

## Fluvial architecture element analysis of the Brushy Basin Member, Morrison Formation, western Colorado, USA

Kenneth G. GALLI<sup>1</sup>

**Key words:** Fluvial Architecture Element Analysis, meandering, anastomosing, Brushy Basin Member, Morrison Formation, Kimmeridgian, Colorado.

**Abstract.** The 85-m Brushy Basin Member of the Morrison Formation in western Colorado, USA, comprises dinosaur-bearing sandstones (architectural element CHR and CH), crevasse-splay deposits and minor levee deposits (architectural element CS), mudstones, marlstones, altered ash beds and minor limestones as well as caliche paleosols and noncalcareous paleosols (architectural element FF). Channel sandstones occur at five stratigraphic levels at Trail Through Time (TT), eleven levels at Fruita Paleontological Research Area (FP), and at five levels at Echo Canyon (EC). River-channel sandstones hosted by floodplain mudstones tend to have cut down to resistant caliche paleosols. Depositional facies and architectural element analysis show that the rivers were low gradient, mainly anastomosing, with perennial flow, but seasonal with “flashy” peaks in discharge. Dinosaur bone accumulations are found in some floodplain ponds. Isolated bones are present in anastomosing channel sandstones at TT and in channel sandstone 2 at EC. At FP, major accumulations of bones were rapidly buried in the deep pools at three bends in the meandering river resulting in the formation of channel sandstone 2. There is no evidence for a large lacustrine or playa system at the three localities.

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### INTRODUCTION

The Morrison Formation is world renowned for its assemblage of dinosaur remains, especially the large herbivorous sauropods. Much work has been done that attempts to place the dinosaurs into a more robustly described ecosystem. A dry climate is thought to have persisted during deposition of Morrison strata due to the basin being in the rain shadow of the western highlands and to prevailing westerlies developed due to a subtropical high over the Paleo-Pacific Ocean (Turner, Peterson, 2004). The Morrison Formation of Late Jurassic age is a mosaic of mostly fluvial and minor lacustrine deposits that cover more than 1.5 million km<sup>2</sup> of the Rocky Mountain, Western Interior and Colorado Plateau regions (Fig. 1; Turner, Peterson, 2004).

Most Morrison Formation streams, sourced in the western highlands, flowed eastward across the depositional basin and were anastomosing in nature. Watering holes formed in the locations of deep erosional scours formed by seasonal stream flooding and accessed the water-table groundwater with this input possibly seasonally controlled by periods of wet and dry conditions. Unionid bivalves are found in a few fluvial sandstones and due to their obligate parasitism with fish, this indicates that fish were present in the Morrison ecosystem in perennial streams (Good, 2004; Turner, Peterson, 2004).

The purposes of this study are to: (1) describe the stratigraphic details of the stream channel deposits present in the Brushy Basin Member of the Morrison Formation of western Colorado; (2) show, in detail, their vertical and lateral distribution, architecture and bounding surface hierarchy; and (3) interpret the fluvial and associated depositional subenvironments.

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<sup>1</sup> Department of Earth and Environmental Sciences, Boston College, Chestnut Hill, MA 02467 USA; e-mail: kenneth.galli@bc.edu

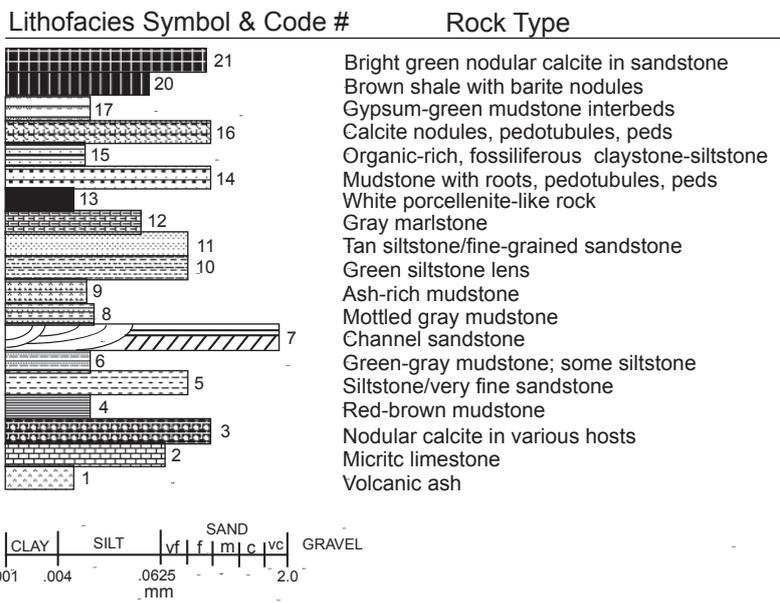
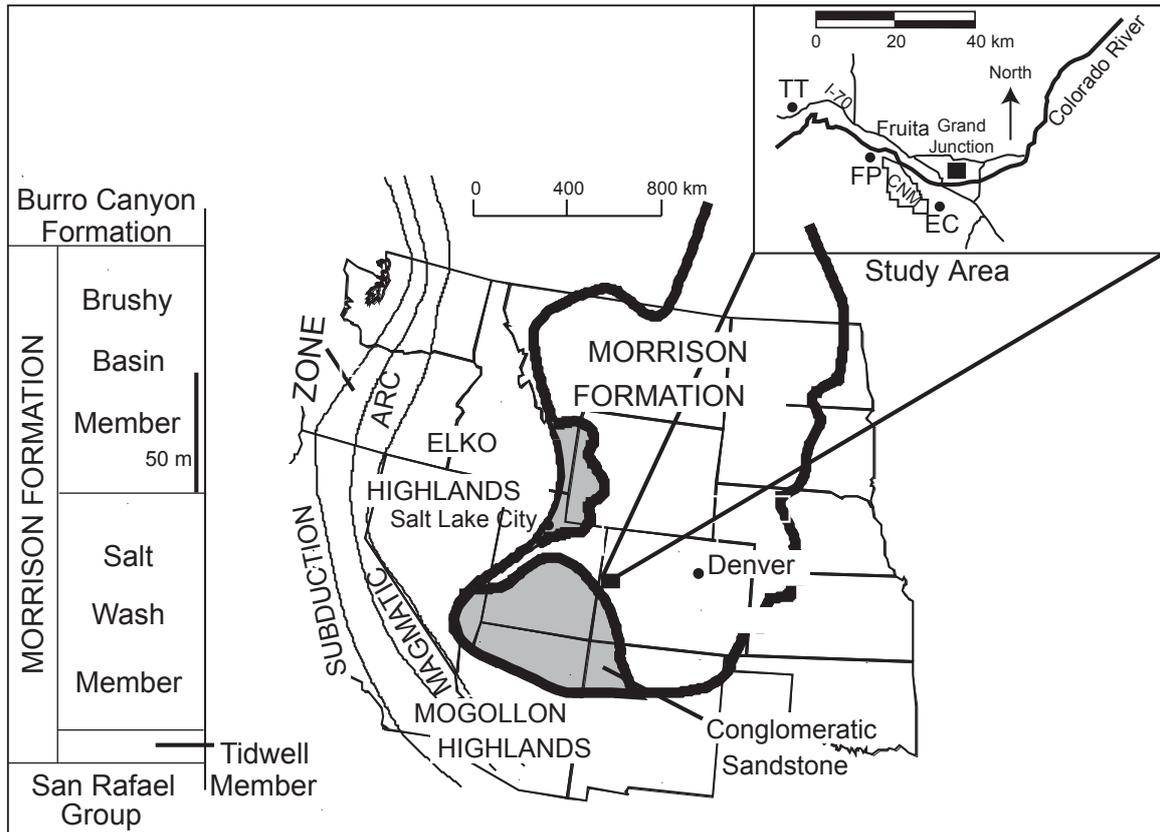


Fig. 1. Study locus, stratigraphic section, facies

Areal extent, source areas, and stratigraphy of Morrison Formation, after Brenner (1983) and Hintze (1988). TT – Trail Through Time; FP – Fruita Paleontological Research Area; EC – Echo Canyon; CNM – Colorado National Monument. General legend for facies used in all vertical measured sections and architectural panels

## REGIONAL SETTING

The Morrison Formation was deposited in the most landward, back-bulge basin of a foreland basin system developed during Late Jurassic subduction of the paleo-Pacific (Farallon) oceanic plate to the west of the preserved Morrison basin (DeCelles, Giles, 1996). Perhaps the relative thinness of the Morrison strata is explained by plate-margin activity during deposition that prevented the foredeep from subsiding (Miall, 2000). Morrison strata are typically 152 to 183 m thick compared to the tens of thousands of meters of Cretaceous strata in nearby basins.

Cadigan (1967) showed clearly that the source areas for the Morrison were to the west and the southwest, based on the position of the proximal conglomeratic facies associated with the sandstones and finer facies. The basin was separated from the Paleo-Pacific Ocean by several mountainous regions, some of which contributed sediment to the depositional basin. Abundant volcanic ash was sourced from calderas in the remnant of an arc-graben depression and in the transtensional rift zone that extended from southern Arizona to central eastern California. The prevailing winds in the Western Interior during the Late Jurassic blew from the southwest. Clastics in the depositional basin were mainly derived from highlands that extended from northern Mexico to British Columbia. The highlands are interpreted to have been rift shoulders and uplifts in the back-arc region. A relatively minor amount of clastic material was derived from local topographic highs in the largely buried Ancestral Rockies and perhaps in other local areas farther north (Turner, Peterson, 2004).

The J-5 unconformity underlies the basal Morrison Formation of Early Kimmeridgian age. The regional J-5 unconformity is present below the base of the Tidwell Member and the regional K-1 unconformity is present at the top of the Brushy Basin strata (Pipiringos, O'Sullivan, 1978; O'Sullivan, 1980; Peterson, 1994).

Most of the Morrison Formation is Kimmeridgian in age with only the uppermost section being Tithonian in age (Litwin *et al.*, 1998; Schudack *et al.*, 1998). This is based on palynological studies and studies of charophytes and freshwater ostracods. The Morrison was deposited from 155 to 148 Ma based on isotopic dates of sanidine from smectitic tuffs (Kowallis *et al.*, 1998).

The Brushy Basin is the most widespread member of the Morrison Formation, thinning northward and northeastward from 157 m in southwestern Colorado and eastern Utah, to 79-138 m in the Grand Junction area. It then thickens northwestward to 236 m locally in northwestern Colorado and northeastern Utah (Lohman, 1965), closer to the source areas.

## LOCATION OF THIS STUDY

In the study area in and around Fruita in western Colorado, the Morrison Formation consists of 120 to 250 m of mostly terrestrial strata deposited primarily during Kimmeridgian (155 Ma) to Tithonian (148 Ma) time (Kowallis *et al.*, 1998). The 85-m Brushy Basin Member of the Morrison Formation in western Colorado is dominated by a 30-m lower division (lower Brushy Basin Member (Jmbl)) mostly made of red-brown mudstone and a 55-m upper division (upper Brushy Basin Member (Jmbu)) characterized by variegated smectitic mudstones of floodplain origin where the smectite is altered silicic ash blown eastward by the prevailing winds. This change is discerned in the field by the change from non-swelling red-brown floodplain mudstones typical of the lower Brushy Basin strata to the puffy-weathering aspect typical of upper Brushy Basin ash-rich mudstones. However, X-ray diffraction (XRD) analysis and scanning electron microscopy (SEM) of lower Brushy Basin mudstones and upper Brushy Basin ash-rich mudstones showed that in most cases, both facies were rich in the swelling clay smectite. This color change is the sole basis of the division of the two Brushy Basin lithosomes.

River-channel sandstones are embedded in the mudstones and tend to have cut downward to resistant caliche paleosol horizons. Also present are thin beds of lacustrine micritic limestone and four major zones of altered silicic ash falls. These strata were studied at three locations, from west to east: Trail Through Time (TT), Fruita Paleontological Research Area (FP), and Echo Canyon (EC). This paper presents the analysis of the many hierarchical orders of fluvial architecture observable in the Morrison strata. Description of bounding surfaces and lithofacies details allow the interpretation of the fluvial styles of Brushy Basin Member rivers and their associated facies.

## LOCATION OF SECTIONS MEASURED

The three sections in western Colorado are in the northeastern portion of the Colorado Plateau Physiographic Province (Fig. 1). From west to east, they are: Trail Through Time (TT), Fruita Paleontological Research Natural Area (FP), and Echo Canyon (EC). The TT section is adjacent to and east of the Mygatt-Moore Dinosaur Quarry in the Rabbit Valley Research Natural Area. The TT locality is situated on the north side of I-70, 3 km east of the Utah-Colorado border, accessible by exit 2 off I-70. The FP and TT localities are active dinosaur dig-sites. FP is south of the Colorado River approximately 1–2 km southwest of Fruita and is accessible from old uranium roads off Colorado 340, just north

of the western entrance to Colorado National Monument. FP is approximately 28 km east of the Utah-Colorado border. EC is a side canyon of No Thoroughfare Canyon located near the eastern margin of the Colorado National Monument. The stratigraphy of No Thoroughfare Canyon was described by Lohman (1965). The EC locality is accessible from Little Park Road, proceeding south from Grand Junction, Colorado. The site is approximately 42 km east of the Utah-Colorado border.

At the Fruita Paleontological Research Natural Area (FP) there is a remarkable abundance and diversity of Upper Jurassic terrestrial fossils preserved within an area of approximately one square kilometer. Utah State Paleontologist Dr. James Kirkland has overseen exploration at both FP and TT and graciously invited me to conduct my dissertation research in western Colorado at FP and TT. Kirkland identified six facies at FP: (1) ribbon sandstone facies – bank-controlled, gravelly, low-sinuosity river channels; (2) levee facies – characterized by clay with well-sorted sandstone of proximal crevasse splay deposits best seen at channel bends; (3) drab floodplain facies – drab, poorly drained alkaline floodplains with carbonate-cemented crevasse splays and poorly developed paleosols; (4) dark red floodplain facies – oxidized well-drained floodplains with well-developed paleosols containing nodular carbonates; (5) pond/marsh facies – more or less permanent spring-fed marshes that locally overlie channel thalwegs; and (6) alkaline pond facies – ephemeral alkaline floodplain ponds with barite nodules. Each facies also preserves a unique suite of fossils (Kirkland, 2006).

## METHODS

Lithofacies descriptions were assigned to each distinct rock type and its contained features and detailed vertical stratigraphic sections were measured at the three localities. Lateral profiles for architectural analysis were drawn in the field, using photomosaics at and adjacent to measured sections, and other select locations. Sketches were made of the lateral and vertical extent of lithofacies, thickness trends in trough cross-bed cosets, grain-size trends, thickness of cross-bed cosets, surfaces that cut through cosets, gravel at the base of channels, size, type, and alignment of intraclasts and gravel, and alignment of dinosaur bones.

Specimens of many facies were collected at TT and EC. XRD analysis was performed on about twenty specimens at each locality. SEM analysis augmented the petrographic analysis. Twenty-one samples were analyzed from six depositional environments: (1) red-brown mudstone (floodplain deposits), (2) puffy-weathering green or purple silty mudstone (altered volcanic ash/ashy flood mudstones), (3) green-

ish-gray mudstone (high water-table regions of floodplains), (4) mottled brown mudstone (phase-one paleosols), (5) thin clay lens in channel sandstone, and (6) non-calcareous mottled red-brown mudstone with peds and roots (incipient paleosol).

The samples were prepared for clay-mineral analysis following the procedures of Gibbs (1971). 1) Samples were broken to pea-size pellets, using mortar and pestle and then crushed to powder in a Spex ball mill. 2) The powders were saturated in a buffered solution of sodium acetate to dissolve calcite cement without dissolving clays and to saturate expandable clays with  $\text{Na}^+$ . 3) The powders were further disaggregated with a mechanical shaker and an ultrasonic probe. 4) Liquid was separated from the clays by centrifugation at 2000 rpm for 20 minutes. 5) Powders were washed in deionized water, resuspended, and recentrifuged to remove the sodium acetate. 6) The <2-micron clay fraction was obtained by centrifugation at 500 rpm for 8 minutes-37 seconds and then pouring off the suspensate containing the clay fraction. 7) Slides were prepared after the method of Gibbs (1971) by evaporating the suspensate to a paste then smeared onto glass slides.

Three slides were prepared for each sample. One was air-dried and untreated. The second was solvated in an ethylene glycol saturated chamber for at least 24 hours. The third slide was heated to 550°C for one hour. Unoriented mounts of 6 samples were prepared by mixing a small quantity of powder with acetone, forming a slurry, which was dropped onto the slide and allowed to dry. All samples were analyzed on a Siemens X-ray diffractometer, using Cu K- $\alpha$  radiation at 35 kV and 20 mA. The goniometer scanning speed was 2° per minute and chart recorder speed 2 cm per minute. All oriented slides were run from 2° to 30° 2 $\theta$ . Random-mount slides were measured to 50° 2 $\theta$  to examine the non-basal diffraction peaks in illite and to 65° 2 $\theta$  to examine the non-basal diffraction peaks in smectite.

The identification of smectite was based on expansion of the (001) peak from 12.5 Å to 16.8–17.0 Å on glycolation and collapse to 10.0 Å when heated to 550°C. Diffraction traces of random mounts of 6 samples consisting almost entirely of smectite display a (060) peak at 1.53–1.54 Å, typical of trioctahedral smectite (Dyini, 1976). Adapting the procedure of Greene-Kelley (1973), these 6 smectite samples were saturated in a 3M lithium chloride solution. Then, the slides were heated to 300°C and placed in a glycol-saturated chamber. These samples re-expanded when glycolated after heating; dioctahedral smectites do not re-expand (Green-Kelley, 1973).

To examine interstitial clay in sandstones by scanning electron microscopy, three 9-mm-size samples of sandstone were mounted with double-sided carbon tape onto aluminum stubs and sputter-coated with gold-palladium for 90 to 120 seconds. Samples were analyzed at Mt. Holyoke Col-

lege (South Hadley, Massachusetts) using 20 Kv on a JEOL JSM-35CF with a Tracor-Northern energy dispersive system (Galli, 2003).

## FACIES AND STRATIGRAPHY OF THE BRUSHY BASIN MEMBER

### INTRODUCTION

In the Brushy Basin Member, 21 facies (19 in the Morrison Formation; facies 18, 19 are in overlying formations) were identified in the field based on lithology, geometry, sedimentary structures, and fossils (Table 1). The TT and FP sections have the largest variety of facies and the best-developed paleosols. The EC section, farthest east, has the fewest number of facies. The three measured sections are annotated with paleocurrent roses of selected channel sandstones, and primary sedimentary structures such as ripple cross-lamination (Sr), planar cross-bedding (Sp), trough cross-bedding (St) and horizontally laminated or bedded sandstones (Sh), noted by facies codes and by the sketch of the internal bedding features of each channel sandstone. The general legend for facies used in the vertical stratigraphic sections, architectural panels and throughout the manuscript, and the lithofacies codes, descriptions, and architectural elements containing these facies, are presented in Table 1 (Galli, 2003).

