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STRATIGRAPHIC NOMENCLATURE OF ROCK STRATA ADJACENT TO THE CRETACEOUS-TERTIARY INTERFACE IN THE SAN JUAN BASIN

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Abstract—During the last two decades, several changes in the stratigraphic nomenclature of rocks adjacent to the Cretaceous-Paleogene (K-T) boundary in the San Juan Basin have been recommended. All of these changes have been suggested by vertebrate paleontologists working in limited areas (those containing vertebrate fossils) in the southern part of the San Juan Basin. Because of their provincial view of the formations under discussion and a clear lack of understanding of the North American Stratigraphic Code, these geologists' suggested stratigraphic changes do not stand close scrutiny and are thus rejected.

Suggested deletion of the lithic component of two formations: the Ojo Alamo Sandstone of Paleocene age, and the Upper Cretaceous Farmington Sandstone Member of the Kirtland Formation is rejected. Recommendations were to eliminate the word "Sandstone" from the names of these two rock units and substitute the word "Formation" in their stead. Because these rock units are characterized by their sandstone components, the use of the word Sandstone in both instances is in accordance with the Stratigraphic Code and thus no change in nomenclature is warranted.

It has been suggested that the Ojo Alamo Sandstone be divided into two members in the southwest part of the San Juan Basin; the Naashoibito and Kimbeto Members, and only consist of one member in the southeast part of the basin. No lithologic criteria have been established for a two-member Ojo Alamo in the southwest part of the basin, thus this subdivision is rejected. Moreover, the suggestion that the Ojo Alamo consists of a single member in the southeast part of the basin is contrary to the Stratigraphic Code. A formation cannot consist of a single member.

It has been recommended that the long established names for subdivisions of the Kirtland Formation: lower shale member, Farmington Sandstone Member, and upper shale member, be changed to the Hunter Wash Member, Farmington Sandstone Member, and the De-na-zin Member, respectively. Because these new names apply to exactly the same lithologic intervals as the old names, there is no valid reason to change the old names that had been in print in various media for 76 years, prior to these suggested name changes. The Stratigraphic Code rejects frivolous changes to long-established nomenclature, therefore, these name changes are rejected. Furthermore, the Hunter Wash name has been previously applied to other rocks in this stratigraphic section in this same area, thus the use of the name "Hunter Wash" for the lower member of the Kirtland Formation has been preempted and is thus improper.

It has been suggested that a sandstone bed named the Bisti Bed marks the base of the Kirtland Formation throughout the San Juan Basin. This implies that the Bisti Bed can be traced continuously throughout the San Juan Basin. It is abundantly clear that no such bed exists in the lower Kirtland Formation throughout the basin. Random fluvial channel-sandstone beds occur sporadically in the uppermost Fruitland Formation and lowermost Kirtland Formation, but field mapping has shown conclusively that none of these sandstone beds are continuous even locally, let alone basin-wide. Fruitland and Kirtland Formation rocks are more than two million years older in the southwest part of the San Juan Basin than they are in the northeast part of the basin, therefore, it is physically impossible that a sandstone bed named the Bisti Bed in the southwest part of the basin could be the same bed in the northeast part of the basin.

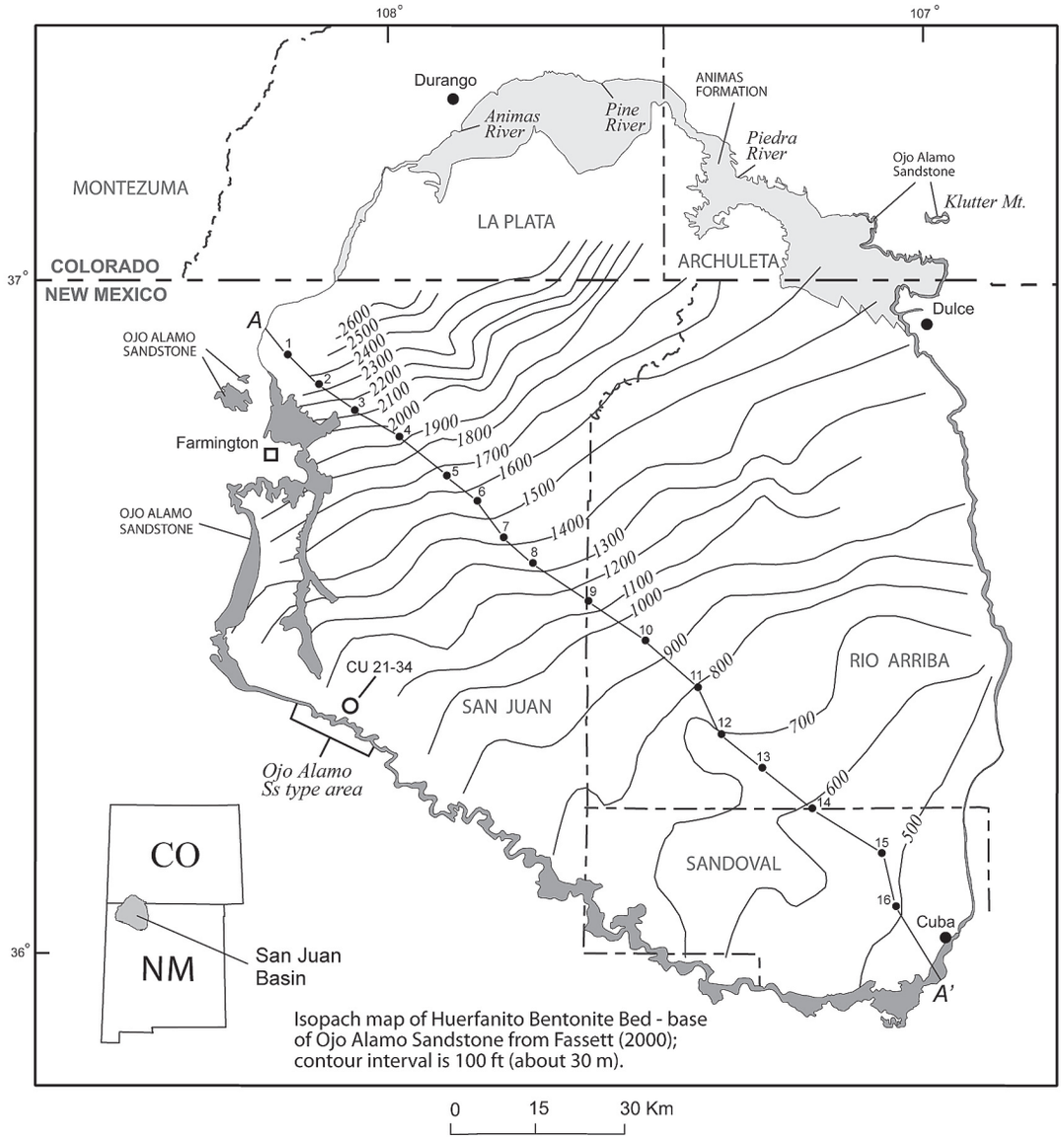
It has been suggested that the Fruitland Formation be subdivided into two members: the Ne-nah-ne-zad (lower member) and the Fossil Forest (upper member). There are no lithologic criteria to validate such a subdivision of the Fruitland, thus these new member names are rejected.

