A SEDIMENTOLOGICAL AND SEQUENCE STRATIGRAPHIC RE-INTERPRETATION OF THE UPPER CRETACEOUS PRAIRIE CANYON MEMBER (''MANCOS B'') AND ASSOCIATED STRATA, BOOK CLIFFS AREA, UTAH, U.S.A.

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ABSTRACT: The Mancos Shale, Book Cliffs, eastern Utah, USA, represents the open-marine mudstones of the Cretaceous Western Interior Seaway and encloses the Prairie Canyon Member, which is located over 50 km seaward of interpreted contemporaneous highstand shoreline deposits in the Blackhawk Formation. Examination of the Member reveals that it does not wholly represent offshore deposition, as previously interpreted, but instead contains three nearshore facies associations: (1) tidally influenced fluvial channel fills, (2) fluvial-dominated delta fronts, and (3) weakly storm-influenced shorefaces. Tidally influenced fluvial channel fills are commonly stacked into multistory bodies that can be traced for tens of kilometers at discrete stratigraphic levels, defining incised-valley-fill networks. Four such incised-valley networks are identified at outcrop. Fluvial-dominated deltas and weakly storm-influenced shorefaces are eroded into by, and lie at the down-dip terminations of, incised-valley fills and are interpreted as forced regressive and lowstand shoreface deposits. One incised-valley fill appears to be onlapped by additional fluvial-dominated deltas, which represent pulses of shoreface progradation during an overall transgression.

Forced regressive, lowstand, and transgressive shorefaces in the Prairie Canyon Member differ significantly from highstand shorefaces in the Blackhawk Formation. The former are sand-poor and weakly wave/storm-influenced, whereas the latter are sand-rich and wave-dominated. This change in shoreface style reflects increased mud supply and an enhanced embayment paleogeography during periods of relative lowering of sea level.

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INTRODUCTION

The Upper Cretaceous Mancos Shale of east-central Utah and west-central Colorado contains an anomalously sandy interval that crops out in a series of low hills at the base of the Book Cliffs (Fig. 1). This interval occurs within the recently defined Prairie Canyon Member of the Mancos Shale (Willis 1994; Cole et al. 1997), previously referred to as the informal ''Mancos B'' interval (e.g., Kopper 1962; Kellogg 1977; Cole and Young 1991). The Prairie Canyon Member forms a mappable subsurface unit in the Douglas Creek Arch and parts of the southern Uinta and Piceance Creek Basins (Kellogg 1977; Johnson and Finn 1986; Cole and Young 1991), where it produces commercial quantities of natural gas (Fig. 1).

At present, the Prairie Canyon Member is interpreted as an offshore unit related to the deltaic shoreline systems of the Blackhawk Formation, which are exposed in the Book Cliffs (Cole and Young 1991; Cole et al. 1997). This interpretation is based on the paleogeographic location of the Member, which is enclosed in the offshore Mancos Shale and is not attached to contemporaneous shoreface deposits in the Blackhawk Formation, combined with sedimentological data from a few outcrop localities (e.g., Pinto Wash and Prairie Canyon, Fig. 1). This former, paleogeographic criterion has been widely used to justify an offshore origin for other sandstones enclosed by the Mancos Shale (e.g., Swift and Rice 1984). In this paper, we present an alternative interpretation for the Prairie Canyon Member, based on detailed mapping and sedimentological logging of the outcrop belt in east-central Utah (Fig. 1). In the first part of the paper we assess the sedimentology of the Prairie Canyon Member and associated units at outcrop, in order to establish their depositional environments. The second part of the paper documents the stratigraphic organization of these strata as mapped at outcrop and observed in the nearby subsurface. The stratigraphic relationship between the Prairie Canyon Member and the Black-

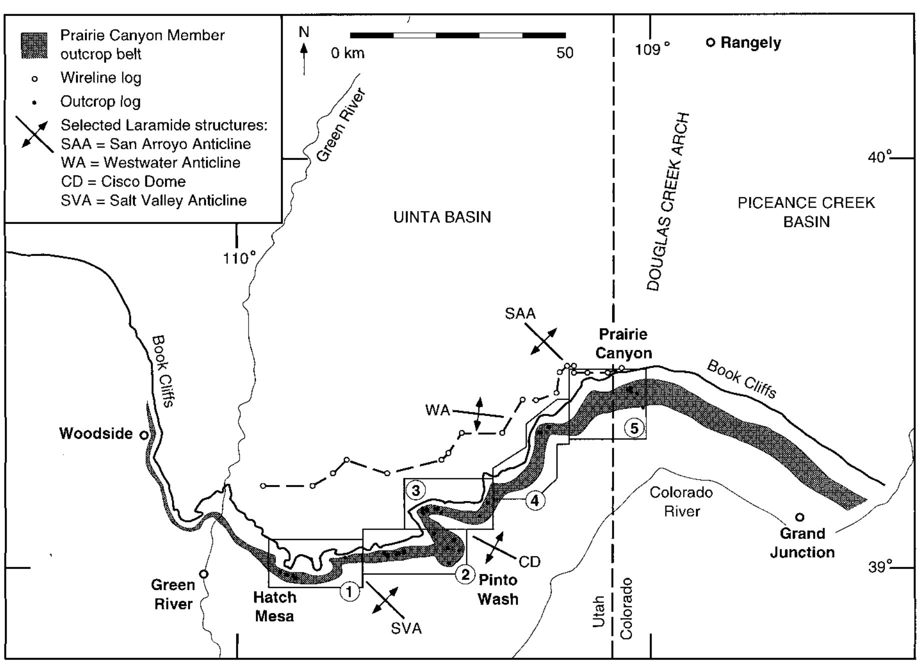

FIG. 1.—Map of the study area showing the Book Cliffs and the location of the Prairie Canyon Member outcrop belt south of the cliff line. The positions of detailed outcrop map and correlation panels 1–5 (Figs. 9–13) are referred to by circled numbers, and a subsurface correlation panel (Fig. 16) is shown as a dashed line north of the Book Cliffs. Key outcrop locations, discussed in the text, are shown in bold. Selected Laramide structures are also shown.

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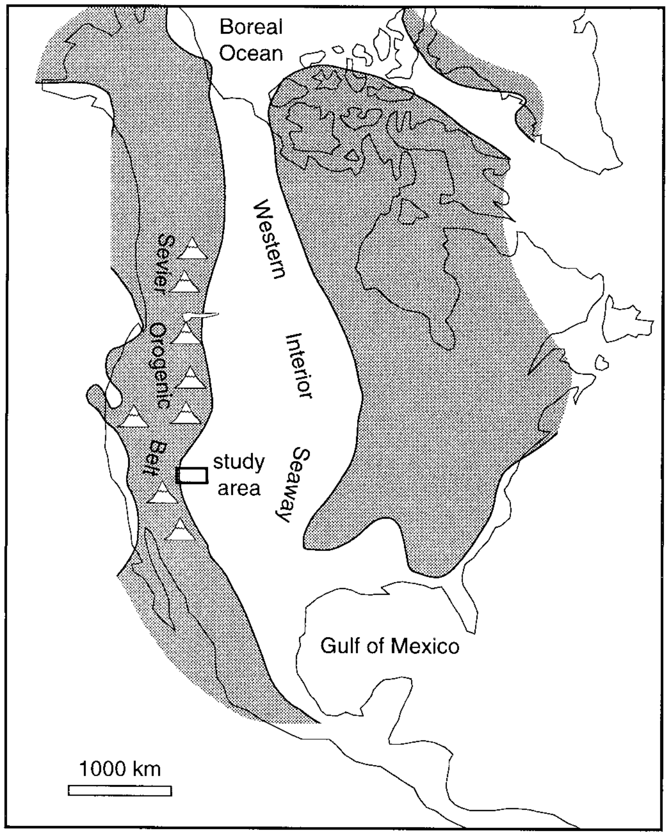


FIG. 2.—Paleogeographic reconstruction of the Western Interior Seaway foreland basin during late Campanian times (after Kauffman and Caldwell 1993), showing the location of the study area.

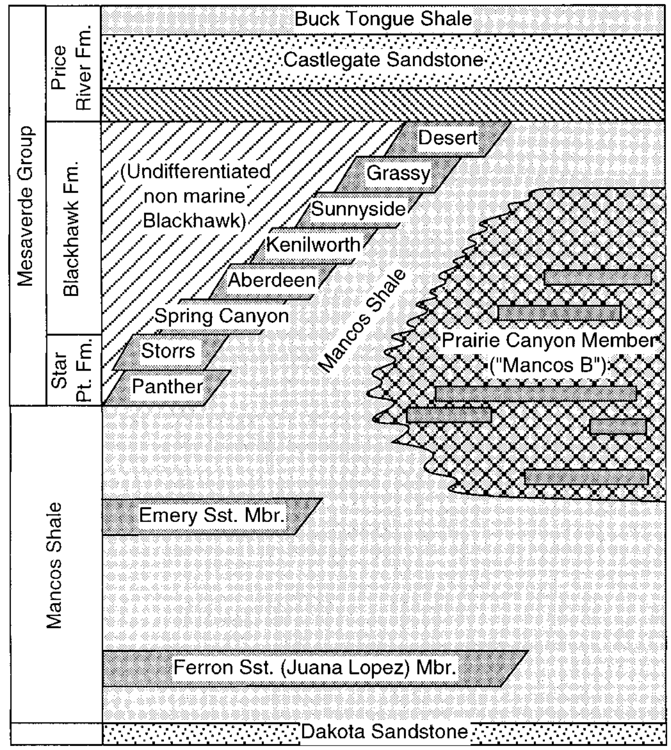


FIG. 3.—Lithostratigraphy of upper Campanian strata, comprising the Mancos Shale and lower Mesaverde Group, in eastern Utah and western Colorado (after Young 1955).

hawk Formation is addressed in the final third of the paper. The existing interpretation of the Prairie Canyon Member as an offshore unit (Cole and Young 1991; Cole et al. 1997) implies that coeval shoreface and coastal-plain deposits were confined to Blackhawk Formation strata in east-central Utah. These strata have recently been comprehensively described in a series of outcrop-based sequence stratigraphic case studies (Van Wagoner et al. 1990; Van Wagoner et al. 1991; Kamola and Van Wagoner 1995; O'Byrne and Flint 1995, 1996; Pattison 1995; Taylor and Lovell 1995; Van Wagoner 1995). As a result, incised valleys defining sequence boundaries are well documented in these strata, but little is known about possible contemporaneous lowstand shorelines, some of which may lie within the Mancos Shale.

GEOLOGIC SETTING AND LITHOSTRATIGRAPHY

The Cretaceous Western Interior Seaway, USA lay within a foreland basin that formed in response to thrust-sheet loading in the Sevier orogenic belt at the western basin margin (Fig. 2; Kauffman and Caldwell 1993). The basin fill comprises mainly clastic sediment that was eroded from the orogenic belt and transported eastward into the Seaway. There it was deposited as a series of basinward-thinning wedges, each comprising coastal-plain and shallow-marine strata. The Blackhawk Formation forms one such clastic wedge, which thins basinward into the open marine mudstones of the Mancos Shale (Fig. 3; Young 1955).

The Blackhawk Formation comprises six shallow-marine members and undifferentiated nonmarine deposits, and is everywhere erosionally overlain by the fluviatile Castlegate Sandstone (Fig. 3; Young 1955). Directly underlying the Blackhawk Formation is the shallow-marine Star Point Formation, which represents the preceding clastic wedge (Fig. 3; Young 1955). The Emery and Ferron Sandstone (Juana Lopez) Members are two underlying sandstone intervals in the Mancos Shale (Fig. 3; Fouch et al. 1983). The nonmarine and marginal-marine Dakota Formation underlies the Mancos Shale throughout the study area (Fig. 3). The Prairie Canyon Member of the Mancos Shale (Willis 1994; Cole et al. 1997) is enclosed in the Mancos Shale and lies east of the Blackhawk Formation and Star Point Formation (Fig. 3). In the western part of the study area, the Prairie Canyon Member encompasses two lenticular sandstone units. One unit occurs near Woodside (Fig. 1), and is referred to below as the Woodside Sandstone, and the other unit is called the Hatch Mesa Sandstone, after its type locality (Fig. 1; Swift et al. 1987; Chan et al. 1991; Taylor and Lovell 1995).

Previous workers have correlated the Prairie Canyon Member westwards over long distance using lithostratigraphic techniques. For example, Kellogg (1977) and Fouch et al. (1983) correlated the Mancos B interval to the Emery Sandstone. Swift et al. (1987), Chan et al. (1991), and Taylor and Lovell (1995) correlated the Hatch Mesa Sandstone to the Kenilworth Member of the Blackhawk Formation, although Pattison (1995) recently re-evaluated this relationship. The Woodside Sandstone has been correlated to both the Ferron Sandstone (Cotter 1975) and the Emery Sandstone (Swift et al. 1987; Chan et al. 1991). The tentative and disputed nature of these correlations reflects sparse biostratigraphic control, combined with relatively poor, discontinuous outcrop and the absence of detailed mapping over much of the area. Biostratigraphic data imply that the Prairie Canyon Member may be partly time-equivalent to the Emery Sandstone, the Star Point Formation, and the lower Blackhawk Formation (Cole and Young 1991; Cole et al. 1997).

