaceous mammals is not as extensive as is the understanding of the reptiles; and (3) the Edmontonian is not recognizable on the basis of mammal fossils (Lillegraven and McKenna, 1986), but can be distinguished on the basis of dinosaurs (see below).

Although we appreciate that mammalian paleontologists are just extending a successful scheme ("land-mammal ages") from the Tertiary back into the Cretaceous, there are many differences between the Tertiary and the late Mesozoic. Notable among these is the fact that mammals are the most numerous and diverse larger vertebrates in the Tertiary and thus it is logical to build biochronologies around them. However, in the Mesozoic, mammals were not so numerous and it is ridiculous to ignore the most common animals (dinosaurs) in constructing biochronologies. Furthermore, at our current state of knowledge, dinosaurs provide better time discrimination (e.g., allow recognition of the Edmontonian) than mammals in the Late Cretaceous. Therefore, we strongly advocate the use of multi-element biochronologies that utilize both mammals and dinosaurs, as well as other biochronologically significant taxa where applicable (Lucas, 1991).

Many authors have speculated on the age of the Fruitland and Kirtland Formations on the basis of fossil vertebrates. We do not review all the literature and discuss only taxa that are biochronologically significant. The Fruitland fauna contains mammal taxa that are stratigraphically restricted elsewhere (Lillegraven and McKenna, 1986), including *Cimolodon electus*, from Aquilan strata; *Paracimexomys magnus, Meniscoessus intermedius, Alphadon halleyi, Gypsonictops lewisi* (Fruitland specimen is *G.* cf. *G. lewisi*), *Paranyctoides sternbergii* (Fruitland specimen is *P.* cf. *P. sternbergii*) from Judithian strata; and *Alphadon wilsoni* (Fruitland specimen is *A.* cf. *A. wilsoni*) and *Pediomys cooki* (Fruitland specimen is *P.* cf. *P. cooki*) from Lancian strata. In conclusion, the evidence from mammalian fossils strongly supports a Judithian (late Campanian) age for the Fruitland Formation. The dinosaur fauna does not contradict this age but does not strongly support it. *Pentaceratops* is endemic to the San Juan Basin, *Kritosaurus* is elsewhere known only from Judithian strata and *Parasaurolophus* is known from Judithian and Lancian strata outside New Mexico. The Lancian age of the Kaiparowits Formation of Utah, which contains *Parasaurolophus*, is usually attributed to palynological stata, but the presence of *Ornithomimus velox* and cf. *Triceratops* in this fauna also indicates this age (DeCouten and Russell, 1985; Weishampel, 1990).

The pre-Naashoibito portion of the Kirtland Formation is hard to date on the basis of vertebrate fossils because of the paucity of specimens. The lower four members of the Kirtland have a small mammal fauna which does not include any taxa restricted to a single biochron elsewhere. In addition to the same taxa as are found in the Fruitland, the lower Kirtland contains cf. *Chasmosaurus* and cf. *Euplocephalus*. If these two identifications were definite they would respectively indicate Judithian and Judithian or Edmontonian ages for the lower Kirtland. Given the fact that the lower Kirtland conformably overlies a unit yielding a Judithian fauna, is very thick and conformably underlies a unit yielding a Lancian fauna (see below), it is reasonable to assume that the lower Kirtland is at least partly Edmontonian in age.

The Naashoibito mammal fauna is very small but includes *Essonodon browni* which is elsewhere restricted to Lancian strata (Lillegraven and McKenna, 1986). In addition, the dinosaur fauna includes *Alamosaurus sanjuanensis*, cf.*Tyrannosaurus, Edmontosaurus saskatchewanensis* and *Torosaurus* cf. *T. latus*, which are all restricted to Lancian strata elsewhere. The presence of ?*Panoplosaurus* would indicate a Judithian age if this identification were confirmed. In conclusion, the bulk of the vertebrate fauna indicates a Lancian age for the Naashoibito Member.

