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Regional paleoclimatic and stratigraphic implications of paleosols and fluvial/overbank architecture in the Morrison Formation (Upper Jurassic), Western Interior, USA

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Abstract

Paleosols in the Morrison Formation (Upper Jurassic) from the Western Interior and Colorado Plateau regions occur in fluvial/overbank and marginal-lacustrine depositional facies associated with aggradational settings, and at sequence-bounding unconformities that mark divisions between major aggradational and degradational successions. Pedogenic features within these horizons preserve important contextual information about the local and regional paleoclimate and paleoenvironment in which the soils formed. Floodplain and lake-margin paleosols show evidence that most of the Morrison basin was characterized by a semi-arid to tropical wet–dry paleoclimate with fluctuating groundwater conditions, a low precipitation to evaporation ratio, and weak to moderately seasonal precipitation. Paleosol ichnofauna show evidence of a diverse and opportunistic flora and fauna that exploited changing conditions and existing nutrient and moisture regimes. Changes in paleosol type and degree of development over the basin indicate the overall regional paleoclimate was drier in the western and southern portions of the basin. Vertical trends indicate paleoclimatic conditions over the basin became steadily more humid through time. Laterally continuous, well-developed, deeply weathered paleosols formed during times of little or no deposition and mark regional unconformities. The paleosols at these sequence-bounding unconformities serve as useful regional stratigraphic markers to trace genetic packages across the Morrison depositional basin and to determine regional accommodation trends.

Keywords: Paleosols; Morrison Formation; Unconformities; Sequence stratigraphy; Paleoclimate

1. Introduction

The Morrison Formation (Upper Jurassic) of the Rocky Mountain, Western Interior and Colorado Plateau regions (USA) was deposited in an almost completely terrestrial (continental) environmental setting. Paleosols are a very common feature in most Morrison exposures, and, in fact, play a large role in giving the formation a distinctive, color-

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banded appearance. Paleosols, like modern soils, were formed during times of relatively slow or no accumulation of sediment. During these times, the land surface and near-subsurface were exposed to chemical and physical weathering processes (dissolution, precipitation, wetting, drying, illuviation of particles, etc.) and biological activity (rooting, burrowing, trampling, etc.). All of these processes were mediated and modulated by the local and regional paleoclimatic, tectonic, and paleohydrologic conditions. Features within ancient soils, which can be interpreted to have been created by these physical, chemical, and biological soil-forming (pedogenic) processes, can give important clues to what the climate and other environmental conditions were like during their formation (Mack and James, 1994). Since soils record average conditions over a relatively long period of time, environmental interpretations from paleosols compliment those made from successions of actively deposited sediments (stream channels, lakes, etc.) that record conditions over comparatively very short (even instantaneous) periods of time.

1.1. Objective

The purposes of this study are to: (1) describe the pervasive pedogenic features present in the Morrison Formation; (2) show, in general, their vertical and lateral distribution; and (3) interpret the implications for depositional architecture and paleoclimatic and tectonic setting. The paleosols interpreted within this study can be divided into two groups, based largely on the degree of maturity and regional extent. The first group of paleosols includes floodplain/overbank and marginal-lacustrine paleosols, which recorded local paleohydrologic and paleoclimatic conditions over the time scale of deposition of individual channels, channel belts, and lacustrine highstand/lowstand cycles. The second group includes paleosols at major unconformities, which bound larger-scale depositional packages and marked significant changes and rearrangement of the landscape. Summaries of the pedogenic features in these two broad groups will be described separately and the implications for interpretations of basin-wide paleoclimatic and tectonic affects on deposition will be explained.

1.2. Methods and study area

Exposures of the Morrison Formation were examined in the Western Interior, Rocky Mountain, and Colorado Plateau regions (Fig. 1). Pedogenic features are ubiquitous in most Morrison Formation exposures, although not every lithostratigraphic interval exhibited these features at every locality. A consistent set of field criteria was used to identify macroscopic pedogenic features in the Morrison Formation regardless of their degree of development. Paleosols were characterized on the basis of: (1) grain size; (2) dry, fresh colors (mottles and matrix from Munsell Soil Color Charts); (3) presence and intensity of rooting; (4) ichnofauna (abundance and identification); (5) aspect of preserved ped structures; (6) composition, size, and abundance of nodules and other mineral segregations; and (7) presence and geometry of slickensides and other fractures. Vertical measured sections were measured through intervals that had macroscopic evidence of possible pedogenic modification (including color banding, root traces and rhizoliths, nodule horizons, disruption of original sedimentary fabric, etc.). As much of the entire formation as possible was measured at each locality in order to place the section within a regional stratigraphic context, although observations were collected at a higher resolution within exceptionally exposed pedogenically modified intervals and at key stratigraphic intervals. Sections were chosen for measurement based on relative stratigraphic position, areal distribution, and accessibility. Detailed studies were undertaken at several well-exposed areas including: Purgatoire River (Comanche National Grasslands), Colorado, Cañon City area, Colorado, Fruita/Grand Junction area, Colorado, San Rafael Swell area, Utah, San Juan basin area, New Mexico, and Four Corners area, New Mexico/Colorado/Utah (Fig. 1). In these areas, samples were taken for laboratory analysis, including petrographic description and geochemical analysis. Sampled intervals were chosen to broadly cover the range of pedogenic features that occur in the Morrison Formation across the basin. This study was designed as a reconnaissance of the type and distribution of macromorphological features of pedogenesis in the Morrison Formation, and a detailed, systematic study of the micromorphology of these paleosols was not attempted.

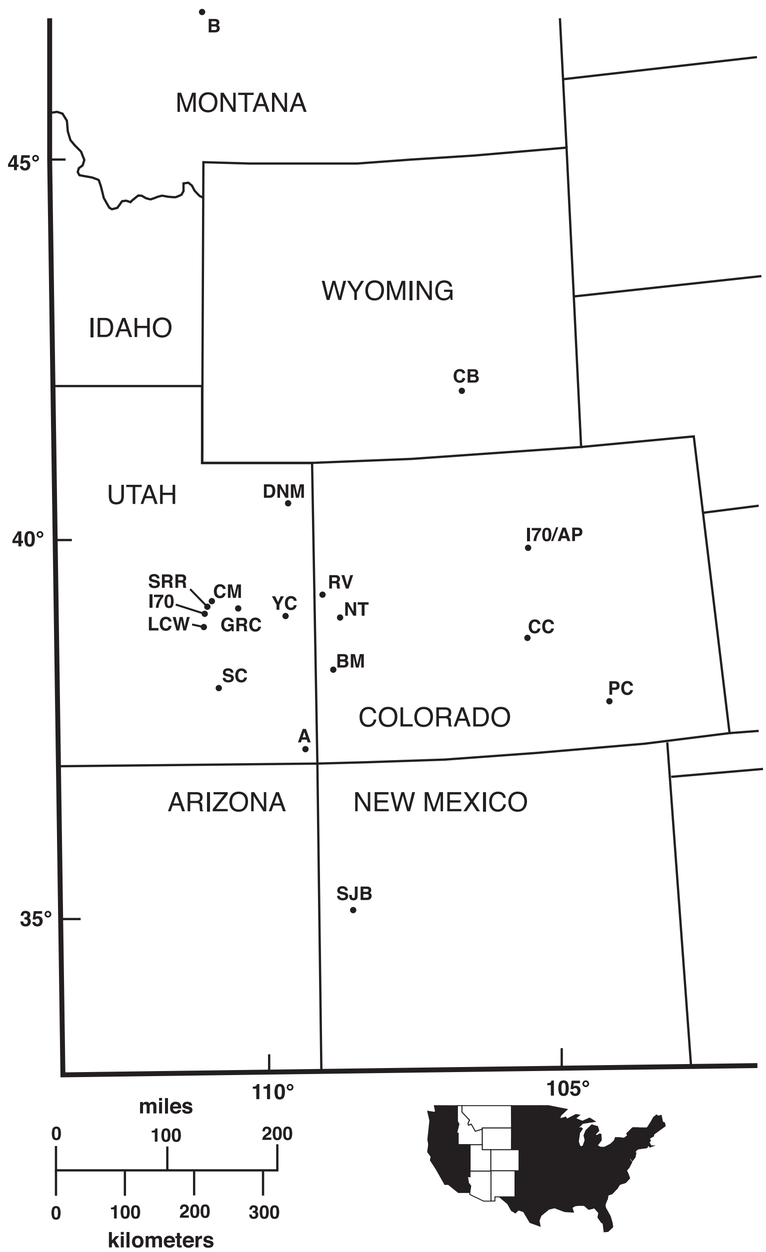


Fig. 1. Location map of measured sections and other studied outcrops mentioned in text. A: Aneth, UT; B: Belt, MT; BM: Blue Mesa, CO; CC: Cañon City, CO; CB: Como Bluff, WY; CL: Cleveland-Lloyd Quarry, UT; CM: Cedar Mountain and Little Cedar Mountain, UT; DNM: Dinosaur National Monument, UT; GRC: Green River Cutoff, UT; I70: Highway I-70 roadcut, UT; I70/AP: Highway I-70 roadcut/Alameda Parkway, CO; LCW: Last Chance Wash, UT; NT: No Thoroughfare Canyon, CO; PC: Purgatoire Canyon, CO; RV: Rabbit Valley, CO; SC: Shootering Canyon, UT; SJB: San Juan Basin, NM; SRR: San Rafael River, UT; YC: Yellow Cat, UT.

This study of paleosols and fluvial and overbank architecture in the Morrison Formation was completed with cooperation and collaboration of several other workers within the Morrison Extinct Ecosystems Project. Since soils are an intrinsic part of the landscape, paleosols are often found intimately associated with other types of environmentally important sedimentary rocks and with paleontological accumulations. Therefore, the study of the Morrison paleosols was intertwined with the concurrent studies of trace fossils (Hasiotis, this volume), stable isotopic paleoclimatic indicators, and the carbonate deposits in lakes (Dunagan and Turner, this volume), and the large-scale architecture of the sedimentary rocks (Turner et al., this volume).