The base of the TT section was the upper 16 m of exposed Salt Wash Member strata topped by the uppermost Salt Wash sandstone. The base of the FP section was the contact between the Entrada Sandstone and the overlying Summerville Formation, which contained sand crystals and salt casts, and my vertical stratigraphic section closely followed that measured by Kirkland and Rassmussen (J. Kirkland, person. commun., 1989). The base of the EC section was the contact between the Kayenta Formation and the overlying Entrada Sandstone. At TT, the upper Brushy Basin was marked by a silica-replaced limestone, marked as volcanic ash zone IV within the Brushy Basin strata and correlated to the other silica-replaced units at the top of the Brushy Basin at FP and EC. This may mark the disconformity that separates the Upper Jurassic Brushy Basin strata from the Lower Cretaceous Burro Canyon strata. The top of the section at TT was the lowermost sandstone of the Cretaceous Burro Canyon Formation. The Burro Canyon sandstone is salt and pepper (black/white) in color and contains green mudchips.

At FP, the uppermost Brushy Basin is marked by a meter-thick puffy green-weathering, volcanic ash bed (my ash IV) that is overlain by a distinctive 2-m-thick bright green probable paleosol of green siltstone with green nodular carbonate and sandstone with bright green matrix, mottled in some

places and botryoidal in other places. At EC, the Brushy Basin/Burro Canyon contact is marked by a partially silica-replaced micrite of the Brushy Basin, overlain by a meter-thick salt and pepper-appearing black/white pebble conglomerate of the Burro Canyon Formation.

The sandstone to fines (SS:F) ratio, one parameter often used to discern fluvial style, with fines including all floodplain facies such as mudstones, ashy mudstones, paleosols and tabular very-fine grained sandstones, was calculated for the lower Brushy Basin Member (Jmbl) and the upper Brushy Basin Member (Jmbu) at each section. For each locality, I present the stratigraphy of the uppermost Salt Wash Member to contrast it with that of the lower, middle, and upper Brushy Basin Member. At TT, the SS:F ratio of Salt Wash strata is 29:71; at FP, the SS:F ratio of Salt Wash strata is 25:75; and at EC, the SS:F ratio of Salt Wash strata is 54:46. Clay mineralogy was determined by XRD analysis for various facies at TT and EC. At TT, upper Salt Wash strata contain 85.2% illite, 0.6% smectite and mixed-layer illite-smectite, and 14% chlorite. At EC, upper Salt Wash strata contain 86.9% illite-smectite and illite, 2.1% smectite, and 11.0% chlorite.

### LOWER BRUSHY BASIN MEMBER (JMBl)

At TT, the 31-m-thick lower Brushy Basin Member is overlain by the 48-m-thick upper Brushy Basin strata (Figs 2A, B). Channel sandstones 1, 3, 4, and 5 are single stories while channel sandstone 2 displays an amalgamated 2-story section locally. Channel sandstones 1, 2, and 3 occur in the lower 20 m of the Brushy Basin within the lower Brushy Basin whereas channel sandstones 4 and 5 (and possibly a thin, discontinuous 6<sup>th</sup> and 7<sup>th</sup> channel or lens) occupy the upper Brushy Basin Member. At TT, the SS:F ratio of the lower Brushy Basin is 23:77. The outcrop azimuth of channel sandstone 2 is N45°E and the strike is N50°W. Channel sandstone 3 strikes N40°W. Where channel sandstone 4 ties into the vertical stratigraphic section, it strikes N75°W. Channel sandstone 4 and/or 5 strike directly toward the main channel sandstone on which the "Trail Through Time" is located. In this area approximately 300 m west of the main stratigraphic section, there exist at least 3 sandstones, possible small channels or lenses, above the channel sandstone 4 at the base of the "Trail Through Time" and these units strike approximately east-west. The K-1 unconformity is at Jmb 79 m.

At FP, the color change (CC) occurs at 31m in the section, and thus the lower Brushy Basin Member is 31-m thick; overlain by the 70-m thick upper Brushy Basin strata. Lower Brushy Basin strata contain channel sandstones 1–8, whereas upper Brushy Basin strata contain channel sandstones 9–11 (Figs 3A–C). The SS:F ratio for lower Brushy Basin

Table 1

## Lithofacies codes, descriptions, and architectural elements observed in this study. Architectural elements after Miall (1996)

Facies #	Lithofacies	Description	Architectural element containing this facies
1	Volcanic ash	Green to green-gray, very fine-grained, puffy-weathering	FF: Overbank Fines
2	Micritic limestone	Brown-gray or mottled red-green, some with chert replacement near top, depositional bases and erosional tops	FF: Overbank Fines
3	Nodular calcite layers	Discontinuous, thin, nodular calcite units, commonly in mudstone, often at tops of caliche paleosols	FF: Overbank Fines
4	Red-brown mudstone, locally ash-rich	Red-brown mudstone, calcareous or non-calcareous, sandy or silty, locally mottled, interbedded with facies 1, 2, 5, 10, 14 and 16	FF: Overbank Fines
5	Tabular, dense, hard, calcareous brown-gray siltstone and fine-grained sandstone, locally mottled	Prominent ledge-formers adjacent to and below facies 7 channel sandstones	CS: Minor Sandstone Sheets
6	Green-gray mudstone and fine-grained sandstone	Greenish gray mudstone, silty mudstone and rare fine-grained sandstones of limited extent	FF: Overbank Fines
7	Channel sandstone	Channel form with basal scour surfaces overlain by gravel, locally fine upward, often cross-bedded	CHR: Major Sandstone Ribbons (most Ch SSs) CH: Major Sandstone Element (FP Ch 2)
8	Red-brown-mottled gray mudstone, weathers black with conchoidal fracture	Gray mudstone, calcareous or non-calcareous, with relict red-brown mottles. Sometimes steel blue-gray, dendritic shrinkage patterns, weathers black and with conchoidal fracture.	FF: Overbank Fines
9	Ash-rich mudstone, puffy weathering	Puffy-weathering green, purple, or gray silty mudstone, weathers whitish with rusty halos around biotite. Interbedded ash beds and ashy mudstone.	FF: Overbank Fines
10	Very-fine-grained sandstone, thin-bedded, rippled locally, blocky weathering	Fine- to very fine-grained sandstone, weathers green due to illite and/or chlorite, thin-bedded, lens laterally, shallow 40-cm channels present locally, associated with green, puffy-weathering mudstone	CS: Minor Sandstone Sheets
11	Tan, fine-grained sandstone, weathers orange	Tan, fine-grained sandstone, grades laterally into major stream channel sandstones at TT. Facies 11 is absent at FP and EC	CHm: Minor Sandstone Element
12	Gray mudstone	Hard, dense marlstone with locally abundant plant fossils and some calcite-filled root tubes. Associated with facies 8.	FF: Overbank Fines
13	White, porcellenite-like rock	White, porcellenite-like rock, conchoidal fracture, writes like chalk, horizontal laminae, tan and peach-colored mottles	FF: Overbank Fines
14	Reddish-brown mudstone with roots, pedotubules, peds	Facies 14 is a variation on facies 4. Mottled red-brown mudstone, may be siliceous, has peds, pedotubules, root casts, sometimes purple	FF: Overbank Fines
15	Organic-rich claystone -siltstone with greater than 4% total organic content with wood, plant, and dinosaur bones, weathers orange	Organic-rich claystone-siltstone with plant fossils and a few small logs. Claystones are dark gray; siltstones are light gray. Siltstones have minor green micaceous lamina, occasional calcite nodules and animal fossils. Weathers orange.	FF: Overbank Fines
16	Red-brown mudstone with calcite nodules, pedotubules, peds	Calcareous red-brown mudstone with calcite-filled root tubes, well-developed peds, including granular peds, subangular blocky peds, layered calcite nodules, crystallaria, rhizoconcretions, drab halos	FF: Overbank Fines
17	Interbedded gypsum and green mudstone	Interbedded gypsum and green mudstone	FF: Overbank Fines
20	Brown shale with barite nodules	Brown shale, mudstone with barite nodules (average: 1- to 4-cm) but some cobble-sized	FF: Overbank Fines
21	Green nodular, silica-replaced calcite and sandstone with bright green matrix, botryoidal in places	This facies is only present as 1.5-m bed at top of Brushy Basin Member beneath Buckhorn Conglomerate of the Burro Canyon Formation	FF: Overbank Fines

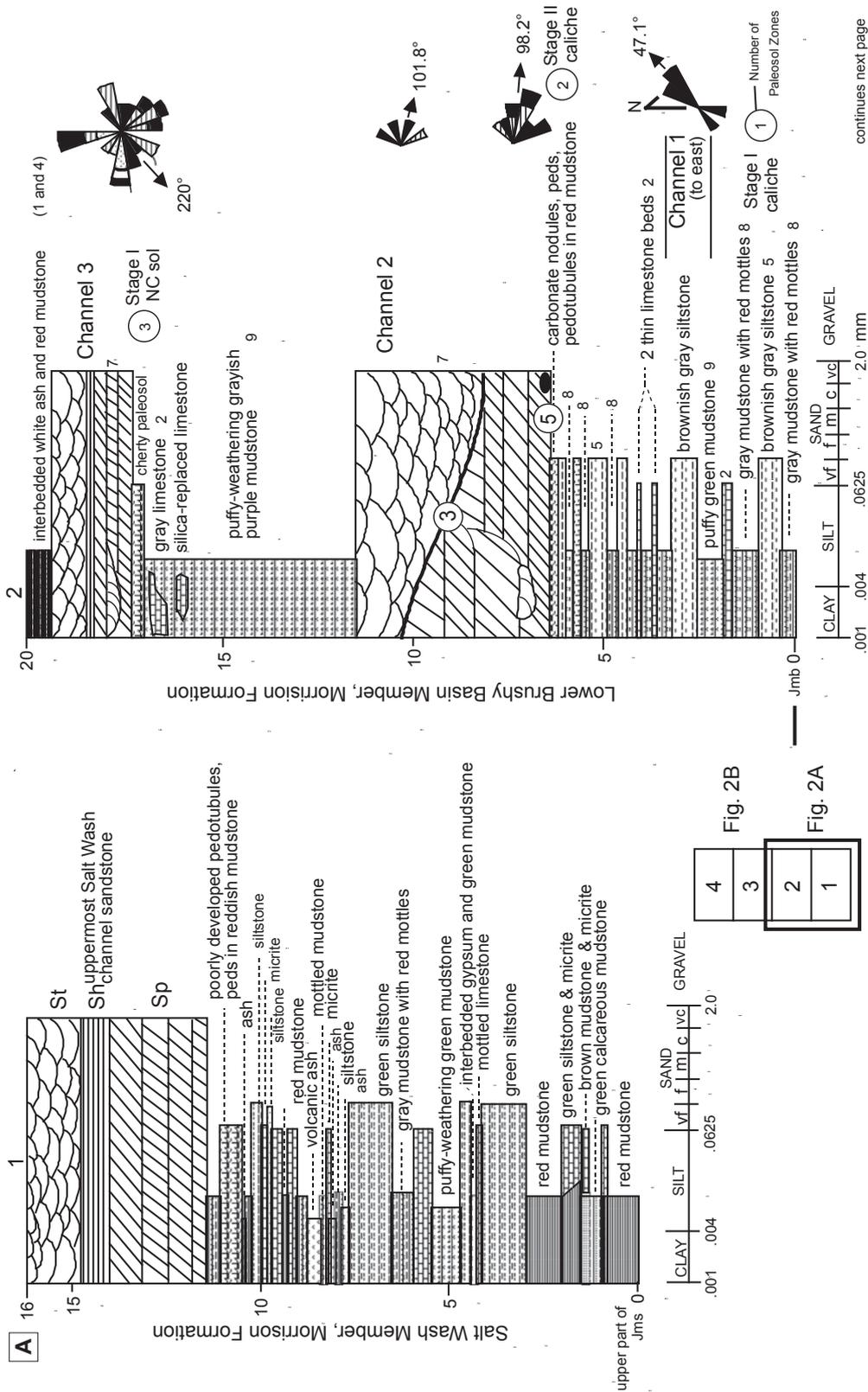


Fig. 2. Trail Through Time (TT) stratigraphic sections

A. The lower stratigraphic section at TT for the uppermost Salt Wash and lower Brushy Basin strata from 0 to 20 m. Vertical scale is in meters in all sections. St – rippled sandstone; Sp – planar cross-bedded sandstone; Sh – trough cross-bedded sandstone; Sh<sub>u</sub> – horizontally laminated/bedded sandstone; NC – noncalcareous; NC – noncalcareous. B. Upper stratigraphic section at TT. Lower Brushy Basin strata from 20 to 30 m and upper Brushy Basin strata from 30 to 60 m

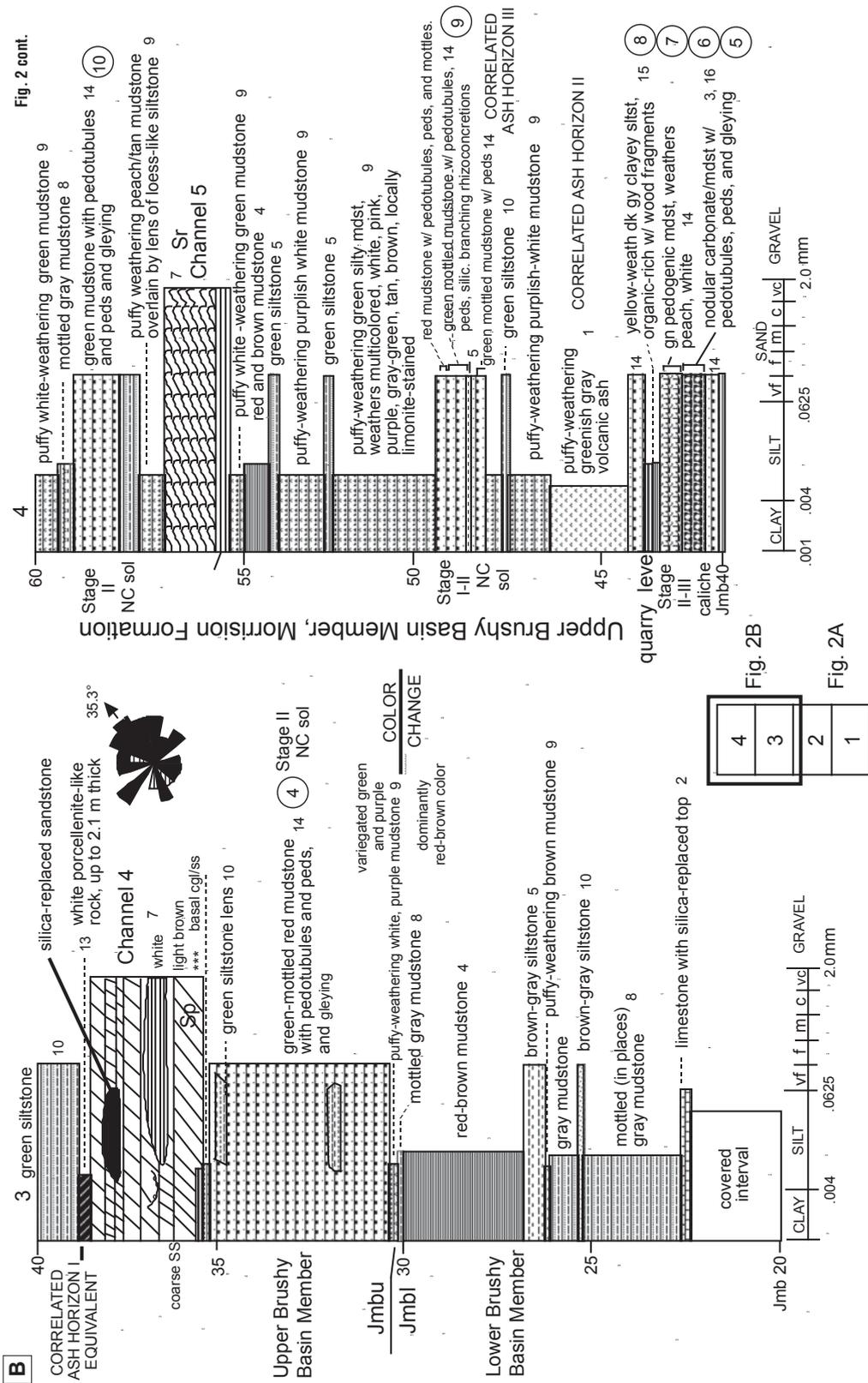


Fig. 2 cont.