Invertebrate fossils

The age of the underlying marine strata below the Fruitland Formation constrain the maximum age of this unit. Unfortunately, the only extensive faunas in the Lewis Shale are in the southern and eastern portions of the basin (Cobban, 1973; Cobban et al., 1974) and most of the vertebrate paleontology, magnetostratigraphic and radiometric studies have been conducted in the west-central portion of the basin. Given that the epicontinental sea was regressing to the northeast during this time interval, and that the shoreline was oriented northwest-southeast, it is evident that the base of the Fruitland becomes younger to the northeast. Based on fossil collections and shoreline extrapolations, Fassett (1987, fig. 5) demonstrated that the base of the Fruitland Formation (or more exactly the youngest age of the underlying marine strata) varied from the zones of *Baculites scotti* to *Baculites compressus* of the standard Western Interior zonation. These zones are late, but not latest, Campanian in age and are associated with radiometric dates elsewhere that suggest, at the 95% confidence level, that they range from 71.8 to 75.5 Ma (Fassett, 1987). However, the oldest date is based on the *Didymoceras nebrascense* zone and the oldest *Baculites scotti* zone has not been radiometrically dated. Thus, the age of the base of the Fruitland, by extrapolation, is no younger than late, and not latest, Campanian in age.

Since the Fruitland Formation represents dominantly paludal environments near the shoreline, it is reasonable to assume that the Fruitland can be approximately dated as late Campanian on the basis of the main invertebrates. However, it is not possible to further deduce that the marine invertebrates indicate that the entire Kirtland is also late Campanian in age (contra Fassett, 1987). The Kirtland is superjacent, and thus demonstrably younger than the Fruitland, and sedimentological considerations indicate that the deposition of the Kirtland was related to a different paleoslope and structural regime than that of the Fruitland. Thus, it is not possible to draw timelines through the Kirtland from the Lewis Shale (contra Fassett, 1987, fig. 6) and marine invertebrates do not help in precisely evaluating the age of the Kirtland.

Palynomorphs

Palynological studies have consistently resulted in ages that are older than those obtained by other methodologies. Thus, Tschudy (1973) and Newman (1987) concurred that the "Fruitland Formation" of the Gasbuggy core in the east-central basin is late Campanian in age. This would be a reasonable age if the sampled sequence only represented

the Fruitland and if the Kirtland had been removed by the putative angular unconformity at the base of the Ojo Alamo. However, it is clearly evident that the Gasbuggy core contains a coal-bearing interval that is about 100 ft (30 m) thick, overlain by a thicker barren interval and thus, that both the Fruitland and Kirtland Formations are present (contra Fassett, 1968; Tschudy, 1973; Newman, 1987). All other lines of evidence suggest that only the Fruitland is late Campanian in age.

Newman (1987) summarized extensive work on the Fruitland and Kirtland Formations and concluded that a portion of the upper Farmington Member, the De-na-zin Member and the Naashoibito Member were early Maastrichtian in age. This is consistent with the Fassett and Hinds (1971) model of a large unconformity at the base of the Ojo Alamo, but is inconsistent with vertebrate age evidence and would require very rapid sedimentation rates (>500 m in a couple of million years).

Magnetostratigraphy

E. H. Lindsay and R. F. Butler of the University of Arizona measured magnetostratigraphic sections through much of the Fruitland Formation and all of the Kirtland Formation in the west-central and southern San Juan Basin (summarized in Lindsay et al., 1981; Butler and Lindsay, 1985). This work has been subject to much criticism (e.g., Lucas and Schoch, 1982 and references therein). One major problem was removed when Butler and Lindsay (1985) realized that some of their samples in the Naashoibito Member and Ojo Alamo Sandstone were of reversed, rather than normal polarity, with the result that the Cretaceous-Tertiary boundary was in a reversed interval, as at other localities around the world. However, the paleomagnetic correlation for the Fruitland-Kirtland sequence (Fig. 11) consists of two long intervals of normal polarity split by a short reversed interval with a moderately long reversed interval at the top. Lindsay and Butler (e.g., Lindsay et al., 1981; Butler and