2. Fluvial and overbank architecture

Floodplain deposits, including crevasse-splay/levee beds, abandoned channels, lacustrine limestones, and paleosols, are associated with the fluvial sandstones of the Morrison Formation. Fluvial sandstones in the Salt Wash, Westwater Canyon, Recapture, Jackpile Sandstone and Brushy Basin Members (Fig. 2) in the Colorado Plateau and San Juan Basin regions represent deposition by streams and rivers of various

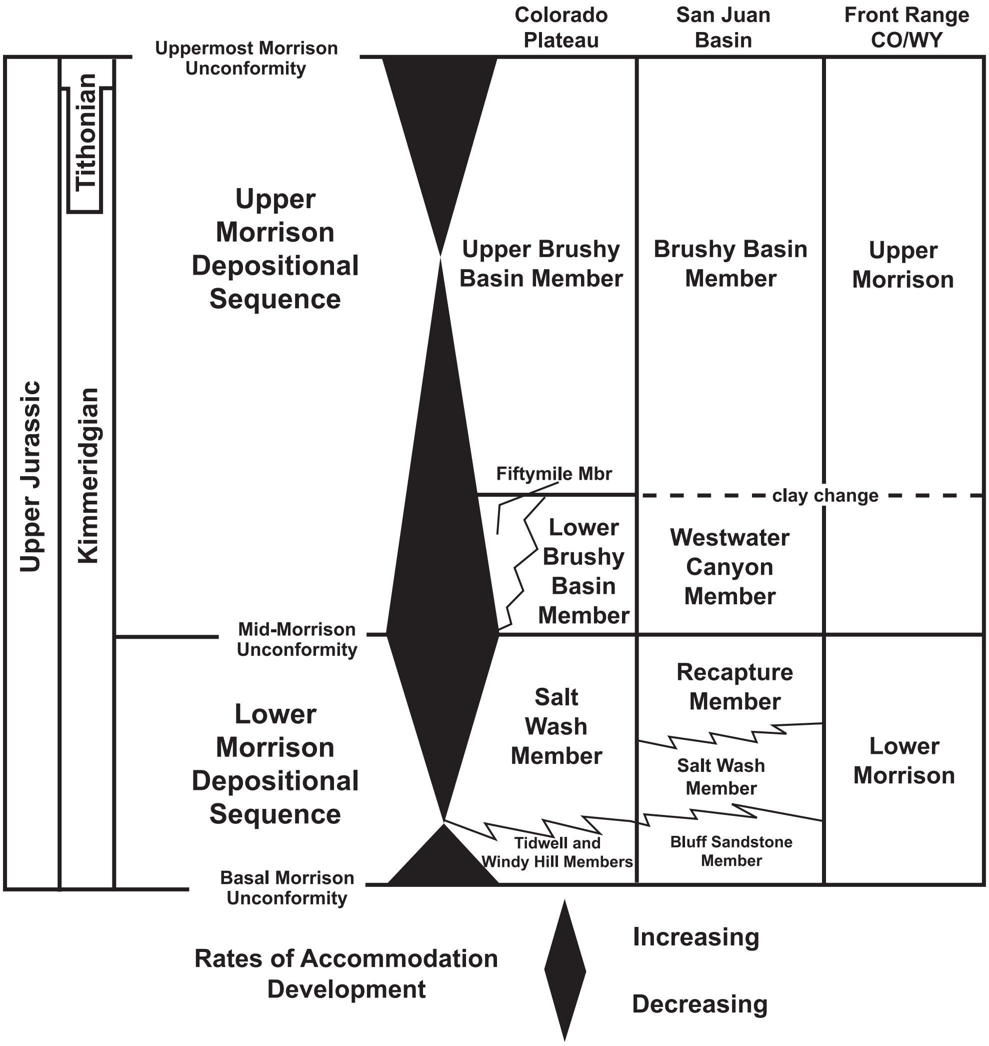


Fig. 2. Diagram showing stratigraphic relationships of the lithostratigraphic units in the Morrison Formation to the two depositional sequences defined by regional unconformity paleosols and the relative trends in accommodation space generation.

fluvial styles, discharge regimes, and sediment loads. Because of this regional and stratigraphic variation in fluvial style, the relationships of the fluvial sandstones to their contemporaneous floodplain deposits also vary in space and time. In order to put the floodplain/overbank paleosols in the Morrison Formation into depositional context, a brief summary of the fluvial sedimentology and architecture follows.

The sandstones in the Salt Wash and Westwater Canyon Members, which have been intensively studied for over 50 years because of the uranium ore bodies that they host (Wood, 1956), were deposited dominantly by low-sinuosity, braided fluvial systems. Peterson (1980, 1984) interpreted the Salt Wash Member in central and south-central Utah as deposits of prograding, braided stream and alluvial complexes derived from sources located to the southwest and west of the outcrop belt. Sandstone bodies in the Salt Wash were described by Peterson (1984) as dominantly sheet-like (10's km wide), but with a minor component of ribbon channels 30–300 m wide. Peterson (1986) also showed that the lower, middle and upper Salt Wash sandstones in the Henry Mountains area had northeasterly, southeasterly, and east-northeasterly directed crossbed dip vectors, respectively. Tyler and Ethridge (1983a,b) interpreted the Salt Wash sandstones in southwestern Colorado as deposits of a network of low-sinuosity trunk channels and higher-sinuosity (meandering) tributaries. Tyler and Ethridge (1983a,b) also described the amalgamation of the larger trunk channels into multilateral channel belts, and occurrence of distinctive thin (< 2 m), upward-coarsening, sandstones interpreted as crevasse channels and splays intercalated within overbank mudstones. Robinson and McCabe (1997, 1998) interpreted the Salt Wash in the Henry Mountains region of southern Utah (same study area as Peterson, 1980, 1984) as deposits of braided streams flowing towards the northeast. They identified channel, abandoned channel-fill, and overbank/floodplain deposits within the Salt Wash, and describe a vertical progression from thinner, amalgamated (sheet-like), multistorey channel complexes in the lower Salt Wash, to thicker, relatively coarser-grained, and more isolated sheet sandstones in the upper. Robinson and McCabe (1997, 1998) link the vertical changes in fluvial style and architecture in the Salt Wash to two allogenic causes. They attribute a change in the locus of alluvial deposition in the basin to tectonism in the hinterland and call on a change to a wetter climate that resulted in greater bank stability and a rise in base level due to expansion of a downdip lacustrine system. Although previous workers (Craig et al., 1955; Galloway, 1980) had interpreted the Westwater Canyon Member as a distal alluvial fan, Campbell (1976), Turner-Peterson (1986), Miall and Turner-Peterson (1989), Cowan (1991), and Godin (1991) interpreted this unit as a series of amalgamated sheet sandstones deposited in a braided fluvial environment not directly linked with alluvial fan deposition. Although these authors differed somewhat in their interpretations of vertical facies and grain-size trends, they all agreed that the Westwater Canyon is characterized by a hierarchy of depositional units consisting of macroforms and channels amalgamating laterally and stacking vertically into sheets. The Fiftymile Member of the Kaiparowits region was interpreted by Peterson (1988) as deposits of streams that carried sandy and gravelly sediment, dominated by bedload transport, in a flashy discharge regime, down distinct channel belts which drained sediment source areas to the west and south of the Morrison basin. Peterson (1988) correlated the Fiftymile Member with the Westwater Canyon Member and much more mudstone-dominated facies of the Brushy Basin Member down depositional dip.

Because the sandstones in the Recapture and Brushy Basin Member do not, for the most part, host major uranium ore bodies, they have not attracted as much study as those in the Salt Wash and Westwater Canyon Members. Condon and Peterson (1986) and Kirk and Condon (1986) interpreted the fluvial sandstones in the Recapture Member in the San Juan Basin as having been deposited in erg- and playa-margin settings, although they also observed that this unit contains abundant overbank mudstones. In the current study, the sandstones in the lower part of the Brushy Basin Member were interpreted as the deposits of high- and moderate-sinuosity fluvial systems. These streams are interpreted to have carried sandy sediment as bedload and fine-grained material in suspension in a discharge regime more consistent than was typical for the Salt Wash, Westwater Canyon, Fiftymile, or Recapture fluvial systems. Because of the fine-grained component in the sediment load, the lower Brushy Basin streams were able to construct levee and extensive floodplain deposits. The channel sandstones in these intervals are commonly intercalated with stacked floodplain paleosols and crevasse-splay/levee sandstones. Sandstones in the upper part of the Brushy Basin Member were deposited in both high- and low-sinuosity fluvial systems. Smaller low-sinuosity channel sandstone bodies in this interval were deposited by low-sinuosity, straight and possibly anastomosing fluvial systems (Newell, 1997). Thicker conglomeratic sandstones, which are present mainly in the upper part of the member, but less commonly throughout the member in the northern Colorado Plateau region, were deposited by low- and high-sinuosity channels and narrow channel belts (Peterson, 1994; Currie, 1998).

3. Floodplain and lake-margin paleosols

Most of the Morrison Formation was deposited in a fully terrestrial setting and only the basal members or parts of the Morrison in the northern part of the Front Range of Colorado, northern Utah, Wyoming, and Montana are reported to have significant marine influence (O'Sullivan, 1992; Peterson, 1994). The overwhelming proportion of Morrison sediments was deposited in streams, lakes, and areas marginal to these settings. Deposition of sediment on the Morrison landscape therefore occurred under subaerial to shallow subaqueous freshwater conditions in settings that were eventually exposed to pedogenic processes. In areas with relatively high depositional rates, physical, chemical, and biological processes that create soils (weathering, burrowing, etc.) do not have enough time to produce mature soils with well-developed horizons because immature soil horizons are buried before they can be more fully developed. Mature soils form in areas where sediment accumulated slowly and was subject to burrowing and mixing by plants and animals (see Hasiotis, this volume), and fluctuating moisture and chemical conditions, over a longer period of time. The floodplain and lake-margin deposits in the Morrison Formation are characterized by paleosols with varying degrees of development, both laterally across the ancient landscape (catenas), and vertically through geologic time (paleosol chronosequences).

3.1. Description

One of the most distinctive features of a large proportion of pedogenically modified horizons in floodplain and lacustrine-margin settings in the Morrison Formation is the presence of some type of calcium carbonate accumulation, either as distinct layers, nodules, or layers of nodules (Figs. 3 and 4). These accumulations are present at depths less than 3 m, and typically less than 1 m, below the preserved tops of the pedogenically modified intervals (see also Retallack, 1997). Dunagan (1998, 2000), in a petrographic study of carbonate layers and nodules in the Morrison Formation, noted that they have a complex history of precipitation, dissolution, cracking, brecciation, and recrystallization.

The Morrison floodplain paleosols also are characterized by at least some degree of subsurface clay accumulation (Fig. 3). These horizons occur above a carbonate horizon, if present, and are often reddish colored and have slickensides and evidence of distinct blocky or prismatic ped structures. Slickensides and coatings of detrital grains or clay laminae often define peds. Some reddish, slickensided horizons, however, do not show or do not preserve evidence of distinct ped structure, although they are similar in thickness, color, and association with underlying carbonate horizons, with those that do.

Some floodplain paleosols in the Morrison (especially the Salt Wash and lower Brushy Basin Members of the Colorado Plateau region) have vertic features such as distinctive sub-horizontal, slickensided fractures and vertical sand-filled fractures (Fig. 3). These paleosols also exhibit reddish, clay-rich horizons and variable amounts of carbonate accumulation.