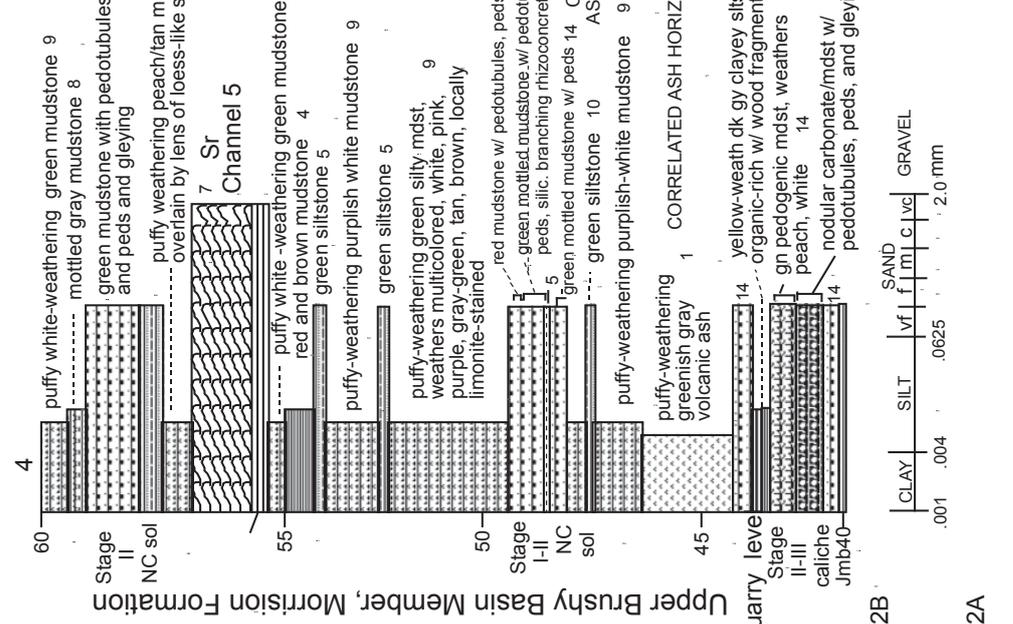
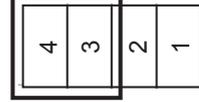
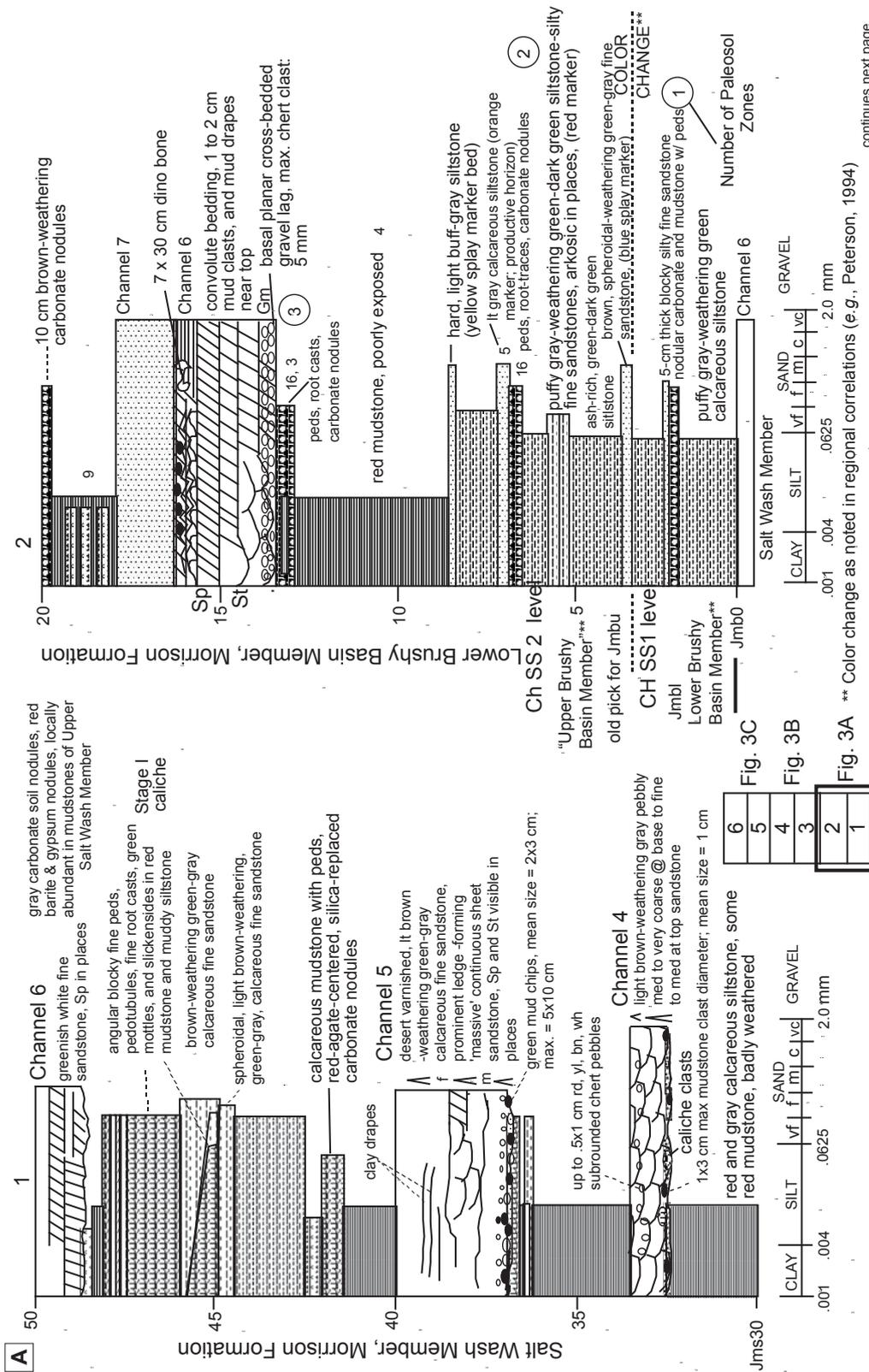


Fig. 2B

Fig. 2A





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Fig. 3. Fruita Paleontological Area (FP) stratigraphic sections

A. The lower stratigraphic Shows the uppermost 20 m of Salt Wash strata and the lower 20m of Brushy Basin strata. B. Fruita Paleontological Area (FP) Middle Stratigraphic Section. Lower Brushy Basin strata from 31 to 60 m. The color change (CC) occurs at 31 m in the section. C. Fruita Paleontological Area (FP) Upper Stratigraphic Section. Upper Brushy Basin strata from 60 to 101 m, the top of the Morrison Formation. Terrace Hill is now called "Flat Top" (Kirkland, 2006)



Fig. 3 cont.

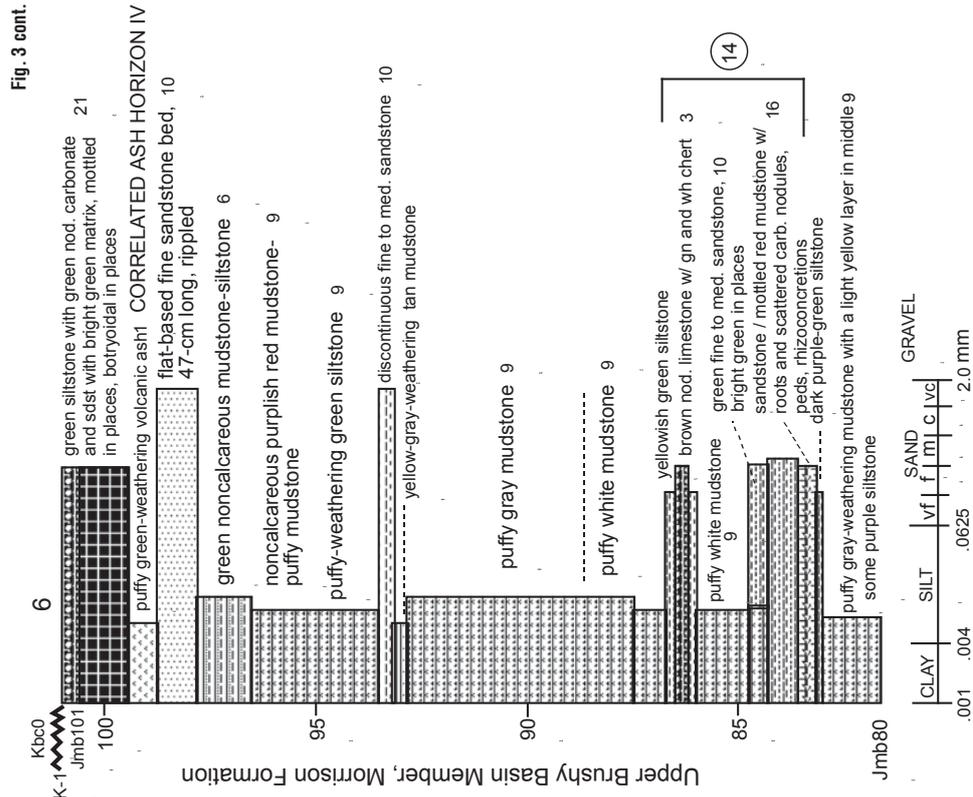


Fig. 3C

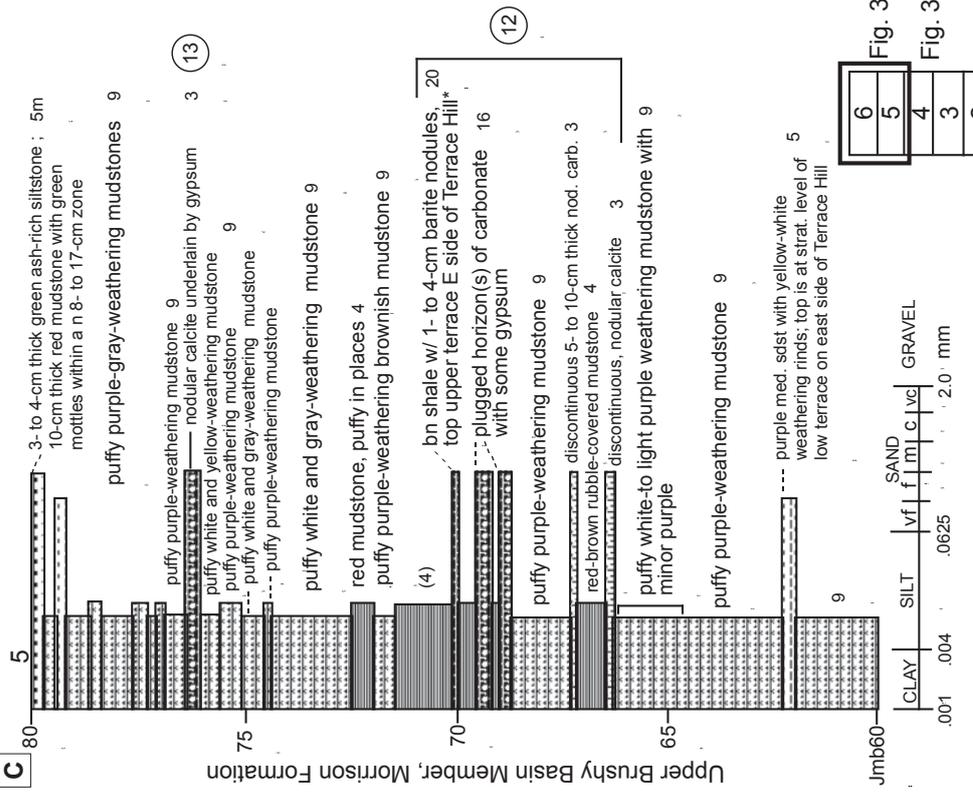


Fig. 3B

Fig. 3A

6
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1

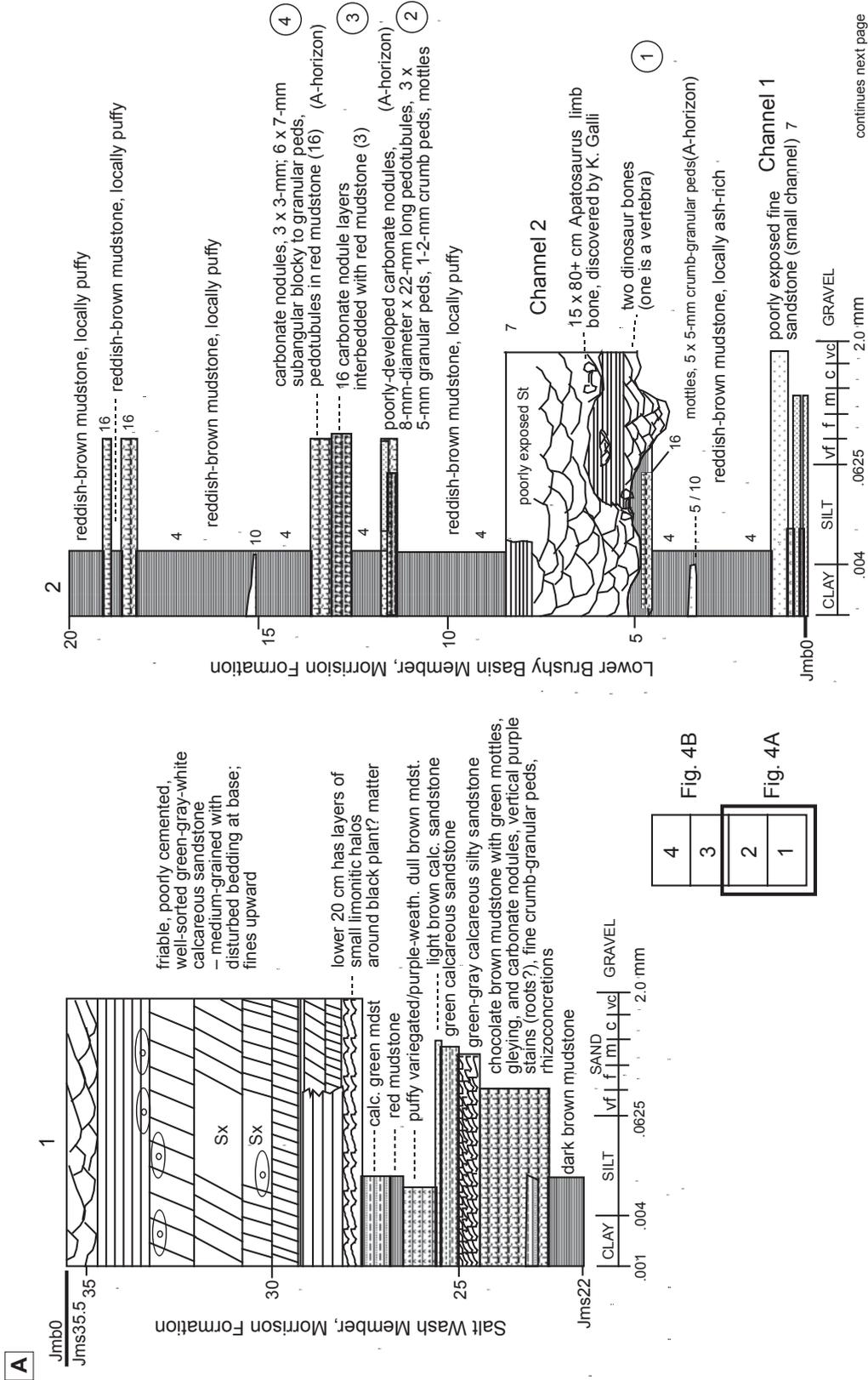


Fig. 4. Echo Canyon (EC) stratigraphic sections

A. Uppermost Salt Wash strata and lower 20 m of Brushy Basin Member including channel sandstones 1 and 2. B. Echo Canyon (EC) middle stratigraphic section includes top of lower Brushy Basin strata (from 20 to 24 m) and lower part of upper Brushy Basin strata, from 24 to 60 m

Fig. 4 cont.

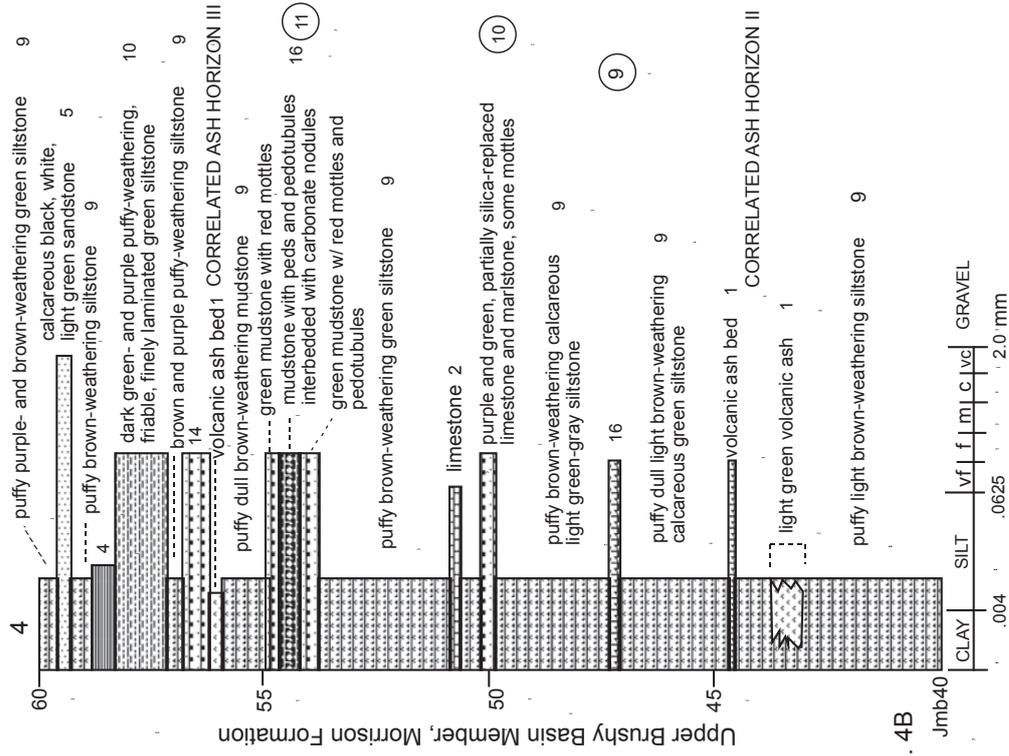


Fig. 4B

Fig. 4A

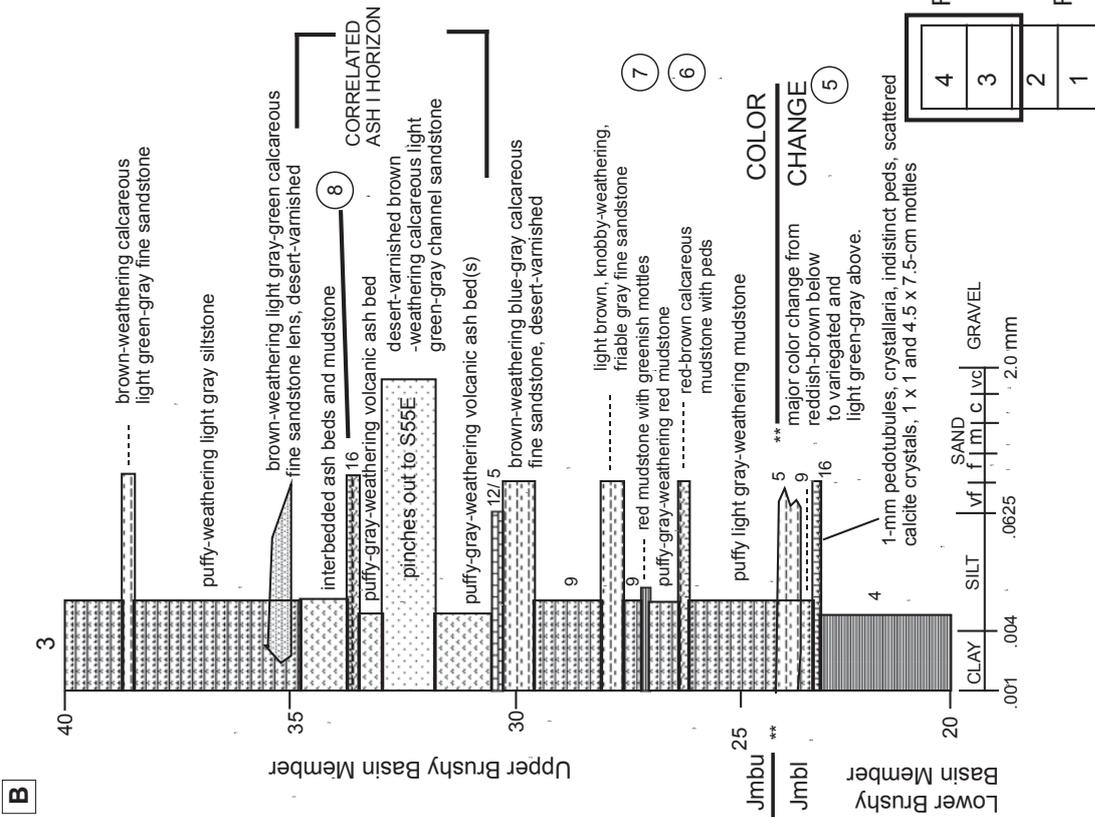


Fig. 4B

Fig. 4A

strata at FP is 14 : 86. Lower Brushy Basin strata here are dominated by 3–5-m thick facies 4 red-brown mudstones, whereas the lower portion of upper Brushy Basin strata (Jmb 31–54 m) are characterized by finely intercalated variegated purple-gray, puffy-weathering, ash-rich mudstones and crevasse splays, paleosols, and volcanic ash zones. The uppermost 47 m of Brushy Basin strata (Jmb 54–101) exhibit much thicker facies 9 ashy mudstones, averaging approximately 4–5 m in thickness as well as thicker paleosol zones. The K-1 unconformity is at Jmb101m.