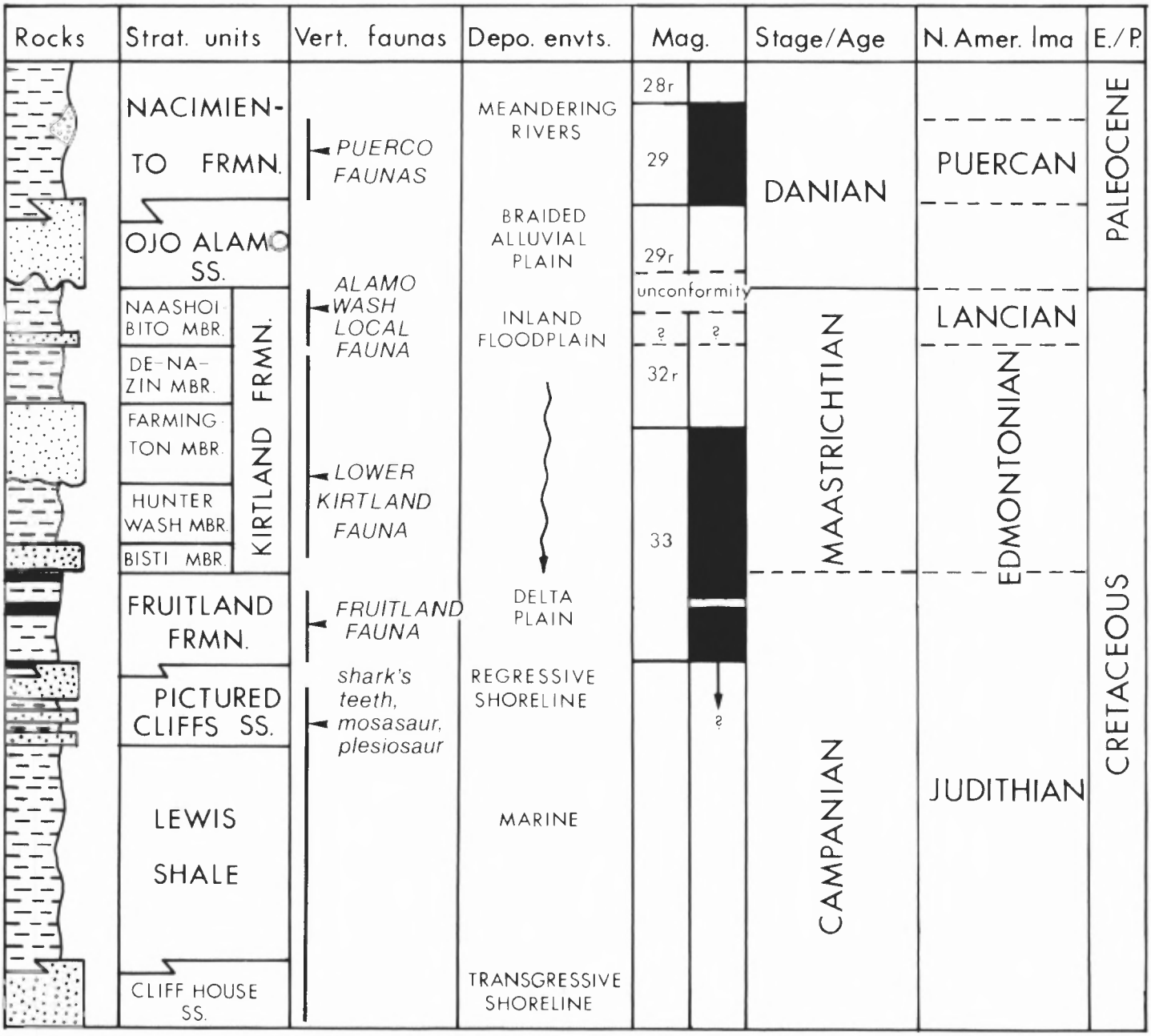

FIGURE 11. Lithology, nomenclature, distribution of faunas and age of the uppermost Cretaceous and earliest Tertiary strata of the San Juan Basin. The magnetostratigraphic zonation scheme for the Fruitland and Kirtland Formations is obviously in error. Abbreviations: E, Epoch; lma, "land mammal age"; P, Period.

Lindsay, 1985) have consistently correlated the two long normals with polarity chrons 30 and 31 (e.g., Harland et al., 1990). However, these polarity chrons are of late Maastrichtian age and thus, Lindsay and Butler are suggesting that all of the Fruitland and Kirtland are of this age. This contradicts all lines of evidence and, as Lucas and Schoch (1982) pointed out, is at odds with the entire chronology of the Late Cretaceous of the Western Interior, which indicates that there was no sea in northwestern New Mexico during the late Maastrichtian and therefore there should be no coastal plain deposits (e.g., Fruitland Formation) of this age in the San Juan Basin. Alvarez and Vann (1979) and Lucas and Schoch (1982) both proposed alternative correlations based on the assumption that there is a significant unconformity at the base of the Ojo Alamo Sandstone. However, now that it is apparent that this unconformity is not present (e.g., Lucas et al., 1987), these alternative correlations are also untenable.

Three facts seem clear: (1) the Fruitland-Kirtland sequence represents most of later Campanian time and virtually all of Maastrichtian time (see discussion below); (2) the Fruitland-Kirtland magnetostratigraphic zonation bears no resemblance to the worldwide standard for this time interval (there should be six normal intervals instead of the reported two; Harland et al., 1990); and (3) the magnetostratigraphic zonation, at least in its upper part, is consistent around the western and southern portions of the basin (Butler and Lindsay, 1985, fig. 12).