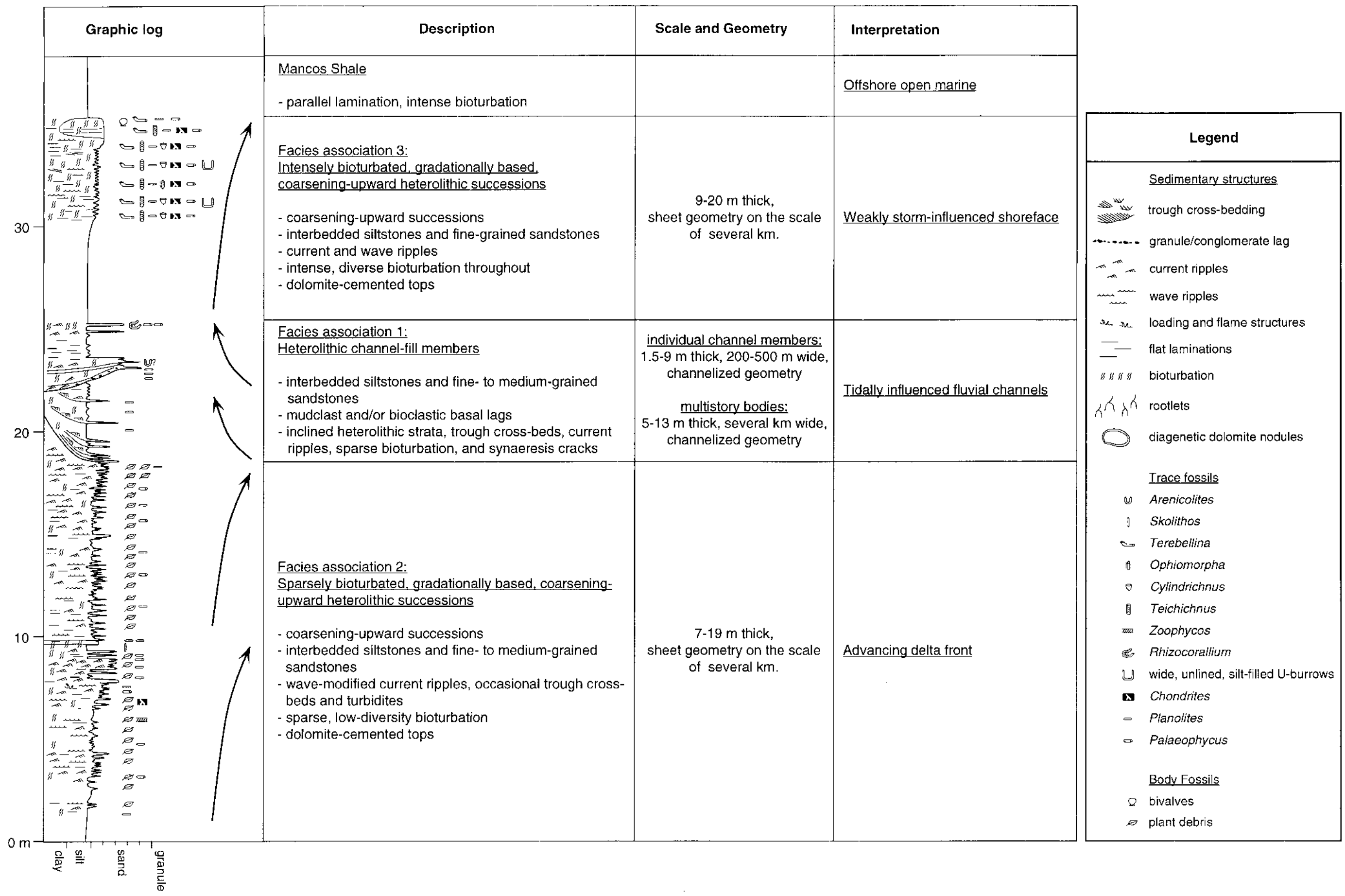


FIG. 4.—Schematic graphic log summarizing facies associations within the Prairie Canyon Member. Arrows to the right of the graphic log illustrate coarsening- and fining-upward trends. Note that most (approximately 60%) of the Prairie Canyon Member comprises open-marine Mancos Shale (Cole and Young 1991; Cole et al. 1997).

SEDIMENTOLOGY AND FACIES ANALYSIS

Detailed examination of the Prairie Canyon Member, the Hatch Mesa Sandstone, and associated deposits in the upper Mancos Shale was undertaken at outcrop using 40 logged sections, totalling 920 m in thickness. Several prominent intervals within the Prairie Canyon Member outcrop belt were mapped from Green River, Utah to Prairie Canyon at the Utah/Colorado border (Fig. 1). We observe three principal facies associations in these intervals, which are absent in the surrounding open-marine Mancos Shale.

Facies Association 1: Heterolithic Channel-Fill Units

Description.—This facies association comprises interbedded carbonaceous siltstones and very fine-, fine-, and medium-grained sandstones that lie within channelized scours. Individual channel-fill units are 200–500 m wide and 1.5–9 m thick (Figs. 4, 5). Some channel-fill units have discontinuous basal lags of mudclasts, quartz granules, reworked burrows, phosphorite clasts, and/or shell hash and sharks' teeth (Figs. 4, 5B). Overlying deposits exhibit variable sand:silt ratios, commonly with a weak fining-upward trend. Sandstones occur as beds up to 90 cm thick that typically contain trough cross-sets 5–30 cm thick and current-ripple lamination (Figs. 4, 5C). Thin (millimeter- to centimeter-scale) siltstone drapes are present at the top of many current-ripple-laminated sets and on the foresets of some trough cross-sets (Fig. 5C). Soft-sediment folding, wave ripples, and synaeresis cracks are also observed. On a larger scale, interbedded sandstones and siltstones define inclined heterolithic strata up to 5 m thick in some channel-fill units (Fig. 5A). Inclined strata are oblique to in-channel paleocurrents, they drape channel margins, and, in a few examples, they have a weak sigmoidal shape. The facies association contains a low-diversity ichnofauna dominated by *Paleophycus* and *Planolites,* although other trace fossils (cf. *Rosselia, Rhizocorallium, Terebellina, Arenicolites,* and/or *Skolithos*) occur sporadically.

In several localities (e.g., Sagers Wash, Pinto Wash, and Nash Wash, Fig. 1), channel-fill units are stacked into larger, multistory bodies 5–13 m thick and several kilometers wide (Fig. 5D). Where these bodies can be mapped out, they are bounded by erosion surfaces of markedly greater relief than the channel-fill units that they contain. Individual channel fills are rarely completely preserved within multistory bodies. Instead, their tops are typically eroded by overlying channels. Only the uppermost channel-fill unit in each multistory body is fully preserved. The top of this unit invariably comprises a distinctive interval of interbedded siltstones and fine-grained sandstones up to 2 m thick. Sandstones in these intervals occur as flat-laminated beds up to 2 cm thick with rare current ripples, some with bimodal paleocurrent directions. These intervals contain either an anomalously diverse ichnofauna of *Paleophycus, Planolites, Rhizocorallium, Conichnus, Chondrites, Arenicolites,* and/or *Skolithos*, or, alternatively, a monospecific ichnofauna of sparse *Skolithos.* The top surface of each interval is intensely bioturbated by a diverse ichnofauna.

Our facies association 1 corresponds roughly, but not exactly, to the ''scour fill'' sediments described by Fouch et al. (1983, p. 311), the ''lag

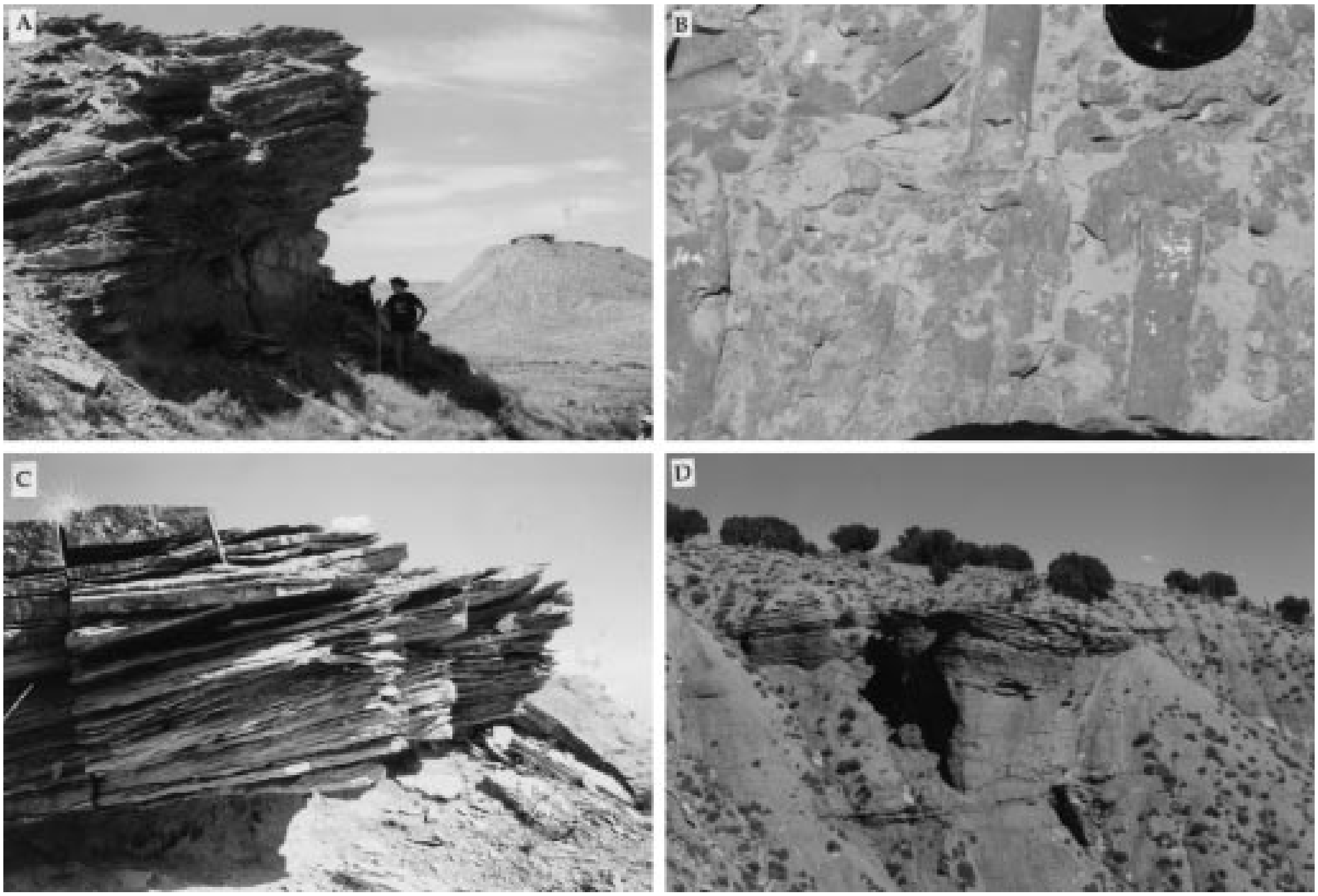


FIG. 5.—Photographs showing the sedimentology and facies relationships in facies association 1. **A**) Angular erosional unconformity between the Mancos Shale and a heterolithic channel fill (X interval in the Nash Wash area, SE section 9, T21S R22E). Heterolithic strata within the channel fill are inclined obliquely towards the viewer. **B**) Basal lag of reworked, cemented sand-filled burrows (X interval in the Pinto Wash area, central section 11, T21S R21E). **C**) Heterolithic cross-strata (hammer for scale) comprising alternating current-ripple-laminated sandstone beds and siltstone drapes (Y interval in Corral Canyon Wash measured section 1, NE section 19, T20S R23E). These strata are inclined, with a depositional dip towards the left of the photograph. **D**) Stacked heterolithic channel fills forming a multistory body (Y interval in Cisco Dome measured section 1, central section 19, T20S R21E). The exposed cliff face is approximately 25 m high.

sandstone and channel fill lithofacies'' of Swift et al. (1987), the ''channel fill facies'' of Chan et al. (1991) and the ''channelized sandstone-and-shale lithofacies'' of Cole et al. (1997). We do not assign the scour-fill deposits around Woodside and Green River (our Woodside Sandstone, the ''Emery Sandstones'' of Swift et al. 1987; Chan et al. 1991) to our facies association 1, because published accounts indicate that the former exhibit different grain size (siltstone and very fine-grained sandstone), structures (no trough cross-beds, few current ripples) and fauna (*Inoceramus* in life position; Kamola and Holland 1996). Only one unit comparable to the Woodside Sandstone scour fills is present in the study area, at Sagers Wash (Fig. 10). This unit contains three stacked channel fills, each comprising thinly laminated siltstones and very fine-grained sandstones that drape the channel margins.

Interpretation.—Channelized scours in the Mancos Shale have previously been regarded as submarine erosion features infilled by offshore marine deposits (Fouch et al. 1983; Swift et al. 1987; Chan et al. 1991; Cole and Young 1991; Cole et al. 1997). Although we do not dispute a probable submarine origin for the Woodside and Green River scour fills, and the similar scour fill at Sagers Wash, we consider that a submarine interpretation does not fully account for the sedimentology of the scour fills included in our facies association 1.

Sandstone beds in facies association 1 are dominated by trough cross-sets and current-ripple lamination, recording the migration of sinuous-crested dunes and ripples in response to unidirectional tractional currents. Siltstone drapes in the cross-stratified sandstone beds indicate frequent fluctuations in flow strength, as do the inclined heterolithic strata. The orientation of these inclined strata, draping channel margins and oblique to in-channel paleocurrents, implies a lateral-accretion origin (Fouch et al. 1983). These structures are not diagnostic of a particular environment, but they imply stronger and more persistent tractional currents than those inferred from the Woodside and Green River scour fills. Four additional features of facies association 1 deposits aid interpretation. (1) Inclined heterolithic strata contain sandstone beds and siltstone interbeds of a regular, repeated thickness, suggesting variations in flow strength of greater frequency and coherence than those implied by a submarine interpretation. We attribute these fluctuations, combined with the sigmoidal shape of some inclined heterolithic strata, to the influence of tidal processes. (2) The presence of synaeresis cracks indicates fluctuating salinities and contradicts an open-marine setting for rocks of facies association 1. (3) The low-diversity ichnofauna that predominates in deposits of facies association 1 is not typical of offshore, open-marine rocks in the Mancos Shale and Blackhawk Formation (e.g., Balsley 1980; Chan et al. 1991;

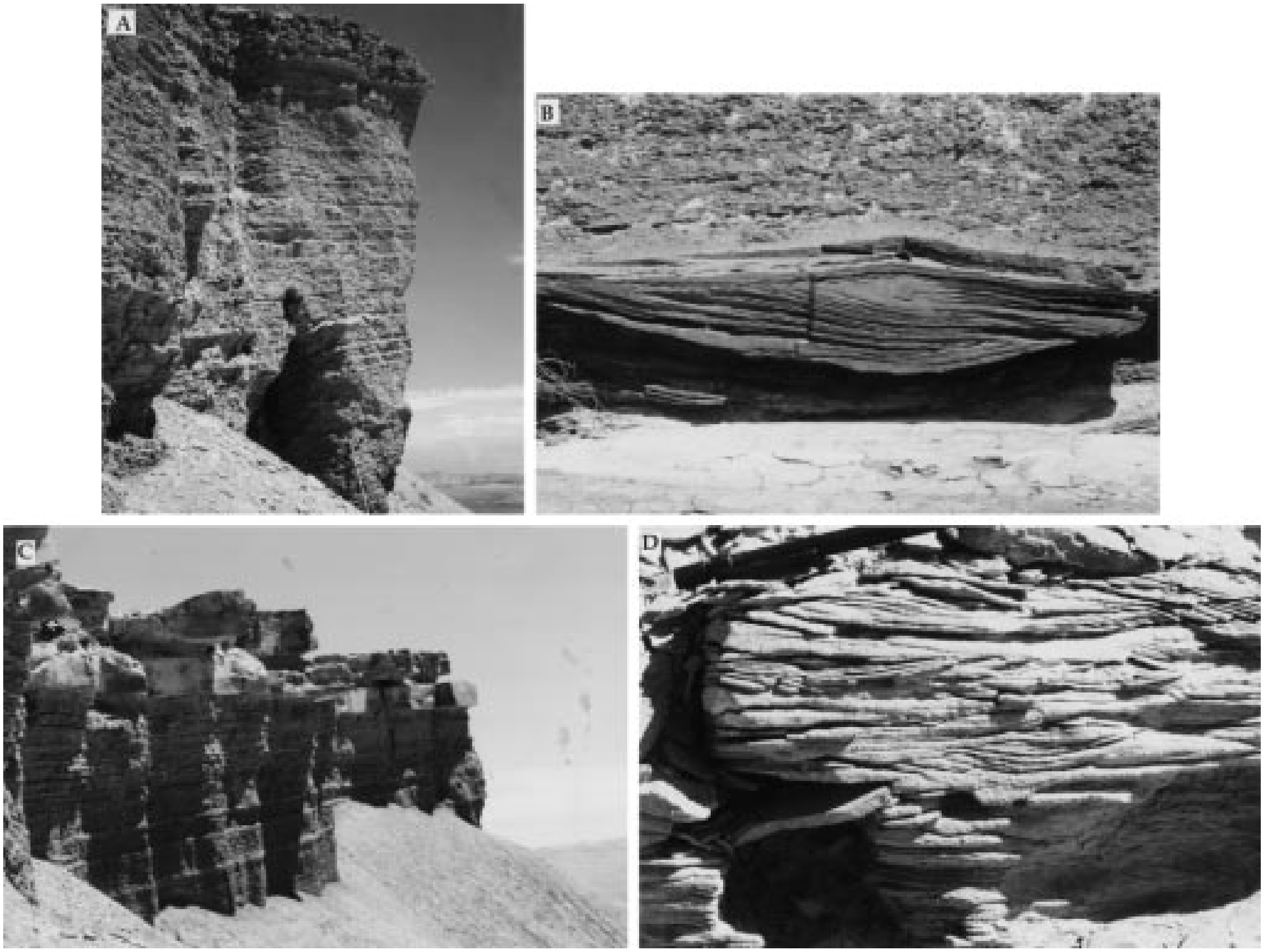


FIG. 6.—Photographs showing the sedimentology and facies relationships in facies association 2. **A**) A typical facies association 2 succession approximately 10 m high with thin, ''ratty'' sandstone beds (X2, X interval in Cisco Springs measured section 1, S central section 5, T20S R23E). Note protruding, dolomite-cemented top. **B**) Meter-scale trough cross-bed from a typical facies association 2 succession (hammer for scale) (Z1, Z interval in Bootlegger Wash measured section 3, SE section 23, T21S R20E). **C**) The Hatch Mesa Sandstone, an atypical facies association 2 succession approximately 15 m high with relatively thick, ''clean'' sandstone beds (Hatch Mesa Sandstone, central section 32, T21S R18E). Note the pinch-and-swell geometry of the 1 m thick, uppermost sandstone beds. **D**) Wave-modified current ripples from the Hatch Mesa Sandstone succession (Hatch Mesa Sandstone, Hatch Mesa measured section 1, NE section 3, T22S R18E).