Floodplain paleosols in the Morrison preserve a diverse assemblage of trace fossils (Hasiotis and Demko, 1996, 1998; Hasiotis, this volume). Although plant rooting traces (rhizotubules, rhizoliths, root casts, and rhizocretions) are the most abundant traces within paleosols, burrows interpreted to have been formed by insects and other arthropods can be commonly found in all horizons in the floodplain paleosols. Upper horizons are characterized by back-filled and meniscate burrows whereas lower horizons have collapsed and infilled chambers. These trace fossils often occur in crudely tiered assemblages, and in thicker paleosol horizons, there is often overprinting of older traces by younger (Hasiotis and Demko, 1996, 1998; Hasiotis, this volume).

In the Four Corners and San Juan Basin areas, the lower Salt Wash and Tidwell Members interfinger with

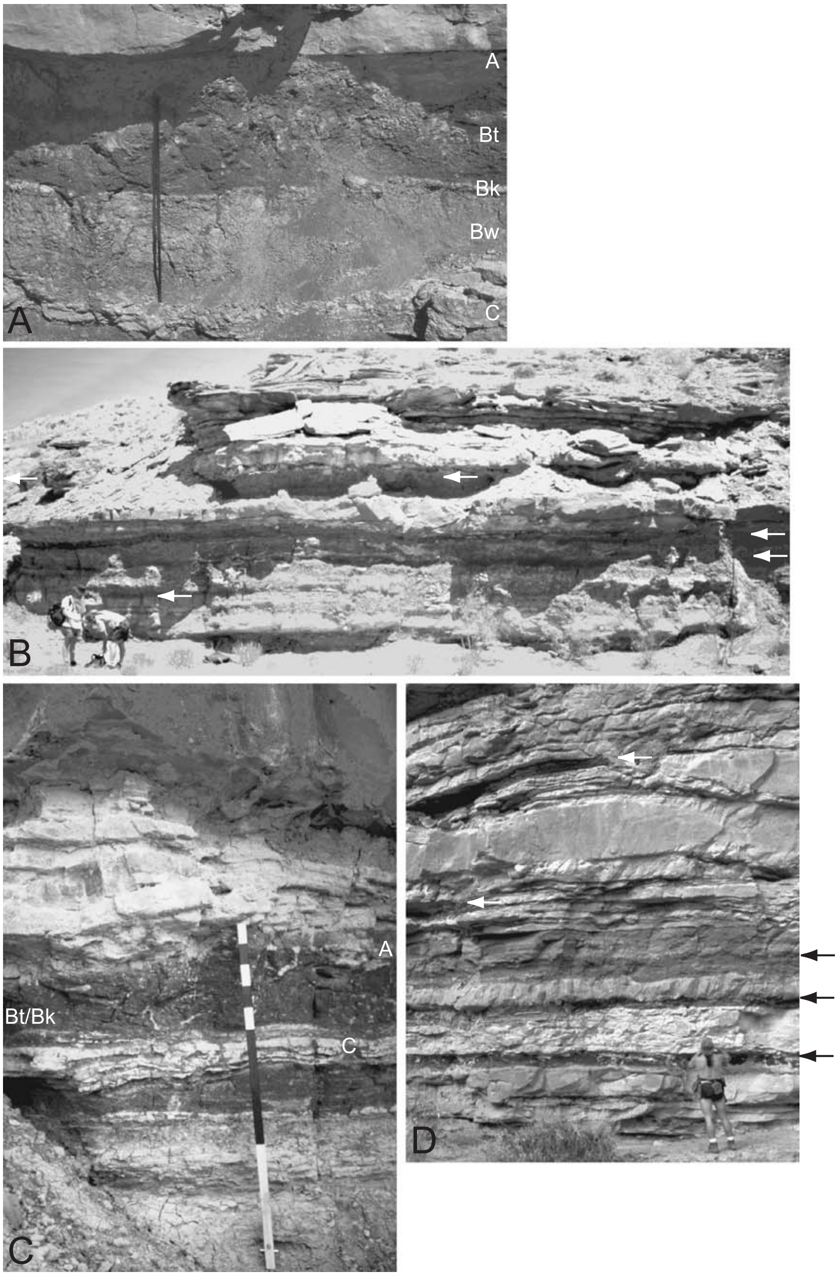


Fig. 3. Floodplain paleosols in the Morrison Formation. (A) Calcic Argillisol in Tidwell Member, Blue Mesa, CO, showing characteristic paleosol horizons (A: leached mineral horizon, Bt; subsurface clay accumulation; Bk: subsurface carbonate horizon; Bw: structured horizon; C: unaltered mineral horizon). (B) Stacked Calcisols (white arrows) and crevasse-splay/levee beds in Recapture Member, Aneth, UT. (C) Calcic Argillisol and thin crevasse-splay/levee beds in Salt Wash Member, Yellow Cat, UT (abbreviations same as Fig. 2A). (D) Stacked Argillisols and Entisols (black arrows) intercalated with crevasse-splay/levee sandstones and small fluvial channels in Salt Wash Member, Shootering Canyon, UT.

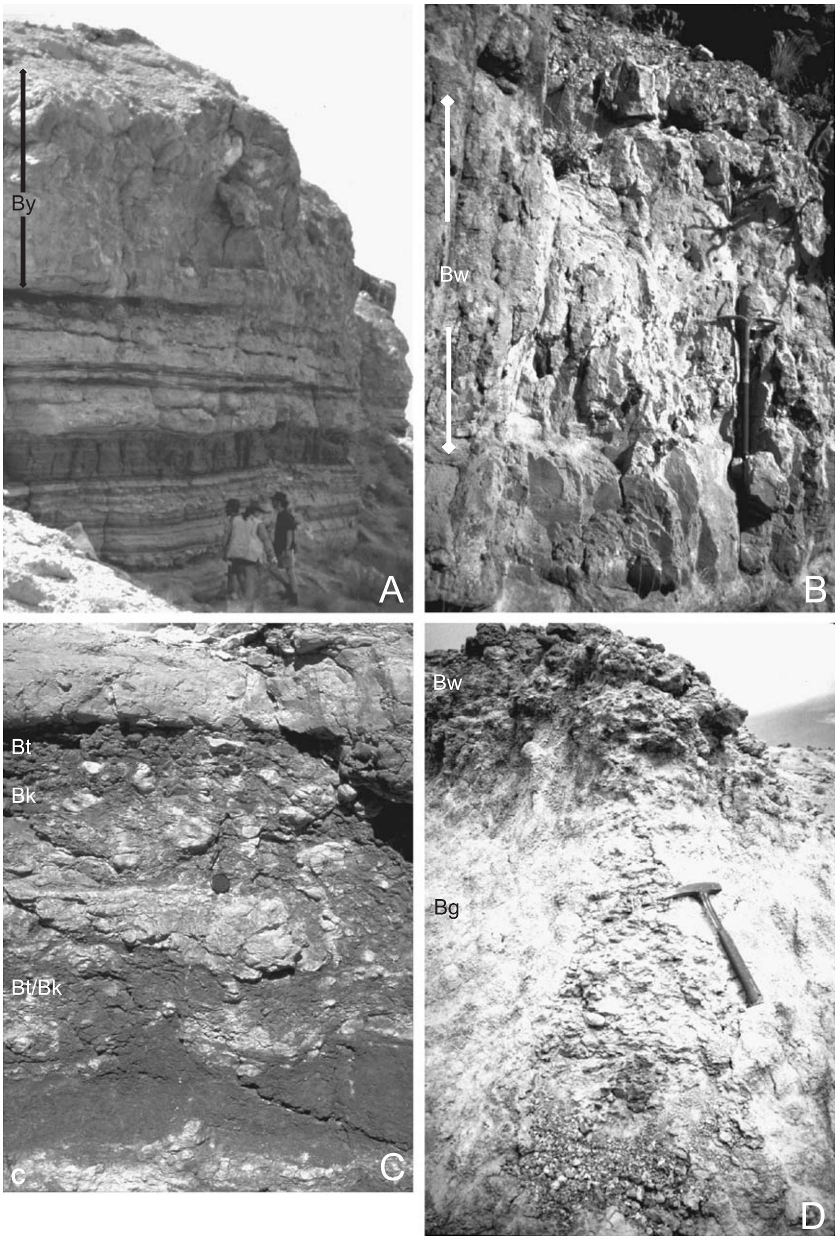


Fig. 4. Unconformity paleosols in the Morrison Formation. (A) Thick Gypsisol, basal Morrison unconformity, Tidwell Member, San Rafael River, UT, geologists for scale (By: subsurface gypsum horizon). (B) Iron mineral-rich horizons with prismatic peds developed on Middle Jurassic Entrada Sandstone, basal Morrison unconformity, Purgatoire Canyon, CO, hoe pick for scale (Bw: structured horizons). (C) Mature calcic Argillisol, basal Morrison unconformity, developed on Middle Jurassic Wanakah Formation, Blue Mesa, CO, lens cap for scale (abbreviations same as 3A). (D) Hydroximorphic horizons in Gleysols, uppermost Morrison unconformity, Brushy Basin Member, Yellow Cat, UT, rock hammer for scale (Bw: structured horizon; Bg: gleyed horizon).

the Bluff Sandstone Member–Junction Creek Sandstone Member eolian deposits. In the transitional areas, where Salt Wash fluvial deposits and Tidwell playa deposits are interbedded with eolian sand sheets, paleosols in the Salt Wash and Tidwell are very weakly developed. In some outcrops, thin, deeply penetrating permineralized roots, rhizocretions and rootlets are the only visible evidence of soil formation. Thin gypsum layers are also common in some of the lowest intervals and a thicker, discontinuous gypsum bed (0–3 m thick) marks the base of the formation in the central-western Colorado Plateau area (San Rafael Swell).

3.2. Discussion

Pedogenic features are common in all lithostratigraphic intervals in the Morrison Formation over the depositional basin. However, there are distinct differences in the type, degree of maturity, and lateral extent of paleosols in each interval and broad paleogeographic region.

Paleosols in the lowest members of the Morrison (Tidwell, Bluff, and lower Recapture of the Colorado Plateau region, Windy Hill Member and time-equivalent Ralston Creek Formation of the Colorado Front Range, and the lower Morrison of Wyoming and Montana) are typically marginal-lacustrine, palustrine Calcisols (sensu Mack et al., 1993), and weakly developed floodplain argillic Calcisols (Fig. 3A). Lacustrine and palustrine carbonates in marginal-lacustrine and fringing wetland areas, exposed during lake-level lowstands, were pervasively pedogenically modified (Dunagan and Turner, this volume). The carbonate horizons are dominantly groundwater-formed, although there is pervasive and sometimes complete pedogenic overprinting. Subsurface clay accumulations within these paleosols, interpreted as similar to argillic (Bt) or structural B horizons (Bw) in modern soils, are locally present, although not laterally continuous or thickly developed. These paleosols were formed under conditions of relatively high, although fluctuating, groundwater conditions associated with lake levels and regional groundwater discharge. However, the presence of a time-equivalent erg (Bluff and Junction Creek Members), eolian sand sheets (Recapture Member), and evaporite deposits (Tidwell Member) indicates that the paleoclimate was dominantly dry (Demko and Parrish, 1998) and pedogenic carbonate formed in the soils due to a low precipitation to evaporation ratio (P/E ratio). The gypsum horizons present in the Tidwell Member are interpreted as gypsic Protosols (sensu Mack et al., 1993) formed in the fringing area around the sand sheet deposits and playas in an arid paleoclimatic setting.