We are not able to reconcile the magnetostratigraphic sequence in the Fruitland and Kirtland Formations presented by Butler and Lindsay (1985) with the worldwide standard. An obvious answer could be that the Fruitland-Kirtland sequence is riddled with unconformities, possibly at the base of extensive sandstones (e.g., Bisti, Farmington, and basal conglomerate of Naashoibito Members). We reject this hypothesis for the following reasons: (1) the vertebrate fauna of the Fruitland and pre-Naashoibito Members of the Kirtland are so similar that there cannot be a major unconformity at the base of the Bisti Member; (2) the vertebrate faunas of the Hunter Wash and De-na-zin Members are similar and the Farmington Member interfingers with the Hunter Wash Member, so we discount the possibility of a major unconformity at the base of the Farmington; and (3) the presence of "Naashoibito-aspect" mudrocks with high volcanic content in the upper De-na-zin Member suggests that there is no major unconformity at the base of the Naashoibito. Thus, although we cannot explain where the errors have arisen, we are confident that the magnetostratigraphic polarity zonation proposed for the Cretaceous of the San Juan Basin by Lindsay and Butler is seriously flawed. However, we note that the Tertiary portion of their San Juan Basin zonation correlates well with the standard timescale and with studies in other basins (e.g., Butler et al., 1980).

Radiometric dating

Several volcanic ashes occur in the upper Fruitland Formation and in the Hunter Wash Member of the Kirtland Formation, although only three have been dated (Lindsay et al., 1981; Hunt, 1984, 1991; Brookins and Rigby, 1987). Brookins and Rigby (1987) reviewed the age determinations from these ashes and concluded that they are all consistent with an age of 73.5 ± 2.2 Ma. The Campanian-Maastrichtian boundary is currently placed at 74.0 Ma (Harland et al., 1990).

Conclusions

We conclude that the evidence from marine invertebrates, mammals, dinosaurs and pollen indicates that the Fruitland Formation is Judithian (late Campanian) in age (Fig. 11). The age of the lower four members of the Kirtland is more difficult to assess, but radiometric dates, palynology and the conformable position between Judithian and Lancian strata suggest that the lower Kirtland is Edmontonian (early Maastrichtian) in age. Mammalian and dinosaurian evidence indicate that the Naashoibito Member of the Kirtland Formation is of Lancian (late Maastrichtian) age (Fig. 11).

DINOSAURIAN DEFINITIONS OF THE JUDITHIAN, EDMONTONIAN AND LANCIAN

Lillegraven and McKenna (1986) listed all the first, last and unique occurrences of fossil mammal taxa from the Judithian, Edmontonian and Lancian of the United States and Canada. Here we follow this format and list similar information for dinosaur taxa. Most of the data derives from papers in Weishampel et al. (1990).

Judithian

Main formations: Judith River, Belly River, Two Medicine (Canada), Cape Sebastian, upper Two Medicine (USA), lower Bearpaw, Meeteetse, "Mesaverde" (Wyoming), Castlegate, Fruitland, San Carlos, Aguja.

First occurrences: Albertosaurus sarcophagus, Aublysodon mirandus, Struthiomimus altus, Chirostenotes pergracilis, Troodon formosus, Euoplocephalus tutus, Edmontia longiceps, Thescelosaurus neglectus, Anchiceratops ornatus, Pentaceratops sternbergii.

Last occurrences: none.

Unique occurrences: Albertosaurus libratus, Daspletosaurus torosus, Dromiceiomimus samueli, Elmisaurus elegans, Caenagnathus collinsi, Caenagnathus sternbergi, Dromaeosaurus albertensis, Saurornitholestes langstoni, Edmontia rugosidens, Panoplosaurus mirus, Orodromeus makelai, Kritosaurus navajovius, Brachylophosaurus canadensis, Brachylophosaurus goodwini, Maiasaura peeblesorum, Prosaurolophus maximus, Corythosaurus casuaris, Lambeosaurus lambei, Lambeosaurus magnicristatus, Parasaurolophus walkeri, Parasaurolophus cyrtocristatus, Gravilothus albertae, Ornathotholus browni, Stegoceras validum, Avaceratops lammersi, Brachyceratops montanensis, Centrosaurus apertus, Monoclonius crassus, Styracosaurus albertensis, Styracosaurus ovatus, Chasmosaurus belli, Chasmosaurus russelli, Chasmosaurus canadensis, Chasmosaurus mariscalensis.