O'Byrne and Flint 1995; Pattison 1995). Instead, it bears more similarity to the brackish-water ichnofaunas described by Pemberton and Wightman (1992). (4) The distinctive heterolithic intervals that cap multistory bodies contain rare bimodal paleocurrents, which imply reversing current directions and possible tidal influence. Some of these intervals also contain a monospecific ichnofauna, suggesting an ecological stress, possibly fluctuating salinity on a tidal flat.

We consider that, in combination, these four features provide strong evidence for restricted salinities and tidal action during deposition of facies association 1. Their channelized geometry and sedimentary structures suggest that these rocks are tidally influenced fluvial deposits similar to several documented within the Blackhawk Formation (e.g., valley-fill bodies in the Grassy Member; O'Byrne and Flint 1995). This interpretation is supported by the mapped stratigraphic context of these deposits (see later) and the predominance of nonmarine palynofacies in three such deposits (localities Y and Z, corresponding to the Sagers Wash and Pinto Wash areas, in Oboh-Ikuenobe 1996). Intense, high-diversity bioturbation at the tops of bodies comprising facies association 1 records increased marine influence here.

Facies Association 2: Sparsely Bioturbated, Gradationally Based, Coarsening-Upward Heterolithic Successions

Description.—Representative successions of facies association 2 are exposed at Salt Wash, Bootlegger Wash, Sagers Wash, Calf Canyon, Strychnine Wash, Cisco Springs (Fig. 6A), Westwater Creek, and Prairie Canyon. The Prairie Canyon succession is documented by Cole and Young (1991) and Cole et al. (1997) (their ''sequence A'', comprising mainly ''silty claystone'' and ''sandstone–claystone'' lithofacies). A more extensively studied, but atypical, succession at Hatch Mesa has been described in detail by several workers (Balsley 1980; Pattison 1995; Taylor and Lovell 1995; and as the ''interbedded sandstone and shale lithofacies'' of Swift et al. 1987 and the ''transitional turbidite facies'' of Chan et al. 1991).

Facies association 2 comprises thick (7–19 m), coarsening-upward successions of sparsely bioturbated, interbedded siltstones and very fine- to medium-grained sandstones. Successions gradationally overlie open-marine Mancos Shale. In a typical succession, sandstones coarsen and thicken up-

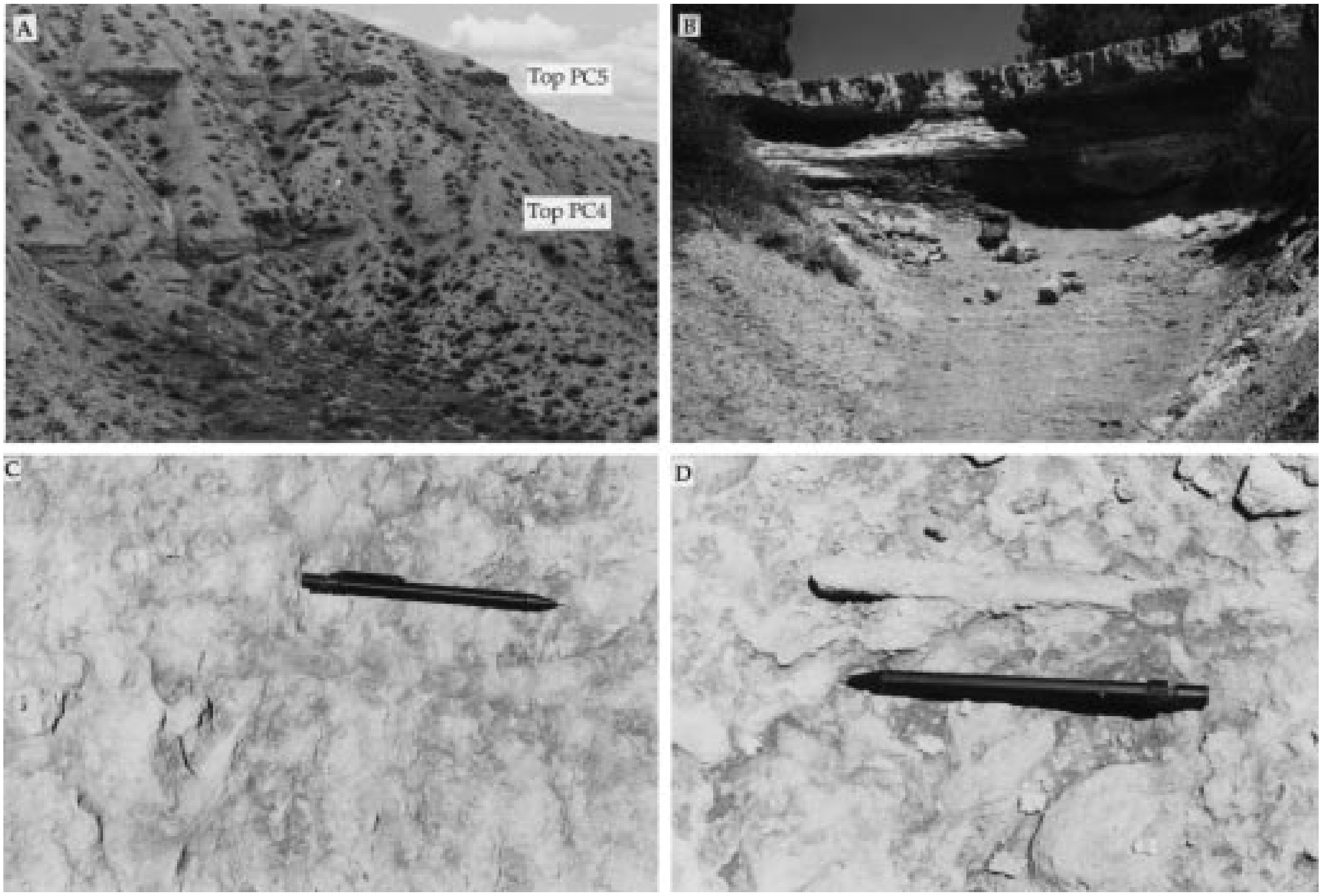


FIG. 7.—Photographs showing the sedimentology and facies relationships in facies association 3. **A**) Poorly exposed, stacked facies association 3 successions with dolomite nodules at their tops (PC3–5, Prairie Canyon measured section 1, SW section 29, T8S R104W). The photographed section is approximately 15 m high. **B**) Dolomite-cemented marker horizon (W marker) and nodules capping a facies association 3 succession (PC5, Prairie Canyon measured section 2, NE section 29, T8S R104W). **C**) and **D**) Examples of intense, diverse, shallow-marine bioturbation in such shorefaces (PC5, Prairie Canyon measured section 2, NE section 29, T8S R104W); **C**) *Teichichnus*, **D**) *Paleophycus.*

ward from laminae to thin (1–2 cm), current-ripple-laminated beds with varying wave modification. Sandstone beds are generally amalgamated toward the top of each succession. A few successions contain sandstone trough cross-beds up to 80 cm thick (Fig. 6B). Successions are sparsely bioturbated throughout by a low-diversity ichnofauna of *Planolites* and *Paleophycus,* in some places supplemented by *Chondrites* and/or *Rhizocorallium.* The upper 30–100 cm of each succession is marked by an abrupt increase in the diversity and intensity of bioturbation, in some cases associated with shell hash. Trace fossils here include *Paleophycus, Planolites, Rhizocorallium, Arenicolites, Skolithos, Aulichnites, Ophiomorpha, Chondrites,* and/or *Asterosoma.*

The Hatch Mesa succession (Fig. 6C) contains the features described above but is unique in several aspects. Sandstones in the succession are unusually well sorted, with more abundant wave-modified ripples and enhanced bed amalgamation (Fig. 6C, D). Thick ($>$ 1 m) sandstone beds with a broad, lenticular ''pinch-and-swell'' geometry occur near the top of the succession (Swift et al. 1987; Chan et al. 1991; Taylor and Lovell 1995). The Hatch Mesa succession also contains decimeter-scale sheet-like beds with scoured, tool-marked bases and which show an upward transition from massive stratification to flat lamination to current ripples (reminiscent of a–c Bouma sequences; Balsley 1980; Chan et al. 1991; Taylor and Lovell 1995). Finally, the succession contains an anomalously diverse ichnofauna, including *Paleophycus, Planolites, Rhizocorallium, Cylindrichnus,* and *Ophiomorpha.*

Interpretation.—Facies association 2 is characterized by the interaction of current and wave processes within coarsening-upward successions. The pronounced heterolithic interbedding and prevalence of current-generated structures suggests that sand was deposited from intermittent, unidirectional tractional flows. Wave modification records later reworking by oscillatory wave action. These characteristics suggest deposition in a regressive shallow-water environment with minor wave agitation. However, these rocks have a much lower-diversity ichnofauna than the open-marine environments documented in the Mancos Shale (which contain *Asterosoma, Arthrophycos, Chondrites, Helminthopsis, Paleophycus, Planolites, Scolicia, Teichichnus, Terebellina,* and *Thalassinoides*; e.g., Balsley 1980; Chan et al. 1991; O'Byrne and Flint 1995; Pattison 1995), implying that salinities were not fully marine during their deposition. Consequently, we interpret facies association 2 as the deposits of advancing delta fronts in which marine salinities were diluted by fluvially derived fresh water. The scarcity of wave-derived structures suggests that the delta fronts were fluvially dominated. More intense and diverse bioturbation at the tops of successions of facies association 2 records increased marine influence there, in response to delta-front abandonment and marine flooding.