The paleosols in the Salt Wash Member and equivalent strata on the Colorado Plateau are typically floodplain argillic Calcisols (Fig. 3C,D). They are associated with fine-grained overbank units laterally equivalent to contemporaneous large braided streams or associated with the abandonment phases of these streams. These paleosols show a range of thickness and maturity. Some paleosols are thin and weakly developed, often buried by a sandy levee deposit, crevasse-splay, or fluvial channel (Fig. 3C,D). Retallack (1997) interpreted these types of paleosols at Dinosaur National Monument, Utah to represent pioneering colonization of frequently flooded riparian areas. Others are thick, mature, and have multiple, stacked subsurface clay accumulations and carbonate horizons, similar to Bt/Bk horizons in modern soils. These simple and cumulate paleosols are distributed across the ancient landscape according to the relative rate of sedimentation on the floodplains. Areas of rapid and periodic deposition are characterized by abundant thin and simple paleosols (Protosols), whereas those areas that accumulated slowly and episodically have thick, well-developed, cumulate paleosols. In outcrops of the Salt Wash Member that expose a complete vertical succession, a crude stratigraphic progression from braided stream sand bodies with laterally adjacent overbank deposits characterized by thin Protosols to overlying muddier intervals characterized by thicker, well-developed argillic Calcisols and vertic Calcisols is often evident. These progressions are interpreted to be the result of the progradation of the Salt Wash braided channels and channel belts, their inevitable migration and abandonment, and the reoccupation of the area by active river deposition. These progressions, and the lake-level highstand/lowstand progressions in older and contemporaneous deposits, may be linked to larger-scale, and long-term, paleoclimatic cycles (Robinson and McCabe, 1998). Paleosols in the lower Brushy Basin Member and upper Recapture Member in the Colorado Plateau and San Juan Basin areas are typically weakly to well-developed floodplain vertic and argillic Calcisols (Fig. 3B).

These paleosols are in floodplains associated with meandering and moderate sinuosity streams. They tend to be, on the whole, better developed than those in the Salt Wash Member and are the most mature paleosols in the Morrison outside of the unconformity paleosols discussed below. Carbonate nodule horizons are common, as are well-developed, reddened clay accumulations and a distinctive, ant- and termite-nest dominated ichnofauna. Crayfish burrows are also common in paleosols in these intervals (Hasiotis, this volume), especially in areas close to contemporaneous channels. The distinctive reddish coloration of these members is due to, among other reasons, the predominance of abundant, stacked, ped-structured, reddened, clay horizons. The upper boundary of these units is often is expressed in the central Colorado Plateau and Rocky Mountain areas as a distinct color change to the overlying upper Brushy Basin Member, which has fewer horizons of this nature. The upper Brushy Basin Member in the western Colorado Plateau region (e.g., San Rafael Swell area), however, also exhibits these types of pedogenically modified horizons. The time-equivalent Westwater Canyon Member of the Four Corners and San Juan Basin regions also has these types of pedogenic features, although they are associated with a large braided and moderate-sinuosity stream system, are less abundant, and are intercalated with thick, channel- and bar-sandstones.

Paleosols in the upper Brushy Basin Member of the Colorado Plateau region and the upper Morrison of the more eastern portions of the basin are typically weakly to moderately developed floodplain Protosols and Calcisols and weakly developed, non-calcareous marginal-lacustrine paleosols (Newell, 1997). Floodplain paleosols in this interval are associated with thin fluvial channel sandstones deposited by straight and anastomosing streams (Newell, 1997). Some paleosol horizons are marked only by shallow-penetrating filamentous rootlets in otherwise undisrupted mudstones. Much of the distinctive color banding of the upper Brushy Basin Member in the eastern Colorado Plateau area, although somewhat similar to appearance to other pedogenic color-banded intervals in the Morrison, is actually due to differing concentrations of diagenetic zeolite and associated minerals related to evaporative lake processes (Turner and Fishman, 1991).

The overwhelming abundance of smectitic clays and other products of weathered volcanic ash in the upper Brushy Basin Member suggest that during this time the Morrison basin was periodically blanketed by ash-fall deposits blown and washed in from the active volcanic arc to the west and southwest. The relative immaturity and types of paleosols, the types of stream deposits, and the common presence of both large and small lake deposits in the upper part of the Morrison suggests that at this time the landscape was characterized by sluggish, low-gradient streams and playa and perennial lakes. Retallack (1997) interpreted these types of paleosols at Dinosaur National Monument to represent waterlogged soils on the floodplain. The groundwater tables were higher than those present during either lower Brushy Basin or Salt Wash times, and did not seem to have the same magnitude of fluctuations. However, the upper part of the Fiftymile Member of the Morrison, present only in the far southwestern portion of the basin, is time-equivalent to the lower beds of this interval and represents a higher gradient/higher energy river system that existed more proximal to the sediment source area (Peterson, 1988). Paleosols in the Fiftymile Member are similar to those associated with near channel environments in the Salt Wash Member. Overall, evidence from the paleosols suggests that conditions in the Colorado Plateau and San Juan Basin regions were wetter during upper Brushy Basin time than those of earlier Tidwell–Salt Wash–lower Brushy Basin-equivalent times. Paleosols in the upper Morrison Formation in Montana, in and around the Belt-Great Falls coal region, and in the uppermost Morrison in Wyoming and the northern Front Range formed in wetland environments (peat mires, clastic swamps, marginal lake wetlands). These paleosols are moderately to well-developed, non-calcareous, and often rich in organic material (Gleysols and Histosols, sensu Mack et al., 1993). These types of paleosols, which include high-ash and high-sulfur coals, suggest a paleoclimatic and paleohydrologic setting (landscape with areas of perennially high water table to preserve peat) wetter than any other Morrison interval, although still characterized by seasonal dry periods. Overall, floodplain and lake-margin paleosols of the Morrison Formation record both regional and temporal paleoclimatic trends. Regional trends are evident both south to north (for example, dry: Calcisols to wet: Histosols and marginal-lacustrine Protosols) and west to east (for example, dry: vertic Calcisols to wet: palustrine Protosols and argillic Calcisols) in any one stratigraphic interval. In addition, throughout Morrison deposition, evidence suggests that conditions were getting wetter, and possibly less seasonal, through time.

In the case of the Morrison floodplain paleosols, carbonate was precipitated by soil-forming processes, groundwater processes, or both. Carbonate accumulations in soils (Bk horizons), form above the groundwater table due to reprecipitation of dissolved bicarbonate, in some cases biologically mediated, from dust or carbonate sediment from layers above, or reworked pre-existing soil carbonate (Goudie, 1973, Naiman et al., 2000). Carbonate can also accumulate at or near the groundwater table due to precipitation from the capillary fringe or upper parts of the groundwater that are saturated with calcium carbonate (Goudie, 1973). However, most of these processes seem to have occurred in soil-forming or shallow groundwater environments. This is an important observation because the implication is that these carbonate accumulations were formed under geochemical conditions that had carbon isotope ratios similar to the Late Jurassic atmosphere, rather than a later deep burial (diagenetic) signature (D.D. Ekart, personal communication, 1998). The occurrence and distribution of Calcisols in the Morrison floodplains suggests that the paleoclimatic and paleohydrologic conditions were characterized by greater evaporation than recharge of shallow groundwater, probably in a seasonally dry setting. Marginal-lacustrine paleosols also have Bk horizons, although the original source of this carbonate was primary deposition in shallow lacustrine settings or as palustrine carbonates in the shallow subsurface below a fringing wetland (Dunagan and Turner, this volume). However, subsequent exposure, brecciation, dissolution, and reprecipitation of these lake and wetland carbonates in some cases has produced a pedogenic overprint, both in the morphology and geochemistry of the carbonate (Dunagan and Turner, this volume).

Clay-rich horizons (Bt) form by the illuviation or translocation of clay particles from overlying horizons in the soil, the coating of grains, peds, and open fracture surfaces, and entrapment in a less porous and permeable layer. Once clay begins to accumulate in these layers, the porosity and permeability are reduced further, and more clay accumulates. The reddish colors in the Morrison horizons, interpreted to be similar to Bt and Bw horizons in modern soils, are due to increased concentrations of iron-bearing minerals (oxides and hydroxides) trapped with the clays and adsorbed onto them. Although these red colors are distinctive, and a great aid to identifying paleosols in the Morrison, they may not be the original colors of the Jurassic soils. The original soils could have been brown and dark reddish brown, and burial and geologic time may have changed the mineralogy (and, in turn, the color) of the iron compounds (Retallack, 1991). However, the reddish horizons would still reflect the original relative abundance of iron-bearing minerals in the soils, and the horizons they delimit would still be valid and identifiable. On the other hand, Kraus (1997) argues that the co-occurrence of both reddish (due to hematite) and yellow-brown (due to goethite) colors in paleosols (such as is the case in the Morrison Formation) would largely be original pedogenic features since burial alteration would be pervasive and not produce such a mixture. However, the pervasiveness of goethite-to-hematite diagenesis is poorly known (Blodgett et al., 1993) and analysis of Triassic continental rocks in Colorado suggests that goethite may persist in reddish rocks (Blodgett, 1990). The accumulation of clay and iron minerals in the Morrison floodplain paleosols suggests that there was significant downward movement of water and finer-grained soil material during soil-forming processes. Although the presence of carbonate in these paleosols indicates drier conditions, the clay- and iron-rich horizons are evidence that wetter conditions prevailed at some times. The co-occurrence of these two types of features in the same paleosols, in turn, with the vertic features formed by repeated wetting and swelling, and drying and shrinkage, of expandable clays within the soil, are good evidence of fluctuating soil moisture conditions that we may interpret as resulting from the seasonality of precipitation (i.e., a rainy season and a dry season) (Duchaufour, 1982; Blodgett, 1985). Retallack (1997) compared the floodplain paleosols in the Morrison to modern soils typical of dry climates that support open vegetation, such as the cypress woodlands of southeastern Australia or the pinyon-juniper woodlands of south-central USA. The type of interpreted trace makers, their diversity, and their interpreted behavior (often opportunistic) also support a setting characterized by fluctuating moisture conditions (Hasiotis and Demko, 1996, 1998; Hasiotis, this volume).