Edmontonian

Main formations: Horseshoe Canyon, St. Mary River, Prince Creek, Horsethief, lower Kirtland, Ripley.

First occurrences: Edmontosaurus regalis, Stegoceras edmontonense.

Last occurrences: Albertosaurus sarcophagus, Ornithomimus edmontonensis, Struthiomimus altus, Chirostenotes pergracilis, Eoplocephalius tutus, Edmontia lonciceps, Kritosaurus navajovius, Anchiceratops ornatus, Pentaceratops sternbergii.

Unique occurrences: Dromiceimimus brevitertius, Parksosaurus warreni, Saurolophus osborni, Hypacrosaurus altispinus, Parasaurolophus tubicen, Montanoceratops cerorhynchus, Pachyrhinosaurus canadensis, Arrhinoceratops brachyops.

Lancian

Main formations: Scollard, Willow Creek, Frenchman, Hell Creek, Pinyon Canyon, Medicine Bow, Evanston, Ferris, Lance, lower North Horn, Kaiparowits, Laramie, Arapahoe, Denver, Cimarron Ridge, Naashoibito Member of Kirtland, McRae, Javelina, El Picacho.

First occurrences: none.

Last occurrences: Aublysodon mirandus, Troodon formosus, Thescelosaurus neglectus, Edmontosaurus regalis, Stegoceras edmontonense.

Unique occurrences: Alamosaurus sanjuanensis, Avisaurus archibaldi, Nannotyrannosaurus lancesis, Tyrannosaurus rex, Ornithomimus velox, Ankylosaurus magniventris, Denversarus sclessmani, ?Thescolosaurus garbani, Anatotitan copei, Edmontosaurus annectens, Edmontosaurus saskatchewanensis, Pachycephalosaurus wyomingensis, Stygimoloch spinifer, Leptoceratops gravilis, Torosaurus latus, Triceratops horridus.

Summary

Two features are very clear from these data. Firstly, dinosaurs provide robust definitions of all these vertebrate biochrons. Secondly, the Edmontonian is well defined by dinosaurs, although this biochron is not definable on the basis of fossil mammals. Thus, this is strong support for our contention that multiple-element biochronologies should be constructed.

THE CRETACEOUS-TERTIARY BOUNDARY

Fassett and others (e.g., Fassett and Hinds, 1971; Fassett, 1987) have argued in the past twenty years that there is a significant unconformity at the base of the Ojo Alamo Sandstone, which has removed most, if not all, Maastrichtian strata. Recent vertebrate correlations bear on the temporal extent of this unconformity, at least in the west-central basin (Lucas, 1991). The Naashoibito Member and its Alamo Wash local fauna (Fig. 12) is of Lancian age, and the base of this biochron is either in chron 30 or 31 of the standard polarity timescale. There is a 3-m-thick unfossiliferous interval at the top of the Naashoibito and Paleocene pollen (Baltz et al., 1966) and ?reworked dinosaur bones in the Ojo Alamo Sandstone (Fassett et al., 1987). The upper Ojo Alamo interfingers with the lower Nacimiento Formation, which contains a Puercan (early Paleocene) mammal fauna (Fig. 13). The top of the Ojo Alamo, or the very lowest Nacimiento, marks the start of chron 29 (Lindsay et al., 1981; Butler and Lindsay, 1985). The unfossiliferous interval in the upper Naashoibito must encompass Bugcreekian time plus possibly part of Lancian time (Lucas, 1991). Given the vertebrate evidence, there is only space for 3 million years to be missing at the base of the Ojo Alamo between the base of chron 31 and the base of chron 29. If the base of the Lancian is in chron 30 or/and if the Naashoibito represents more than a few hundred thousand years, then the portion of time missing, if any, is much less. This, together with the stratigraphic and sedimentological evidence presented above, indicates that there is no major angular unconformity at the base of the Ojo Alamo Sandstone in the San Juan Basin.