OJO ALAMO SANDSTONE

Lithology

Disagreements regarding the stratigraphic nomenclature of the Ojo Alamo Sandstone began shortly after the name "Ojo Alamo beds" was coined by Barnum Brown (1910) for dinosaur-bearing strata in the Ojo Alamo Sandstone type area (Fig. 1). The early evolution of the use of the name Ojo Alamo Sandstone is described in detail in Fassett (1973) and is brought up to date in Fassett (2000), Fassett et al. (2002), and Fassett (2009). At the present time, there are two main schools of thought regarding the rock-stratigraphic definition of the Ojo Alamo: The first holds that the Ojo Alamo consists of all of the coarse-grained conglomeratic sandstones (and finer-grained interbeds) unconformably overlying the fine-grained beds of the Cretaceous Kirtland Formation. The second school maintains that the Ojo Alamo Sandstone consists only of the "restricted Ojo Alamo Sandstone" of Baltz et al. (1966); this definition excludes the lower, conglomeratic and middle shaly parts of the original Ojo Alamo Sandstone of Bauer (1916) that contain abundant dinosaur fossils (Fig. 2). The lower, dinosaur-bearing part of the original Ojo Alamo Sandstone is thus referred to by some workers as the "Naashoibito Member of the Kirtland Formation". Figure 2 portrays these contrasting definitions of the Ojo Alamo Sandstone.

A variation on the second school's definition of the Ojo Alamo has recently been suggested: somewhat ambiguously, by Lucas and Sullivan (2000), and later unequivocally by Sullivan and Lucas (2003) and Sullivan, Lucas, and Braman (2005). Sullivan and Lucas, for many years, members of the Naashoibito-Member-of-the-Kirtland school, have now changed their minds in these recent papers and recommend (Sullivan and Lucas, 2003, p. 369) that: "Following Fassett (various papers) and Lucas and Sullivan (2000) we now place the Naashoibito Member back in the Ojo Alamo Formation (sic; see discussion of the name 'Ojo Alamo Formation', below)." Other authors, however (for example,



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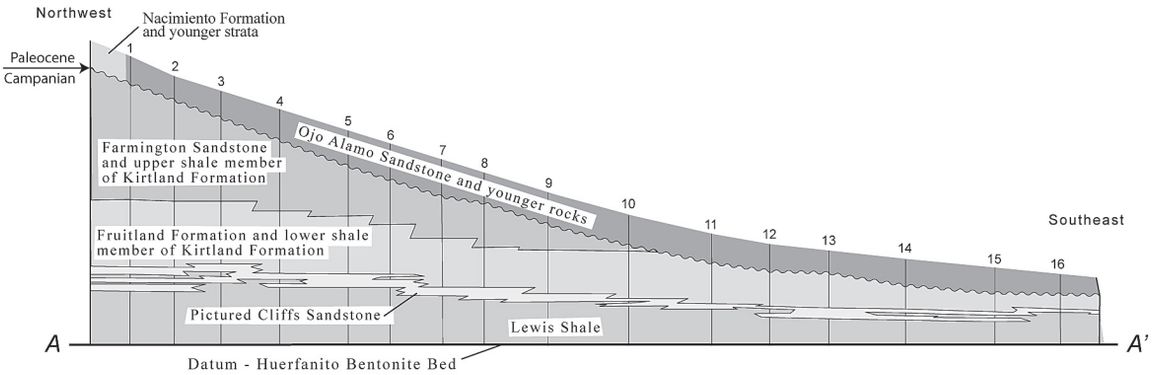


1.2

FIGURE 1. Index map of San Juan Basin area showing outcrops of Ojo Alamo Sandstone and Animas Formation plus isopach lines showing thickness of Huerfanito Bentonite Bed – Top of the Pictured Cliffs Sandstone interval (1.1); 1.2 is a southeast-trending cross section of Huerfanito Bentonite Bed – Top of the Pictured Cliffs Sandstone interval. Map is modified from figure 1 of Fassett (2009).

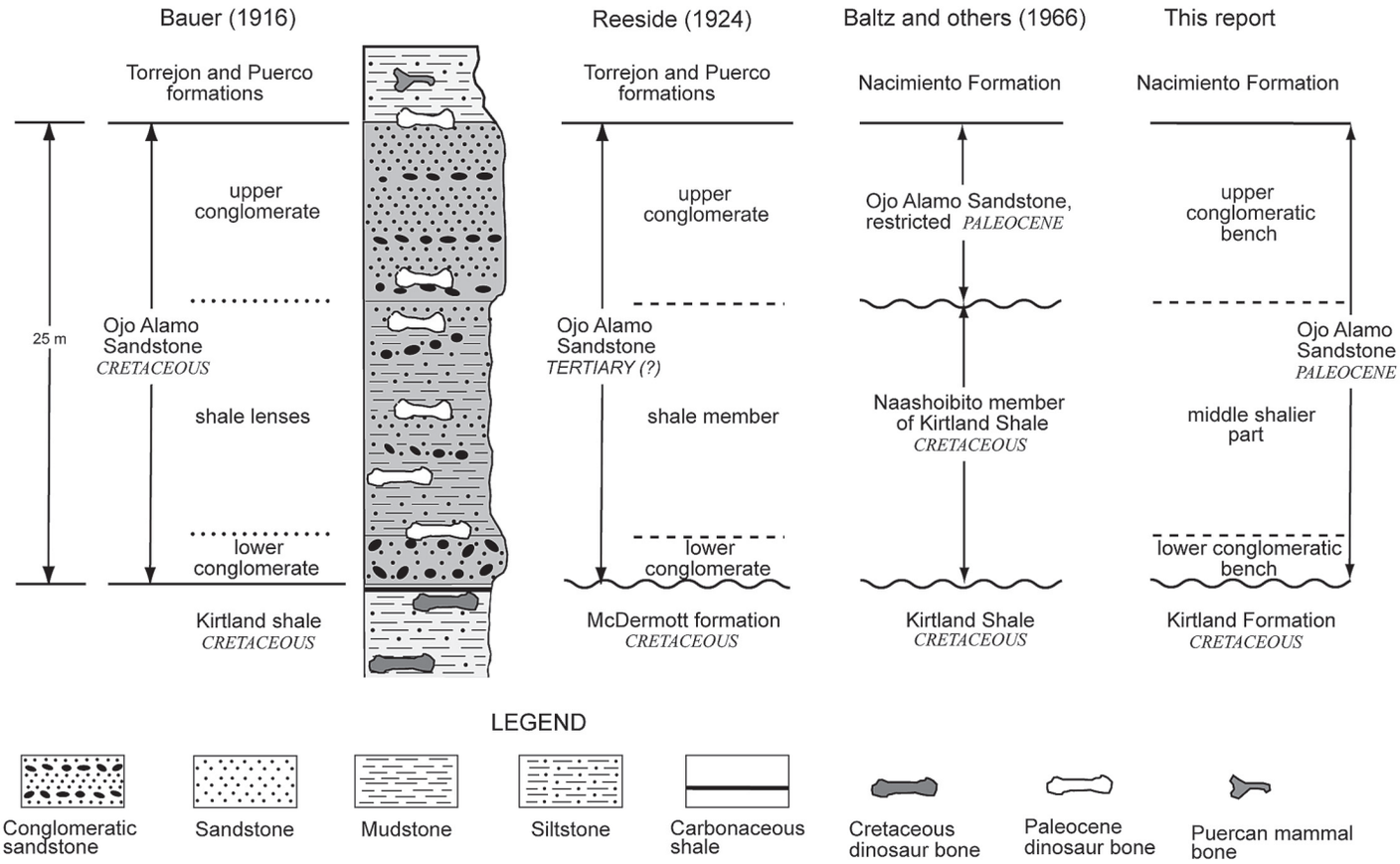


FIGURE 2. Stratigraphic column of Ojo Alamo Sandstone and adjacent strata with stratigraphic nomenclature of various workers and preferred nomenclature of this report. Figure is modified from figure 2 of Fassett (2009).