Delta-front and prodelta plume origins have been proposed for the Hatch

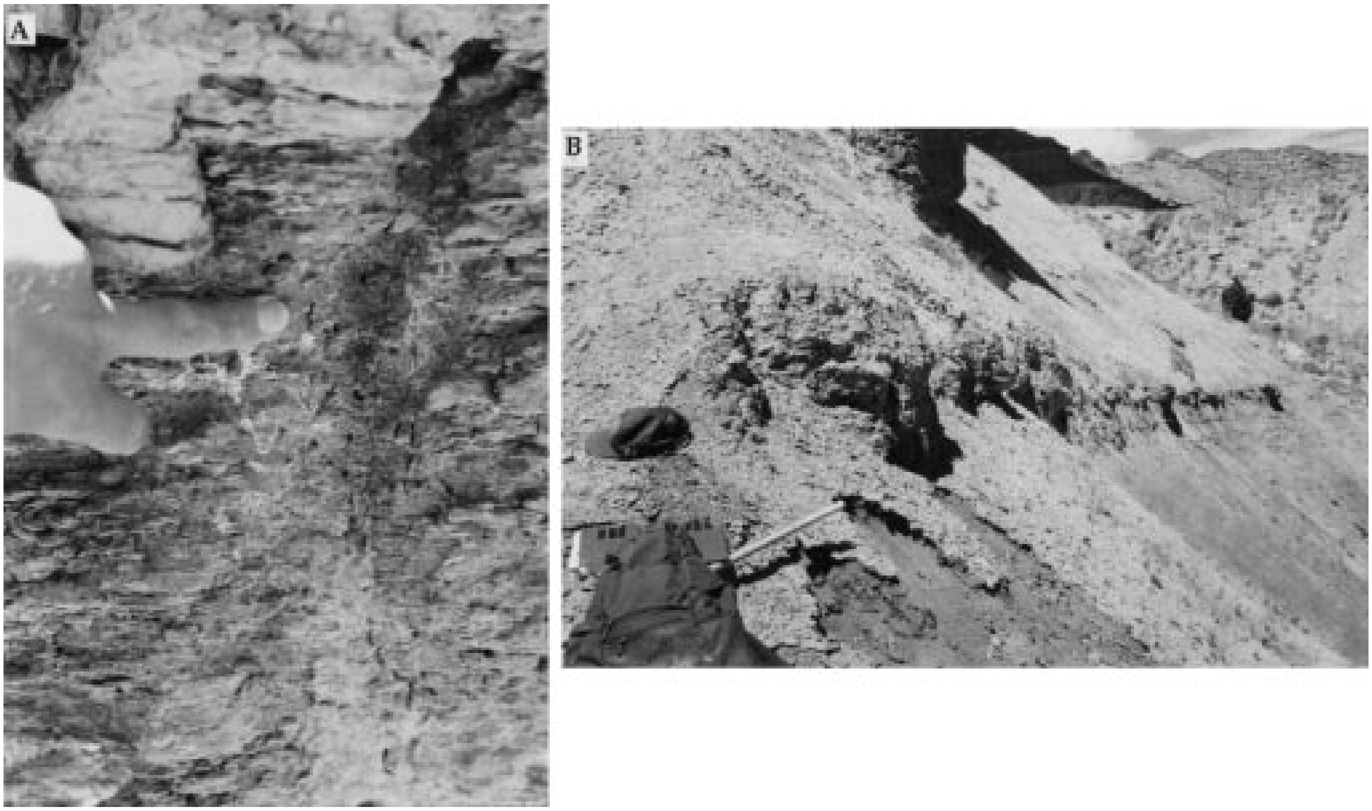


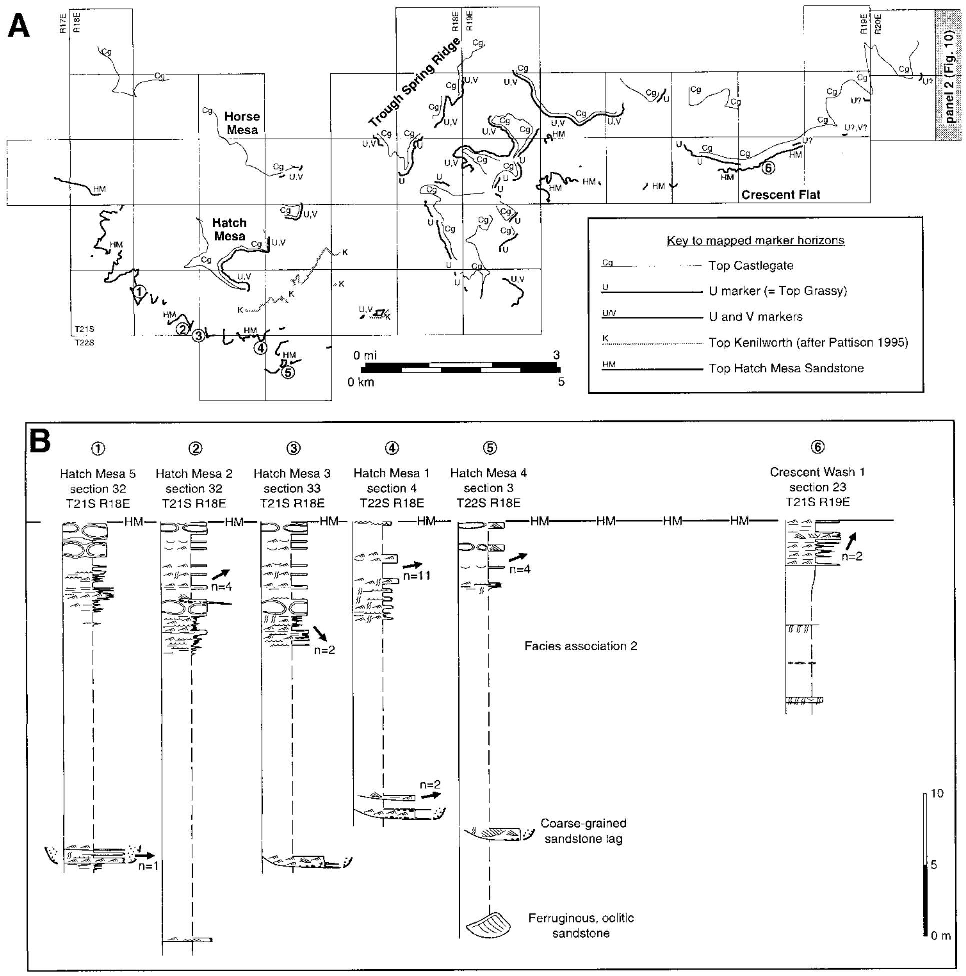
FIG. 8.—Photographs showing probable pedogenic structures. **A**) vertical root stem with attached small horizontal rootlets (X interval in Salt Wash measured section 2, NE section 23, T21S R20E). **B**) Thin (1–2 m) oxidized shale layer interpreted as a paleosol horizon in the Mancos Shale (from the Mancos Shale, Strychnine Wash area, central section 7, T20S R22E).

Mesa succession (Swift et al. 1987; Chan et al. 1991; Taylor and Lovell 1995). We favor the former interpretation, for the reasons given above. The better sorting, more abundant wave modification, and enhanced sandstone bed amalgamation observed in the succession imply greater wave reworking than in typical facies association 2 deposits. Also, the relatively diverse ichnofauna within the Hatch Mesa succession suggests enhanced marine influence, perhaps reflecting vigorous wave action, which caused increased mixing of marine and fresh waters. Sandstone beds displaying Bouma sequences are interpreted as turbidite deposits triggered by rapid sand accumulation (Chan et al. 1991) or occasional storm events (Swift et al. 1987). Thick, lenticular ''pinch-and-swell'' beds may represent proximal deposition, possibly in a distributary mouth bar (Chan et al. 1991; Taylor and Lovell 1995).

Facies Association 3: Intensely Bioturbated, Gradationally Based, Coarsening-Upward Heterolithic Successions

Description.—Rocks of facies association 3 are well exposed only in the Prairie Canyon area (Fig. 1), where they have been described in detail by Cole and Young (1991) and Cole et al. (1997) (their ''sequences B, C, and D'', comprising mainly ''sandy siltstone'' and ''bioturbated muddy sandstone'' lithofacies). The facies association comprises thick (9–20 m), coarsening-upward successions of interbedded carbonaceous siltstones and very fine- to fine-grained sandstones (Figs. 4, 7A). Sandstones occur in beds 1–2 cm thick, which contain wavy lamination and wave- and current-ripple lamination. A few beds have broad, shallow basal scours and contain low-angle cross-lamination. Siltstones are interbedded with the sandstones in a regular, cyclical pattern. Bedding and sedimentary structures are strongly obscured throughout facies association 3 by intense bioturbation (Fig. 7C, D). Despite the indistinct character of many individual burrows, a high-diversity ichnofauna is identified, containing *Paleophycus, Planolites, Rhizocorallium, Teichichnus, Skolithos, Terebellina, Ophiomorpha, Chondrites, Cylindrichnus, Thalassinoides* and large (decimeter-scale) siltstone-filled, unlined U tubes. Shell fragments are also found in this facies association.

Interpretation.—Facies association 3 is characterized by an intimate association of current and wave ripple lamination. Its heterolithic interbedding suggests episodic sand deposition from tractional currents, although the finer grain size and more intense bioturbation of these deposits, relative to facies association 2, implies deposition from weaker and, possibly, less frequent currents. Also, the high-diversity ichnofauna in facies association 3 suggests deposition in open marine conditions. This facies association has previously been interpreted to represent shallow-marine deposition on an inner shelf/ramp (Cole and Young 1991; Cole et al. 1997), and the processes interpreted above support this view. We consider that deposition may have occurred in three possible inner shelf/ramp settings. (1) An offshore sandstone complex is suggested by Cole and Young (1991) and Cole et al. (1997). This interpretation is open to the general criticisms of ''offshore bar'' models for isolated sandstones in the Western Interior Seaway: how was the sand transported across the coeval shoreface?, why is sand unevenly distributed across the shelf/ramp?, and why is sand progressively concentrated at the top of the succession? (Walker and Plint 1992). For the Prairie Canyon Member, sand transport is attributed to either a prodelta plume (Cole and Young 1991) or lowered wave base during a relative sea-level fall (Cole et al. 1997), while sand distribution is inferred to reflect shelf/ramp topography (Cole and Young 1991). (2) Thin (< 5 m; Kamola and Van Wagoner 1995)



FIGS. 9–13.—Detailed outcrop maps and correlation panels of the Prairie Canyon Member. The position of each panel is shown in Figure 1, and the key to graphic logs is the same as for Figure 4. Mean paleocurrents are shown by solid black arrows to the right of the graphic logs, with the number of paleocurrents represented by each arrow noted alongside. Details of the stratigraphy are discussed in the text.

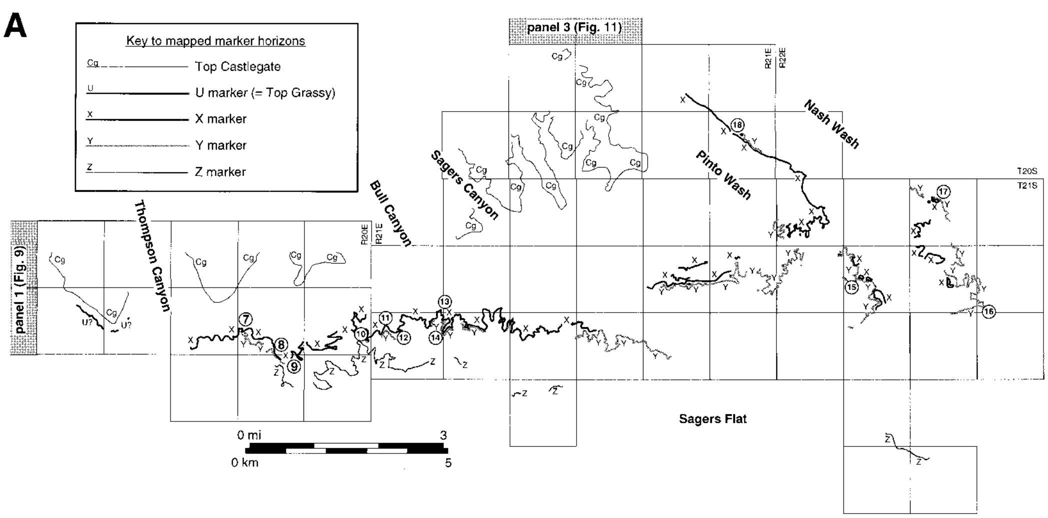


FIG. 10a.

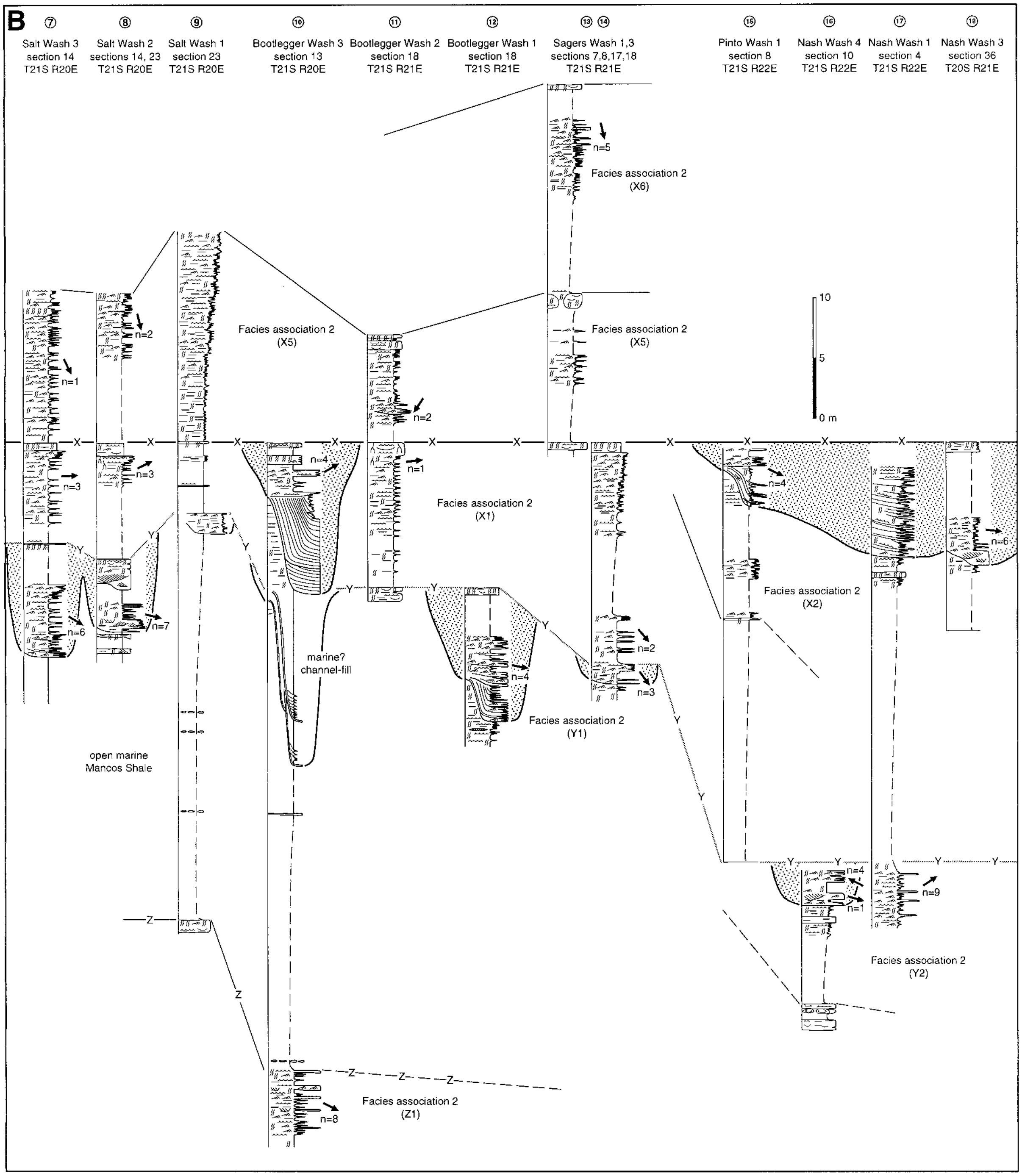
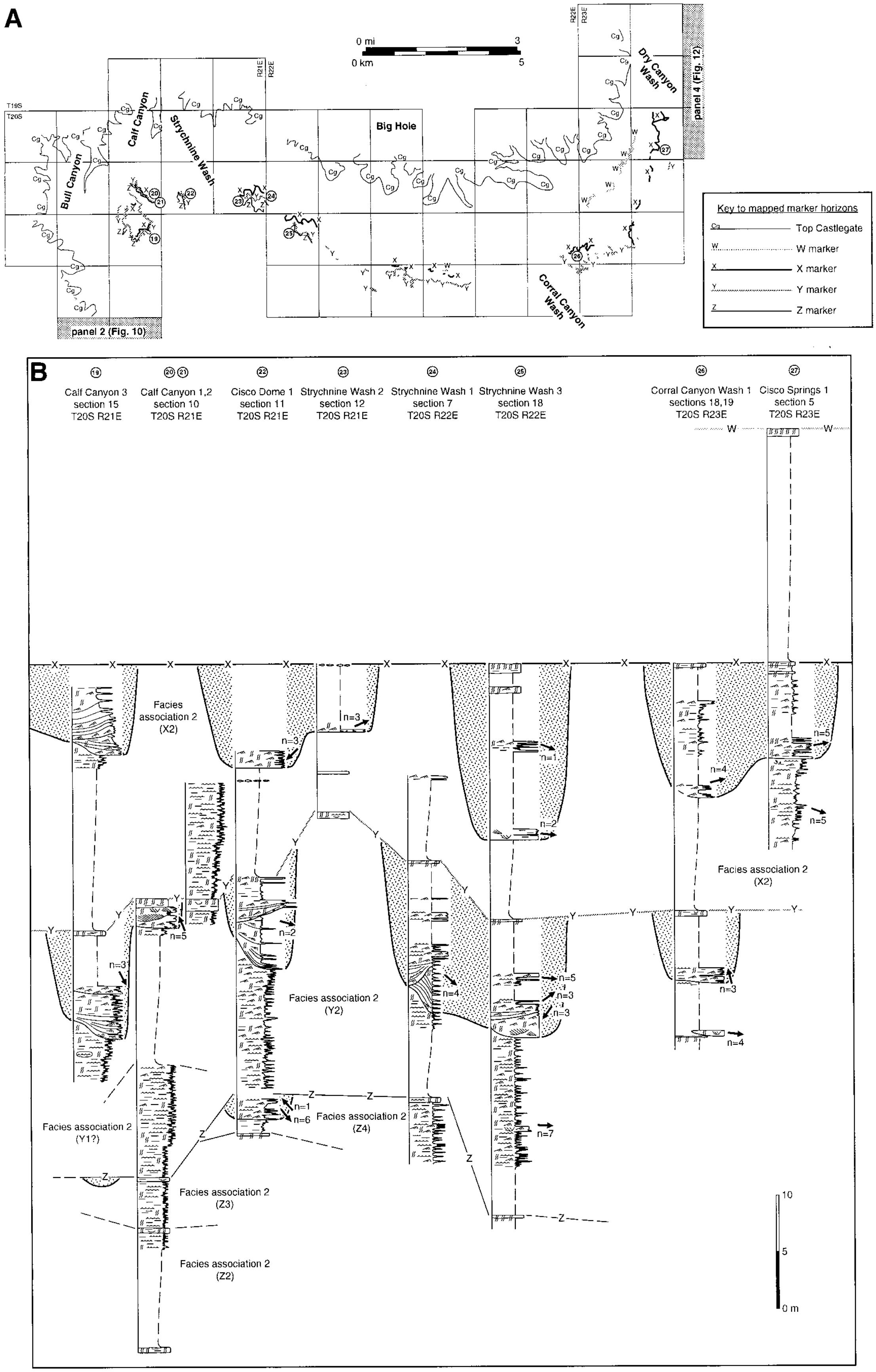