4. Unconformity paleosols

Unconformity paleosols in the Morrison Formation developed over much longer periods of time than those represented by the floodplain and marginal-lacustrine paleosols discussed above. These mature, well-developed paleosols represent relatively large breaks in the stratigraphic record and occur at boundaries between large-scale sedimentary packages in the Morrison. The strata on either side of these horizons were deposited in very different environments and, in some cases, under different paleoclimatic and paleohydrologic conditions. Unconformities were formed in the stratigraphic record by the processes of relative base-level fall and erosion, by periods of very little or no deposition of sediment, or some combination or succession of both. During these times, previously deposited sediment is either stripped away and transported during landscape degradation (drainage system incision, mass wasting, etc.) or is subject to weathering, soil formation, and the near-subsurface effects of fluctuating water tables. If little or no erosion takes place, over a long period of time (thousands to tens of thousands of years), under conditions where there is at least some precipitation and vegetation, a well-developed soil will form at the surface. Weathering will penetrate at least to the lowest level of the water table. If the time of soil formation is long enough to span changes in climate and vegetation at the surface, the resulting soil may show a complex mixture of younger and older, relict features. Unconformity paleosols were identified at three horizons in the Morrison Formation: (1) At the base of the formation in the western (San Rafael Swell, Utah and Uncompahgre Uplift, Utah/Colorado) and southeastern (Purgatoire Canyon, Colorado) portions of the basin (Figs. 4–6); (2) At the boundary between the Salt Wash and Brushy Basin Members on the Colorado Plateau (and equivalent horizons in the San Juan Basin, southern Wyoming, and the Cañon City area) (Figs. 5 and 6); and (3) At the top of the formation at the boundary between Upper Jurassic Morrison rocks and overlying Lower Cretaceous strata in the Colorado Plateau, Front Range, and southern Colorado (Figs. 4, 5 and 7). The paleosols at each of these horizons have different features that reflect the paleoclimate, biological activity, time of formation, and original parent materials.

4.1. Basal Morrison unconformity

Paleosols at the basal unconformity of the Morrison in the San Rafael Swell of Utah are well-developed Gypsisols (sensu Mack et al., 1993) and Calcisols formed on and penetratively into the underlying Middle Jurassic Summerville Formation. The Morrison Formation thins westward drastically in the San Rafael Swell, especially around the town of Moore, Highway I-70, and the northern portion of Capitol Reef National Park. The thinning is at the expense of the lower members of the formation; that is, the Salt Wash and Tidwell Members lap onto a surface (the J-5 unconformity of Pipiringos and O'Sullivan, 1978) on the underlying Middle Jurassic strata. The paleosol at this onlap surface is in some places characterized by massive gypsum (By) horizons 0.5–4 m thick (Figs. 4A and 5). This gypsum was likely dissolved, reprecipitated, and reworked from underlying gypsiferous playa mudstones in the Summerville Formation by soil formation and fluctuating and rising groundwater. The regional paleoclimate changed from arid–hyperarid during the Middle Jurassic to semi-arid during the early Late Jurassic (early Kimmeridgian), and groundwater tables must have risen enough to remobilize evaporite minerals from the underlying Middle Jurassic strata. In the northern Capitol Reef area (Last Chance Wash section in Fig. 5 and section LCW in Fig. 6), the unconformity paleosol exhibits multiple stacked Bk horizons superimposed on fluvial sandstones and lacustrine mudstones in the uppermost Summerville. These Bk horizons are composed of discrete carbonate nodules and continuous and brecciated carbonate layers. These horizons record a complex history of cumulate pedogenesis and groundwater fluctuations that probably occurred over a time span equivalent to that of the time of deposition of the Tidwell and Salt Wash Members to the east. East of the Salt Anticline region in easternmost Utah and westernmost Colorado, the Morrison rests unconformably (also the J-5 unconformity of Pipiringos and O'Sullivan, 1978) on the Middle Jurassic Wanakah Formation, which is probably time-stratigraphically older than the Summerville Formation (O'Sullivan and Pierce, 1983). A well-developed argillic Calcisol also marks this surface (Fig. 4C). The same horizon in the Purgatoire River canyon region (Comanche National Grasslands) of southeastern Colorado also has a well-

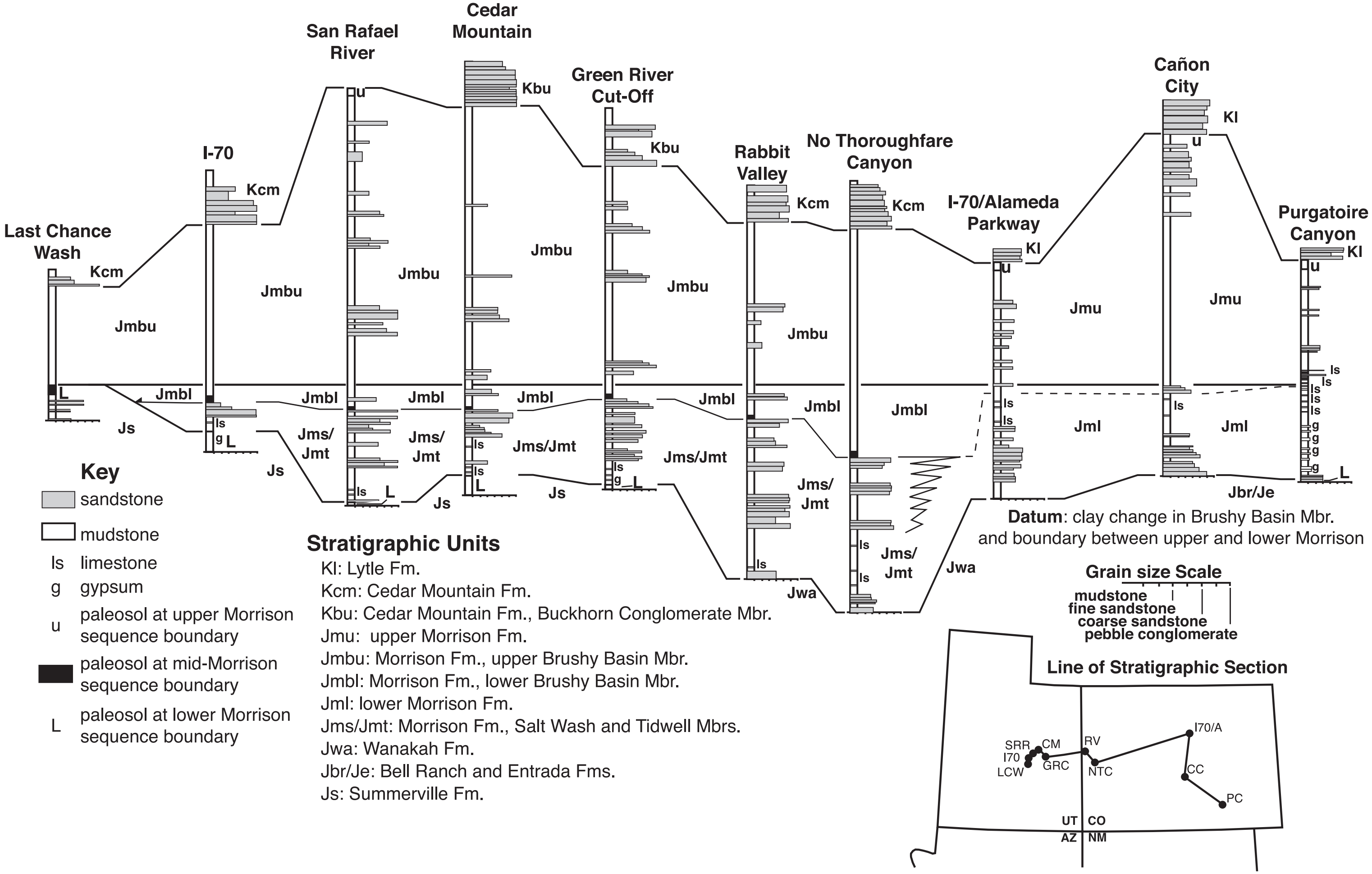
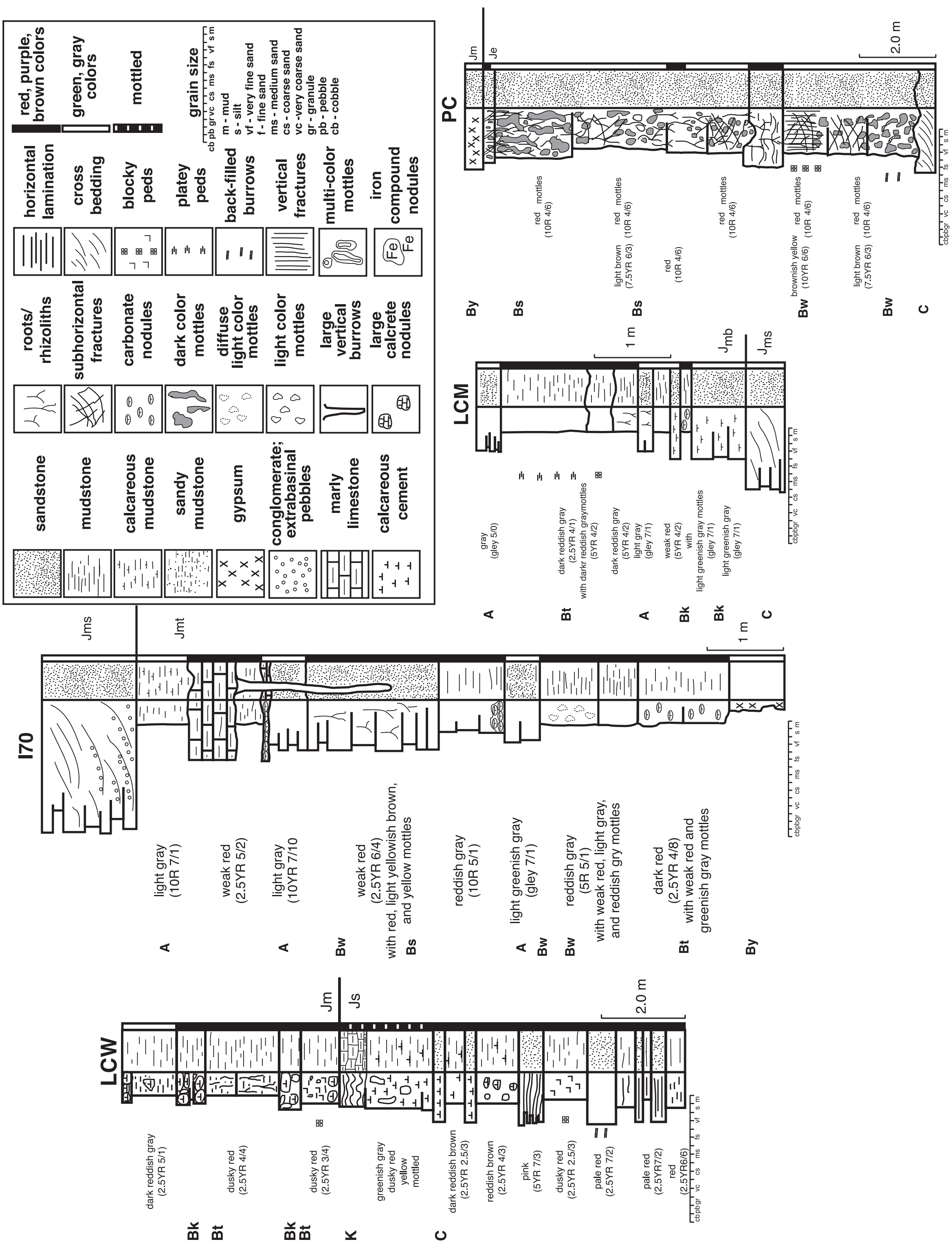


Fig. 5. Regional stratigraphic cross-section showing position and correlation of the basal Morrison, mid-Morrison, and uppermost Morrison unconformity paleosols. Datum is change in clay mineralogy in Brushy Basin Member documented by Turner and Fishman (1991).