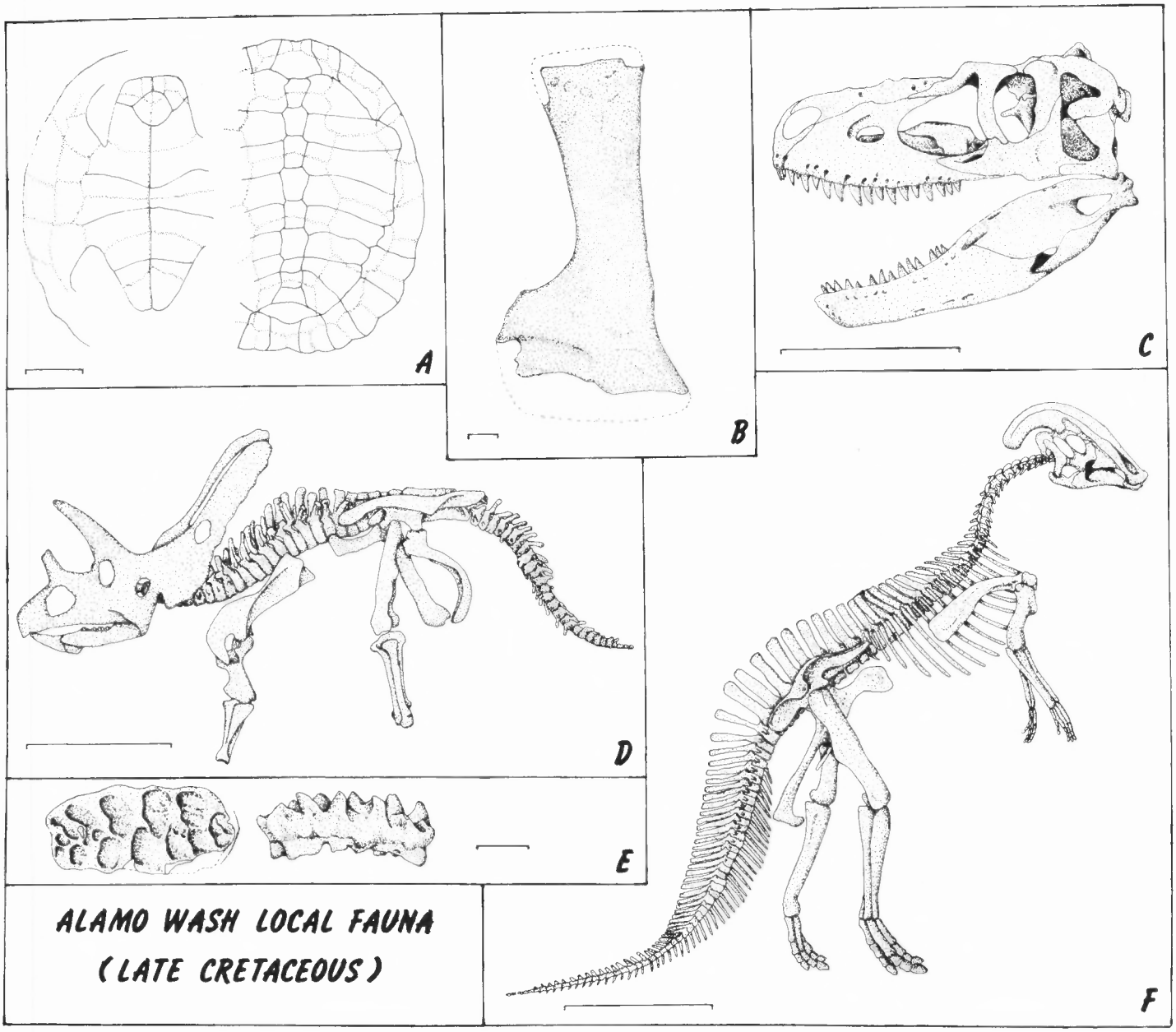

FIGURE 12. Representative fossil vertebrates of the Late Cretaceous (Maastrichtian) Alamo Wash local fauna, Naashoibito Member of the Kirtland Formation, San Juan Basin, New Mexico (from Lucas, 1989). A, Baenid turtle *Neurankylus eximius*, plastron (left) and carapace (right) (after Gaffney). B, Holotype left scapula of sauropod dinosaur *Alamosaurus sanjuanensis* (after Gilmore). C, Skull of theropod dinosaur *Albertosaurus* (after Russell), which is represented by fragmentary specimens in the Alamo Wash local fauna. D, Small *Pentaceratops*-like ceratopsian represented by the holotype skull of *Pentaceratops fenestratus* and an indeterminate ceratopsian skeleton (after Wiman). E, Left M_1 of multituberculate mammal *Essonodon browni*, occlusal (left) and side (right) views (after Lehman). F, Hadrosaurian dinosaur *Parasaurolophus* represented by the holotype skeleton of *P. cyrtocristatus* (after Ostrom) from the Fruitland Formation. *Parasaurolophus* is represented in the Alamo Wash local fauna by the holotype skull of *P. tubicen*. Scale bars are 10 cm for A–B, 0.5 m for C, 1 m for D and F and 2 mm for E.