FIG. 10b.

offshore transition deposits at the bases of shoreface successions in the Blackhawk Formation are similar in character to facies association 3 (e.g., Balsley 1980; Chan et al. 1991; O'Byrne and Flint 1995; Pattison 1995). Hence deposits of facies association 3 may represent the offshore transition zone, although they are not overlain by lower-shoreface deposits and they occur in markedly thicker successions than in the Blackhawk Formation. (3) Alternatively, successions of facies association 3 may represent shorefaces in which storm energy was insufficient to generate hummocky cross-stratification. Nearly identical successions documented elsewhere in the Western Interior Seaway are interpreted as weakly storm-affected shorefaces (MacEachern and Pemberton 1992; Raychaudhuri et al. 1992). We favor this last interpretation, because it accounts for the thick, non-hummocky and coarsening-upward character of facies association 3 successions without recourse to a somewhat problematical ''offshore bar'' model. The mapped stratigraphic context of the deposits provides additional support for this interpretation (see later).



A
0 mi 3
0 km 5
Calf Canyon
Strychnine Wash
Bull Canyon
Big Hole
Dry Canyon Wash
Corral Canyon Wash
panel 2 (Fig. 10)
panel 4 (Fig. 12)
Key to mapped marker horizons
Top Castlegate
W marker
X marker
Y marker
Z marker
B
Calf Canyon 3 section 15 T20S R21E
Calf Canyon 1,2 section 10 T20S R21E
Cisco Dome 1 section 11 T20S R21E
Strychnine Wash 2 section 12 T20S R21E
Strychnine Wash 1 section 7 T20S R22E
Strychnine Wash 3 section 18 T20S R22E
Corral Canyon Wash 1 sections 18,19 T20S R23E
Cisco Springs 1 section 5 T20S R23E
Facies association 2 (X2)
Facies association 2 (Y2)
Facies association 2 (Y1?)
Facies association 2 (Z4)
Facies association 2 (Z3)
Facies association 2 (Z2)

Fig. 11.

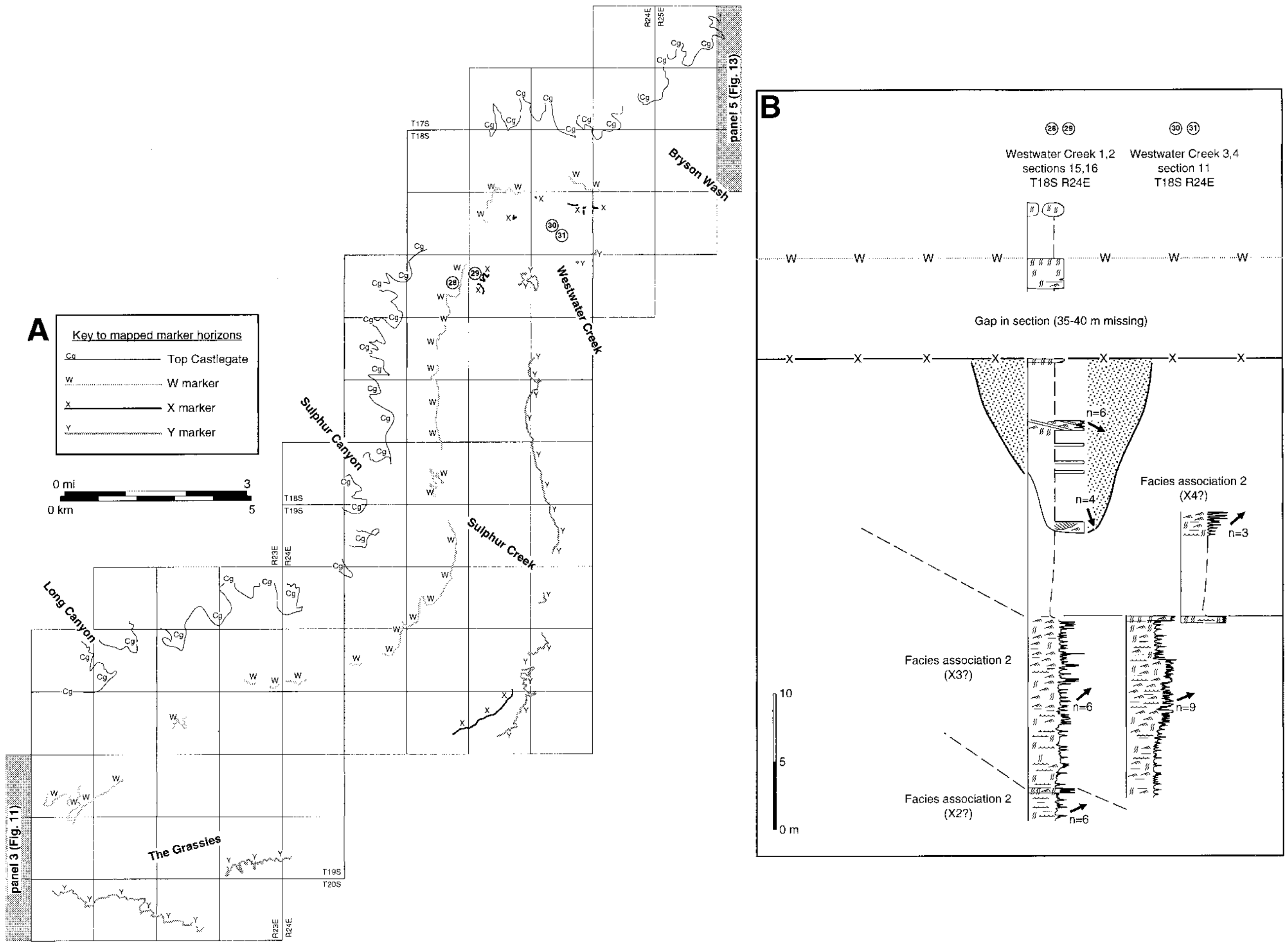


FIG. 12.

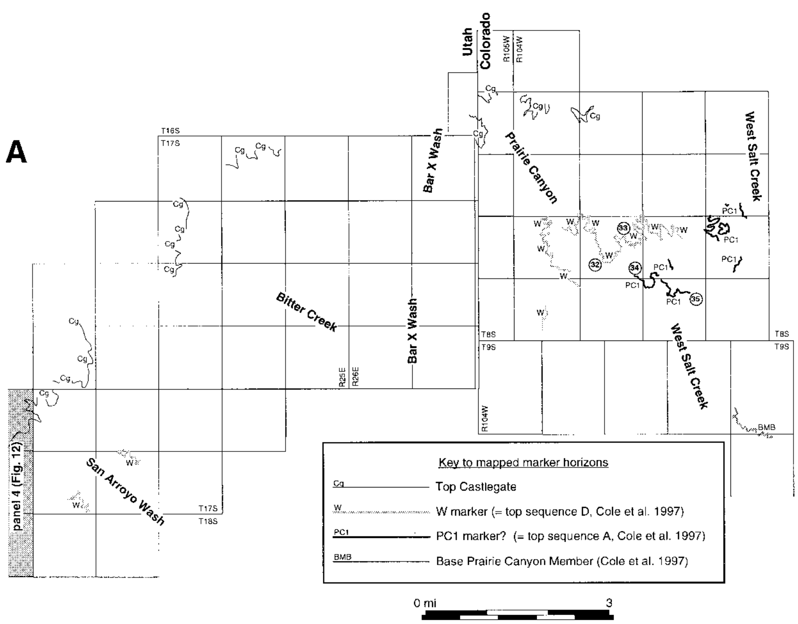


FIG. 13a.

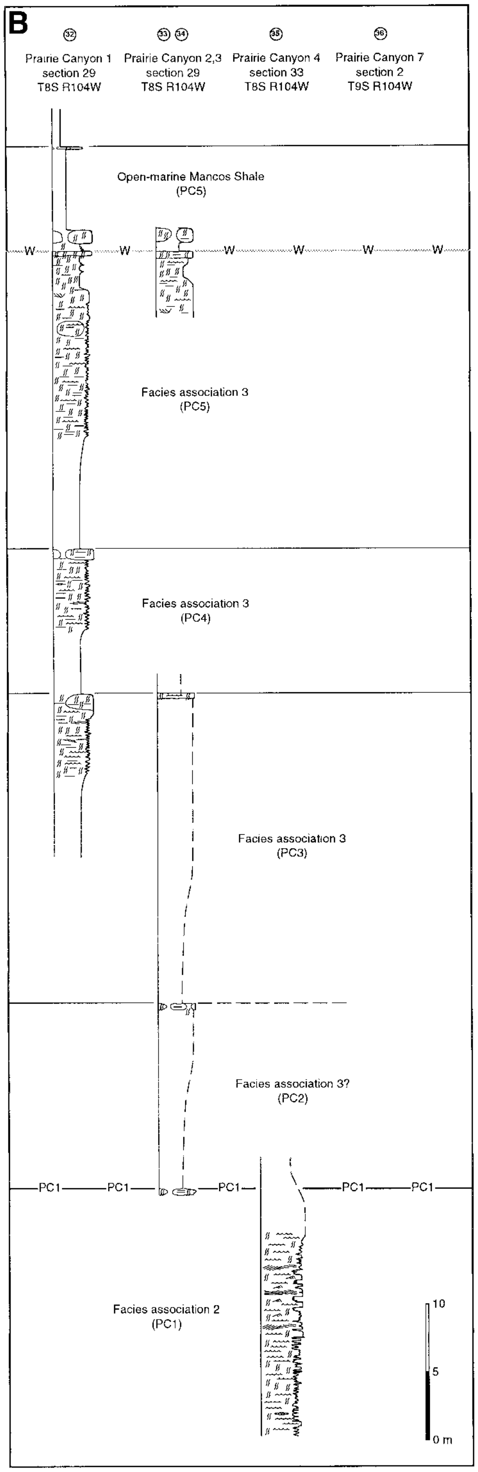


FIG. 13b.

Dolomite Concretions and Cemented Horizons

Dolomite cement is present in each of the facies associations described above (''sandy dolomite'' lithofacies of Cole and Young 1991; Cole et al. 1997). Cement generally occurs in sandstone bodies bounded by shales as small (centimeter-thick) lenses and thick (up to 1 m) horizons and concretions (e.g. Fig. 7A, B). Dolomite-cemented horizons and concretion layers occur at the tops of many coarsening-upward successions (facies associations 2 and 3; Fig. 7A, B) and also at the tops, bases, and within channel-fill deposits (facies association 1). Specific horizons and concretion layers form stratigraphic markers that can be mapped over several kilometers or tens of kilometers (see below). Petrographic and XRD analyses of the dolomite indicate an authigenic origin (Klein et al. 1996).

Dolomite-cemented horizons and concretion layers at the top of channel-fill deposits (facies association 1) and coarsening-upward successions (facies associations 2 and 3) coincide with marine flooding surfaces, which are marked by intense, diverse bioturbation and an upward transition into open marine Mancos Shale. This coincidence may reflect bioclastic carbonate concentrations at marine flooding surfaces, as in many other shallow-marine sandstones (e.g., Bjørkum and Walderhaug 1990). Shell hash certainly occurs preferentially at marine flooding surfaces, although only in minor quantities ($<$ 1% of rock volume, Cole et al. 1997). Shell hash may also be concentrated in channel lags, perhaps accounting for dolomite cements within channel-fill deposits (facies association 1). Alternatively, reduced sediment accumulation rates at hiatal surfaces, including marine flooding surfaces, may have enhanced dolomite cementation here, as interpreted by Taylor et al. (1995) in the Blackhawk Formation. Marine flooding surfaces also represent major lithological breaks between sandstone-prone facies associations and open-marine mudstones. These lithological breaks almost certainly acted as permeability barriers to diagenetic fluid flow, which may have caused preferential cementation at these breaks. Channel-fill deposits (facies association 3) contain complex lithological heterogeneities that form permeability baffles, possibly explaining enhanced dolomite cementation here.

Subaerial Exposure and Pedogenesis

A coarsening-upward succession (facies association 2) at Salt Wash is capped by a mottled interval containing mineralized root structures (Fig. 8A), recording subaerial exposure at this surface. We also observe a thin (1–2 m) oxidized shale layer of limited lateral extent (20 m) in the Upper Prairie Canyon Member at Strychnine Wash (Fig. 8B). This layer is rich in fine-grained carbonaceous material and contains sparse hematite-stained, subvertical, branching tubes interpreted as roots. O'Byrne and Flint (1996) described similar layers of greater lateral extent ($>$ 10 km; U and V marker horizons in Figures 9 and 10), which can be traced to incised valleys in the Grassy Member of the Blackhawk Formation. We interpret these layers as the preserved remnants of paleosols (O'Byrne and Flint 1996).

STRATIGRAPHIC ARCHITECTURE

The Prairie Canyon Member and the surrounding Mancos Shale can be subdivided into five discrete, mappable intervals at outcrop. The oldest interval is the Hatch Mesa Sandstone. The other four intervals are referred to below by letter (in descending stratigraphic order: W, X, Y, and Z). Some intervals can be mapped for several tens of kilometers using persistent dolomite-cemented marker horizons, whereas others are resolved only in specific areas. The internal architecture of each interval at outcrop is described below using a series of map panels and outcrop log correlations (Figs. 9–13), which are summarized in Figure 14.