Farke and Williamson, 2006 and Lehman et al., 2006), continue to refer to the "Naashoibito Member of the Kirtland Formation". Fassett (2000), Fassett et al. (2002), and Fassett, 2009 suggested that the name "Naashoibito" be abandoned because there is no distinct, mappable, lithologically consistent group of rocks to which that name can reasonably be applied, as required by The North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 2005). The definition of the Ojo Alamo Sandstone used in this report, is shown on Figure 2.

Members

Sullivan et al. (2005, p. 404) suggested that the Ojo Alamo should be subdivided into two members, as follows:

> "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 [restricted] 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."

The last sentence of this quote is totally confusing. These authors state that where the "Naashoibito Member cannot be recognized the entire Ojo Alamo Formation is the Kimbeto Member" but they then go on to say in the same sentence that in places where there is no Naashoibito "the lower part of the Ojo Alamo Formation may be . . . equivalent to the Naashoibito Member". On the one hand they state that where there is no Naashoibito Member the Ojo Alamo is the Kimbeto Member and on the other hand they call the part of the formation without a Naashoibito Member the Ojo Alamo Formation.

These authors further suggested that a ~2.5 m.y. unconformity separates their Naashoibito and Kimbeto members of the Ojo Alamo. Figure 3 is a literal diagrammatic representation of the Sullivan et al. (2005) interpretation of the Ojo Alamo Sandstone.

An examination of Figure 3 makes clear that there are many problems with the Sullivan et al. interpretation of the Ojo Alamo Sandstone. For one, this interpretation is a direct violation of the North American Stratigraphic Code (2005) that states in Article 25, p. 1569: "A member is the formal lithostratigraphic unit next in rank below a formation *and is always a part of some formation* [my emphasis]." The Sullivan, Lucas, and Braman suggestion

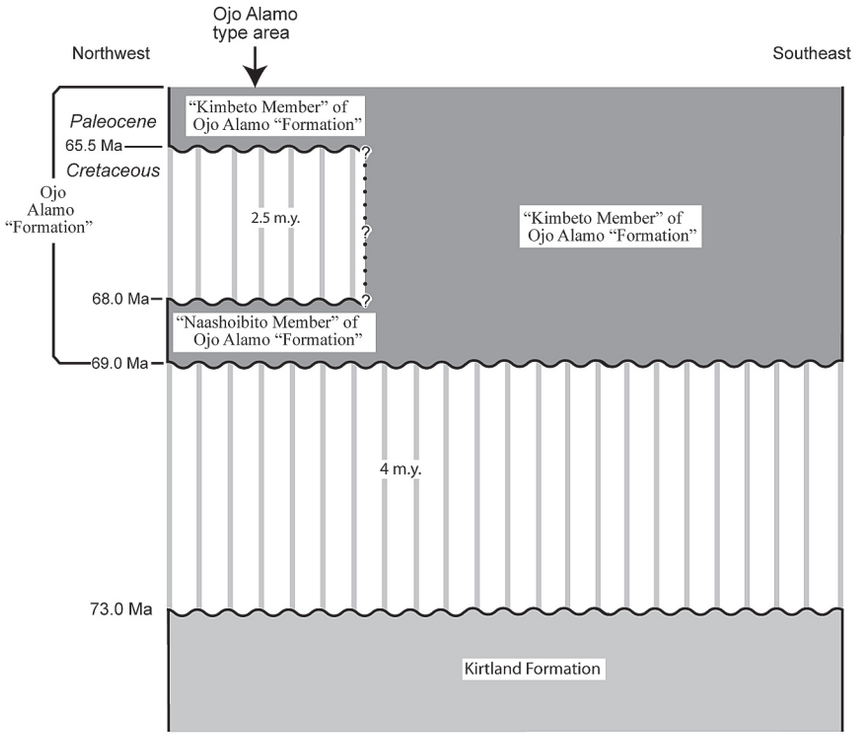


FIGURE 3. Diagram showing interpretation of Ojo Alamo Sandstone in southern San Juan Basin by Sullivan et al. (2005).

would have the Kimbeto Member become the only member of the Ojo Alamo Sandstone rock unit in the southeast part of the basin (right side of Fig. 3) in effect giving the Ojo Alamo there two names at once: the Ojo Alamo Sandstone and the Kimbeto Member of the Ojo Alamo Sandstone; clearly an untenable situation. Furthermore, "where the Naashoibito Member cannot be recognized" neither can the overlying Kimbeto Member be recognized because both members depend on the contact between them to exist. Therefore, a member name cannot replace the name of a two-member formation at the place where one of the members "cannot be recognized". At whatever place one member ceases to be recognizable, both members cease to exist, thus the formation name must become the original rock unit name: the Ojo Alamo Sandstone.

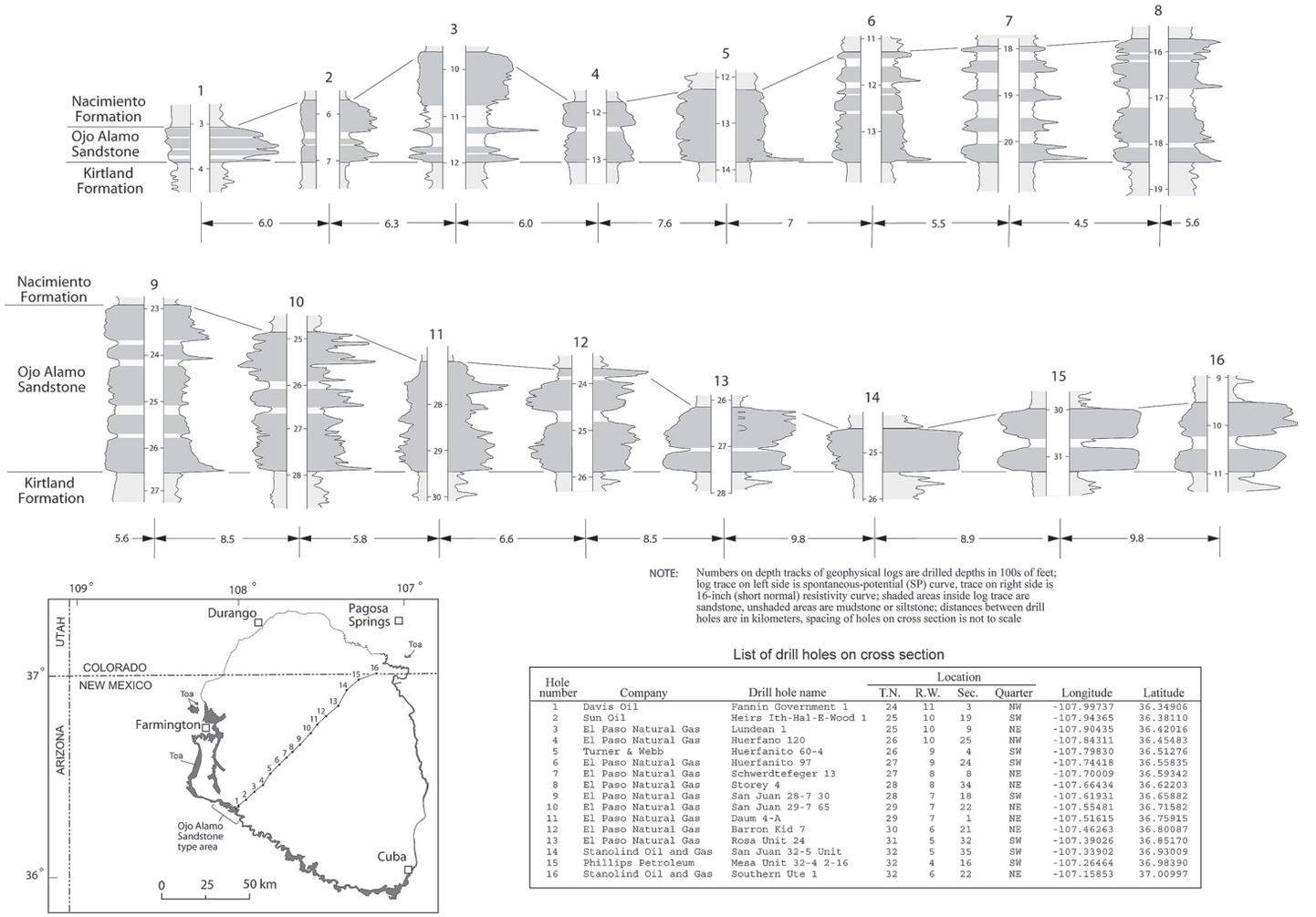
A related problem is the difficulty in explaining how the ~2.5 m.y. hiatus purported to be present in the Ojo Alamo Sandstone type area, disappears so abruptly going to the southeast. These authors offer no explanation for how such a remarkable occurrence could have taken place.