At EC, the color change occurs at 24 m in the section, and so the lower Brushy Basin Member is 24 m thick and overlain by the 52-m-thick upper Brushy Basin Member (Figs 4A, B). The K-1 unconformity is at 76 m, marking the top of the Brushy Basin strata. The SS:F ratio for lower Brushy Basin strata is 15 : 85. At EC, even the facies 4 red-brown mudstones of the lower Brushy Basin Member are smectitic, varying from 74% to 97.3% smectite. Thus, it appears that even though all variegated purple-gray puffy-weathering ashy mudstones are smectitic, not all non-puffy-weathering, red-brown mudstones are low in smectite. Clay mineralogy of the lower Brushy Basin strata here, from the base-up trends from 85.4% illite, 1.7% mixed-layer illite-smectite, and 12.9% chlorite at 0.6 m in the matrix of a facies 5 brownish-gray siltstone, to 92.4% smectite, 3.4% mixed-layer illite-smectite-illite, and 4.2% chlorite from matrix of channel sandstone 2 at ~7 m in section to nearly pure (99.7%) smectite in matrix of channel sandstone 3 at 19 m in the section.

The two dominant facies of the lower Brushy Basin are red-brown mudstones (facies 4) and puffy-weathering ash-rich mudstones (facies 9). Major facies include channel sandstones (facies 7) and their associated crevasse-splay deposits composed of siltstone/very-fine sandstone (facies 5). These crevasse splays are found adjacent to and under their related channel sandstone bodies and the splays are found intercalated with facies 4 floodplain mudstones and ashy mudstones. Caliche paleosols are also a major facies and include mottled incipient caliche developed in floodplain mudstones as well as ashy mudstones. Caliche paleosols with calcite nodules, pedotubules and peds (facies 16) are a major component of the strata as are nodular calcite in various hosts (facies 3), and noncalcareous mudstone with roots, pedotubules and peds (facies 14). Minor facies include thin micritic limestones (facies 2).

The Brushy Basin strata at TT and EC have light gray to tan, tabular, fine-grained sandstones of variable thickness. These sandstones are calcite-cemented and sometimes have desert varnish. Small- to medium-scale cross-bedding is present just above the contact with the Salt Wash Member, commonly over a thin interval of mudstone-rich strata. The majority of the channel sandstones in the Brushy Basin are in the lower Brushy Basin at all localities, with dinosaur bones

present in all TT channel sandstones, in channel sandstone 2 at FP and in channel sandstone 2 at EC. At TT, channel sandstones 1, 2, and 3 are in the lower Brushy Basin, whereas channel sandstones 4 and 5 are in the upper Brushy Basin at TT. At FP, channel sandstones 1–8 are in the lower Brushy Basin, channel sandstone 9 lies near the boundary between the lower and upper Brushy Basin Members, and channel sandstones 10 and 11 are in the upper Brushy Basin Member.

At EC, as at TT, channel sandstones 1 and 2 are in the lower Brushy Basin and channel sandstones 3, 4, and 5 are in the upper Brushy Basin. Lower Brushy Basin strata have a much higher sandstone-to-fines ratio than the upper Brushy Basin at all localities. At EC, the thickest and only dinosaur-bearing channel sandstone (channel 2) at EC is in the lower Brushy Basin strata at 6 meters in Brushy Basin Member. The 24-m lower Brushy Basin section at EC is characterized by reddish-brown mudstones, locally ash-rich. These are interbedded with channel sandstones 1 and 2, thin siltstone/fine sandstone splay units, and caliche horizons, including one thick zone with 16 distinct carbonate nodule layers in a 1-m interval.

## UPPER BRUSHY BASIN MEMBER (JMBU)

The upper Brushy Basin at TT is 49 m thick. It has a channel-sandstone-to-fines ratio of 10 : 90; ashy mudstone makes up 40% of the strata. The upper Brushy Basin siltstones and mudstones at EC and TT are predominantly smectitic, although a few are mainly chlorite.

A chalk-white porcellenite-like rock (facies 13) up to 2.1 m thick at Jmb39 appears to be a silica-replaced ash or mudstone bed. Approximately 2 to 3 m of caliche and silica-replaced caliche are above this in the section, overlain by the Mygatt-Moore dinosaur quarry level at Jmb43 followed by the thickest ash unit (3 m).

At the FP section, the 85-m-thick upper Brushy Basin has a channel-sandstone-to-fines ratio of 8 : 92; ash-rich mudstone makes up 52% of the strata. The greenish mudstones in the lower Brushy Basin and green siltstone at FP possibly suggest illite and/or chlorite, although no clay analyses were performed on these strata. The upper Brushy Basin strata at FP are dominated by thin to thick, ash-rich mudstones; siltstones and mudstones with superimposed paleosols; and continuous, massive, tabular siltstone/fine-grained sandstones. Thick, cross-bedded channel sandstones make up only 7 m of the section. Superimposed sandstone channels are present in at least three locations at FP, including channel sandstones 6 and 7 that are within the stratigraphic section.

Unique at FP are three crevasse-splay deposits intercalated with levee deposits present at the bends of the second channel sandstone. These can be traced away from the chan-

nel for 10s of meters. The three crevasse-splay/levee sequences contain abundant dinosaur bones. Two- to 10-m-thick lacustrine micrites occur predominantly in the southeastern and northeastern part of FP. An especially thick lacustrine interval in the southeastern FP is associated with channel sandstones 3, 4, and 5. Agate Hill in the northeastern FP region is surrounded by another thick lacustrine mudstone interval. Fossils include broken, disarticulated dinosaur bones, fish fossils, conchostrachans, and abundant plant debris, as well as red agatized snails in the Agate Hill area (Kirkland, 2006). Some lacustrine intervals include radial barite and calcite nodules.

## FLUVIAL ARCHITECTURE ELEMENT ANALYSIS

### OBSERVATIONS

#### Introduction

In river systems, the lithofacies (Fig. 1, Table 1) combine to form structures at three scales: mm to cm microforms formed in minutes to hours, like ripples; cm to m mesoforms formed in days to years, such as dunes; and m to 10s of m macroforms, formed in and persisting for years to thousands of years, like point bars and crevasse splays. All levels in the hierarchy may be active simultaneously in a river. Architectural-element analysis uses lithofacies to describe fluvial strata. A hierarchy of physical scales also exists, for example, from the cross-bed foreset to basin-fill. Ideally, at least 14 orders of magnitude are represented, from a few square centimeters in a ripple foreset to the tens of thousands of square kilometers of a basin (Miall, 1996).

First- and second-order surfaces are within microform and mesoform deposits, respectively. First-order surfaces bound ripple sets and represent the continuous sedimentation of a train of ripples. Second-order surfaces bound cosets with different lithofacies above and below the boundary; the surfaces indicate changes in flow conditions or direction, but commonly not a significant time break. A third-order surface is erosional and dips at low angle within macroforms, with the lithofacies the same above and below the surface. These surfaces are sometimes called “reactivation surfaces” (Fig. 2A, channel sandstone 2). A fourth-order surface bounds the upper surfaces of macroforms, and is usually flat to convex upward. Underlying bedding surfaces and first- to third-order surfaces are truncated at low angle, or are locally parallel with, a fourth-order surface, indicating the fourth-order surfaces are due to lateral or downstream accretion. Mud drapes are commonly present along the surface. The basal scours of minor channels, such as chute channels, are fourth-order surfaces.

Fifth-order surfaces bound major sand bodies, such as channel-fill complexes. The surfaces are flat to concave upward, but can have local cut-and-fill relief and lag gravels. Sixth-order surfaces define groups of channels, paleovalleys, or members of formations. Seventh-order surfaces bound depositional systems, commonly members of formations. Eighth-order surfaces bound major basin-fill complexes (Fig. 2A, channel sandstone 2).

The proportions of primary sedimentary structures observed and measured at FP and TT are shown in Table 2.

**Table 2**  
Proportions of sedimentary structures at Fruita Paleontological Area (FP) and the Trail Through Time (TT)

Location	Sp %	St %	Sh %	Sr %
Fruita Paleontological Area				
Channel 2	23	58	6	13
Channel 8	40	60	0	0
Trail Through Time				
Channel 1-1	77	0	23	0
Channel 1-2	100	0	0	0
<b>Channel 1 mean</b>	88	0	12	0
Channel 2-1	73	0	27	0
Channel 2-2	64	0	36	0
Channel 2-3	15	0	80	5
Channel 2-4	46	19	35	0
Channel 2-5	46	4	50	0
Channel 2-6	32	23	45	0
<b>Channel 2 mean</b>	46	8	46	<1
Channel 3-2	44	50	0	6
Channel 3-3	81	19	0	6
Channel 3-4	0	83	16	1
<b>Channel 3 mean</b>	31	56	19	3
Channel 4-1	11	50	39	0
Channel 4-2	26	74	0	0
Channel 4-6	100	0	0	0
<b>Channel 4 mean</b>	46	41	13	0
<b>Grand mean</b>	52	26	22	<1

Sp – planar cross-bedded sandstone, St – trough cross-bedded sandstone, Sh – horizontally laminated sandstone, Sr – rippled sandstone

These include the percentage occurrence of Sp, St, Sh, and Sr within the channel sandstones.

Eight architectural elements, defined by their geometry, bounding surfaces, size, orientation with respect to paleoflow, and containing distinctive lithofacies assemblages were described by Miall (1985) after Allen's (1983) original description of the element in fluvial sediments. These elements are thought to contain all possible lithofacies in a fluvial sequence.

The Brushy Basin Member strata in the study area are dominated by architectural element FF, Overbank Fines. This overbank fines element contains facies 1, 2, 3, 4, 6, 8, 9, 12, 13, 14, 15, 16, 17, 20, and 21 (Table 1).

The next most abundant element is the Major Sandstone Ribbon (CHR) element. This element contains all facies 7 sandstones except channel sandstone 2 at FP, which is contained within the Major Channel Sandstone element (CH). Minor Sandstone Sheet (CS) element contains facies 5 and 10 tabular sandstone bodies that are best observed associated with channel sandstone bodies at FP and to a lesser extent at TT. Rare CHm, Minor Sandstone Element, contains facies 11 tan, fine-grained sandstone bodies.

### Fluvial system at Trail Through Time (TT)

The sandstones at TT are ribbon sandstones, based on their map patterns (Figs 5, 6). The channel sandstones are commonly single-story, for example, channels 1, 3, 4, and 5. Channel sandstones are typically 1-3 m thick, but up to 5 m or more locally. Occasionally, there is a multi-story sandstone, as in channel sandstone 2, but even then, this is a local feature. The east-west-oriented Frontage Road along the southern perimeter of TT, exposes the east-west lateral extent of channels 2 and 3 within the lower Brushy Basin strata and channel 4 in the lower portion of the upper Brushy Basin strata (Fig. 5A) and the thin ribbon aspect of the channel bodies. Channel sandstone 2 was traced and measured for its entire 67-m horizontal breadth or lateral extent. Its thickness varies from 0.25 m at its feather edge at the western end of Frontage Road to a maximum of 7.1 m and then to nothing to the east where it "wings out" which is characteristic for a ribbon sandstone body. From 0 to 9.1 m channel sandstone 2's outcrop azimuth is N80°E. This includes the two-story channel segment from 5 to 10 m, where a 0.4 m to 1.2 m lower story is overlain by a 0.8 m upper story. From 9.1 to 16.5 m, its azimuth is due east and thickness is 1.2 m, from 16.5 to 19.5 m, its azimuth is N30°E and thickness is 1.2 m, from 19.5 to 22.5 m, its azimuth is due east, with thickness of 2.7 m, and then from 22.5 to 67 m its azimuth is N25°E and thickness varies from 2.4 m to 6.7 to 7.1 m and then to 5.5 m and finally 0.9 to 0.7 m near its easternmost edge.

Paleoflow in lower channel 2 is toward 98.2° (to the east) and 101.8° in the upper amalgamated channel (to the east). Paleoflow in channel 3 is toward 220° (to the southeast), and paleoflow in channel 4 is toward 35.3° (to the northeast). The channel sandstones pinch out into associated floodplain facies (Figs 5A, 6). The thalweg gravel of rounded caliche and mudstone small pebbles and granules is present at the base of channel 1 (Fig. 7A). Locally, channel 2 is a two-story amalgamated channel (Figs 6; 7, panel 2). Definition of a macroform story is based on: (1) erosional scour base, (2) gravel lag, (3) laterally extensive, and (4) significant mud top (Miall, 1996). Channel sandstone 2 exhibits oversteepened cross-beds (Fig. 7, Panel 2). Following a rapid drop in river stage, the excess pore pressure of the water in the sand caused down-slope deformation of the cross-beds. Planar cross-bedded sandstone (Sp) overlain by trough cross-bedded sandstone (St), which is overlain by coarser-grained horizontally laminated sandstone (Fig. 7, panel 4) indicates either an increase in flow velocity of the river or more likely, a drop in the river stage, which caused increased flow from lower flow regime features (Sp and St) to upper flow regime features (Sh). Panel 6 photograph shows Sp overlain by St topped by a 4<sup>th</sup> order bounding surface and then upper flow-regime horizontally laminated medium sandstone. Thus, Fig. 7B depicts a non-systematic fill of the channel over time.

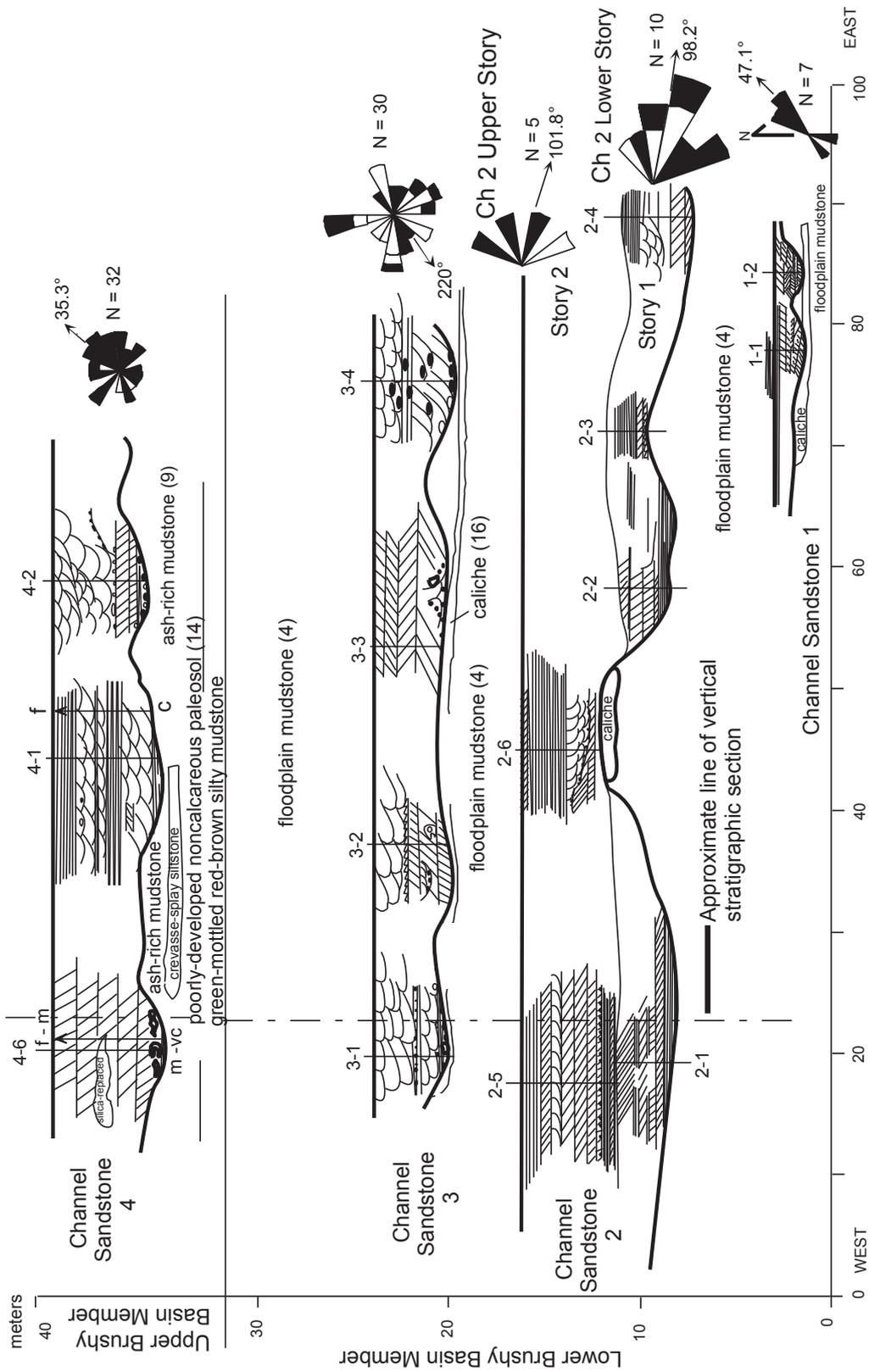
Channel 2 is single-story, with a non-systematic fill of 15-48-cm-thick planar cross-beds. After the channel was scoured out, migration of trains of linguoid bars at or near bankfull discharge constructed the cosets of planar cross-bed sets, with flow consistently to the southeast. The small variation of individual paleocurrent azimuths from the mean suggests an anastomosing pattern. Reactivation surfaces within the cosets reflect separate floods or fluctuations in a flood.

Paleoflow was to the northeast (47.1°) for channel sandstone 1; to the east (98.2°) for the lower story of channel sandstone 2; toward 101.8° for channel sandstone 2's upper story; to the southwest (220°) for channel sandstone 3; to the northeast (35.3°) for channel sandstone 4 (Fig. 6). Channel sandstone 3 displays Sp overlain by a thin interval of ripples (Sr), followed by St. The bedload of the channel contains a 2.0 × 4.5-cm *Stegosaurus* vertebrae (Fig. 8A). The mean of 30 paleocurrent readings show that the paleoflow of channel sandstone 3 was to 220° (southwest) which is different than all the others at TT. The mean flow direction for channels 1, 2, and 4 are to the northeast or east (Fig. 6). Channel 4 is 2.3 to 3.0-m thick and the otherwise friable sandstone is partially silica-replaced in patches, especially along slanting cross-bed strata (Fig. 8B). Where channel sandstone 4 is thinnest, the lower portion exhibits a coset of Sp with divergent paleocurrent flow directions.