The Hatch Mesa Sandstone

At its type locality, the Hatch Mesa Sandstone succession comprises an impersistent ferruginous, oolitic sandstone overlain by a coarse-grained sandstone lag and a sparsely bioturbated, gradationally based, coarsening-upward heterolithic succession (facies association 2) (Fig. 9). Large-scale (1–2 m) cross-bedding in the ferruginous, oolitic sandstones suggests that they are subaqueous bar deposits, while their lens geometry (section 5 in

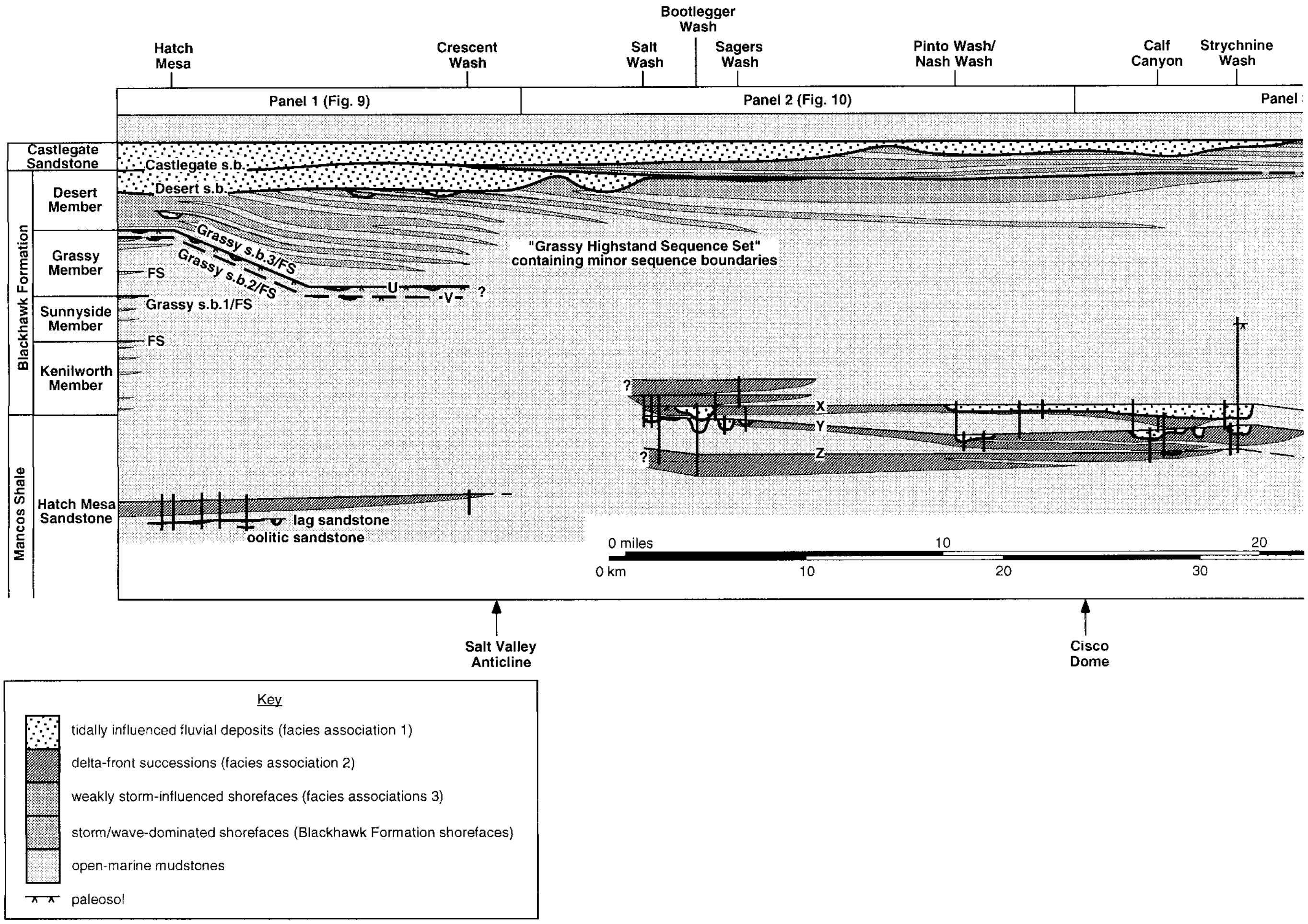


FIG. 14.—Summary correlation panel through the outcrop belt of the Prairie Canyon Member and associated strata, based on the maps and correlation panels shown in Figures 9–13 (see Figure 1 for location of outcrop belt). Letters U, V, W, X, Y, and Z refer to stratigraphic marker horizons within the Mancos Shale and Prairie Canyon Member and are discussed in detail in the text. Facies architecture in the Blackhawk Formation and Castlegate Sandstone is synthesized from O'Byrne and Flint (1995, 1996), Pattison (1995), Taylor and Lovell (1995), Van Wagoner (1995), and our own observations. Measured depths from the datum at the top of the Castlegate Sandstone are estimated from topographic maps. Note that this datum does not represent paleo-horizontal, but comprises several ravinement surfaces.

Figure 9) implies that they occurred as shallow channel-fill deposits or small shoals (Chan et al. 1991; Taylor and Lovell 1995). The occurrence of ferruginous oolites, plant material, and bioclastic debris in the sandstones indicates a high-wave-energy, shallow-water setting above fair-weather wave base. The base of the sandstones therefore marks an abrupt shallowing, relative to the offshore setting of the underlying Mancos Shale. Taylor and Lovell (1995) described a thin grit lag at the base of the oolitic sandstones, recording input of coarse-grained sediment, and a *Glossifungites* ichnofacies in the underlying shales, implying a depositional hiatus across the base of the oolitic sandstone. In combination, these characteristics suggest that this basal surface is a sequence boundary.

The overlying coarse-grained sandstone lag is trough cross-bedded and occurs within isolated, thin ($>$ 2 m) channels (Fig. 9). The lag deposit contains abundant shale clasts, carbonaceous plant material, bioclastic debris, ooids, and bone fragments (Chan et al. 1991; Taylor and Lovell 1995). This lag is traced eastwards to a tidally influenced heterolithic channel fill (facies association 1; Hatch Mesa number 6 section in Taylor and Lovell 1995). The erosional surface at the base of the lag deposits and tidally influenced channel fill cuts down into open marine shales, thereby defining a basinward facies shift at a sequence boundary (Taylor and Lovell 1995). Erosional relief at this surface is attributed to lowstand fluvial incision (Taylor and Lovell 1995), although the concentration of bioclastic debris and ooids in the overlying lag deposit records later transgressive reworking (Chan et al. 1991). Chan et al. (1991) record a marked concentration of continentally derived palynofacies in the shales overlying the lag deposit, supporting a fluvial origin for the coarse-grained sandstone. Paleocurrents in these deposits are directed to the east (Fig. 9).

The upper Hatch Mesa succession comprises the thick (15–20 m), sparsely bioturbated, gradationally based, coarsening-upward heterolithic succession described previously (see description of facies association 2). This succession is interpreted as a shallowing-upward delta-front parasequence and contains east-directed paleocurrents (Fig. 9).

Z Interval

The Z interval crops out east of Hatch Mesa in a ridge of low hills (Figs. 10, 11). At Bootlegger Wash, this interval comprises a single sparsely bioturbated, coarsening-upward heterolithic succession (facies association 2; Z1 in Fig. 10) interpreted as a shallowing-upward delta-front parasequence. Northeast, at Calf Canyon, Cisco Dome, and Strychnine Wash, the Z interval contains three similar successions (facies association 2) (Z2–4 in Figure 11), also interpreted as delta-front parasequences. The upper suc-

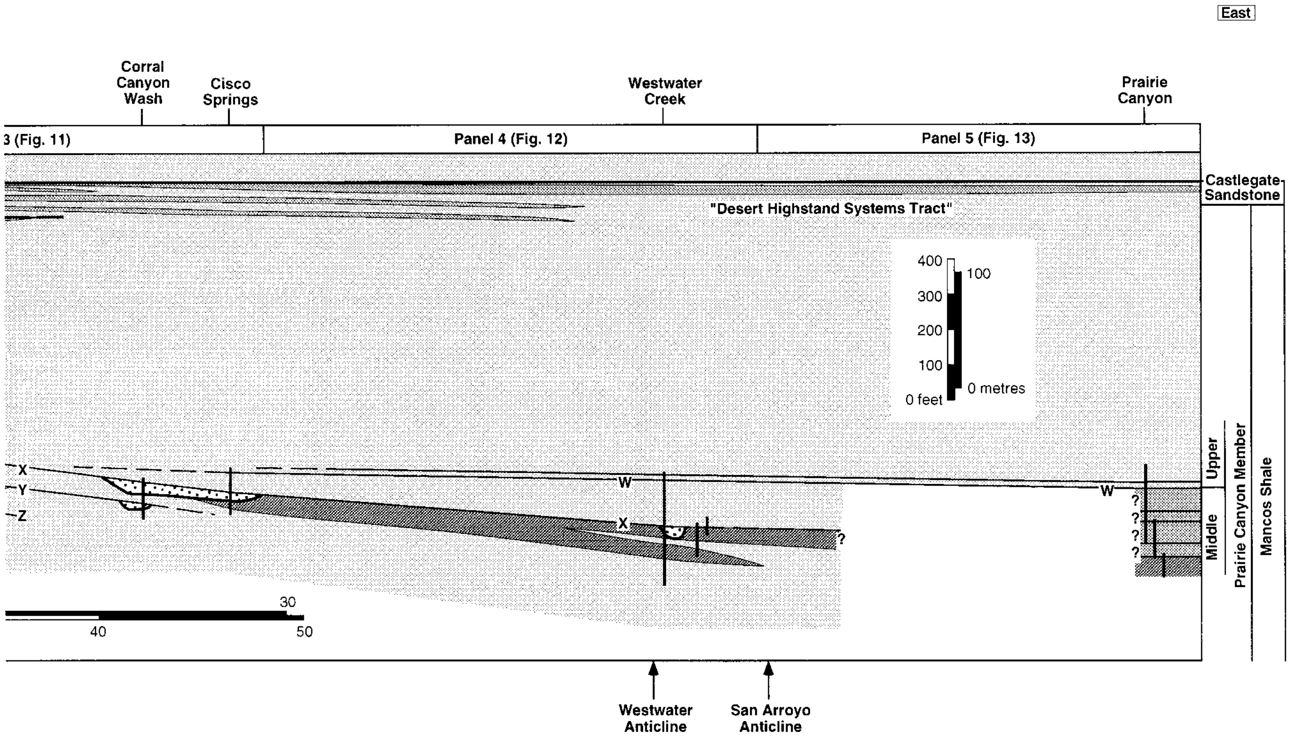


FIG. 14b.

cession (Z4) pinches out to the west at the base of a thin (30 cm), erosionally based bioclastic lag (Fig. 11). This lag traces laterally to several thin ($<$ 4 m), heterolithic channel fills (facies association 1) interpreted as tidally influenced fluvial deposits (Fig. 11). Paleocurrents in these strata are directed to the east and southeast (Fig. 11).

We interpret the architecture of the Z interval at Calf Canyon, Cisco Dome, and Strychnine Wash to represent three delta-front parasequences (Z2–Z4) which are progradationally stacked toward the east. These parasequences are overlain, and partly truncated by, a fluvial erosion surface, possibly part of an incised-valley network, at the base of the tidally influenced channel fills. Transgressive reworking of the interfluves of this erosion surface is recorded by the bioclastic lag. Marine shales overlying the Z interval (directly above the Z marker horizon in Figures 10 and 11) record continued transgression prior to deposition of the Y interval. The facies dislocation associated with this transgression is of greater magnitude than those at the top of delta-front parasequences (Z2–Z4), suggesting that marine shales overlying the Z interval probably represent a maximum flooding event.

Y Interval

The Y interval is mapped over the western part of the study area, from Salt Wash to Corral Canyon Wash (Figs. 10, 11). Over this entire area, deep (up to 15 m) channelized scours cut down from the top surface of the Y interval (Y marker in Figures 10 and 11). These scours are generally filled by stacked heterolithic channel fills (facies association 1) interpreted as multistory tidally influenced fluvial deposits, except for one siltstone-filled scour in the Bootlegger Wash 3 section (Fig. 10), which may represent offshore marine deposition. Channelized scours erode into open-marine shales in the west of the study area (e.g., Salt Wash, Fig. 10) and sparsely bioturbated, coarsening-upward heterolithic successions (facies association 2), representing delta-front parasequences, to the east (Y1–2 between Pinto Wash and Strychnine Wash in Figures 10 and 11). Paleocurrents within the Y interval show a mean trend toward the east and southeast, although tidally influenced fluvial channel-fill deposits contain a significant proportion of paleocurrents in a reversed direction (Figs. 10, 11), which may record landward tidal flows. The Y interval is everywhere overlain by open-marine shales.

Regionally extensive fluvial incision at the top of the Y interval is interpreted as the base of an incised-valley-fill network. Valleys are generally filled by aggrading tidally influenced deposits (facies association 1), although the siltstone-filled scour in the Bootlegger Wash 3 section (Fig. 10) may represent submarine modification and infill of a fluvial valley during later transgression. Underlying delta-front parasequences (Y1–2) are present only in eastern (basinward) exposures. Open-marine shales overlying the Y interval record a maximum flooding event preceding deposition of the X interval.

X Interval

The X interval crops out over almost all the study area, from Salt Wash to Westwater Creek (Figs. 10–12). The interval comprises a regionally extensive erosion surface, defined by the bases of heterolithic channel fills (facies association 1), which cuts into open-marine shales and sparsely bioturbated, coarsening-upward heterolithic successions (facies association 2; X1–4 in Figures 10, 11, and 12). The regionally extensive erosion surface records fluvial incision at the base of an incised-valley-fill network. Underlying sparsely bioturbated, coarsening-upward heterolithic successions (facies association 2; X1–4 in Figures 10, 11, and 12) are interpreted as delta-front parasequences. Parasequence stacking patterns are strongly progradational between Salt Wash and Pinto Wash (X1–2 in Figure 10) and aggradational at Westwater Creek (X2–4 in Figure 12). Paleocurrents in the incised-valley-fill deposits have a mean eastward direction whereas those in the underlying delta-front parasequences are directed to the northeast (Figs. 10, 11, 12).

In contrast to the Y and Z intervals, the incised-valley-fill network in the X interval is not everywhere overlain by open-marine shales. At Salt Wash, Bootlegger Wash, and Sagers Wash (Fig. 10), two further delta-front parasequences (facies association 2; X5–6) overlie the valley network. These parasequences represent pulses of shoreline progradation during a long-lived transgression. Paleocurrents in these two parasequences are directed to the south-southeast (Fig. 10). Farther east, between Pinto Wash (Fig. 10) and Strychnine Wash (Fig. 11), the incised-valley-fill network is overlain by open-marine shales. Between Corral Canyon Wash (Fig. 11) and Westwater Creek (Fig. 12), the W interval (see below) overlies the incised-valley-fill network. Poor exposure prevents mapping of the X interval east of Westwater Creek, but subsurface correlation suggests that it is represented by one or more coarsening-upward heterolithic successions at Prairie Canyon (see below).

W Interval and Prairie Canyon Outcrops

The W interval is present only in the east of the study area, between Cisco Springs and Prairie Canyon (Figs. 11–13). At outcrop, the interval between the W and X marker horizons thickens considerably from west to east, from about 20 m at Cisco Springs (Fig. 11) to 40 m at Westwater Creek (Fig. 12). However, only the W marker horizon is well exposed in these outcrops. At Prairie Canyon, where the W interval is well exposed, the position of the X marker horizon is not clear, although subsurface correlation implies that it lies within the Prairie Canyon measured sections, possibly at the top of unit PC2 or PC3.