LCW
I70
LCM
PC
Jm
Js
Jms
Jmt
Jmb
Je
2.0 m
1 m
sandstone
mudstone
calcareous mudstone
sandy mudstone
gypsum
conglomerate; extrabasinal pebbles
marly limestone
calcareous cement
roots/ rhizoliths
subhorizontal fractures
carbonate nodules
dark color mottles
diffuse light color mottles
light color mottles
large vertical burrows
large calcrete nodules
horizontal lamination
cross bedding
blocky peds
platey peds
back-filled burrows
vertical fractures
multi-color mottles
iron compound nodules
red, purple, brown colors
green, gray colors
mottled
grain size
cb pb gr vc cs ms fs vf s m
m - mud
s - silt
vf - very fine sand
f - fine sand
ms - medium sand
cs - coarse sand
vc -very coarse sand
gr - granule
pb - pebble
cb - cobble
light gray (10R 7/1)
weak red (2.5YR 5/2)
light gray (10YR 7/10
weak red (2.5YR 6/4) with red, light yellowish brown, and yellow mottles
reddish gray (10R 5/1)
light greenish gray (gley 7/1)
reddish gray (5R 5/1) with weak red, light gray, and reddish gry mottles
dark red (2.5YR 4/8) with weak red and greenish gray mottles
A
Bw
Bs
Bt
By
Bk
K
C

developed unconformity paleosol. In this area, the Upper Jurassic Morrison Formation rests unconformably on the Middle Jurassic Bell Ranch (red siltstones and mudstones) and Entrada (thick eolian sandstone) Formations (Fig. 5). The Bell Ranch Formation is present only as erosional remnants between areas where the unconformity has cut down to the top of the Entrada. In the areas where the unconformity at the base of the Morrison cuts through the Bell Ranch, there is a thick, very mature paleosol developed in the uppermost portions of the Entrada Sandstone (Fig. 4B and section PC in Fig. 6). This paleosol (comparable to a modern spodic soil) is characterized by distinctive red, dark reddish-brown and dark reddish-purple color mottling due to iron-mineral segregation (Bs horizons) along roots and burrows. The paleosol is not present beneath the erosional remnants of the Bell Ranch Formation. In many areas in the central and northern part of the Morrison depositional basin, there is little evidence of an unconformity or soil formation at this horizon. Some of these areas (Dinosaur National Monument, northern Front Range) have evidence of marine influence, suggesting that they are regionally down the depositional dip from the paleotopographically higher areas where the unconformity is present.

4.2. Mid-Morrison unconformity

The paleosol at the unconformity between the Salt Wash and Brushy Basin Members of the Morrison on the Colorado Plateau is typically a reddish argillic Calcisol similar to those in the overlying lower Brushy Basin Member in that it has the same kind of soil horizons and trace fossils (section LCM, Fig. 6). However, the degree of development and lateral extent of this paleosol is much greater than any other identified in the lower Brushy Basin Member. The most distinctive feature of this paleosol is the abundance of termite trace fossils (nests and galleries). Extensive galleries and vertical shafts associated with termite nests are found in the lower portions of this paleosol and are especially well-preserved in uppermost Salt Wash sandstones. Particularly termite-trace-rich areas can be found in and around the Fruita Paleontological Area, Colorado National Monument, and Arches National Park. However, the most spectacular examples are from the equivalent horizon in the Morrison in the San Juan Basin near Fort Wingate, New Mexico (at locality SJB in Fig. 1). In this area, the same unconformity paleosol is present at the boundary between the Recapture and Westwater Canyon Members of the Morrison. Giant termite nests are preserved below the unconformity in Recapture sandstones (Hasiotis, this volume). The same horizon is even traceable into the southern Front Range area, near Cañon City, Colorado (Fig. 5). In the Garden Park Paleontological Area near Cañon City, a horizon rich in termite nests is present in sandstones in the uppermost lower Morrison, below a moderately developed argillic Calcisol in the lowermost upper Morrison (also the site of the Marsh-Felch dinosaur quarry) (Hasiotis and Demko, 1998). This unconformity paleosol is probably equivalent to a distinctive, laterally continuous, pedogenically modified, palustrine-lacustrine limestone in the Como Bluff, Casper and Thermopolis areas of southern and central Wyoming, locally called the "Boundary Caliche" by Allen (1996). However, in these areas, there are no thick fluvial or eolian sandstone beds in the lower Morrison and the depositional environments were dominantly lake and lake-margin in both the upper and lower Morrison just above and below the unconformity. There is an isolated, large fluvial complex at a stratigraphic horizon equivalent to the unconformity present in outcrops of the Morrison Formation west of Como Bluff, between Casper and Rawlins, Wyoming (Currie, 1997). In these areas, the unconformity paleosol represents a regional lake-level lowstand, exposure of lake sediments, extensive modification due to soil-forming processes, and progradation of an alluvial complex. In northern Utah and the Dinosaur National Monument area, there is large-scale incision at this horizon, where lower Morrison-Salt Wash strata are truncated, channeled, and reworked into regional paleovalleys (Currie, 1997). Undoubtedly, this horizon represents a significant change in fluvial style, groundwater levels, and paleoclimate throughout the Morrison depositional basin. The depth, abundance, and intensity of burrowing associ-

Fig. 6. Measured sections of the basal and mid-Morrison unconformity paleosols in the Morrison Formation. A: Surface mineral horizon; Bt: Subsurface clay accumulation; Bk: Subsurface carbonate horizon; Bw: Structured horizon; K: Continuous pedogenic carbonate layer; C: Unweathered mineral horizon. Location abbreviations same as Fig. 1. Colors from Munsell Soil Color Charts.

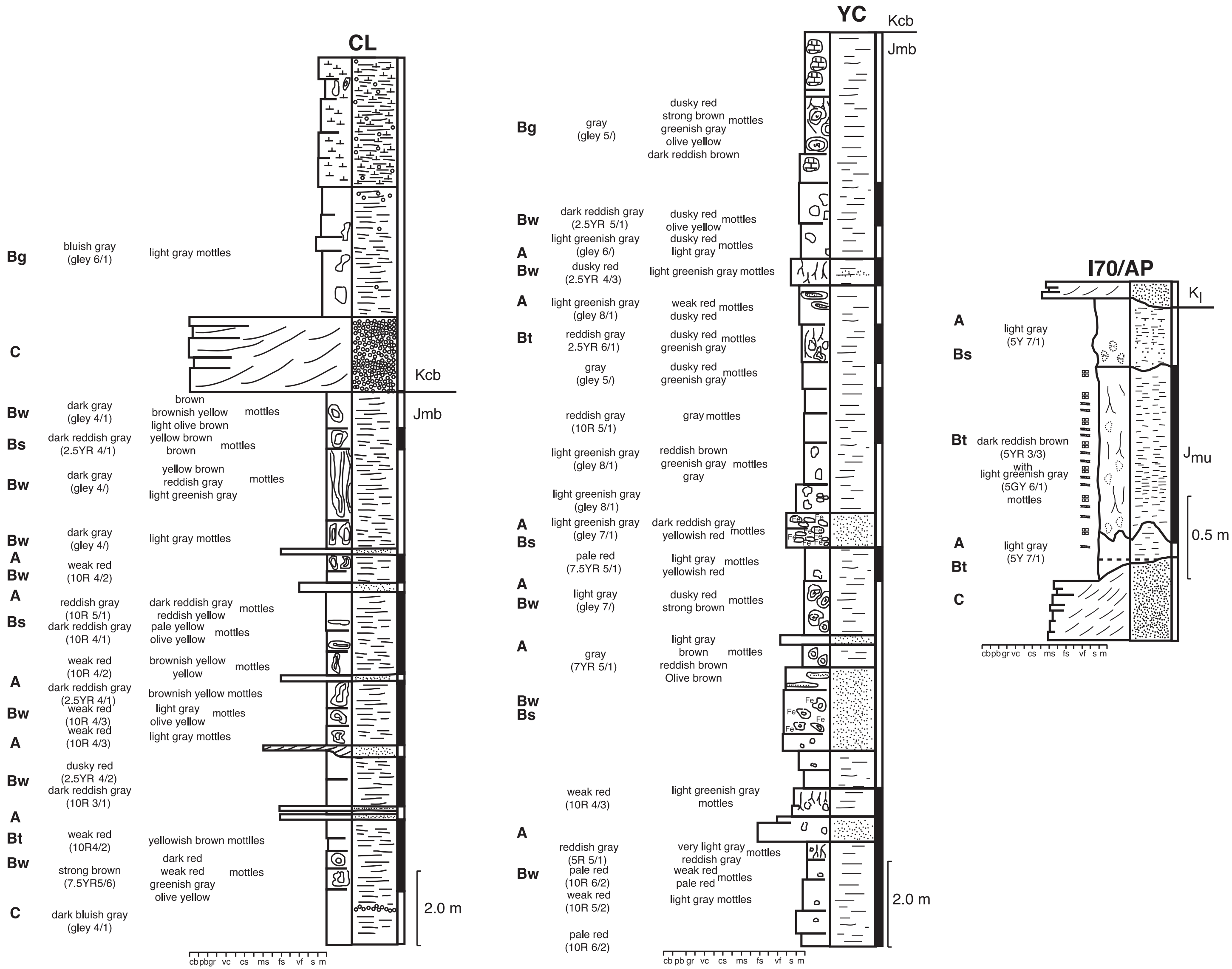


Fig. 7. Measured sections of the uppermost Morrison unconformity paleosols (Symbols same as caption and explanation for Fig. 6). Colors from Munsell Soil Color Charts.

ated with this paleosol, along with the degree of maturity of the Bt/Bk horizons, suggest that the basin underwent a long period (thousands of years?) of very low sediment deposition and local stream incision during the time of soil formation.