**Fig. 5. Photomosaics of Brushy Basin strata at Trail Through Time**

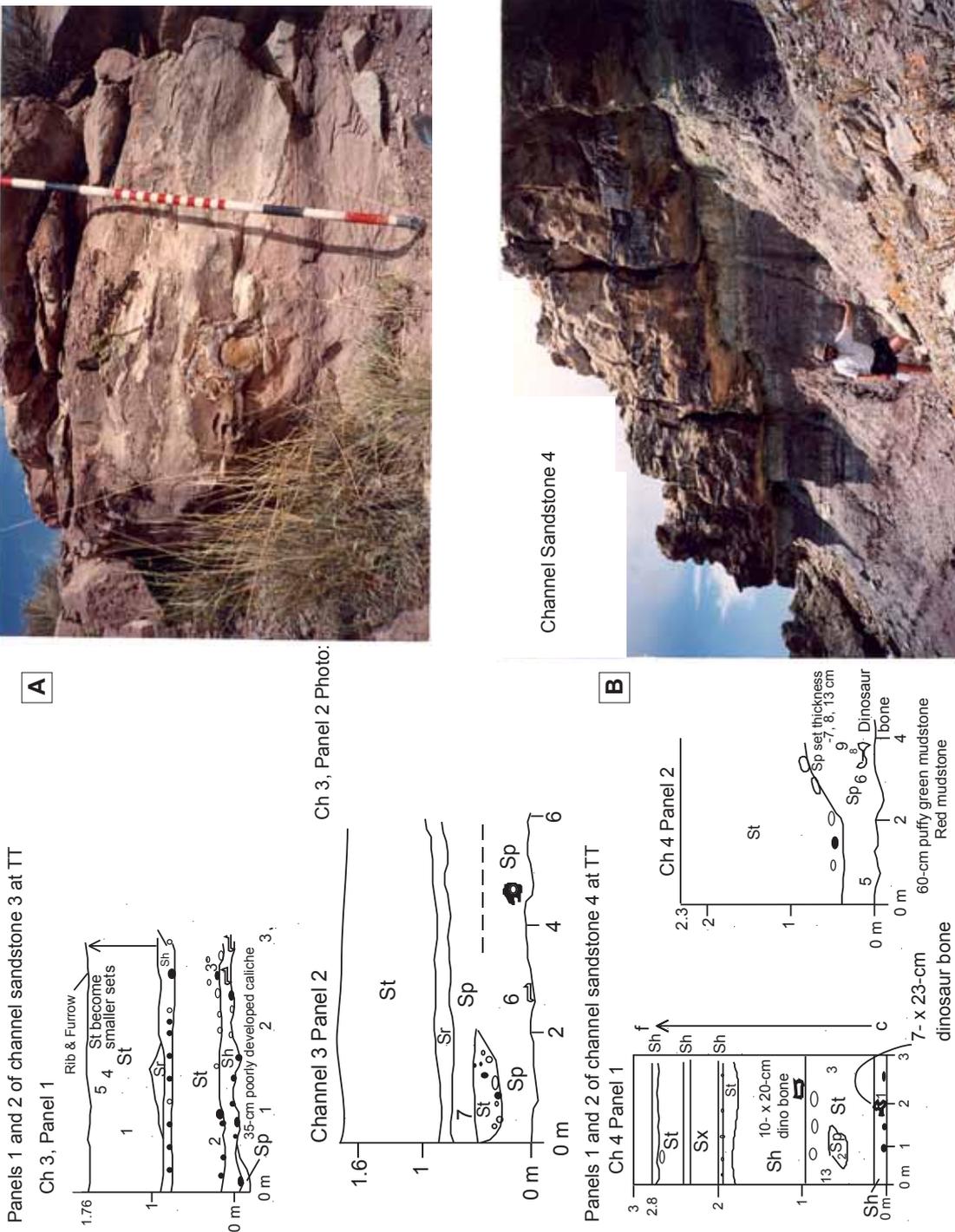
**A.** Photomosaic showing the architecture of channel sandstones 2, 3, and 4 and enclosing floodplain mudstones and associated facies. View is to the north and shows the east-west lateral extent of channels 2 and 3 within the lower Brushy Basin strata and channel 4 in the lower portion of the upper Brushy Basin strata. Note the thin ribbon aspect of the channel bodies. Paleoflow in lower channel 2 is to the east (98°), and to the east-southeast (102°) in the upper amalgamated channel. Paleoflow in channel 3 is toward the southeast (220°), and in channel 4 is toward the northeast (35.3°). Note that the channel sandstones pinch out into associated floodplain facies. **B.** Channel sandstone 2



**Fig. 6. Architecture of channel sandstones (Element CHR) in lower 40 m at Trail Through Time (TT) and the line of section for construction of the vertical stratigraphic section**

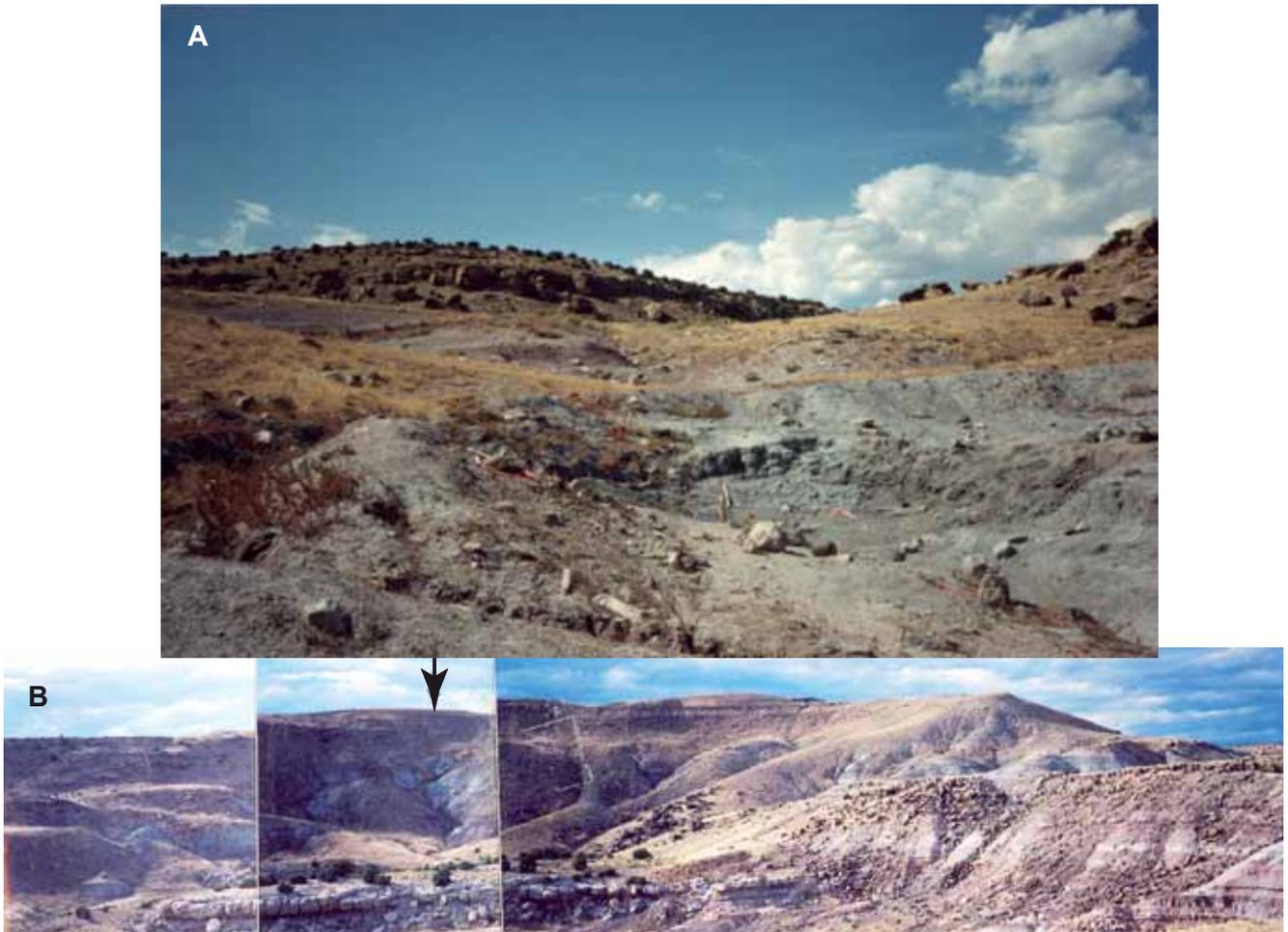
Blank areas, caliche, mudstones, ash-rich mudstones are contained within overbank fines element (FF). Crevasse-splay deposits are element CS. Some thin crevasse splays associated with channel 2 are not shown. Designations 2-1 and 4-6 refer to locations of vertical sections shown in architecture panels. On paleocurrent rose arrow shows average paleoflow direction, N – sample number. Mygatt-Moore Dinosaur Quarry level is ~2-3 m above top of channel sandstone 4. Top of Brushy Basin Member is at 79 m





**Fig. 8. Architecture and photographs of channels 3 and 4 at Trail Through Time (TT)**

**A.** Architecture panels and photograph of channel sandstone 3 at TT. Panel 2 and the photograph depict the base of the channel with a 2 x 4.5-cm *Stegosaurus* vertebrae, with Sp overlain by a thin interval of ripples, followed by St. **B.** Architecture panels and photographs of channel sandstone 4 at TT. Panel 1 and photograph shows the entire 3-m thickness of channel 4. Note silica-replacement-front visible as dark, better-cemented areas of channel sandstone 4 above right. Channel 3 panel 1 illustrates common fossil bones and bone fragments up 30- x 45-cm. Mudstone and chert pebbles occur throughout channel. Burrows are 0.25 to 0.5 cm. Channel 3, Panel 2 illustrates isolated trough cross-beds containing white mud chips and abundant dinosaur bone fragments. Channel 4, panel 1 shows trough cross-beds containing gravel lag. Sandstone is partially replaced by silica in patches



**Fig. 9. Photographs of upper Brushy Basin Member strata from the section at TT**

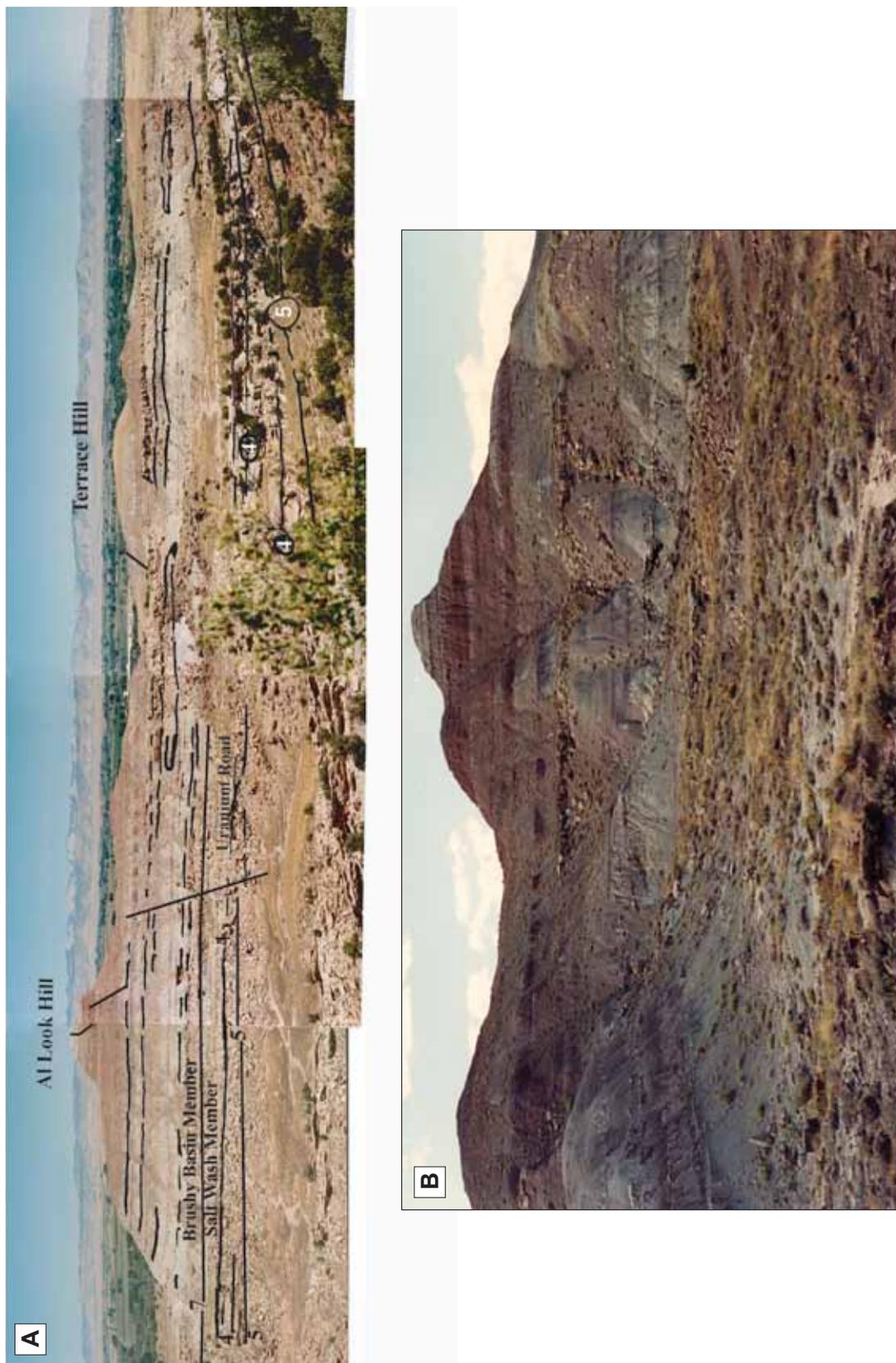
**A.** Mygatt-Moore Dinosaur Quarry in 2-m thick marlstone and associated facies at 43 m. **B.** Upper stratigraphic section. Arrow points to top of measured stratigraphic section. Note channel sandstone (probably channel 3), approximately on strike from the east in middle foreground and the low sandstone to fines ratio of the strata

Much of the upper Brushy Basin at TT is typified by a 2–3-m thick marlstone that makes up much of the Mygatt-Moore dinosaur quarry (Fig. 9A) within predominantly floodplain and associated strata with a very low sandstone-to-fines ratio. The upper portion of the measured stratigraphic section is to the north of the main outcrop belt (Fig. 9B).

#### Fluvial system at Fruita Paleontological Research Area (FP)

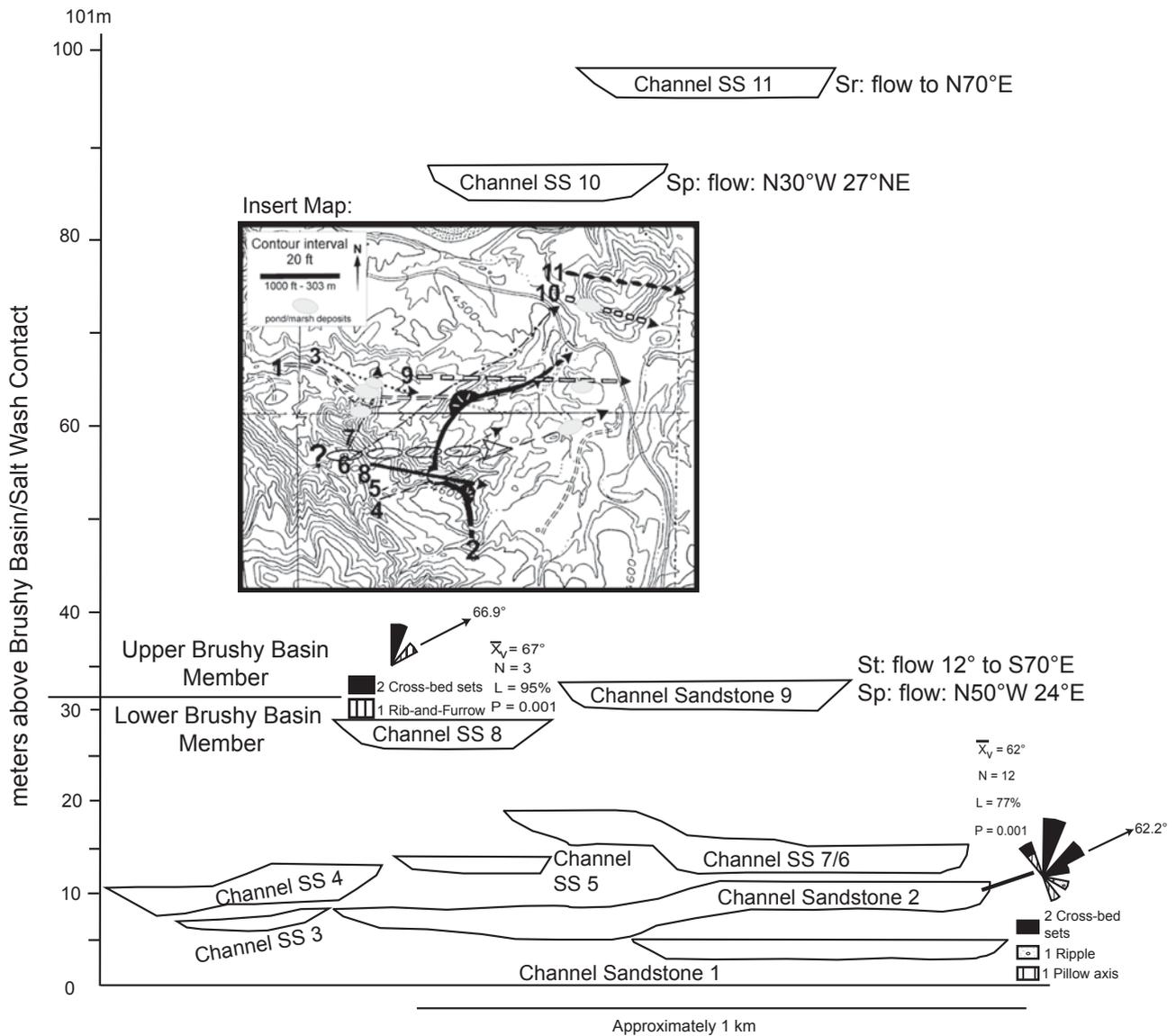
The south side of FP exposes a 7<sup>th</sup>-order bounding surface between the Salt Wash and overlying Brushy Basin Members. 5<sup>th</sup>- and 4<sup>th</sup>-order bounding surfaces bracket the bottom and top of fluvial channel sandstones, respectively (Fig. 10A). The 7<sup>th</sup>-order bounding surface between the

Brushy Basin and Salt Wash members is near the break in slope of Al Look Hill (Fig. 10A). Erosive, flat to concave-up surfaces below major channel sandstones in the Salt Wash Member are 5<sup>th</sup>-order surfaces visible near the base of the mosaic in Figure 10A. Flat to convex-up surfaces at the top of these sandstone bodies are 4<sup>th</sup>-order surfaces. Note the difference between the more laterally continuous, thicker sandstones of the Salt Wash and the thinner, less laterally continuous sandstones in the Brushy Basin. Bounding surfaces on the south side of Al Look Hill mostly continue through to the north side, which is the active side of FP paleontological investigations. Here, one can observe the lateral continuity of tabular-body, crevasse-splay siltstone/very fine-grained sandstones. George Callison's small mammal quarry is in the mound of purple-gray mudstones and siltstones in the left foreground (Fig. 10B).