The Middle Interval of the Prairie Canyon Member (Unit B-2 of the lower Mancos B, Cole and Young 1991) is exposed at Prairie Canyon, the type section (Cole et al. 1997). This section comprises one scarcely bioturbated, gradationally based, coarsening-upward heterolithic succession (facies association 2; PC1 in Figure 13; sequence A of Cole et al. 1997) overlain by four intensely bioturbated, gradationally based, coarsening-upward heterolithic successions (facies association 3; PC2–5 in Figure 13; sequences B–D of Cole et al. 1997). The former represents a delta-front parasequence, but we regard the latter as weakly storm-affected-shoreface parasequences. The prominent W marker horizon, which caps the fourth parasequence (PC5), is a laterally persistent (ca. 20 km) dolomite-cemented horizon overlain by large (meter-scale) dolomite concretions (Fig. 7B). This horizon is overlain by a thin (5–7 m) shale interval capped by a layer of dolomite concretions (PC6 in Figure 13). This shale interval may represent the distal toe of another parasequence.

OUTCROP-TO-SUBSURFACE CORRELATION

A number of hydrocarbon wells from north of the Book Cliffs penetrate the Blackhawk Formation, the Mancos Shale, and the Prairie Canyon Member (Fig. 1), thereby providing wireline-log data to supplement outcrop correlations.

In the subsurface, the Middle Prairie Canyon Member is characterized by subtle ''funnel-shaped'' wireline-log profiles defined by decreasing gamma ray (GR) and increasing resistivity (Ild) values (Fig. 15). These ''funnel-shaped'' profiles are typically 5–20 m thick. Although each profile contains consistently high gamma ray values (90–150 API), indicating a high mud content throughout, their ''funnel'' shape implies an upward increase in sand content. Cole and Young (1991) document similar gamma ray profiles at outcrop through two upward-coarsening successions, comprising facies associations 2 and 3, in the Middle Prairie Canyon Member (their A and D sequences, corresponding to our PC1 and PC5 successions, Fig. 13). Flooding surfaces at the top of the two successions are marked by an abrupt decrease in sand content and an abrupt increase in total gamma ray counts (Cole and Young 1991). Dolomite concretions and cemented horizons in the successions are characterized by low total gamma ray counts (Cole and Young 1991). The Lower Prairie Canyon Member differs markedly in wireline-log character, containing several ''blocky'' and ''inverted

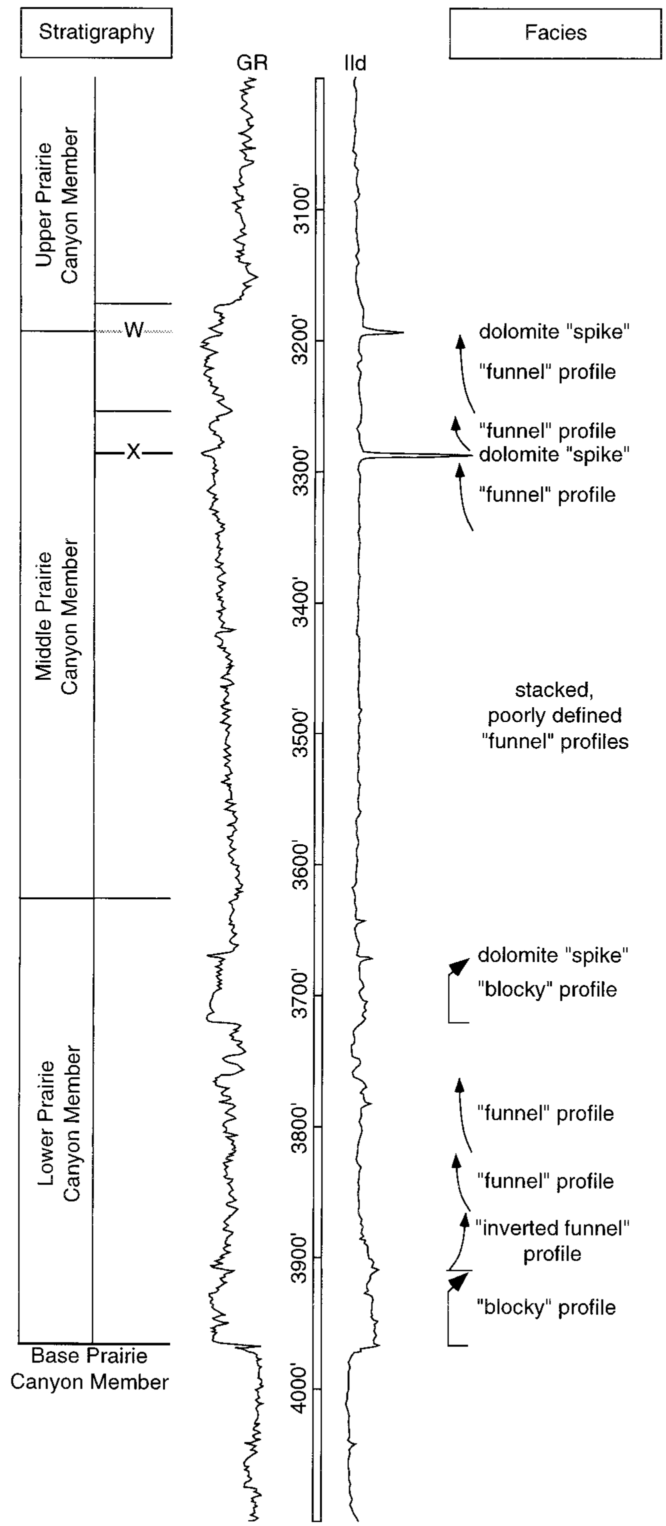


FIG. 15.—Wireline-log section through the Prairie Canyon Member from the Nicor Federal 2 well (section 28, T16S R25E), showing wireline facies and marker horizons.

funnel'' wireline-log profiles (Fig. 15), which are comparable to an outcrop gamma ray profile through a heterolithic channel-fill unit (facies association 1) in the Pinto Wash area (Cole et al. 1997).

Stratigraphy

Wireline logs through the Prairie Canyon Member exhibit stratigraphic marker horizons. The most prominent marker is at the base of the Prairie Canyon Member (previously called the Base Mancos B surface; Cole and Young 1991), which is marked by a well-defined wireline-log ''kick'' (Kellogg 1977; Cole and Young 1991; Cole et al. 1997). This log ''kick'' occurs over a thin interval (0–5 m) and comprises an abrupt decrease in gamma radiation (GR) combined with an abrupt increase in resistivity (ILD) (Figs. 15, 16). This marker can be recognized throughout the easternmost Book Cliffs area in the subsurface (Fig. 16). Other marker horizons include sharp-based ''blocky'' profiles, sharp-based shale packages, which may represent flooding surfaces, and dolomite-cemented horizons. Dolomite cements are evident as distinctive low gamma ray (GR) and high resistivity (Ild) ''spikes'' (Figs. 15, 16). Such markers have been used previously to subdivide the Prairie Canyon Member or ''Mancos B'' interval (Kellogg 1977; Cole and Young 1991; Cole et al. 1997).

Cole et al. (1997) picked the boundary between the Lower and Middle Prairie Canyon Member at a sharp-based shale package, which coincides with an extensive dolomite cement marker near the Utah/Colorado border (e.g., wells between Calvinco 31–12 and Federal 7–1, Fig. 16). This boundary corresponds at outcrop to our W marker horizon (Fig. 15). We interpret a similar shale and dolomite cement marker that lies 5–30 m lower as the X marker horizon (Fig. 15). The Y marker horizon is picked at the base of a sharp-based shale package 10–60 m below this X horizon (Fig. 16). The subsurface X and Y markers both exhibit similar depth relationships relative to the W marker horizon and the top of the Castlegate Sandstone to those mapped at outcrop (Figs. 14, 16). We suggest that the next, underlying shale and dolomite cement marker represents the Z marker horizon at outcrop (Fig. 16). The W, X, and Y intervals defined by these markers each thicken eastward (Fig. 16). The W marker and marker horizons within the W interval also onlap the X marker horizon in a westward direction (Fig. 16). The top of the Hatch Mesa Sandstone is defined by an overlying sharp-based shale package (Fig. 16). This marker loses its integrity east of Rattlesnake Canyon Unit State 6–4 (Fig. 16). Similarly, the base of the Prairie Canyon Member loses definition west of Westwater M-11 (Fig. 16).

CORRELATION WITH THE BLACKHAWK FORMATION

Westward (landward) correlation of the Prairie Canyon Member is problematic. On the basis of outcrop mapping, O'Byrne and Flint (1995, 1996) correlated the X and Y intervals westward to two thin (1–2 m) oxidized shale layers (U and V markers in Figures 9, 10, and 14), representing interfluve paleosols, and then to two incised-valley networks in the Grassy Member of the Blackhawk Formation (Gsb3 and Gsb2 of O'Byrne and Flint 1995, 1996, respectively). This correlation implies that both marker layers dip steeply to the east (basinward) with an average dip of 0.4° relative to the top of the Castlegate Sandstone, over a distance of 18 km, without correcting for sediment compaction. These steep dips imply significant syndepositional movement of the Salt Wash Anticline (O'Byrne and Flint 1996), such that over 100 m of relief was generated prior to deposition of the Desert Member. We favor an alternative interpretation supported by subsurface data (Fig. 16). Provisional correlation of the X and Y marker horizons suggests that the W, X, Y, and Z intervals lie below the Kenilworth Member (Fig. 16), possibly corresponding to sequence boundaries in the Aberdeen Member (Kamola and Huntoon 1992) and underlying strata. This correlation is consistent with published biostratigraphic data for the Middle Prairie Canyon Member (Cole et al. 1997), and it implies no tectonically induced thickness variations in the strata overlying the Kenilworth Member. Cole et al. (1997) correlated the Upper Prairie Canyon Member, which overlies the W marker horizon, to the Kenilworth Member of the Blackhawk Formation. However, our preferred correlation suggests that the Upper Prairie Canyon Member corresponds to the Kenilworth, Sunnyside, and Grassy Members (Fig. 16). At present, there is insufficient published biostratigraphic data from Blackhawk Formation to support either correlation.

DEPOSITIONAL MODEL

We interpret the Hatch Mesa Sandstone and each of the W/X, Y, and Z intervals to record deposition during a half-cycle of relative fall, lowstand, and rise of sea level. The model presented below is based specifically on the W/X and Y intervals, which provide the most comprehensive datasets.

Highstand parasequences in the Blackhawk Formation and/or older strata are deeply eroded by incised valleys that formed in response to relative falls in sea level (e.g., O'Byrne and Flint 1995). Similar incised valleys documented in this paper overlie open-marine shales in the west of the study area and, farther east, delta-front parasequences (Fig. 14), which are interpreted to represent ''detached'' shorefaces (*sensu* Ainsworth and Pattison 1994) deposited during falling sea level. The deltaic shorefaces are separated from the preceding highstand shorefaces by a bypass zone over 50 km wide (using the subsurface correlation shown in Figure 16). Shoreface displacement of this magnitude is favored by a low ramp gradient and a rapid, high-magnitude relative sea-level fall (Posamentier et al. 1992; Ainsworth and Pattison 1994). In the W/X and Y intervals, incised-valley networks erode into, and extend basinward of, the detached deltaic shorefaces (X1–2 and Y12 in Figures 10–12, 14, and 17A, B), indicating that sea level continued to fall after their deposition. Hence, these shorefaces do not record the ultimate lowstand of sea level. Also, coeval coastal-plain deposits are absent, implying that there was no accommodation space behind the shoreface to enable their deposition. This absence is atypical of prograding parasequences in a lowstand wedge. Instead, we interpret the absence of coastal-plain deposits to reflect a ''downstepping'' parasequence stacking pattern, implying forced regression (*sensu* Posamentier et al. 1992). ''Detached'' shoreface parasequences are capped by flooding surfaces, indicating that the overall sea-level fall was punctuated by small, high-frequency rises.

The multistory architecture of incised-valley fills in the W/X and Y intervals reflects rising base level within the valleys, in response to rising relative sea level. Coeval shorelines representing the ultimate sea-level lowstand are not unequivocally identified. However, we suggest that aggradationally stacked, delta-front and weakly storm-influenced-shoreface parasequences comprising the W/X interval at Prairie Canyon (PC 1–5 in Figure 13) correspond to the incised-valley fill in the W/X interval. The W interval appears to onlap the X marker at the top of this incised-valley fill (Fig. 16), but we consider it more likely that each parasequence in the W interval is broadly time-equivalent to a component of the valley fill. In our interpretation, the valley was progressively infilled during slow sea-level rise, while coeval shoreface parasequences aggraded to form a lowstand wedge (*sensu* Van Wagoner et al. 1990). Correlatives to parasequence-bounding flooding surfaces are absent within incised-valley-fill deposits, probably reflecting the low preservation potential of such correlatives within a valley-confined fluviatile environment.

The first flooding surface associated with major shoreface retrogradation (i.e., the initial flooding surface) in the W/X interval is the W marker horizon (Figs. 14, 16). Overlying parasequences (PC6, X5–6 in Figures 10, 12–14, and 17C) are assigned to the transgressive systems tract. The Y interval contains no transgressive parasequences overlying the incised-valley fill in the study area. This absence reflects more rapid flooding and/or a lower-gradient shelf/ramp bathymetry during Y interval times. Poor pres-