4.3. Uppermost Morrison unconformity

The unconformity paleosol at the top of the Morrison Formation is a complex composite paleosol that was formed under the depositional, paleoclimatic, and paleohydrologic conditions of the latest Jurassic and then was subsequently modified by Early Cretaceous paleoclimatic and paleohydrologic processes. This thick paleosol complex is incompletely preserved due to extensive and deep erosional truncation beneath Cretaceous fluvial sandstone beds. The paleosol is only preserved on drainage divides within the Cretaceous regional drainage system. Where the paleosol is preserved (San Rafael Swell, Arches National Park, southern Front Range, Purgatoire Canyon), it is a thick (3–10 m or 10–33 ft), very distinctive, reddish and yellowish color-mottled unit (Figs. 4D and 7). The coloration is due to extensive redistribution of iron minerals within the paleosol. These features (ferruginous nodules, iron and clay depleted and enriched zones) suggest alternating saturated and well-drained (hydroximorphic and redoximorphic) conditions during soil formation (e.g., Vepraskas, 1994). There is no pedogenic carbonate associated with these paleosols. However, in the San Rafael Swell and surrounding Colorado Plateau exposures, there are massive and nodular carbonate horizons present in this paleosol complex (section YC in Fig. 7). Currie (1997) interprets these carbonate accumulations as a pedogenic or groundwater calcrete that formed over an Early Cretaceous uplift due to migration of a flexural forebulge. The well-developed paleosol complex (redoximorphic Gleysol) at the top the Morrison was formed under wetter conditions than any of the paleosols in the lower portions of the formation. The paleosol complex formed under dominantly saturated soil moisture conditions (with periodic drying out) and low sedimentation rates. These paleosols, along with the Histosols and Gleysols preserved in the uppermost Morrison in the Front Range foothills, Wyoming, and Montana, record the beginning of the paleoclimatic shift from seasonally dry to semi-arid conditions that characterized most of Morrison time to more humid and wetter conditions.

4.4. Sedimentary sequences

The unconformity paleosols in the Morrison Formation can be used to distinguish two, large-scale sedimentary sequences (Fig. 2). The Morrison between the lower unconformity paleosol and the middle Morrison unconformity paleosol comprises the lower of these sequences. In the central and northern Colorado Plateau region, this includes the Tidwell and Salt Wash Members; in the San Juan Basin it includes the Bluff/Junction Creek and Recapture Members, and in the Front Range foothills and Wyoming it includes the lower Morrison and Ralston Creek Formation lacustrine units. These units represent an aggradational to progradational sequence set (Currie, 1998). Morrison strata above the unconformity paleosol in the middle of the formation comprise the second sequence. This sequence set includes the lower and upper parts of the Brushy Basin Member and the Westwater Canyon, Jackpile, and Fiftymile Members. Both of these sequence sets are capped by unconformity paleosols that represent relatively long periods of little or no deposition at the end of the aggradational/progradational episodes.

Deposition of the two Morrison sequences was controlled by geodynamic processes associated with the Late Jurassic structural development of Cordillera and plate tectonic interactions along the western margin of North America. Evidence of these controls can be observed in the regional thickness variations in Upper Jurassic strata preserved within the Western Interior. Throughout the basin, the Morrison Formation thins to zero about at the longitude of the Wasatch Plateau in Utah (~111°W). Where this thinning can be observed in outcrop, younger Morrison strata progressively onlap Middle Jurassic rocks towards the west (Fig. 5). This relationship indicates that during the Late Jurassic, a broad positive structural feature existed along the western edge of the Morrison depositional basin. While this regional structure influenced the western extent of preserved Upper Jurassic strata in the western interior, paleocurrent data from Morrison fluvial-channel deposits indicate that it was not a barrier to sediment transport from uplifted areas in the Cordillera to the west (DeCelles and Burden, 1992; Currie, 1998). The origin of this feature can only be inferred, but it may have formed as the foreland was flexurally partitioned in response to thrust-related crustal loading in the Sevier belt in western Utah (Fig. 8) (Camilleri et al., 1997; Currie, 1998, Taylor et al., 2000). The westward pinch out of the Morrison Formation, therefore, represents the depositional onlap of sediments along the eastern side of the forebulge within the developing Cordilleran foreland basin (Currie, 1998). As such, deposition of the majority of the Morrison Formation in the Western Interior occurred in a secondary "back-bulge" basin between the forebulge and the craton (Fig. 8) (DeCelles and Currie, 1996).

The possible presence of a flexural forebulge in central Utah during the Late Jurassic implies the existence of a flexural foredeep in western Utah during the Late Jurassic. Although no Upper Jurassic foredeep deposits are preserved in western Utah, structural reconstructions of the Sevier belt indicate that >4 km of Upper Jurassic–Lower Cretaceous sediment could have been eroded from this area as a result of Cretaceous thrust-related uplift (Royse, 1993; Currie, 1997). Active Late Jurassic thrusting in the central Cordillera is supported by reconstructions of the Canyon Range thrust sheet that indicate >40 km of pre-Aptian displacement in west-central Utah, as well as pre-140 Ma emplacement of thrust ter-

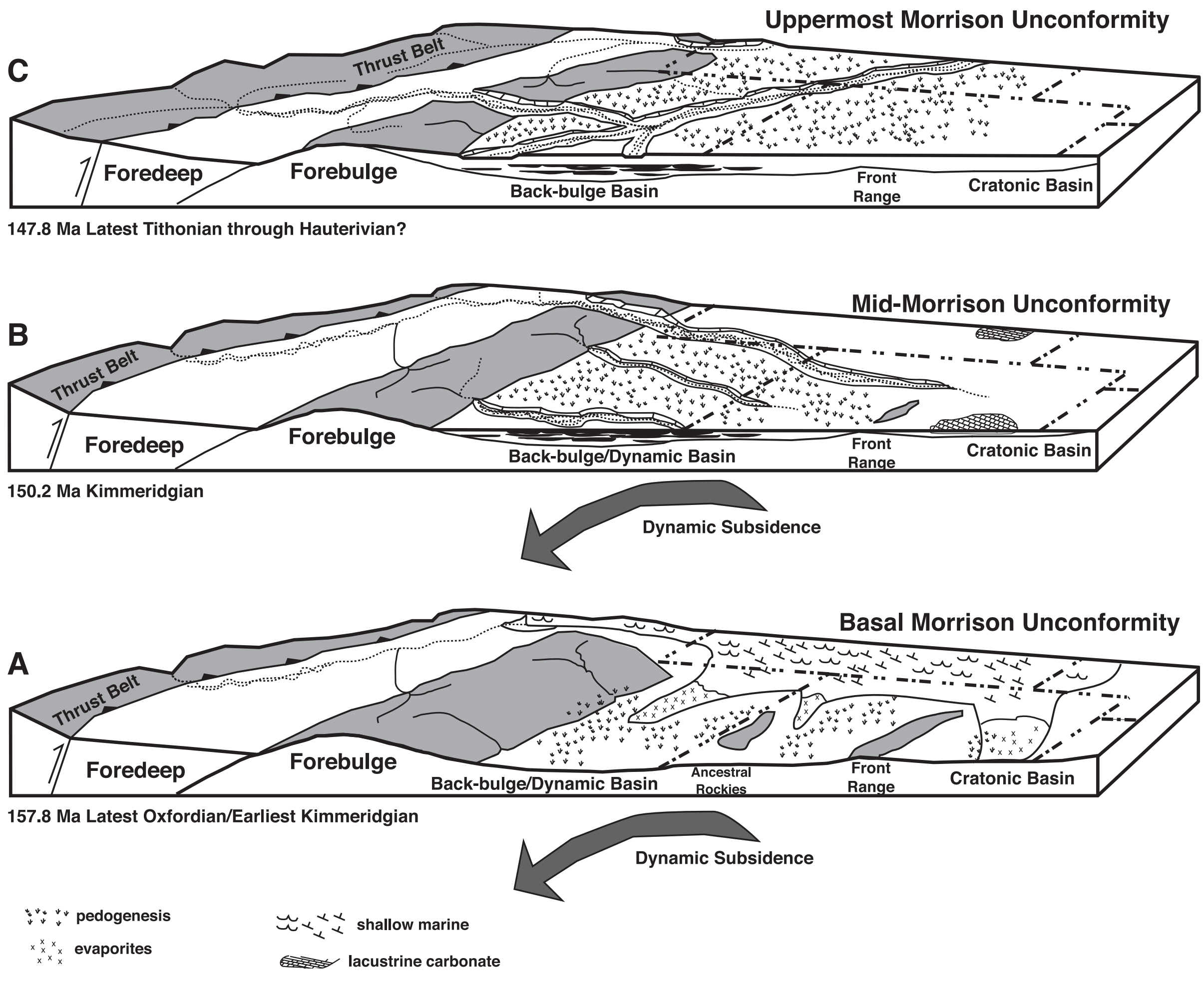


Fig. 8. Schematic block diagrams of the Morrison depositional basin in the Western Interior showing the areas of unconformity-related pedogenesis and relationship to regional tectonic events. Ages from Kowallis et al. (1998).

ranes in northern Utah (Camilleri et al., 1997; Currie, 1998).

Insofar as the amount of flexural subsidence in the back-bulge region predicted by flexural models is very low (< 20 m for normal crustal rigidities), the accommodation of >250 m of Morrison strata in some locations in the western interior must have been facilitated by some other geodynamic process. One possible mechanism is the long-wavelength subsidence that can be generated by subduction-related mantle circulation in areas far from the subduction zone (Mitrovica et al., 1989; Gurnis, 1992). Variations in the overall rate of this regional dynamic subsidence may have been responsible for not only the overall accommodation of Morrison strata across the western interior, but the internal unconformities in the Morrison depositional sequences as well (Lawton, 1994; Currie, 1997, 1998). Ultimately, a cessation of dynamic subsidence during the latest Jurassic (tied to a change in the angle of subduction along the western margin) may have resulted in a decrease in back-bulge accommodation, widespread fluvial incision and development of the upper Morrison unconformity paleosol (Fig. 8) (Currie, 1997).

5. Summary

Soils were an intrinsic part of the Morrison landscape and paleoecosystem. The paleosols exposed in outcrops of the Morrison contain excellent records of the long-term paleoclimatic and paleohydrologic conditions during the Late Jurassic. Floodplain and lake-margin paleosols that formed over tens to thousands of years show evidence that most of the Morrison basin was characterized by a semi-arid to seasonal paleoclimate with fluctuating groundwater conditions, a low precipitation to evaporation ratio, but with at least some seasonal precipitation. This interpretation largely agrees with a previous study that looked at assemblages of other sedimentary paleoclimatic indicators and comparisons with numerical and conceptual climate models (Demko and Parrish, 1998), and a study (concurrent with this one) of the composition and taphonomy of the Morrison Formation fossil plants (Parrish et al., this volume). Trace fossils within these ancient soils are evidence of a diverse and opportunistic flora and fauna. Changes in paleosol type and degree of development over the Western Interior depositional basin indicate that the overall regional paleoclimate was drier in the western and southern portions of the basin. Changes vertically through the Morrison indicate that paleoclimatic conditions over the basin became more humid through time. Finally, laterally continuous, well-developed, deeply weathered paleosols formed during times of little or no deposition and mark regional unconformities that can be traced across the basin and divide the formation into two aggradational sequences.