Another problem with this interpretation is that there is no evidence whatsoever for a ~2.5 m.y. unconformity within the Ojo Alamo Sandstone at the type locality of this formation or anywhere else in the San Juan Basin. There is no physical, paleontological, or other chronological data supporting such a claim and thus it is suggested that Sullivan et al. (2005) have conjured this unconformity out of thin air to support their interpretation. Part of the problem with the Sullivan et al. interpretation of Figure 3 is that they have a very provincial knowledge of the Ojo Alamo Sandstone throughout the San Juan Basin based on their concentrated studies of this formation only in those parts of the southern San Juan Basin where the Ojo Alamo contains dinosaur fossils. Because these authors are vertebrate paleontologists, it is understandable why they would focus on such areas, but it is this narrow focus that has resulted in their lack of understanding of the variability of the Ojo Alamo throughout the entire San Juan Basin. Fassett et al. (2002) presented a geophysical-log cross section showing the enormous diversity of the Ojo Alamo Sandstone across the basin (Fig. 4) and this illustration clearly shows that the Ojo Alamo Sandstone at its type area is not representative of this formation basin wide.

And finally, palynologic and paleomagnetic data prove unequivocally (Fassett et al., 2002; Fassett, 2009) that the Ojo Alamo Sandstone (including the lower part referred to as the "Naashoibito Member" in Sullivan et al., 2005) is Paleocene in its entirety across the San Juan Basin and that a hiatus of about 7.8 m.y. separates the Ojo Alamo from the underlying Cretaceous Kirtland Formation in the southern San Juan Basin (Fassett, 2009). It is thus clear that the Sullivan et al. interpretation of the Ojo Alamo Sandstone as portrayed on Figure 3 is not supported by data. Thus the existence of the Naashoibito and Kimbeto members of the Ojo Alamo Sandstone is here rejected.

Lithic component of Ojo Alamo Sandstone name

As mentioned above, Sullivan and Lucas (2003, p. 699) refer to the Ojo Alamo Sandstone as "Ojo Alamo Formation" without explanation of why this name change was made. Sullivan et al. (2005, p. 395) casually suggest that the name Ojo Alamo Sand-



NOTE: Numbers on depth tracks of geophysical logs are drilled depths in 100s of feet; log trace on left side is spontaneous-potential (SP) curve, trace on right side is 16-inch (short normal) resistivity curve; shaded areas inside log trace are sandstone, unshaded areas are mudstone or siltstone; distances between drill holes are in kilometers, spacing of holes on cross section is not to scale

List of drill holes on cross section

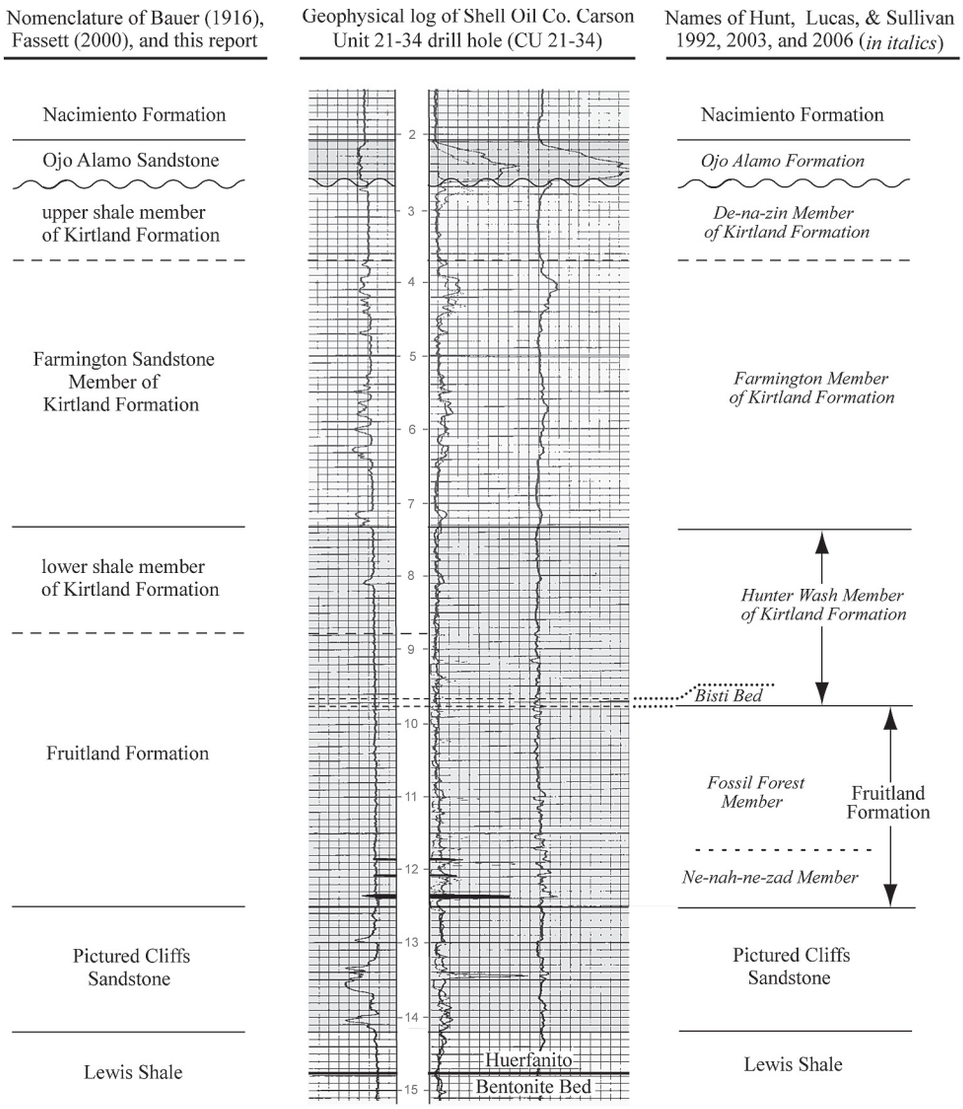
Hole number	Company	Drill hole name	Location T.N.	R.W.	Sec.	Quarter	Longitude	Latitude
1	Davis Oil	Fannin Government 1	24	11	3	NW	-107.99737	36.34906
2	Sun Oil	Heirs Ith-Hal-E-Wood 1	25	10	19	SW	-107.94365	36.38110
3	El Paso Natural Gas	Lundean 1	25	10	9	NE	-107.90435	36.42016
4	El Paso Natural Gas	Huerfano 120	26	10	25	NW	-107.84311	36.45483
5	Turner & Webb	Huerfanito 60-4	26	9	4	SW	-107.79830	36.51276
6	El Paso Natural Gas	Huerfanito 97	27	9	24	SW	-107.74418	36.55835
7	El Paso Natural Gas	Schwerdtefeger 13	27	8	8	NE	-107.70009	36.59342
8	El Paso Natural Gas	Storey 4	28	8	34	NE	-107.66434	36.62203
9	El Paso Natural Gas	San Juan 28-7 30	28	7	18	SW	-107.61931	36.65882
10	El Paso Natural Gas	San Juan 29-7 65	29	7	22	NE	-107.55481	36.71582
11	El Paso Natural Gas	Daum 4-A	29	7	1	NE	-107.51615	36.75915
12	El Paso Natural Gas	Barron Kid 7	30	6	21	NE	-107.46263	36.80087
13	El Paso Natural Gas	Rosa Unit 24	31	5	32	SW	-107.39026	36.85170
14	Stanolind Oil and Gas	San Juan 32-5 Unit	32	5	35	SW	-107.33902	36.93009
15	Phillips Petroleum	Mesa Unit 32-4 2-16	32	4	16	SW	-107.26464	36.98390
16	Stanolind Oil and Gas	Southern Ute 1	32	6	22	NE	-107.15853	37.00997