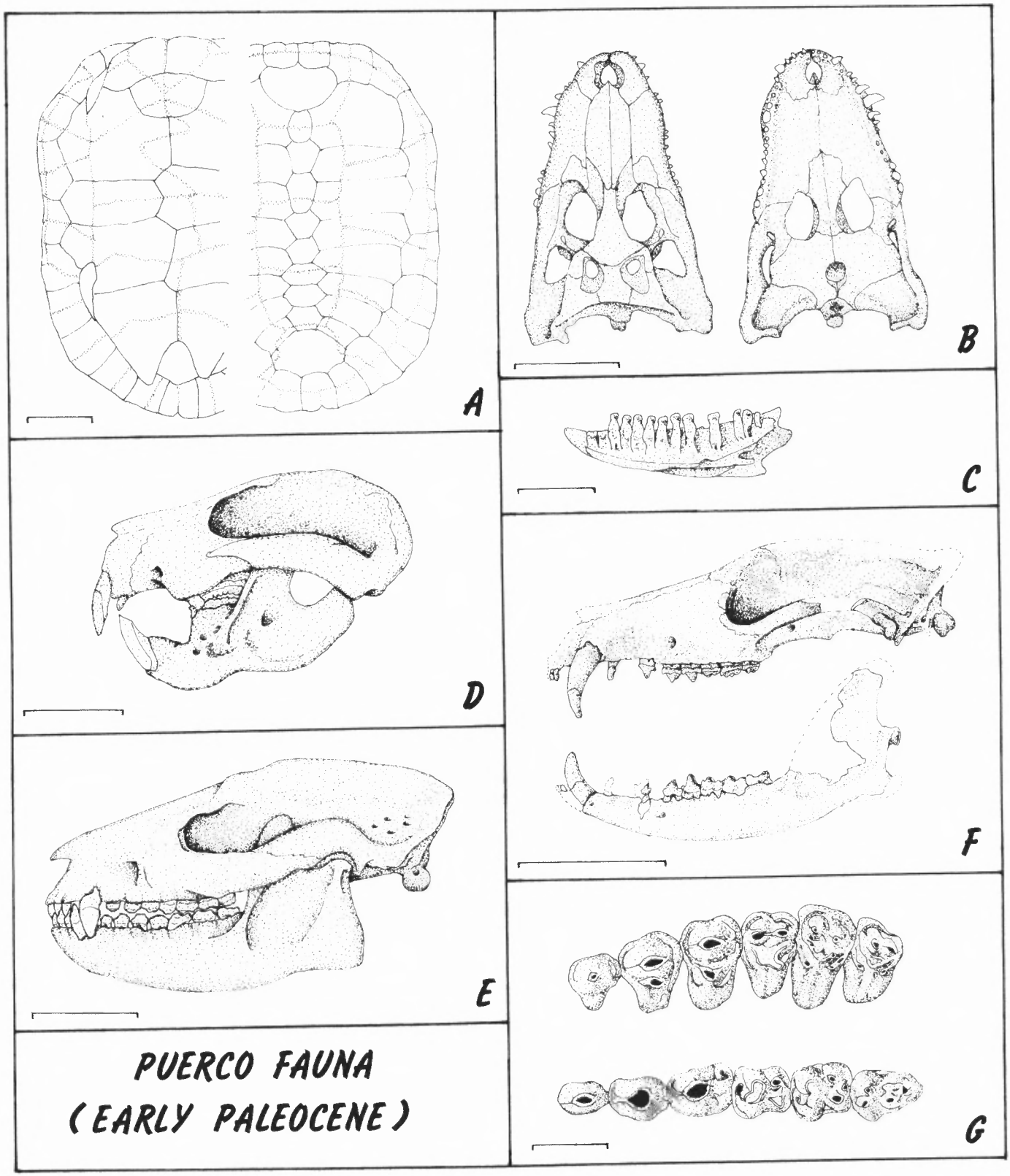

FIGURE 13. Representative fossil vertebrates of early Paleocene Puerco fauna, Nacimiento Formation, San Juan Basin, New Mexico (from Lucas, 1989). A, Plastron (left) and carapace (right) of baenid turtle *Compsemys victa* (after Gaffney). B, Skull of crocodilian *Allognathosuchus meeki*, dorsal (left) and ventral (right) views (after Erickson). C, Part of lower jaw of anguid lizard *Odaxosaurus piger* (after Estes). D, Skull of multituberculate mammal *Taeniolabis taoensis* (after Sloan). E, Skull of periptychine condylarth *Ectoconus ditrigonus* (after Matthew). F, Skull and lower jaws of arctocyonid and condylarth *Loxolophus hyattianus* (after Matthew). G, Upper (above) and lower (below) cheek teeth of anisonchine condylarth *Hemithlaeus kowalevskianus* (after Matthew). Scale bars are 5 cm for A–B, D–F and 5 mm for C and G.