**Fig. 10. Photographs of both south side and main (north) side of Fruita Paleontological Area (FP)**

**A.** View looking north toward the Book Cliffs, from the south side of FP. A seventh-order bounding surface lies between Salt Wash and Brushy Basin Members, Morrison Formation. Fifth- and fourth-order bounding surfaces bracket the bottom and top of fluvial channel sandstones, respectively. Vertical lines show the location of the measured section. **B.** FP, looking south with Al Look Hill in the center. Bounding surfaces on the south side of Al Look Hill mostly continue through to this side. Note the lateral continuity of tabular-body, crevasse-splay siltstone/very fine-grained sandstones. George Callison's small-mammal quarry is in the mound of purple-gray mudstones and siltstones in the left foreground that are at the orange crevasse-splay level



**Fig. 11. Schematic Architecture of Brushy Basin channel sandstones at Fruita Paleontological Research Area (FP).**

Blank areas are floodplain mudstones and associated facies (Element FF). Channel sandstone 2 (Element CH); all other channel sandstone (Element CHR); thin crevasse splay deposits (Element CS) not shown in this schematic. Insert map: FP channel sandstones, arrows show inferred paleoflow directions for channel sandstones 1-11 (Kirkland, 2006). USGS topo 7" minute quadrangle map for Mack, Colorado

The fluvial architecture of the 101 meters of the Brushy Basin strata at FP demonstrates that channel sandstones 1 to 8 lie within the lower Brushy Basin Member; channel sandstone 9 lies near the contact between the lower and the upper Brushy Basin and channel sandstones 10 and 11 are within the upper Brushy Basin Member (Fig. 11). Note also that channel sandstone 2 is the most laterally extensive of all at a bit over 1 kilometer. Channel sandstones 1, 2, and 6/7 are

only separated by a few meters stratigraphically where they crop out at what is called the Parking Lot, in the eastern part of FP, but channel sandstone 2 occupies a lower stratigraphic level in western FP. Channel sandstone 6 occupies a higher stratigraphic level to the southwest in FP. Most other channel sandstones appear to lie at just one stratigraphic level, although, this point should be confirmed.

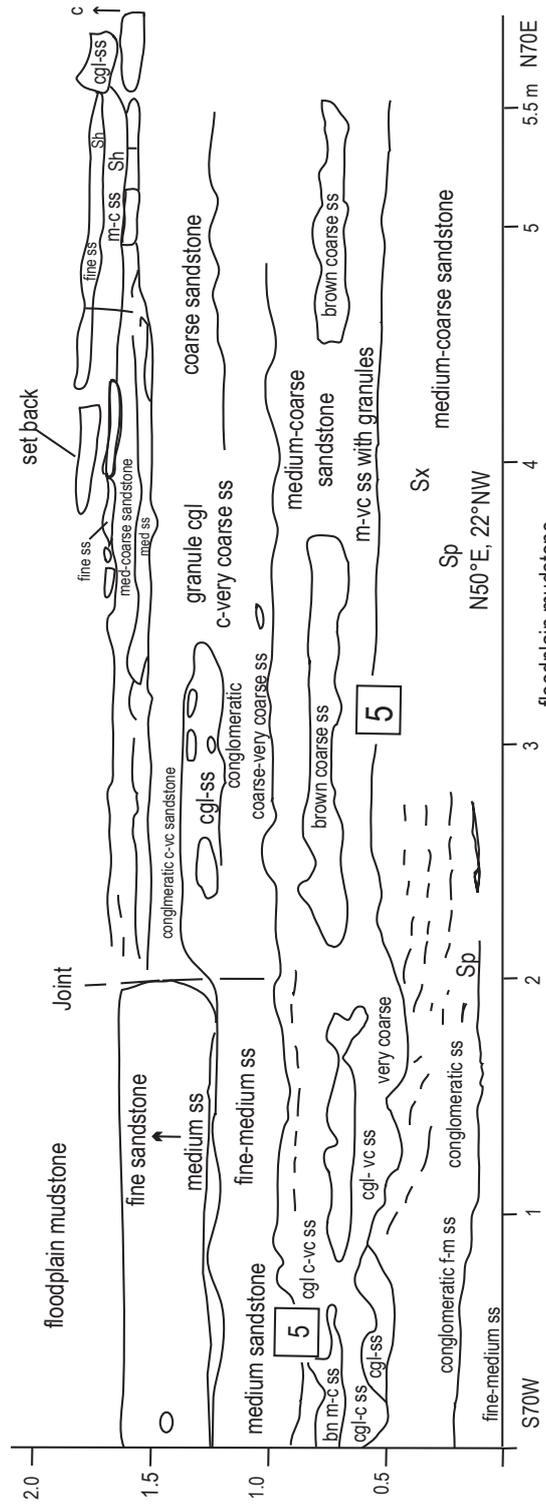
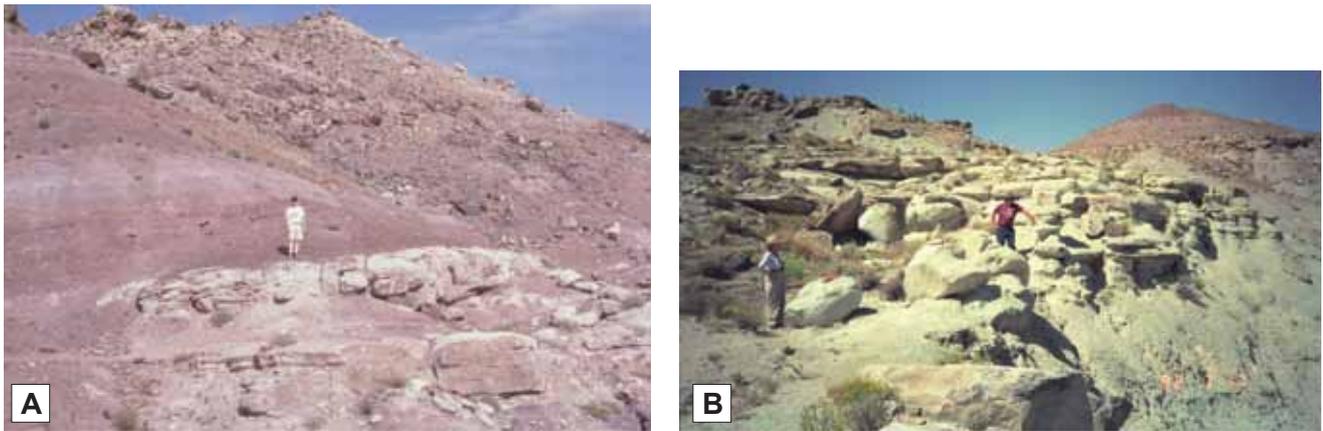


Fig. 12. Fruita Paleontological Area, Brushy Basin channel sandstone 1 and associated levee deposits with crevasse splays

"5" marks the fifth-order bounding surfaces at the base of fluvial channel sandstones



**Fig. 13. Lower Brushy Basin floodplain features at Fruita Paleontological Area (FP)**

**A.** Extensive exposure of floodplain mudstones and ribbon channel sandstones, with low sandstone to fines ratio. **B.** Crevasse splay-levee system associated with channel sandstone 2

The sedimentary structures of channel sandstone 1 (Blue Channel) at FP are largely obscured by bioturbation from plant roots and burrows. Only one or two fining-upward sequences were observed and this channel is medium-very coarse-grained sandstone, coarser than fine-medium-grained channel sandstone 2. Small channel forms are all but absent in channel sandstone 1. The map patterns of channel 1 and all other channels at FP except channel sandstone 2 are relatively straight. Sandstone fills the channel form and two 5<sup>th</sup>-order bounding surfaces mark the bases of two channels within channel sandstone 1. No lateral-accreting surfaces (LAS) were observed; the channel trends N70°E. No mud drapes are present but some sandstone bodies are topped by fine- to very fine-grained sandstone. Channel scours are numerous with relief on the order of 10–15-cm. Large, mostly horizontal burrows or roots are common, mostly filled with coarse-grained sandstone but some with dark mudstone. The thicknesses of the channel fills within channel 1 decrease up-section; from the base up, the thicknesses are 0.54, 0.43, 0.42, 0.18, 0.12 to 1.0 m. Grain-size trends are hard to discern. The sandstone is medium to coarse-grained, silica-replaced and chert-cemented in places. Poikilitic chert occurs in places, mostly in the middle and upper part of the channel. Most units thin to the east; upper units pinch-out to the east. A paleocurrent measured from Sp in the basal, conglomeratic, medium-grained sandstone yielded an azimuth towards 320° (Fig. 12). Most of the lower Brushy Basin strata at FP show extensive floodplain mudstones and ribbon channel sandstones (Fig. 13A).

Channel sandstone 2, near one of its bends, is oriented to the west and then turns north where the channel takes a 90° turn and has associated well-developed levee deposit with

crevasse-splay deposits cutting through. The color change (CC) marking the division between lower and upper Brushy Basin strata is just below the base of the channel. The azimuth of paleoflow of channel 8 was 66.9° (to the northeast) (Fig. 14). The architecture of channel sandstone 8 is similar to many of the channel sandstones at FP, which range in thickness from 1.5 to 4.5 m (channel 4), averaging 2.5 m. Sedimentary structures are heavily bioturbated. The fill of channel 8 is similar to channel 1 and no fining-upward sequences are present. Eight of the 11 channel scour fills within channel 8 are single story with non-systematic fills of 7–30-cm thick, planar cross-beds produced by downriver migration of linguoid bars that prograded at or near bankfull discharge. Paleoflow direction for channel 8 is to N67°E based on three readings (Fig. 14).

As with channels 1 and 2 at TT, each FP channel, except channel 2, has a consistent within-channel paleocurrent flow direction; in most cases the channel sandstone form is a ribbon. Table 2 shows the proportions of sedimentary structures within FP and TT channel sandstones. Channel 2 at FP has a lower proportion of planar cross-bed sets than most channels at TT. FP channel 2 also has a much higher proportion of ripple cross-lamination than any of the TT channels. The architecture of channel sandstone 2 differs from channel 1 by: (1) finer grain size, (2) abundant fining-upward sequences, (3) abundant small channel scours filled by fining-upward sequences, (4) abundant dinosaur bones, including a long bone lying on a bedding plane oriented parallel to the flow, (5) common mud drapes, (6) multi-colored chert granule and fine pebbles at the base of many channels, and (7) sandstone pillows in a few places. Twelve paleocurrent readings indicate that flow was variable, averaging towards 62° (north-

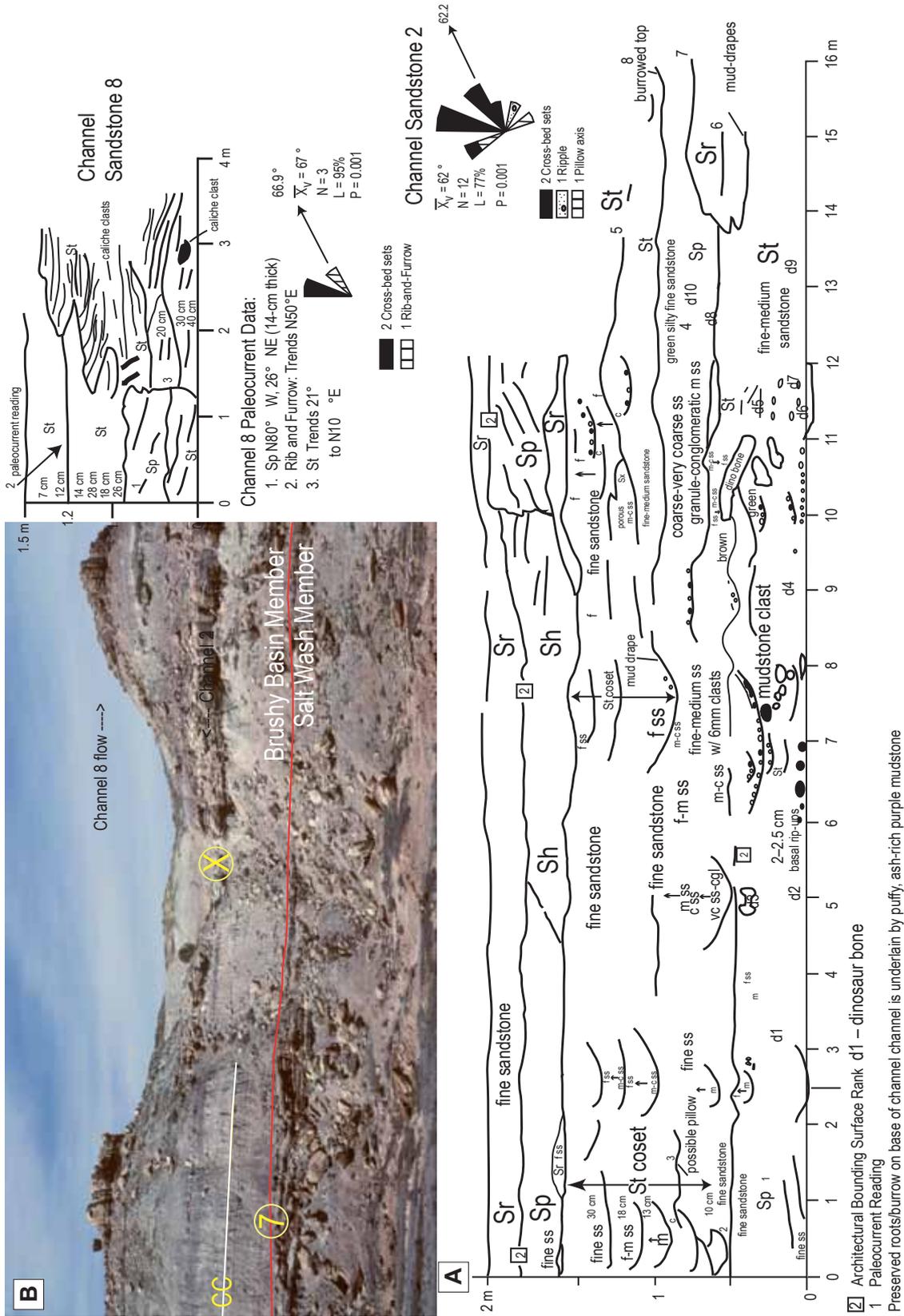
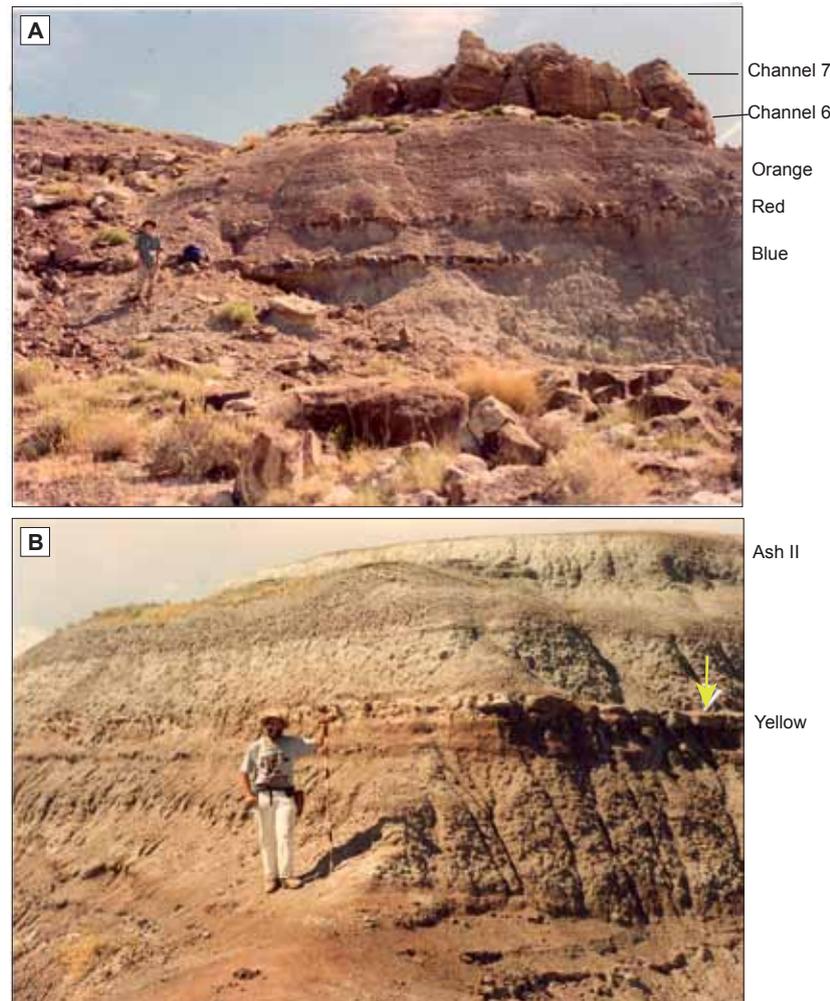


Fig. 14. Channel sandstones 2 and 8 architecture at Fruita Paleontological Area (FP)

A. Architecture panel and paleocurrent rose of channel 2 at FP northeast of "Parking Lot." B. Photograph (courtesy of J. Kirkland). Channel 2 flows west and then bends to north at circled X. Seventh order bounding surface is boundary between Salt Wash and overlying Brushy Basin Members, Morrison Formation at FP. Photograph and architecture panel show that channel 8 flowed to northeast



**Fig. 15. Typical architecture of the lower Brushy Basin Member at Fruita Paleontological Area (FP)**

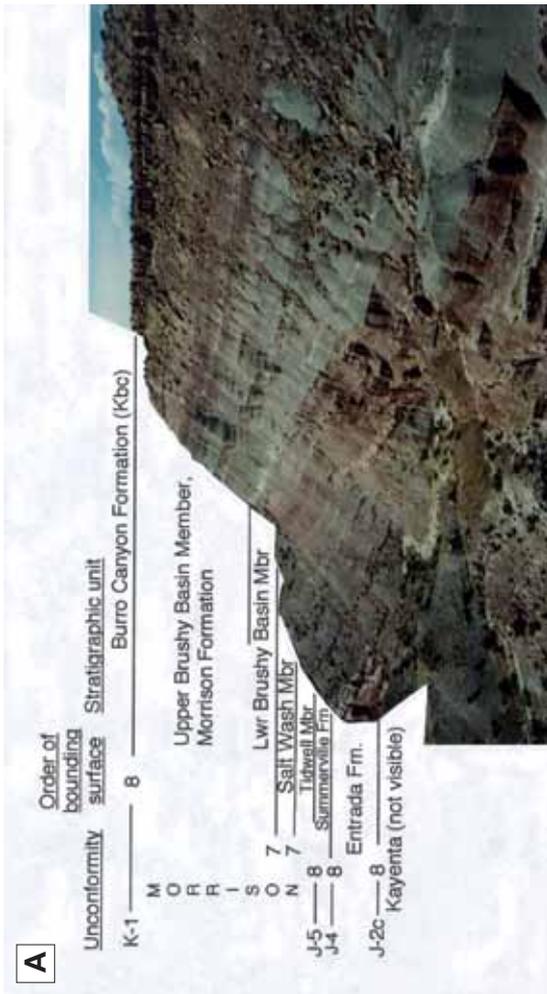
**A.** Photograph showing lowermost lower Brushy Basin strata, with several flagged crevasse-splay deposits noted (blue, red, orange) and a faint yellow splay barely visible, with an amalgamated channel sandstone 6/7 at the top. Field assistant John Bailey for scale. **B.** Floodplain strata from 46.5 to 50.4 m in the Brushy Basin Member at FP. Yellow-flagged crevasse splay is indicated by the arrow. Ash II is at top of photo. Thick puffy-weathering ash-rich floodplain mudstones above the crevasse splay suggest a retreat of the river channel away from the section. Jacob staff is 1.5 m

east). Within the area of study, channel sandstone 2 contained ten sizable dinosaur bones, many lying along bedding surfaces and several as part of a coarse sand-gravel lag deposit, while others are within fine- to medium-grained sandstone. Bones range in size from  $2 \times 2$  cm to as large as  $7 \times 88$  cm. The basal 40–60 cm of the channel contains most of the bones (Fig. 14A).