FIGURE 4. Electric-log cross section showing variability of Ojo Alamo Sandstone across entire San Juan Basin. Figure is modification of figure 5 of Fassett, et al. (2002).

stone be changed to "Ojo Alamo Formation" as follows: "This means that the Ojo Alamo Formation (it is more than a sandstone, lithologically) is a composite unit, both lithostratigraphically and chronostratigraphically." This suggested name-change of "Ojo Alamo Sandstone" to "Ojo Alamo Formation" by these authors is herewith rejected for the following reasons:

1. Sandstone is the distinguishing, dominant, and characteristic lithologic component of this rock unit, both in surface exposures and on geophysical logs (Fassett et al., 2002, p. 311-312; figures 4, 5) and Figures 2 and 4 of this report. These sandstone beds are always the dominant lithology of this formation. The Ojo Alamo does contain thin interbeds of siltstones and mudstones at most localities, but these beds are always a minor part of the formation. The North American Stratigraphic Code (2005) clearly states (Article 30, section b, p. 1570) that: "The lithic part of the name should indicate the *predominant or diagnostic lithology* [my emphasis], even if subordinate lithologies are included." Many other formations in the San Juan Basin, and indeed throughout the world contain the word "Sandstone" as the lithologic component of their names; for example: Pictured Cliffs Sandstone, Point Lookout Sandstone, Cliff House Sandstone, and Dakota Sandstone (to name a few) in the San Juan Basin. These formations all contain thin interbeds of mudstones and siltstones but the lithic part of the name "Sandstone" represents the dominant lithology of these rock units and thus such names should not be changed.

2. Article 5 of The North American Stratigraphic Code (2005, p. 1561) states that: "To be valid, a new unit must serve a clear purpose and be duly proposed and duly described, and the intent to establish it must be specified. Casual mention of a unit . . . does not establish a new formal unit . . . " It is clear that the single sentence quoted above from Sullivan et al. (2005) represents a "casual mention"; these authors do not provide any additional discussion or justification for the name-change from Ojo Alamo Sandstone to Ojo Alamo Formation other than this one sentence, thus this suggested change does not



NOTES: 1. Full citations for publications in heading to right of geophysical-log section: Hunt and Lucas (1992), Sullivan and Lucas (2003), and Lucas, Hunt, and Sullivan (2006).

2. "*Bisti Member*" of Kirtland Formation of Hunt and Lucas (1992) was renamed "*Bisti Bed*" in Sullivan and Lucas (2003); top of "*Ne-nah-ne-zad Member*" of Fruitland Formation "is placed at the base of the first sandstone bed above the stratigraphically highest thick coal bed" per Lucas, Hunt, and Sullivan (2006, p. 3).

FIGURE 5. Geophysical log of Shell Oil Co. Carson Unit 21-34 drill hole showing formation contacts. Location of drill hole is shown and designated CU 21-34 on Figures 1 and 4. Differing stratigraphic nomenclature for rock units shown is indicated on both sides of log. The preferred stratigraphic nomenclature of this paper is shown on left side of log. Figure is modified from figure 64 of Fassett (2009).

meet the criteria specified in Article 5 for a formal name change and therefore it is rejected.

KIRTLAND FORMATION

Figure 5 shows the geophysical log from the Shell Carson Unit 21-34 (CU 21-34) drill hole in the southwest part of the San Juan Basin; this drill hole is only about 6 km northeast (down dip) of the Ojo Alamo type area (Fig. 1.1). The original Kirtland Formation member names of Bauer (1916) are shown on the left side; new member names for parts of the Kirtland Formation suggested by Hunt and Lucas (1992) are shown on the right. The member names for the Kirtland of Bauer (1916, Fig. 5) had been used for 76 years on every published geologic map and report that included these rock units. Fassett and Hinds (1971, p. 280) did question the validity of Bauer's "upper shale member" name. Those authors showed that the contact between the Ojo Alamo Sandstone and the Kirtland Formation was an angular unconformity with the Kirtland being beveled at the top from northwest to southeast across the San Juan Basin (Fig. 1.2). They thus concluded that the "upper shale member" was not a continuous stratigraphic unit throughout the San Juan Basin, but rather only

represented the mudstone interbed present at any specific locality at the top of the Kirtland. Nonetheless, Fassett and Hinds only suggested that the Farmington Sandstone Member and the upper shale member be included together as an undivided unit: they did not recommend that Bauer's (1916) long-established nomenclature be formally changed because his names were so solidly entrenched in the literature.

The new names "Hunter Wash Member" and "De-na-zin Member" of the Kirtland Formation coined by Hunt and Lucas (1992) are not recognized in this report. As noted above, Article 5 of The North American Stratigraphic Code clearly states that "To be valid, a new unit must serve a clear purpose . . ." and Remark C (p. 1562) warns: "Stability of nomenclature is maintained by use of the *rule of priority and by preservation of well-established names. Names should not be modified without explaining the need* [my emphasis]." Hunt and Lucas (1992) do not divulge "what clear purpose" would be served or why "there is a need" to rename Bauer's (1916) "lower shale member" of the Kirtland the "Hunter Wash Member" or rename Bauer's "upper shale member" the "De-na-zin Member" of the Kirtland Formation. To make matters worse, the "Hunter Wash" name was applied earlier by Clemens (1973) to a faunal assemblage in the same area collected from the uppermost Fruitland Formation and lowermost Kirtland Formation that he named the "Hunter Wash local fauna." Thus the suggested use of the name "Hunter Wash Member of the Kirtland Formation" as a new member name to replace Bauer's "lower shale member" of the Kirtland is in direct conflict with The Code's proscription of "Duplication of Names" as spelled out in Remark (b) (p. 1562).