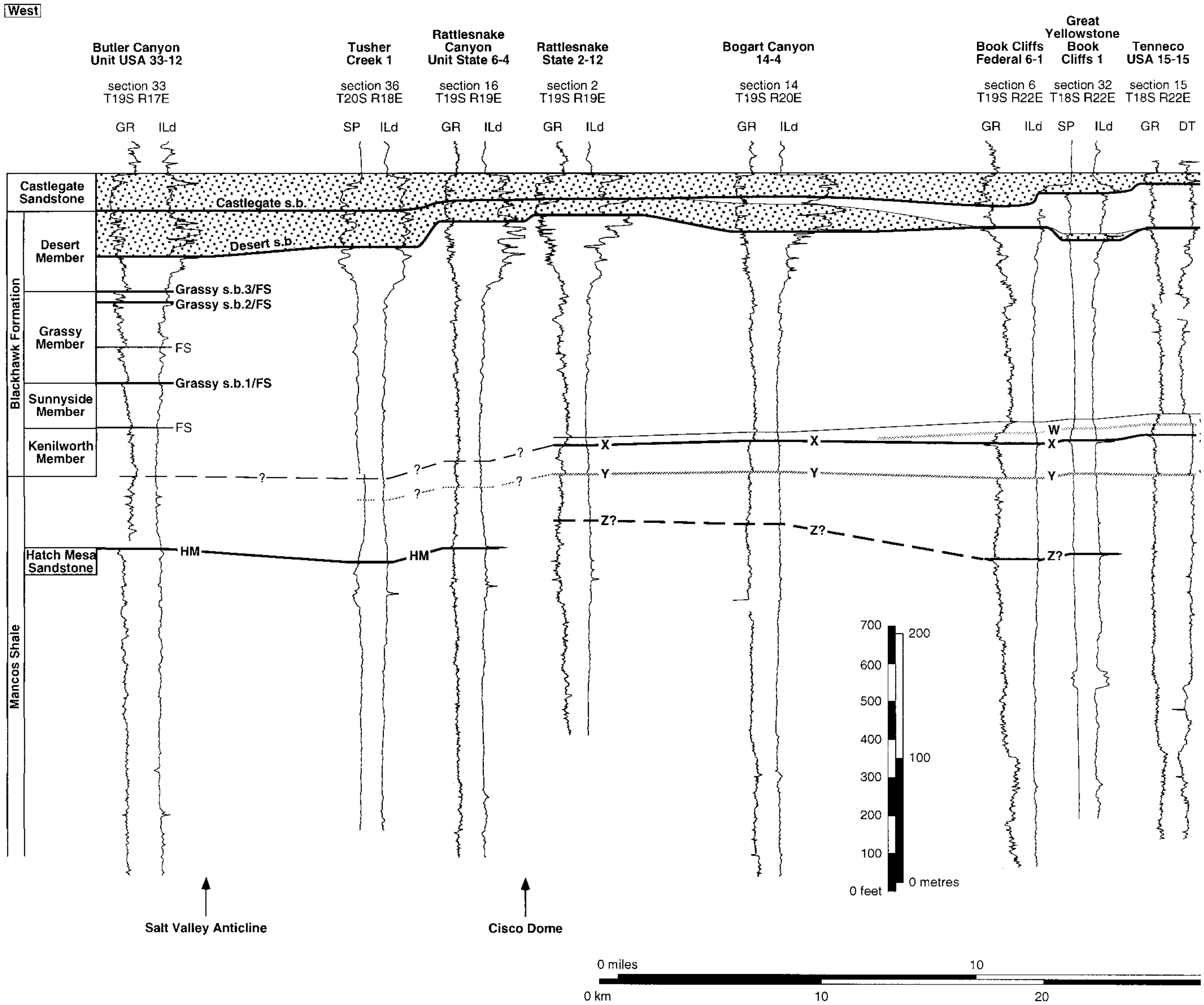


FIG. 16.—Subsurface cross section through the distal Blackhawk Formation and Mancos Shale (see Figure 1 for location) at the same scale as the outcrop section illustrated in Figure 14. Letters U and V refer to oxidized shale layers in the Mancos Shale (O'Byrne and Flint 1995, 1996), and W, X, Y, and Z refer to stratigraphic marker horizons within the Prairie Canyon Member. Details of the stratigraphy are discussed in the text.

ervation of interfluve paleosols in both the W/X and Y intervals is attributed to transgressive wave ravinement at the initial flooding surface.

DISCUSSION: CHANGES IN SHOREFACE CHARACTER

Shorefaces in the Blackhawk Formation, which generally represent highstand deposition, were sandy and wave-dominated (e.g., Balsley 1980). In contrast, forced regressive, lowstand and transgressive shorefaces in the Prairie Canyon Member were muddy and deltaic and/or weakly storm influenced (facies associations 2, 3). Thus, periods of lowered sea level were marked by decreases in sand content and wave energy at the shoreface.

We attribute decreased sand content to reflect reworking, and subsequent deposition, of large quantities of mud eroded from the exposed ramp/shelf by incised fluvial systems during sea-level lowstands. In addition, sandy lowstand shorelines that may have developed at the mouths of incised valleys were probably erosionally reworked by tidal currents during transgression, with the sand having been incorporated into the incised-valley fills. Holocene estuaries of scale similar to those within the incised valleys act as effective sand traps during transgression, with flood tidal currents transporting sand landward from the shoreline into the estuary, where it is subsequently deposited (e.g., Dalrymple et al. 1992; Allen and Posamentier 1993).

The decrease in wave energy during times of lowered sea level is primarily attributed to changing basin paleogeography. Eastern Utah lay within an embayment in the Western Interior Seaway margin during the Late Cretaceous (McGookey et al. 1972; Swift et al. 1987; Franczyk et al. 1992). During times of sea-level highstand, this embayment was open to the wave energy of the Seaway. At these times, shorefaces in the Blackhawk Formation were oriented approximately north–south (Kamola and Van Wagoner 1995; O'Byrne and Flint 1995; Taylor and Lovell 1995). During sea-level lowstands, when the shoreline lay over 50 km farther basinward, this

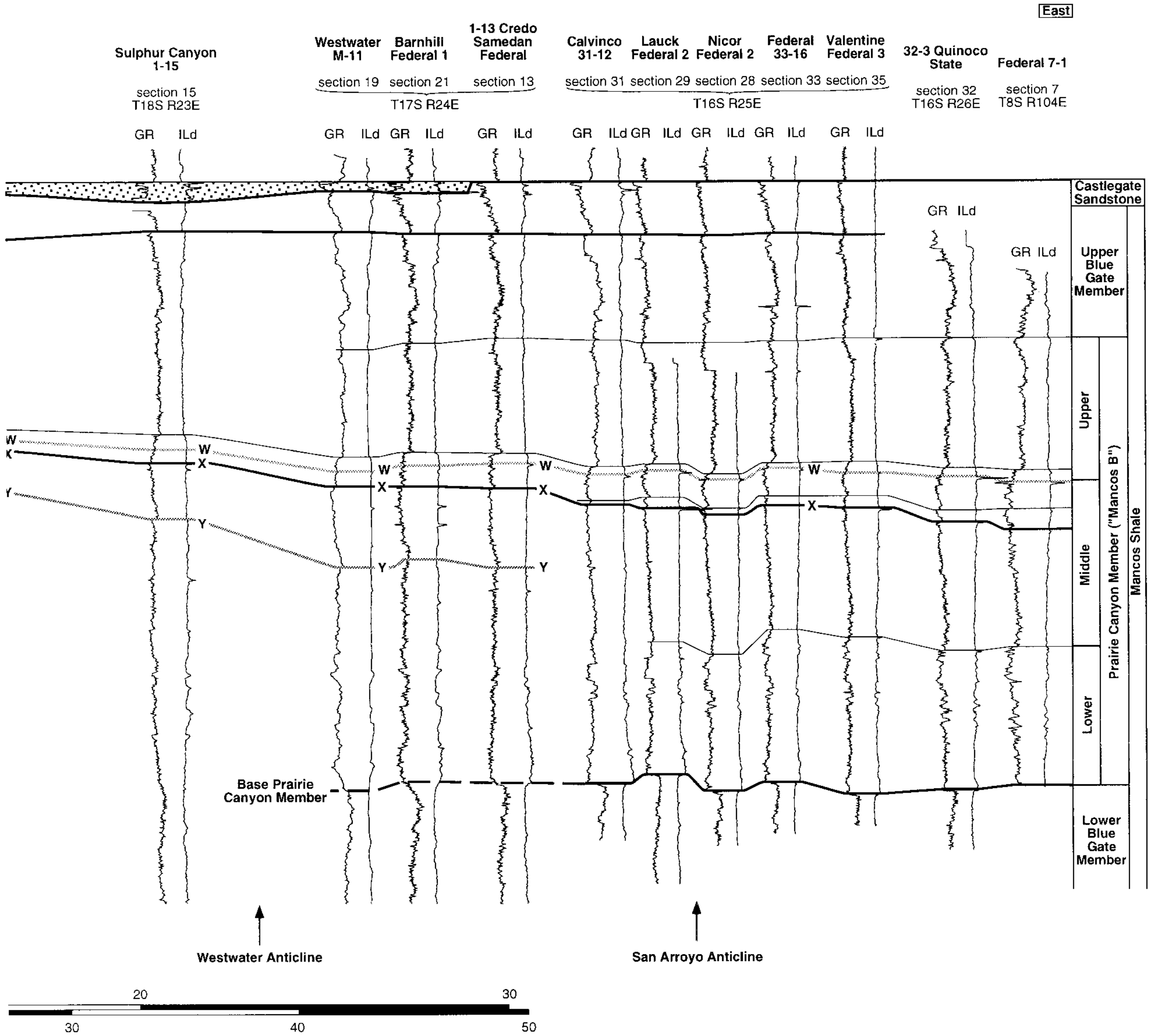
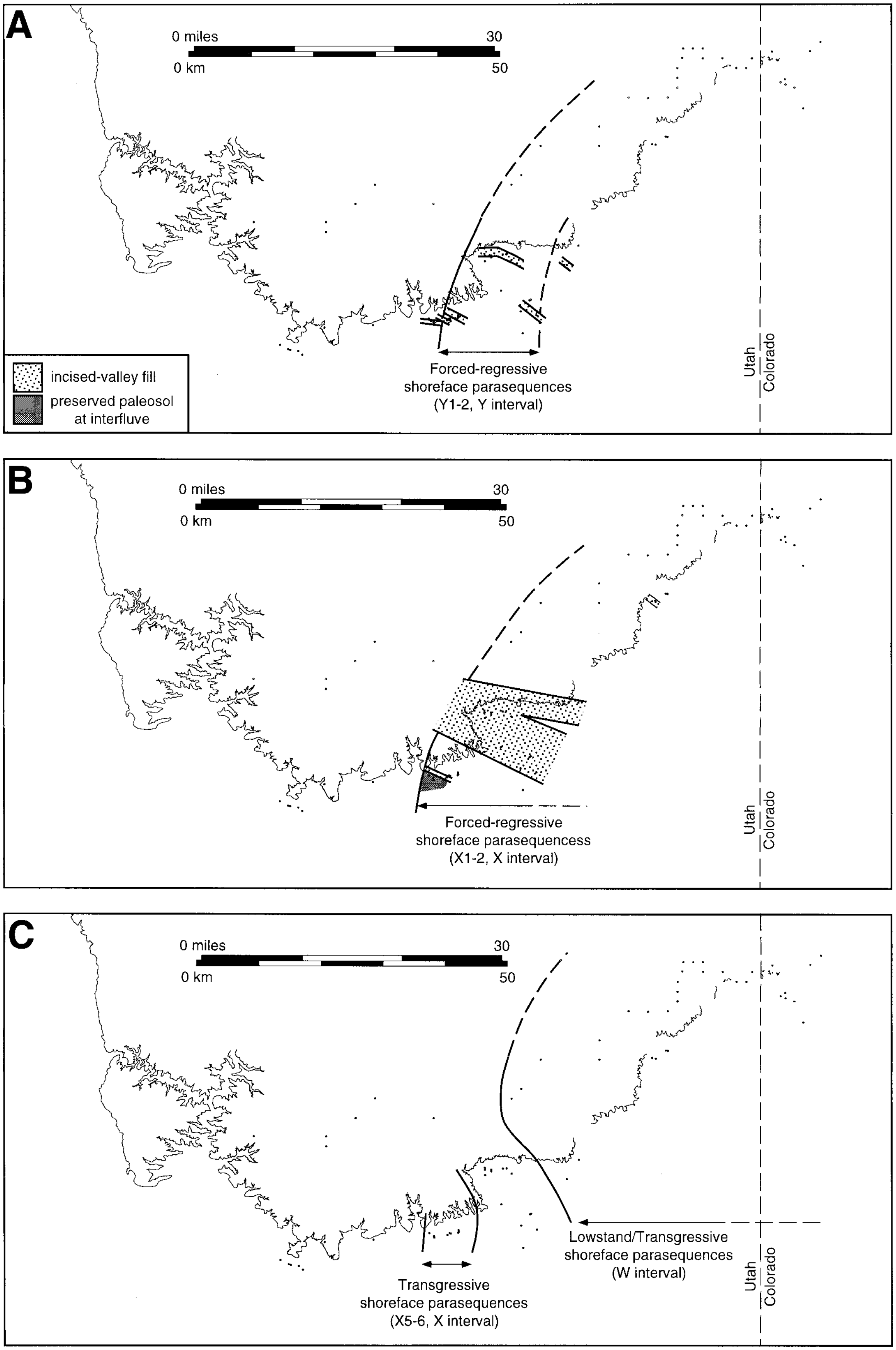


FIG. 16.—Continued.

embayment paleogeography was more pronounced (Fig. 17). For example, lowstand rivers in the Castlegate Sandstone drained toward the south and southwest (Van Wagoner 1995), implying that coeval shorelines were oriented southwest–northeast or west–east. Isopachs in the Prairie Canyon Member also trend southwest–northeast (Johnson and Finn 1986), implying a similar shoreline trend in these strata. We suggest that this pronounced embayment paleogeography sheltered lowstand shorefaces from the wave energy of the Seaway. Changes in the width of the Western Interior Seaway may have exerted a subsidiary control on wave energy: the Seaway was probably 15–25% narrower during sea-level lowstands, which resulted in a reduced wave fetch and lowered wave energy.

IMPLICATIONS FOR HYDROCARBON EXPLORATION MODELS

Sandstones in the Prairie Canyon Member occur as ''detached'' shorefaces and incised-valley fills in a predictable and well-constrained sequence stratigraphic framework. In basins where depositional systems and their paleogeographic trends are well understood, a similar sequence stratigraphic approach may enable prediction of ''detached'' shorefaces forming subtle hydrocarbon reservoirs. However, in the strata described here, there is a marked facies difference between highstand and ''detached'' shorefaces; highstand shorefaces are dominated by ''clean'', wave-reworked sandstones with good reservoir properties, whereas ''detached'' shorefaces comprise thin, impersistent ''ratty'' sandstones with low porosities and permeabilities (10–11% and 0.7 md, respectively, in the Douglas Creek Arch area; Kellogg 1977). Facies variability of this type is rarely documented in the existing literature (Mellere and Steel 1995), but, given that it merely reflects changes in shoreface orientation and wave regime during periods of relative lowering of sea level in shelf/ramp embayments, we suggest that it may also occur elsewhere in the geological record. Such facies variability may explain the apparent absence of lowstand shorelines in some basins and serves as a caveat regarding the likely reservoir quality of such shorelines.


A
0 miles
30
0 km
50
incised-valley fill
preserved paleosol
at interfluve
Forced-regressive
shoreface parasequences
(Y1-2, Y interval)
Utah
Colorado
B
0 miles
30
0 km
50
Forced-regressive
shoreface parasequencess
(X1-2, X interval)
Utah
Colorado
C
0 miles
30
0 km
50
Lowstand/Transgressive
shoreface parasequences
(W interval)
Transgressive
shoreface parasequences
(X5-6, X interval)
Utah
Colorado

ACKNOWLEDGMENTS

Field work and development of the initial ideas for this manuscript were carried out during a post-doctoral research project (GJH) funded by Statoil, who are gratefully acknowledged. Dave Tabet (Utah Geological Survey), Peter McCabe, and Ron Johnson (US Geological Survey) are thanked for their help in acquiring subsurface data. Ideas evolved in discussions with Diane Kamola, Ciaran O'Byrne, and Trevor Elliott, and via constructive reviews by Rex Cole, John Van Wagoner, and Keith Shanley. We also thank the Pogue family and all at Colorado River and Trail Expeditions for their hospitality in the field.

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Received 16 December 1996; accepted 1 August 1998.

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FIG. 17.—Paleogeographic reconstructions of depositional systems in the Blackhawk Formation and the Prairie Canyon Member, based on outcrop mapping and logging (Figs. 9–14) and subsurface data (Fig. 16). Reconstructions are for the following time intervals: **A**) relative sea-level fall associated with the Y interval, **B**) relative sea-level fall associated with the X interval (X1–4), and **C**) relative sea-level lowstand and rise associated with the W interval and the X interval (X5–6).