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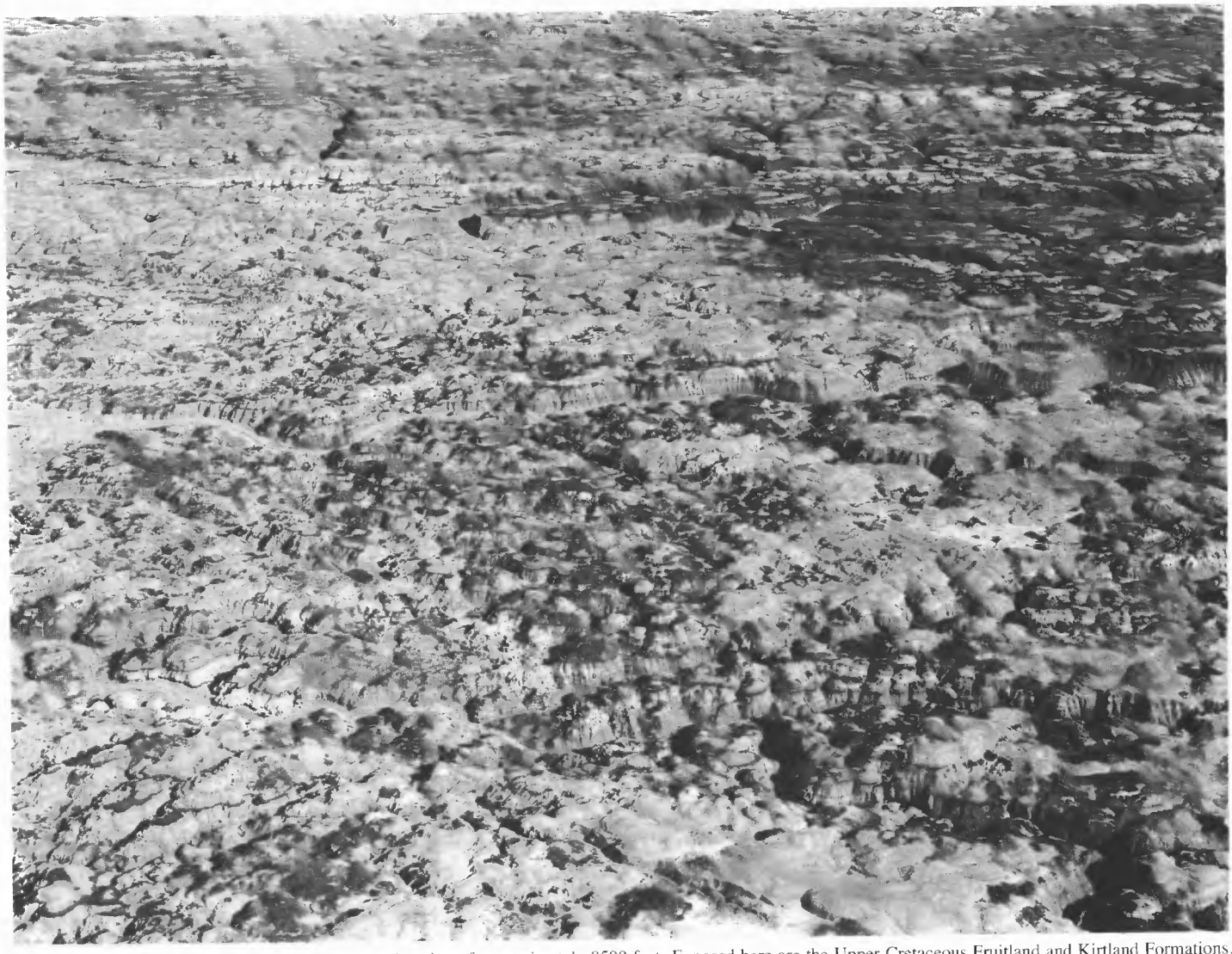

Aerial view of part of the Bisti badlands from an elevation of approximately 8500 feet. Exposed here are the Upper Cretaceous Fruitland and Kirtland Formations. Photograph taken the morning of 13 April 1992. Copyright © Paul L. Sealey, 1992.