Hunt and Lucas (1992, p. 220) also recommend changing the name Farmington Sandstone Member of the Kirtland Formation to Farmington Member because "it also includes conglomerate, mudstone, and siltstone". The Farmington Sandstone Member is characterized by its sandstone beds and The North American Stratigraphic Code (2005) clearly states (Article 30, section b, p. 1570), as discussed above, that: "The lithic part of the name should indicate the *predominant or diagnostic lithology* [my emphasis], even if subordinate lithologies are included." Thus there seems to be no good purpose served or real need to change the name "Farmington Sandstone Member" to "Farmington Member", thus this nomenclature change is also rejected. (This suggested nomenclature change parallels the recommended name change for the Ojo Alamo Sandstone discussed above and indicates a disturbing pattern of a lack of understanding of the Stratigraphic Code by some authors.)

Hunt and Lucas (1992) stated that the name "Bisti Member of the Kirtland Formation" was applied to a single sandstone bed or series of sandstone beds that they thought marked the base of the Kirtland Formation near the Bisti Trading Post and in the Fossil Forest area (Fig. 6). Lucas and Sullivan (2003, p. 369) very casually suggested that the name "Bisti Member of the Kirtland Formation" be changed to "Bisti Bed", as follows: "We now recognize three members of the Kirtland Formation: Hunter Wash, Farmington, and De-na-zin members, and consider the Bisti Member to be a bed of the Hunter Wash Member (Fig. 2)." This name change from "Member" to "Bed" is not accepted because it meets none of the criteria for making such a change specified in The North American Stratigraphic Code (2005).

The designation of a sandstone bed or collection of beds named the "Bisti Member of the Kirtland Formation" marking the base of the Kirtland (Hunt and Lucas, 1992) is rejected for the following reasons:

1. The stratigraphic position of this unit is not specified in terms of its distance from any overlying or underlying geologic contact in its type area. The only position specified is "at the base of the Kirtland Formation." Because the base of the Kirtland rises stratigraphically northeastward across the San Juan Basin (discussed below), this position is ambiguous. No stratigraphic column is presented in the Hunt and Lucas paper showing the stratigraphic position of the "Bisti Member" in its type area (Fig. 6). Thus, a precise, stratigraphic description of this new member, as required by The Code of Stratigraphic Nomenclature (2005) has not been provided.

2. Hunt and Lucas (1992, fig. 4) show that the "Bisti Member" is 260 ft (80 m) above the top of the Pictured Cliffs Sandstone on a geophysical log of a drill hole located nearly 40 km northwest of the "Bisti Member" type area (HL on Fig. 6). Figure 6 shows that the time-transgressive Pictured Cliffs rises stratigraphically northeastward across the San Juan Basin. The Fruitland-Kirtland contact, also time-transgressive, rises in tandem with the top of the Pictured Cliffs (Fassett and Hinds, 1971, Fassett, 2000). Figure 6 is an isopach map showing the interval between the Huerfanito Bed (an isochronous marker bed in the Lewis Shale) and the top of the Pictured Cliffs Sandstone throughout the San Juan Basin. This figure shows that the top of the Pictured Cliffs is about 250 ft (75 m) higher at the location of the well log illustrated by Hunt and Lucas (1992) on their figure 4 than at their type locality near the Bisti Trading Post (see locations on Figure 6). Obviously, this cannot be the same bed at these two localities. Because of the stratigraphic rise of the Kirtland, the Bisti Member of figure 4 of Hunt and Lucas (1992) would have to be 250 ft (75 m) stratigraphically higher at the type area, or well up into the lower part of the Farmington Sandstone (Fig. 5). Conversely, the bed named the Bisti Member at the Bisti Trading Post, if it did exist in the area of the log shown on figure 4 of Hunt and Lucas (1992) would be present only a few meters above the top of the Pictured Cliffs Sandstone at that location; hardly a logical placement for the base of the Kirtland Formation.

Hunt and Lucas (1992) apparently did not have a full understanding of the time-transgressive nature of these rock strata as evidenced by their discussion of the "Bisti Member" of the Kirtland Formation. This is made vividly clear in their comments that: "This unit [Bisti Member] 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." Figure 6 shows that the strati-

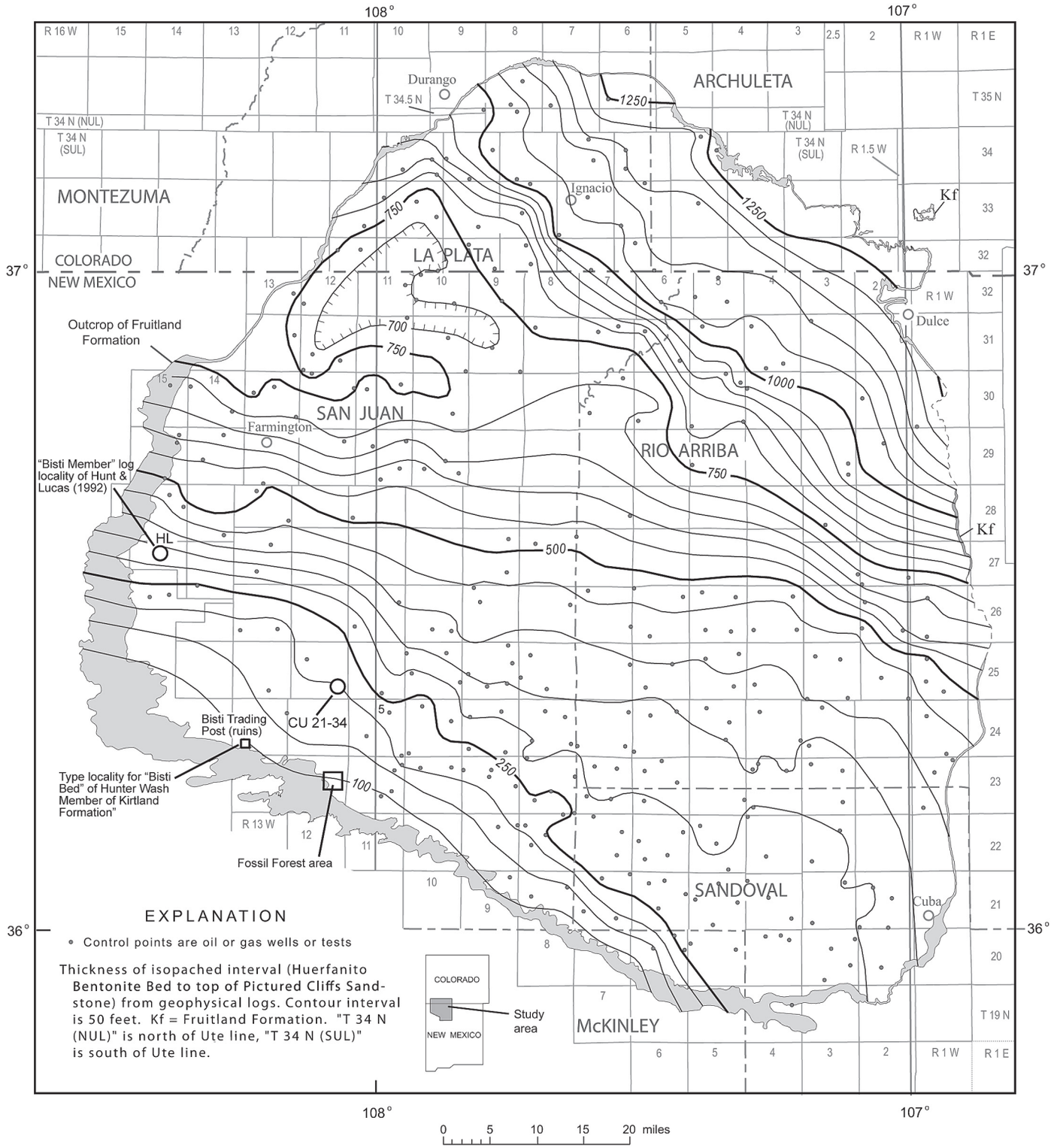


FIGURE 6. Isopach map of San Juan Basin showing thickness of interval from Huerfanito Bentonite Bed to top of Pictured Cliffs Sandstone. Localities discussed in the text are shown in southwest part of map. Map is modified from figure 8 of Fassett (2000).