No mudcracks were observed, which may argue against the climate being semi-arid or alternatively they may be missing due to low preservation potential during flash floods. Some channel sandstones, such as channel 7 at FP, contain mud drapes near their tops as well as the usual mud clasts in the basal lag.

As each flood-cycle waned, the mud mantled the lower-flow-regime bedforms. This probably indicates seasonal variations in discharge. At times a channel shifted abruptly, cutting into older channel sands, producing an amalgamated channel body, for example in channels 6 and 7 at FP.

Upper Brushy Basin floodplain strata from 46.5 to 50.4 m in the Brushy Basin Member contain a crevasse-splay deposit and ash zone II (Figs 15A, B). The thick puffy-weathering ash-rich floodplain mudstones above the crevasse splay suggests a retreat of the river channel away from the section occurred.



**Fig. 16. Photographs of Brushy Basin Member architecture at Echo Canyon**

**A.** Photograph and architecture of complete Echo Canyon section, showing major bounding surfaces. **B.** Echo Canyon. *Apatosaurus* femur within channel sandstone 2 discovered by author. Center of bone was scavenged and is now filled with sand and gravel. **C.** Photograph from Echo Canyon dry wash shows color change (CC) between lower Brushy Basin strata a third of the way from the base of the photograph. The puffy weathering aspect of the volcanic ash-rich mudstones is well displayed

## Fluvial system at Echo Canyon (EC)

Echo Canyon shows the largest scale bounding surfaces seen in this study (Fig. 16A). Morrison Fm. strata are bracketed by 8<sup>th</sup>-order surfaces of discontinuity: (1) the regional J-5 unconformity over the Jurassic Summerville Formation and (2) the regional K-1 unconformity beneath the Cretaceous Burro Canyon Formation. 7<sup>th</sup>-order surfaces are the boundaries between the Tidwell, Salt Wash, and Brushy Basin members of the Morrison Formation; these surfaces typically form over intervals of 10<sup>5</sup> to 10<sup>6</sup> years (Miall, 1996) and are traceable over the extent of the members, an area slightly smaller than the total Morrison Formation.

A possible paleovalley observed within Brushy Basin strata high above the EC dry wash, oriented approximately N 20° E, contains several lens-shaped channel bodies that sit in a larger scale (possibly 7<sup>th</sup> order boundary) concave-up surface that is potentially a paleovalley with the long axis parallels the dry wash. The sandstone bodies indicate that the streams that produced them flowed most likely eastward.

The author discovered an *Apatosaurus* femur in the 3 to 4-m thick channel sandstone 2 at EC (Fig. 16B). This bone is silica-cemented into the sandstone and the central portion is filled with sand and gravel. There is a 1-m scour at the base of Channel 2, indicating that the river scoured deep into the underlying floodplain mudstones.

The color change between lower Brushy Basin and upper Brushy Basin strata a third of the way from the base. The color change occurs just above a crevasse splay zone. The puffy-weathering aspect of the volcanic ash-rich mudstones is well displayed. The “clay change” between the red-brown floodplain mudstones below and the gray, puffy-weathering, ash-rich, smectitic mudstones above occurs twenty-four meters within the Brushy Basin Member middle to upper Brushy Basin strata (Fig. 16C).

## INTERPRETATIONS

### Fluvial complex at Trail Through Time (TT)

Channel 2 is single-story, with a non-systematic fill of 15–48-cm-thick planar cross-beds. After the channel was scoured out, migration of trains of linguoid bars at or near bankfull discharge constructed the cosets of planar cross-bed sets, with flow consistently to the southeast. The small variation of individual paleocurrent azimuths from the mean suggests an anastomosing pattern. Reactivation surfaces within the cosets reflect separate floods or fluctuations in a flood. The second story of channel 2 is also filled with a non-systematic fill of planar cross-strata and trough cross-strata as well as upper flow regime horizontally laminated sandstone.

Commonly, the base of a horizontally-laminated sandstone cuts into a coset of cross-beds, implying shallower flow depth and/or higher velocity. Evidently, there was “flashy” discharge, probably due to seasonal precipitation. With no grasses present, flash floods swept across the floodplains toward the channels. Lacking depth-to-width ratios for the channels, as well as laterally accreting (LA) macroforms, quantitative estimates of the hydrology and morphology of the rivers are not possible. However, because gravel is transported at velocities above about 1.0 m per second, the flow rate was mainly lower than this, assuming the availability of gravel, particularly intraclasts. Gravel lags can occur when flow is 0.4–0.7 m/s (Einsele, 1992).

An analysis of the channel sandstones at TT and all but channel sandstone 2 at FP show the following features in abundance: (1) low sandstone to fines ratio, (2) ribbon sandstone geometry, (3) highly variable paleocurrents, (4) evidence of stable vegetated islands, and (5) single-channel form. Additionally, mature caliche paleosols are common. Features sometimes present are: (1) multi-story channels, (2) crevasse-splay deposits, (3) fining-up channel fills. Features absent for the most part, are: (1) LA or downstream-accreting macroforms (DA) elements, (2) levee deposits, point-bar sequences, (3) sheet sandstone geometry, and (4) large-scale sandy bedforms and gravel bedform elements (Table 3).

The rapid changes between lower flow regime (LFR) and upper flow regime (UFR) structures in the channel sandstones imply that the rivers were “flashy,” low-gradient channels that reached maximum discharge several times per year during the wet season. The rapid alternation of structures of the LFR and UFR can be seen in Figures 5 to 8, which contain St, Sp, Sr, and Sh.

Channel sandstone 1 allows the following interpretations. The paleoflow was to the northeast (47°) in a small, fairly fast-flowing river, with a medium-sandstone to fine-gravel basal thalweg lag of rounded floodplain and caliche clasts. Most flow was in the lower flow regime, with current velocities from 0.4–0.7 m/s (Ashley, 1990). The 23% upper flow regime structures in channel 1 indicate some upper flow regime transport at 0.7–1.2 m/s, for example, when the rip-up clasts were produced, probably by bank collapse. Water depth was shallow as indicated by the 1.3-m thickness of the channel sandstone.

The rivers at TT and at FP (excepting channel 2) were narrow and shallow. During floods they streams overflowed the floodplain and deposited crevasse-splay silts and very fine sands near the channels. Crevasse splays are particularly well developed at FP, where many of them can be correlated to specific channel sandstones (J. Kirkland, person. comm., 1992, 2006).

In summary, the fluvial style at TT has features of both meandering and anastomosing rivers, but tends more toward

Table 3

Qualitative presence of sedimentologic and architectural features in Brushy Basin Member channel sandstones at Trail Through Time (TT), and Channel Sandstone 2 at Fruita Paleontological Area (FP) compared to generalized anastomosing, meandering, and braided rivers

Item #	Possible features	Features observed		Typical features (from literature)		
		Channel SSs at TT	CH 2 at FP	Anastomosing	Meandering	Braided
1	Low sandstone to fines ratio	++	++	++	++	-
2	Ribbon sandstone	++	+/-	++	-	-
3	Highly variable paleocurrents	++	++	++	++	-
4	Stable vegetated islands	++	+	++	-	+/-
5	Abundant mature paleosols	+	+	++	+	-
6	Abundant LA or DA elements	-	-	-	++	++
7	Multi-story channels	+/-	-	+	+	++
8	Crevasse-splay deposits	+/-	++	+	++	-
9	Single channel	++	++	+/-	++	-
10	Levee deposits	-	++	-	++	-
11	Point-bar deposits	-	++	-	++	-
12	Fining up channel fill	+/-	++	+/-	++	-
13	Sheet sandstone	-	-	-	++	-
14	Large-scale SB and GB elements	-	-	-	-	++
15	Low channel width to depth ratio	?	?	+	+	-
16	High sinuosity	?	+	++	++	-

++ abundant, + common, +/- sometimes present, - absent

anastomosing. Only panel 2 of channel sandstone 4 (Fig. 8B) is close to an ideal point-bar sequence. River discharge was flashy, with rapid changes in velocity and/or depth, producing interbedded upper flow regime beds and lower flow regime planar and trough cross-beds with rare ripples. River depths were variable, based on the heights of individual St and Sp sets (4 to 36 cm) and thicknesses of the channel sandstone bodies (1.0 to 5.2 m). Avulsions were common, with the hard, underlying caliche horizons contributing to a tendency to avulse. The few fining-up channel sequences reflect progressive filling, but also may be due, in part, to decelerating flow during a major flood. The anastomosing rivers probably had some meander reaches. Paleocurrent flow variability is much higher in channel sandstones 3 and 4 than in channel sandstones 1 and 2, which might indicate a change in the fluvial regime through time at TT. These sandstones bracket the lower Brushy Basin-upper Brushy Basin contact and may indicate that the style of rivers changed in response to the increasing volcanic ash input.

Migrating subaqueous two-dimensional lingoid bars under lower flow regime conditions formed the planar cross-bed sets. Three-dimensional sinuous-crested dunes formed the larger trough cross-bed sets. Horizontal laminations in medium- to coarse-grained sandstones, some with parting-step lamination, are upper flow regime forms. A braided river at TT is unlikely because of a low ratio of sandstone to mudstone (31 : 69), the common to locally abundant caliche paleosols, lack of downstream-accreting macroforms and gravel, the absence of large-scale sandy or gravelly bedforms, and especially, the lack of numerous channel cross-sections.

The Brushy Basin Member anastomosing river system (Fig. 17) is similar to the Rio Flumen section of the Oligo-Miocene Huesca Formation, Ebro Basin, Spain (Hirst, 1991). Hirst (1991) describes a ribbon-dominated alluvial architecture of a section along the east side of the Rio Flumen approximately 3 km south of the basin margin. The cross section of this sequence is similar to that at TT. Ribbon sandstones are mired in floodplain mudstones. Some channel

stacking or amalgamation occurs, but most sandstone bodies are single-story or two-stories at most. The section at TT could possibly be part of a larger fluvial system that has nearly the dimensions and large-scale architecture of the Rio Flumen system. The Rio Flumen (Hirst, 1991) shares two things with the strata at TT: (1) the proximal strata are tectonically disrupted, and/or eroded away, and (2) regional correlation is imprecise, with the age of the sequence determined by a few vertebrate horizons (Hirst, 1991). Until ash beds were recently dated (Kowallis *et al.*, 1991), the same was true for TT. To this day, some of the Brushy Basin sequence is not well-constrained and time-markers are hard to find.

Typical of anastomosing systems, the central, thick sandstones commonly “wing-out,” a geometry present in channel sandstones 2 and 3 at TT (Fig. 5A). A sheet sandstone with poorly channelized flow, in a course with poorly defined banks, has a channel form that wedges out laterally without clear cutbanks (Hirst, 1991). Channels 2 and 4 at TT may be

of this type. This type of river channel commonly is filled with horizontally-laminated sandstones, as at the tops of channel 2 and part of channel 4 at TT. Hirst’s sheet sandstones are the product of unconfined overbank flow, equivalent to the thin crevasse-splay sheet sandstones at TT and FP. These are wide relative to their thickness and lack cutbanks (Hirst, 1991).

The sequence at TT has predominantly ribbon-sand geometry due to the stable river banks cut in mudstone. Bank collapse shed mud and caliche clasts that were incorporated in the basal lags during flood events (Fig. 7A). The moderately to well-developed caliche paleosols locally prevented river downcutting, resulting in avulsion from the shallow channel to a new one. This typically occurs when the channel is filled to about 50% of the depth (Parker, pers. comm., 2002). At TT, small ponds and lakes dotted the landscape, yielding micritic limestone. Episodically, ash covered the landscape, so that at shallow burial depths some caliche and other paleosols were hardened to the silicified paleosols

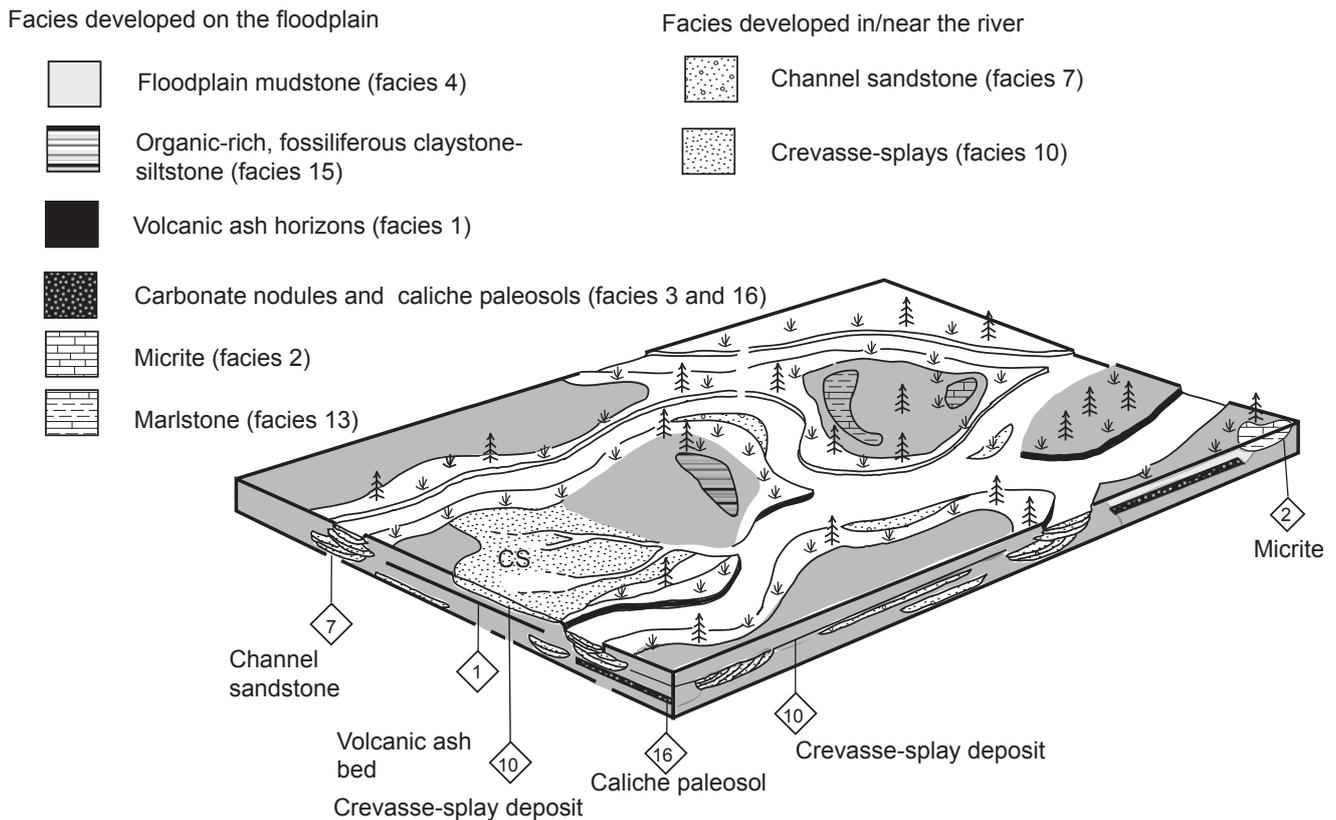


Fig. 17. Paleogeographic reconstruction of Brushy Basin anastomosing rivers at Trail Through Time (TT) and Fruita Paleontological Area (FP) and probably at Echo Canyon (EC) (after Miall, 1985, river model 8)

common at TT. Later, silica became more abundant, as evidenced by the silica-replacement front(s) in channel sandstone 4 (Fig. 8B) where the friable sandstone was converted to a hard silica-replaced sandstone and thus increasing the likelihood of preservation of dinosaur bones.

The anastomosing fluvial system of Figure 17 is similar to one for the Morrison strata in southwest Montana, where Cooley and Schmitt (1998) retrodict “a north flowing, low-gradient, mud and sand-dominated fluvial system.” Channel sandstones in their study area are “encased in extensive overbank-derived mudstone” as at TT and most of FP. They also interpret Morrison rivers as having rapid fluctuations in discharge.

### Fluvial Complex at Fruita Paleontological Research Area (FP)

Analysis of channel sandstone 2 at FP show the following abundant features: (1) low sandstone to fines ratio, (2) highly variable paleocurrents, (3) crevasse-splay deposits, (4) single channel geometry, (5) levee deposits, (6) fining-upward point-bar sequences, and (7) fining-upward channel fill. Common channel sandstone 2 features are: (1) mature paleosols, and (2) high sinuosity, and (3) highly bioturbated (stable vegetated islands) (Table 3). Even with FP’s excellent outcrop exposure, no lateral accreting or downstream accreting elements were observed within channel sandstone 2. This system is similar to the model for the Miocene Lower Freshwater Molasse of Switzerland (Platt and Keller, 1992).

I envision a small meandering river similar to the model 6, sand-bed meandering stream of Miall (1996) (Fig. 18). Abundant mudstone and caliche rip-up clasts in the basal lag deposits of channel sandstone 2 indicate that bank collapse was an important process. Although caliche paleosols are not as abundant at FP as at TT, the base of channel sandstone 2 directly overlies a 13-cm well-developed stage III-IV caliche. The lowermost part of the FP channel sandstone 2 in Figure 14 contains most dinosaur bones.

Facies of channel sandstone 2 in common with the Lower Freshwater Molasse are: levee, crevasse-channel, and crevasse-splay deposits, floodplain fines, and abandoned channels. Organic-rich, fossiliferous claystone and siltstone (facies 15) is locally abundant, and interpreted as a standing water body, such as an oxbow lake. The levee deposits described by Platt and Keller (1992) are a little larger than those at channel 2, which are on the order of centimeters thick, versus the 2–6 m-thick deposits of the Lower Freshwater Molasse. The lateral extent is also smaller at FP.

It is possible that the north- to northeastward-flowing, meandering channel sandstone 2 represents a longitudinal trunk stream developed during the period of most persistent

humid climate and that the other channel sandstones at FP represent transverse streams that flowed directly away from the north-south oriented source area. Most of these other channel sandstones trend more or less from west to east. This arrangement puts channel 2 parallel to the north-south strike of the Morrison depositional basin. Kirkland (2006) interprets that the channel 2 river re-occupied the position of the channel 1 river. This is similar to a partially abandoned or avulsed channel of the Rio Colorado, Altiplano, Bolivia, that is seen to diverge away from the present-day channel (Donselaar *et al.*, 2013). This is interpreted as a channel that was the direct precursor of the present-day active channel and was abandoned by avulsion.

It is possible that some of the other anastomosing streams may have fed other meandering streams that were either not preserved or were eroded away. Indeed, there is a “Ghost Channel” interpreted by Kirkland (2006) based on a map pattern of desert varnished individual boulders arranged in a pattern interpreted to be a ribbon river channel active between the times of deposition of ribbon channel sandstones 9 and 10. These boulders possibly weathered out and are now found “high and dry” on the recent landscape.