graphic rise of the top of the Pictured Cliffs Sandstone from the type area of the Bisti Member near the Bisti Trading Post to the San Juan River and Durango areas is 600 ft (180 m) and nearly 1000 ft (300 m) respectively, thus making it impossible for the "Bisti Member" of the "Bisti Member type area" (Fig. 6) to be present in the northern part of the San Juan Basin. Fassett (2000, 2009), on the basis of eight $^{40}Ar/^{39}Ar$ ages obtained for altered volcanic ash beds (ranging from the Huerfanito Bentonite Bed in the Lewis Shale to the top of the Kirtland Formation) (Fassett and Steiner, 1997; Fassett, 2000), has shown that the top of the Pictured Cliffs in the northern San Juan Basin is about 2.72 m.y. younger than in the southern part of the basin. From the "Bisti type area" to the Durango area, the age difference is about 1.5 m.y., thus a channel-sandstone bed at the base of the Kirtland in the Durango area would also be about 1.5 m.y. younger than a channel-sandstone bed at the base of the Kirtland in the "Bisti type area" making abundantly clear the impossibility that the same sandstone bed, the "Bisti Member", marks the base of the Kirtland Formation in the northern and southern parts of the basin.

Figure 5 shows the geophysical log from drill hole CU 21-34 less than 20 km northeast of the Bisti Trading Post (location on Fig. 6). Figure 6 shows that the Pictured Cliffs Sandstone is 30 m (100 ft) stratigraphically higher at CU 21-34 than it is at the "Bisti type area", thus the "Bisti Member" (if it existed) would have to be at a depth of 970 ft on this geophysical log (100 ft below the base of the Kirtland Formation). A careful examination of this geophysical log shows no sandstone beds at that level or anywhere in the upper Fruitland or lower Kirtland that might be considered to be the "Bisti Member of the Kirtland Formation" of Hunt and Lucas (1992). There is a stray sandstone bed in the lower Kirtland Formation on Figure 5 between the depths of 710-720 ft but this bed is much too high in the section – 530 ft above the top of the Pictured Cliffs Sandstone – to be the "Bisti Member."

The author's studies of the Fruitland and Kirtland Formation on surface outcrops and in geophysical logs, over the years, have shown that random channel-sandstone beds are often found in the upper part of the Fruitland Formation and lower shale member of the Kirtland Formation. This is to be expected because runoff from the land surface southwest of the retreating Pictured-Cliffs-Sandstone shoreline had to be flowing northeastward toward the sea through stream channels in Fruitland and Kirtland time. All of these channel-sandstone beds, however, are lensing, random, and discontinuous (as is the case in any continental rock sequence) and none form a continuous bed or zone of beds marking the base of the Kirtland Formation.

In summary, the names lower shale member, Farmington Sandstone Member, and upper shale member of the Kirtland Formation of Bauer (1916) have been used by all subsequent geologists until 1992 (for 76 years) and these names have become entrenched in the subsequent voluminous San Juan Basin literature on geologic maps, stratigraphic columns, and text. For this reason, and because no real need has been articulated to change these names by Hunt and Lucas (1992), as discussed above), the nomenclature changes for the members of the Kirtland Formation suggested by those authors are herewith totally rejected. Therefore, the original names applied by Bauer (1916) of lower shale member, Farmington Sandstone Member, and upper shale member, are still the preferred names to be used for the members of the Kirtland Formation.

Fruitland Formation

Members

The Fruitland Formation was subdivided into two members by Hunt and Lucas (2003) in the Fossil Forest area (Fig. 6): an upper "Fossil Forest Member" and a lower "Ne-nah-ne-zad Member" (Figure 5). The contact between these members was placed at the top of the "highest coal greater than 30 cm thick in the Fruitland Formation" (Hunt and Lucas, 2003, p. 387). Lucas et al. (2006) revisited the definition of the Fruitland Formation, established a new type area for the Fruitland members (near Hunter Wash in the Ojo Alamo type area), and changed the placement of the contact between the Ne-nah-ne-zad and Fossil Forest Members (p. 3) to "the base of the first sandstone bed above the stratigraphically highest thick coal bed." An exact thickness for their "thick coal bed" was not specified, thus, this definition is somewhat ambiguous. Figure 5 shows these two members of the Fruitland projected on the geophysical log from the CU 21-34 drill hole, down-dip from the Hunter Wash type area. The recommended placement of the contact between the Ne-nah-ne-zad and Fossil Forest Members in the Hunter Wash type area in Lucas et al. (2006) is ambiguous. On figure 4 of these authors, labeled "Hunter Wash reference section", this contact is shown at the base of a sandstone bed (their unit 23) and the top of a 2.1-m thick coal bed (their unit 22). However, on their measured section at the type area (p. 6) the contact is shown to be at the base of their unit 28, an 8.1-m thick sandstone bed. The next-lower coal bed on their measured section is their unit 26 and is 0.6-m thick.

The reason for subdividing the Fruitland into two members was apparently, according to Hunt and Lucas (2003), to separate the relatively thin, upper "fossiliferous interval" (Fossil Forest Member) from the lower, thicker, less fossiliferous part of the Fruitland (the Ne-nah-ne-zad Member). (The word "fossiliferous" as used by these authors applies only to vertebrate fossils.) The use of "thick coal beds", however, to differentiate these parts of the Fruitland does not seem to work very well as exemplified by the placement of this contact on the geophysical log of Figure 5. When this contact is placed at the base of the first sandstone above the "highest thick coal bed" of the Fruitland, as specified by these authors, the resulting thickness of the Ne-nah-ne-zad Member is only 9 m (30 ft), whereas the Fossil Forest Member is about 75 m (250 ft) thick. Clearly the criterion of Lucas et al. (2006) for separating out the thin, upper fossiliferous part of the Fruitland from the lower, thicker part that is less fossiliferous does not work for the subdivision of the Fruitland in the well log of Figure 5. Because the subdivision of the Fruitland Formation into two members by Hunt and Lucas (2003) and Lucas et al. (2006) serves no apparent useful purpose and is ambiguous, the subdivision of the Fruitland Formation into two named members is herewith rejected.

Upper Contact of Fruitland Formation

Historical review

The placement of the upper contact of the Fruitland Formation has evolved since it was first defined by Bauer (1916). Bauer (p. 274) defined the Fruitland as consisting of "sandstone, shale, and coal" but did not specify how the top of the formation should be defined, except to say that:

The Fruitland formation is more sandy than the overlying Kirtland shale, into which it merges by a gradational zone containing in many places sandstone lenses that are apparently of fluviatile origin.