Crevasse-splay deposits (facies 5, 10) were identified by concave-up channel floor (4<sup>th</sup> order surface) or nearly flat base, proximity to the main channel sandstone unit, and sheet-like bodies tens to hundreds of meters across and in some cases up to a kilometer, and approximately 10 or so cm thick that thin and pass laterally into element FF, overbank/floodplain fines. Both upward-coarsening and upward-fining successions may be present, indicating progradation or gradual abandonment, respectively (Miall, 1996). Therefore, channel sandstone 2 was deposited by a small, meandering, highly sinuous, river as inferred by the size of the oxbow-lake deposits, the crevasse-splays, and the spacing of the bends and their associated levee/crevasse-splay deposits.

The mass concentrations of dinosaur bones in channel sandstone 2 are present at the bends of the meandering river, evidently produced by a sequence similar to that described by Hubert and Panish (2000) for the formation of the dinosaur-bearing sandstone channel in the Morrison Formation on Dinosaur Ridge at Morrison, Colorado: (1) accumulation of bones along dry river bed during prolonged drought; (2) heavy rainfall produces flood waters that fill and overflow the channel and scour sand from its floor and the dinosaur bones and sand are transported down the river, along with pebble-sized mud and paleosol rip-up clasts; (3) rapid deposition of the sand and bones in the deeper parts of the channel, more likely to be preserved; (4) an interval of hours to a day of deposition results in the bones being covered within cross-bedded and/or horizontally-laminated sand, thus protecting them from decay or scavenging. Mass accumulations of dinosaur bones in channel sandstones in the Morrison basin

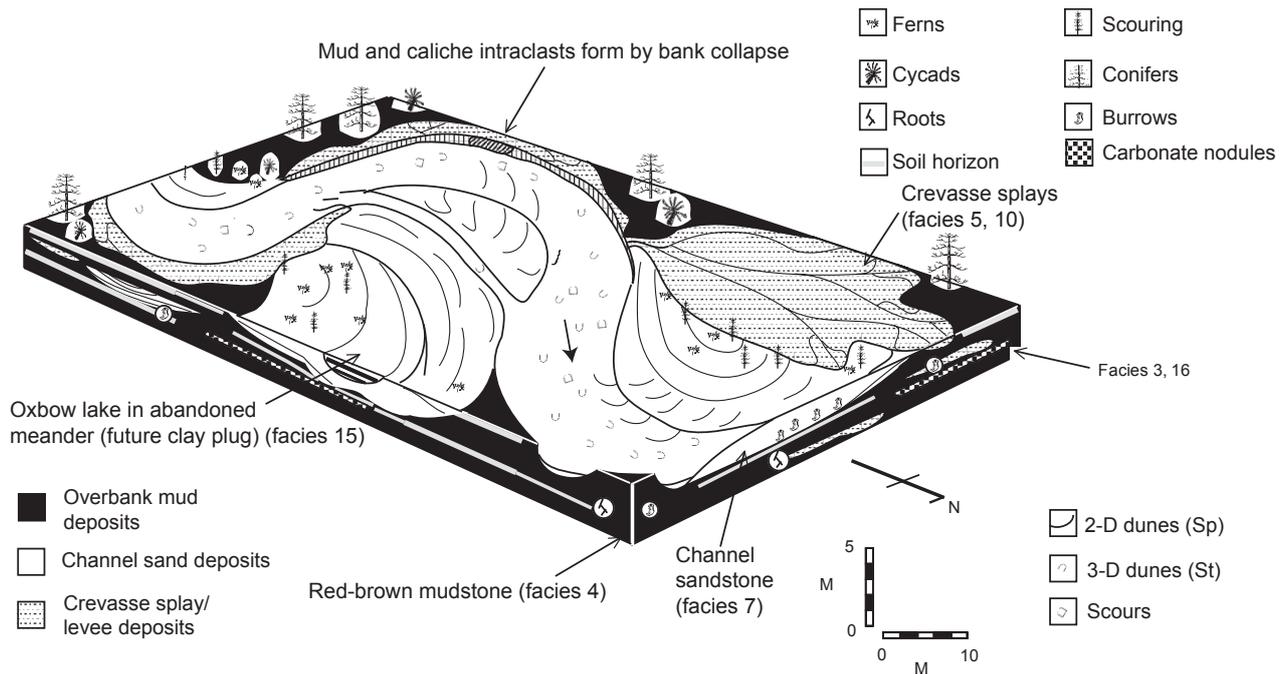


Fig. 18. Meandering river reconstruction of Brushy Basin Member Channel Sandstone 2 at Fruita Paleontological Area (FP) (after McInerney, 1993, similar to Miall, 1996, river model 6: sand-bed meandering stream)

occur at: (1) the outcrop at Dinosaur Ridge (Hubert, Panish, 2000); (2) the Carnegie quarry at Dinosaur National Monument where there were two pulses to a flood or two closely-spaced floods (Bilbey *et al.*, 1974; Lawton, 1977); (3) Dry Mesa Quarry 60 km south of Grand Junction, Colorado (Richmond, Morris, 1998); (4) the Bone Cabin quarry 16 km north of Como Bluff, Wyoming (Osborn, 1904); and (5) the Felch quarry at Garden Park, Colorado (Carpenter, 1998). A prolonged drought prior to deposition of channel sandstone 2 is supported by the stage IV caliche that underlies the channel. This caliche has a nodular carbonate-plugged horizon about 13-cm thick, and required thousands of years of overall semi-aridity, a slow sedimentation rate, and seasonal precipitation.

The Brushy Basin Member at FP is unique in that it contains both dinosaur body fossils and theropod tracks (Kirkland, 2006; Eriksen, 1976). The tracks are associated with the Main Callison Microvertebrate Quarry. Dinosaur tracks are also found at the bases of some channels (Engelmann, Hasiotis, 1999). Commonly, dinosaur-bearing formations contain either dinosaur tracks (as in the Portland Formation, Hartford Basin) or dinosaur bones, but not both. Possibly, many of the Brushy Basin subenvironments such as the pond/marsh facies (Kirkland, 2006) developed within islands that existed between the strands of the anastomosing

channels (Makaske, 2001). For example, the morphology of alluvial islands is a feature found in the anastomosing river system of the Solimes River of the Amazon basin (Baker, 1978) where there was a “saucer-like” geometry due to the bounding natural levees. Kirkland (2006) found his pond/marsh facies to occur at FP, always accompanying an underlying ribbon sandstone in the case of channel sandstones 1, 2, 3, 4, 7, 9, and 10 and that the facies association typified the lower two-thirds of the Brushy Basin Member at FP. Possibly, this facies records evidence of islands that were subsequently eroded away.

The Brushy Basin rivers, with the exception of channel 2 at FP, may have belonged to the organo-clastic system subtype (Smith, Smith, 1980) of the type-1 cohesive-sediment anabranching rivers category of Nanson and Knighton (1996) and Knighton (1998). In this type of river system, shifting of channels occurs as a result of long-term, large, floodplain-scale via avulsion instead of the deposition or dissection of within-channel bars (Knighton, 1998). The organo-clastic type of river was first described by Smith and Smith (1980) with respect to alluvial valleys near Banff, Alberta, Canada.

Ash-fall events were common throughout Brushy Basin time, especially during the deposition of the upper Brushy Basin Member. The possible correlation among the three

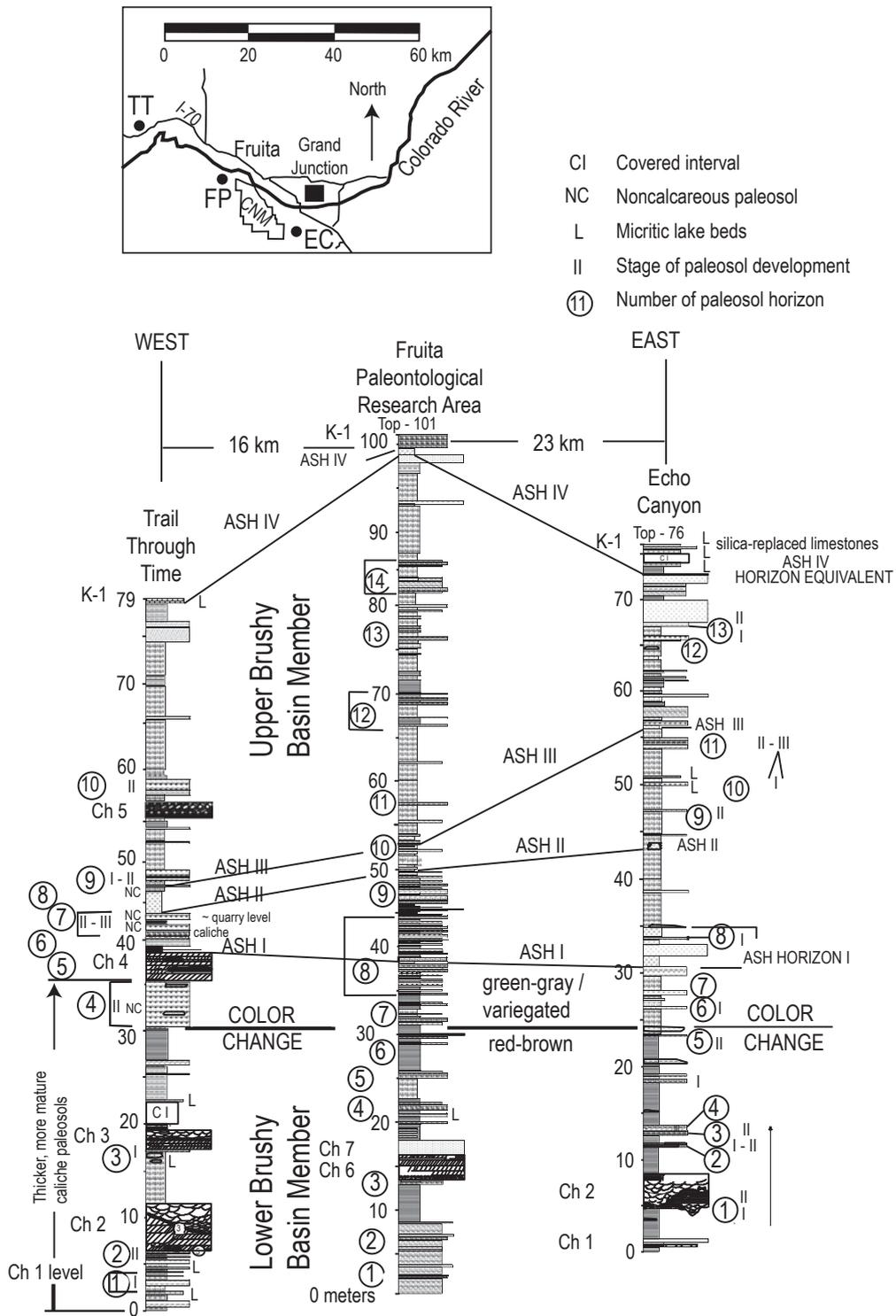


Fig. 19. Correlation among stratigraphic sections in this study

See Figure 2 for legend to facies patterns. The color change at 31 m at FP is the basis for correlation of: (1) color change, (2) zones of the channel sandstones, (3) paleosol horizons, (4) volcanic ash beds, and (5) positions of some thin lake beds

sections using the distinctive four volcanic ash bed zones is significant. It is probable that the capacity of some of the Brushy Basin rivers was taxed due to their becoming overwhelmed with fine ash. The distance west to the volcanic belt was about 800 km (Turner, Peterson, 2004). The significant increase in both the number of and the thickness of ash beds and puffy-weathering ashy mudstones of the upper Brushy Basin strata probably reflect an increase in volcanism at that time (Galli, 2003). Most bentonites similar to those observed are produced due to diagenetic alteration of the silicic vitric fallout ash (Slaughter, Earley, 1965). Indeed, Newell (1997) interpreted Brushy Basin sandstones of FP as being formed by suspended-load rivers where their carrying capacity was overwhelmed due to the large amount of volcanoclastics coming in as both air-fall ash on floodplains and channels and that carried by the streams.

Avulsions were an important process by which the Brushy Basin rivers sculpted their floodplains and spread their load, especially during flooding events. Kirkland (2006) and Newell (1997) both retrodict that major flooding events were important in producing the observed levee-crevasse-splay systems associated with channel 2 at FP. Crevasse-splay deposits were produced as sediment-choked stream water overtopped the levees and spread across the floodplain. In the process, they formed basal erosional surfaces as well as built up the levees so that, eventually, the rivers stood higher the adjacent floodplain (Kirkland, 2006). Some aspects of the present-day Rio Colorado, Bolivia seem to be quite similar to those observed or inferred for the Brushy Basin rivers. In the Rio Colorado, near an avulsion point in the main river, the height of the abandoned-channel floor is 30- to 50-cm above the present-day river and it has a covering of sand with current ripples (Sr) that indicate a flow direction that is away from the present-day river (Donselaar *et al.*, 2013). It is quite possible that the anastomosing rivers of the Brushy Basin Member are dryland rivers like the Rio Colorado. These rivers can occur in a wide range of climates, from arid to sub-humid (Donselaar *et al.*, 2013). The low vertical accommodation space of the Brushy Basin Member is similar to that observed for the Rio Colorado, Bolivia, where it is thought to have caused a thin series of successive meandering-channel belt deposits, forming laterally to each other due to repeated channel avulsions (Donselaar *et al.*, 2013). At FP, perhaps all channel sandstones formed in a similar manner.

### Fluvial complex at Echo Canyon (EC)

Echo Canyon channel sandstones are less accessible than those present at TT and FP. A channel sandstone that may be channel 1 within the Brushy Basin Member or the top sand-

stone of the Salt Wash Member is located high above the dry wash at the base of Echo Canyon. The lens shape and the channel width is estimated to be 3–5-m at its thickest, thinning to 1.5–2.5-m thick at either end. The channel is underlain by floodplain mudstones and three crevasse-splay deposits that are most likely related to flood events associated with this channel. There is a possible paleovalley that has two to three channel sandstones within it. The lens shape and low sandstone to fines ratio at EC also argue for an anastomosing stream system. However, the shape and size of this channel could also be produced perhaps by a meandering stream oriented longitudinally with respect to the viewer.

### Regional Interpretations and probable correlations

The three localities provide a nearly east-west cross-section orthogonal to the N–S-trending source area to the west. The correlations shown in Figure 19 for TT and FP are consistent with those of Kirkland (2006).

## PALEOGEOGRAPHIC RECONSTRUCTION

### FLUVIAL STRATA

Most of the channel sandstones formed as anastomosing rivers that crossed muddy floodplains. These sandstone bodies are typically 1–3 m thick but reach 5 m; most are single story and do not meander where plan view can be seen. The abundant pebbles of floodplain red-brown mudstone and caliche paleosols along the channel floors show that erosion and collapse of the mud banks were common. No lateral accretion surfaces were found and the channels have a non-systematic fill of lithofacies. Meander-channel sandstones are rare, but channel sandstone 2 at FP is the most prominent example. This sandstone body has a sinuous outcrop pattern and small channel forms that typically fine up from medium/coarse to fine gravel size to fine/very fine-grained sand. Levee and crevasse-splay units are associated with the channel bends.

In both the lower and upper divisions, the mudstones can be definitively assigned a floodplain origin rather than playa/playa-lake origin because: (1) they are mostly non-sandy and rarely laminated; (2) where sandy, the sand content decreases away from channel sandstones and levee deposits; (3) the levee bodies thin and fine away from the channel sandstones; and (4) ripple cross-lamination is rare.

The Brushy Basin paleo-landscape was an open plain with scattered vegetation and distinct wet and some prolonged dry seasons, and where the trees and shrubs were concentrated along the river courses. Dinosaurs roamed the

riparian ecosystems and rare scattered bones are preserved in anastomosing-river channel sandstones. Major accumulations of bones are restricted to the pools at three bends of meandering-river channel sandstone 2 at FP where preservation potential was enhanced.

## PALEOCLIMATE

In general, the paleoclimate during accumulation of the Brushy Basin strata was semi-arid to sub-humid, but there undoubtedly were many short and long-term fluctuations in precipitation. In Late Jurassic time, the study area was slightly south of its present latitude, with strong westerlies. The variegated floodplain mudstones of the upper division contain numerous non-calcareous and calcareous paleosols that vary from incipient scattered calcite nodules to stage III caliche. The caliche horizons are best developed at TT and FP, and to a lesser extent at EC. The caliche paleosols imply semi-aridity and seasonal precipitation, particularly for the upper division.

A 70-cm cherty limestone near the top of the Brushy Basin at Dinosaur National Monument was cited as an occurrence of Magadiite-type chert (Billbey, 1991). However, this unit contains stromatolites and ostracods, and is evidently a lacustrine limestone with volcanic ash that altered to smectite. A 50- to 70-cm silicified limestone near the top of the Brushy Basin sections examined in this study is also a micritic limestone partly replaced by silica. Furthermore, the clay-mineral assemblages in the floodplain mudstones, caliches, and micrites do not contain evaporite-type minerals, for example, zeolites, Mg-smectite, palygorskite, and sepiolite. Due to the small amount of illite, the proportion of the 1Md soil illite was not determined (Srodon, Eberl, 1984). However, most illite is degraded, presumably 1Md. Detrital kaolinite was a minor detrital clay. No arid-region, Magadiite-type chert was found in any of the strata. This precludes an arid climate interpretation.

## CONCLUSION

The 85-m Brushy Basin Member of the Morrison Formation in and around Fruita, Colorado is dominated by a 30-m lower division dominated by red-brown mudstone and a 55-m upper division dominated by variegated smectitic mudstones of floodplain origin. The fluvial system may have been similar to a dryland river system that commonly is deposited under conditions of very low gradient and accommodation space, within a back-bulge basin. River-channel sandstones are embedded in the mudstones and tend to have cut

downward to resistant caliche paleosol horizons. Four zones of altered volcanic ash appear at approximately the same stratigraphic level in all three sections; these may allow correlation among Brushy Basin strata within western Colorado.

Abundant pebbles of floodplain red-brown mudstone and caliche paleosols along the channel floors show that erosion and collapse of the mud banks were common. No lateral accretion surfaces were found and the channels have a non-systematic fill of lithofacies. In both the lower and upper divisions, the mudstones are of floodplain origin rather than playa/playa-lake origin. Features diagnostic of playa/playa-lakes are absent.

The overbank fines (FF) architectural element is the dominant element at all localities and contains the majority of the observed lithofacies. Major sandstone ribbon element (CHR) is the next most prevalent element and contains all lithofacies of the channel sandstones with a straight geometry and exhibiting very few fining upward cycles. Most of these channel sandstones are found in the lower Brushy Basin Member. Channel sandstone 2 at FP is the only instance of the major channel sandstone element (CH). Both CHR and CH elements grade or pinch out into the associated FF element. Minor sandstone sheet element (CS) as seen by crevasse-splay and levee deposits are common at FP and fairly common at TT and less so at EC.

The Brushy Basin paleo-landscape was an open plain with scattered vegetation and distinct wet and potentially prolonged dry seasons, and where the trees and shrubs were concentrated along the river courses. Dinosaurs roamed the riparian environments and rare scattered bones are preserved in anastomosing-river channel sandstones. Major accumulations of bones are restricted to the pools at three bends of meandering-river channel sandstone 2 at FP where preservation potential was enhanced. In general, the paleoclimate during accumulation of the Brushy Basin strata was semi-arid to subhumid.

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