Plate LXV of Bauer's paper is a cross section containing seven stratigraphic columns representing measured sections along the west edge of the San Juan Basin. On this illustration, the top of the Fruitland is placed at the top of a sandstone bed above the highest Fruitland coal bed on five of the columns shown and in shales on the other two. Bauer and Reeside (1921, p. 167) stated that coal beds were the most persistent lithology of the Fruitland and were "distributed throughout the formation". These authors were not specific about where the top of the Fruitland should be placed except to say that the contact was "gradational" with the Fruitland being sandier than the Kirtland. On a series of columnar sections along the west side of the San Juan Basin, Bauer and Reeside (1924, plate XXII) placed the top of the Fruitland at the top of shale beds on three of the columns and at the top of sandstone beds on four columns. On all of these columns the top of the Fruitland is shown to be well above the highest Fruitland coal beds shown. Reeside (1924, p. 20) stated that the Fruitland:

> . . . grades continuously upward into the overlying Kirtland Shale. It may be distinguished in the aggregate from the Kirtland shale in that it includes coal beds and indurated brown sandstone. Usually the highest of the sandstones has been taken as the top of the Fruitland formation . . .

Dane (1936) studied the Fruitland Formation in the southeast part of the San Juan Basin and discussed the contact of the Fruitland with the overlying Kirtland Formation as follows (p. 113):

> The Fruitland formation grades continuously upward into the Kirtland shale and differs from it only by having a higher content of coal and sandstone, particularly indurated brown sandstone. The separation of the two formations is altogether an arbitrary one, and in the mapping the line between the two was drawn at the top of the stratigraphically highest brown sandstone.

Silver (1950) offered the first interpretations of the subsurface geology of uppermost Cretaceous strata in the northern San Juan Basin based on geophysical-logs. Silver did not specify in his text where the top of the Fruitland Formation should be placed; however, he depicted the relations of these strata on an east-trending geophysical-log cross section (Silver, 1950, figure 1) whereon he placed the top of the Fruitland Formation at the top of the highest coal bed. Colbert (1950) briefly discussed the Fruitland and Kirtland Formations and wrote (p. 68) that "the Fruitland is distinguished from the Kirtland largely by the presence of coal in the former." Barnes (1953) suggested that the top of the Fruitland be placed so as to "include within the Fruitland formation all persistent coal beds and all prominent sandstone beds". Barnes et al. (1954) stated that the Fruitland-Kirtland contact be placed so as to include in the Fruitland "all coal beds more than 1.2 feet thick and the associated shale and resistant sandstone beds".

Fassett and Hinds (1973) were the first geologists to examine the Fruitland Formation throughout the entire extent of the San Juan Basin both on the outcrop and in hundreds of geophysical well logs throughout the subsurface of the basin. These authors determined that the only consistent way to map the top of the Fruitland Formation (Fruitland-Kirtland contact) throughout the basin was to place the contact "at the top of the highest coal or carbonaceous shale bed" (Fassett and Hinds, p. 19). These authors also determined that using the top of the highest sandstone bed as the top of the Fruitland was a poor criterion because the channel-sandstone beds in the interval near the Fruitland-Kirtland contact were discontinuous, random, and erratically positioned, stratigraphically. Fassett and Hinds (1973, Plate 2) presented five geophysical-log, stratigraphic cross sections across the San Juan Basin at differing orientations showing the contact of the Fruitland and Kirtland Formations at the top of the highest coal or carbonaceous shale bed seen on the logs.

In the late 1970s and early 1980s, the U.S. Geological Survey (USGS) initiated a project to map the Fruitland Formation and adjacent strata around the west and south sides of the San Juan Basin. The primary purpose of this mapping project was to provide basic geologic data in support of the preparation of environmental impact statements related to the possible surface mining of Fruitland coal beds along its outcrop. This mapping was done at 1:24,000 scale and resulted in the mapping of 23, 7 ½ minute quadrangles that were ultimately published as USGS Miscellaneous Field Studies (MF) maps. Both bedrock geology and a detailed subdivision of Quaternary alluvium deposits were mapped for this project. Most of these MF maps did not specify in their texts what criteria were used to map the upper contact of the Fruitland Formation, however at least three of them stated that this contact was placed to include in the Fruitland "important coal" (Scott et al., 1979) or "principal coal beds" (Weide, Scott, and Mytton, 1980 and Weide, Mytton, and Scott, 1980). It is presumed that the top of the Fruitland was mapped to include the "principal" or "important" Fruitland coal beds on the other 20 or so maps for which the tops' criteria were not specifically stated. A USGS Coal Investigations Map of the Chaco Canyon 30' x 60' quadrangle (Mytton, 1983) stated that "the contact between the Fruitland and Kirtland is arbitrarily placed at the top of uppermost principal coal bed." None of these authors quantified "important" or "principal" coal beds, but presumably they meant to include the strippable coal beds in these categories. It is clear that the intent of these USGS mappers was to include in the Fruitland only those coal beds that might be strip mined because the intent of the mapping project was to provide geologic data for environmental-impact statements related to the potential strip mining of Fruitland coal beds. Thus none of these mappers were concerned with the niceties of picking the top of the Fruitland on the basis of the "highest sandstone" or "highest coal or carbonaceous shale" as previous geologists had done.

Fassett (2000) reviewed the coal resources of the Fruitland Formation in the San Juan Basin. He addressed the problem of picking the Fruitland-Kirtland contact on the basis of a lithologic boundary and because of the ambiguity of the contact declined to show a contact between the lower shale member of the Kirtland and the top of the Fruitland. On a detailed, geophysical-log cross section trending northeast across the basin Fassett (2000, plate I) showed the Fruitland Formation and lower shale member of the Kirtland undivided. Fassett, however, did not suggest redefining the stratigraphic nomenclature of the Fruitland-Kirtland interval. A relatively consistent top of the Fruitland can be located on geophysical logs (albeit with a degree of uncertainty) on the basis of the highest coal bed or carbonaceous mudstone, as is done on Figure 5 of this report; however, generally speaking, there is no useful geologic purpose achieved in trying to fix this contact. The base of the Farmington Sandstone can be picked on geophysical logs (Fig. 5) and on outcrops with far less ambiguity, and in a practical sense, the Fruitland Formation and lower shale member of the Kirtland Formation could be combined, for mapping purposes, with an upper contact placed at the base of the overlying Farmington Sandstone Member of the Kirtland.

Coal-bed methane

The name "Fruitland Formation" has attained instant, worldwide recognition over the past two decades among the oil and gas fraternity because of the discovery and production of enormous natural-gas reserves from the coal beds of the Fruitland. It is now estimated that Fruitland Formation coal beds in the San Juan Basin contain resources of as much as 80 trillion cubic feet (TCF) of methane. As of October 2009, Fruitland coals had produced 15.7 TCF of gas from nearly 8,000 wells making this gas field easily the largest coal-bed methane field in the world (Fassett and Boyce, 2005). The New Mexico part of this gas field is named "The Basin Fruitland Gas Pool". Thus the Fruitland Formation, in terms of its gas production from nearly 8,000 wells in the San Juan Basin, has come to be characterized strictly by its coal beds that contain and produce large amounts of coal-bed methane. This, of course, has nothing to do with a formal rock-stratigraphic definition of the Fruitland Formation, but it does represent another powerful de facto argument for defining the top of the Fruitland on the basis of its contained coal beds.

Lucas, Hunt, and Sullivan (2006)

Lucas et al. (2006) have recommended that the rock-stratigraphic definition of the Fruitland be changed back to the way it was defined in the early 1900s (see discussion above) with the top of the Fruitland placed at the top of the highest sandstone bed in the section "except that we put the Bisti Bed in the Kirtland Formation". (See the discussion of the "Bisti Bed" above.) These authors fail to state what useful purpose would be served by this regressive redefinition of the Fruitland Formation. Thus, for that reason and the reasons outlined above, it is here recommended that the top of the Fruitland Formation should continue to be placed at the top of the highest coal bed or carbonaceous shale and that the suggested redefinition of the Fruitland by Lucas et al. (2006) be rejected.

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