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References

Allen, A., 1996. Morrison Formation stratigraphy between the classic Como Bluff and Thermopolis areas, Wyoming. In: Hunter, R.A. (Ed.), Paleoenvironments of the Jurassic. Tate Museum Guidebook. Tate Museum, Casper, Wyoming, vol. 1, pp. 19–28.

Blodgett, R.H., 1985. Paleovertisols—their utility in reconstructing ancient fluvial floodplain sequences. Third International Fluvial Sedimentology Conference, Abstracts, 10.

Blodgett, R.H., 1990. Nonmarine depositional environments and paleosol development, Upper Triassic Dolores Formation, southwestern Colorado. PhD dissertation, The University of Texas at Austin. 646 pp.

Blodgett, R.H., Crabaugh, J., McBride, E.F., 1993. The color of red beds; a geologic perspective. In: Bingham, J.M., Ciolkosz, E.J. (Eds.), Soil Color. Soil Science Society of America Special Publication, vol. 31, pp. 127–159.

Camilleri, P., Yonkee, A., Coogan, J., DeCelles, P., McGrew, A., Wells, M., 1997. Hinterland to foreland transect through the Sevier Orogen, northeast Nevada to north central Utah; structural style, metamorphism, and kinematic history of a large contractional orogenic wedge. In: Link, P.K., Kowallis, B.J. (Eds.), Proterozoic to Recent Stratigraphy, Tectonics, and Volcanology, Utah, Nevada, Southern Idaho and Central Mexico-Geology Studies. Brigham Young University, Provo, Utah, vol. 42, pp. 297–309.

Campbell, C.V., 1976. Reservoir geometry of a fluvial sheet sandstone. American Association of Petroleum Geologists Bulletin 60, 1009–1020.

Condon, S.M., Peterson, F., 1986. Stratigraphy of the Middle and Upper Jurassic rocks of the San Juan basin: historical perspective, current ideas, and remaining problems. In: Turner-Peterson, C.E., Santos, E.S., Fishman, N.S. (Eds.), A Basin Analysis Case Study: the Morrison formation, grants uranium Region, New Mexico. American Association of Petroleum Geologists Studies in Geology. American Association of Petroleum Geologists, Tulsa, Oklahoma, vol. 22, pp. 7–26.

Cowan, E.J., 1991. The large-scale architecture of the fluvial Westwater Canyon Member, Morrison Formation (Upper Jurassic), San Juan basin, New Mexico. In: Miall, A.D., Tyler, N. (Eds.), The Three-dimensional Facies Architecture of Terrigenous Clastic Sediments and Its Implications for Hydrocarbon Discovery and RecoverySociety of Economic Paleontologists and Mineralogists Concepts in Sedimentology and Paleontology. Society for Sedimentary Geology, Tulsa, Oklahoma, vol. 3, pp. 80–93.

Craig, L.C., Holmes, C.N., Cadigan, R.A., Freeman, V.L., Mullens, T.E., Weir, G.W., 1955. Stratigraphy of the Morrison and related formations, Colorado Plateau region—a preliminary report. U.S. Geological Survey Bulletin 1009-E, 125–168.

Currie, B.S., 1997. Sequence stratigraphy of nonmarine Jurassic–Cretaceous rocks, central Cordilleran foreland-basin system. Geological Society of America Bulletin 109, 1206–1222.

Currie, B.S., 1998. Upper Jurassic–Lower Cretaceous Morrison and Cedar Mountain formations, NE Utah–NW Colorado: relationships between nonmarine deposition and early Cordilleran foreland-basin development. Journal of Sedimentary Research 68, 632–652.

DeCelles, P.G., Burden, E.T., 1992. A field test of foreland basin models in the overfilled, nonmarine part of the Jurassic–Cretaceous Cordilleran foreland basin, central Wyoming. AAPG Annual Meeting Abstracts. American Association of Petroleum Geologists, Tulsa, Oklahoma, p. 29.

DeCelles, P.G., Currie, B.S., 1996. Long-term sediment accumulation in the Middle Jurassic–Early Eocene Cordilleran retroarc foreland-basin system. Geology 24, 591–594.

Demko, T.M., Parrish, J.T., 1998. Paleoclimatic setting of the Upper Jurassic Morrison Formation. Modern Geology 22, 283–296.

Duchaufour, P., 1982. Pedology Allen and Unwin, London.

Dunagan, S.P., 1998. Lacustrine and palustrine carbonates from the Morrison Formation (Upper Jurassic), east-central Colorado, USA: implications for depostitional patterns, paleoecology, paleohydrology, and paleoclimatology. PhD dissertation, University of Tennessee, Knoxville. 276 pp.

Dunagan, S.P., 2000. Constraining late Jurassic paleoclimate within the Morrison paleoecosystem: Insights from the terrrestrial carbonate record of the Morrison Formation (Colorado, U.S.A.)P-Proceedings of the Fifth International Symposium on the Jurassic System, vol. 6. Trans Tech Publications, Switzerland, pp. 523–532.

Dunagan, S.P., Turner, C.E., 2004. Regional paleohydrologic and paleoclimatic settings of lacustrine depositional systems in the Morrison Formation (Upper Jurassic), Western Interior, U.S.A. Sedimentary Geology 167, 269–296 (this volume).

Galloway, W.E., 1980. Deposition and early hydrologic evolution of the Westwater Canyon wet alluvial fan system. In: Rautman, C.A. (Ed.), Geology and Mineral Technology of the Grants Uranium Region. New Mexico Bureau of Mines and Mineral Resources Memoir. New Mexico Bureau of Geology & Mineral Resources, Socorro, New Mexico, vol. 38, pp. 59–69.

Godin, P.D., 1991. Fining-upward cycles in the sandy braided-river deposits of the Westwater Canyon Member (Upper Jurassic), Morrison Formation, New Mexico. Sedimentary Geology 70, 61–82.

Goudie, A., 1973. Duricrust in Tropical and Subtropical Landscapes Clarendon Press, Oxford. 174 pp.

Gurnis, M., 1992. Rapid continental subsidence following the initiation and evolution of subduction. Science 255, 1556–1558.

Hasiotis, S.T., 2004. Reconnaissance of Upper Jurassic Morrison Formation ichnofossils, Rocky Mountain Region, U.S.A.: Paleoenvironmental, stratigraphic, and paleoclimatic significance of terrestrial and freshwater ichnocoenoses. Sedimentary Geology 167, 179–270 (this volume).

Hasiotis, S.T., Demko, T.M., 1996. Terrestrial and freshwater trace fossils, Upper Jurassic Morrison Formation, Colorado Plateau. In: Morales, M. (Ed.), The Continental Jurassic Museum of Northern Arizona Bulletin. Museum of Northern Arizona, Flagstaff, Arizona, vol. 60, pp. 355–370.

Hasiotis, S.T., Demko, T.M., 1998. Ichnofossils from Garden park Paleontological Area, Colorado: implications for paleoecologic and paleoclimatic reconstructions of the Upper Jurassic. Modern Geology 22, 461–479.

Kirk, A.R., Condon, S.M., 1986. Structural control of sedimentation patterns and the distribution of uranium deposits in the Westwater Canyon Member of the Morrison Formation, northwestern New Mexico—a subsurface study. In: Turner-Peterson, C.E., Santos, E.S., Fishman, N.S. (Eds.), A Basin Analysis Case Study—The Morrison Formation, Grants Uranium Region, New Mexico. American Association of Petroleum Geologists Studies in Geology. American Association of Petroleum Geologists, Tulsa, Oklahoma, vol. 22, pp. 105–143.

Kowallis, B.J., Christiansen, E.H., Deino, A.L., Peterson, F., Turner, C.E., Kunk, M.J., Obradovich, J.D., 1998. The age of the Morrison Formation. Modern Geology 22, 235–260.

Kraus, M.J., 1997. Lower Eocene alluvial paleosols: pedogenic development, stratigraphic relationships, and paleosol/landscape associations. Palaeogeography, Palaeoclimatology, Palaeoecology 129, 387–406.

Lawton, T.F., 1994. Tectonic setting of Mesozoic sedimentary basins, Rocky Mountain region, United States. In: Caputo, M.V., Peterson, J.A., Franczyk, K.J. (Eds.), Mesozoic Systems of the Rocky Mountain Region, U.S.A. SEPM Rocky Mountain

Section, Denver, CO. Society for Sedimentary Geology, Tulsa, Oklahoma, pp. 1–25.

Mack, G.H., James, W.C., 1994. Paleoclimate and the global distribution of paleosols. Journal of Geology 102, 360–366.

Mack, G.H., James, W.C., Monger, H.C., 1993. Classification of paleosols. Geological Society of America Bulletin 105, 129–136.

Miall, A.D., Turner-Peterson, C.E., 1989. Variations in fluvial style in the Westwater Canyon Member, Morrison Formation (Jurassic) San Juan Basin, Colorado Plateau. Sedimentary Geology 63, 21–60.

Mitrovica, J.X., Beaumont, C., Jarvis, G.T., 1989. Tilting of continental interiors by the dynamical effects of subduction. Tectonics 8, 1079–1094.

Naiman, Z., Quade, J., Patchett, P.J., 2000. Isotopic evidence for eolian recycling of pedogenic carbonate and variations in carbonate dust sources throughout the southwest United States. Geochimica et Cosmochimica Acta 64, 3099–3109.

Newell, D.L., 1997. Geology of the Brushy Basin Member of the Morrison Formation, Fruita Paleontological Resource Area, Colorado. MS Thesis. Colorado State University. 197 pp.

O'Sullivan, R.B., 1992. The Jurassic Wanakah and Morrison Formations in the Telluride–Ouray–western Black Canyon area of southwestern Colorado. U.S. Geological Survey Bulletin 1927 (24 pp.).

O'Sullivan, R.B., Pierce, F.W., 1983. Stratigraphic diagram of Middle Jurassic San Rafael Group and associated formations from the San Rafael Swell to Bluff in southeastern Utah. U.S. Geological Survey Oil and Gas Investigations Chart OC-119.

Parrish, J.T., Peterson, F., Turner, C.E. Jurassic "savannah"—Plant taphonomy and climate of the Morrison Formation (Jurassic, Western U.S.A). Sedimentary Geology (this volume).

Peterson, F., 1980. Sedimentology of the uranium-bearing Salt Wash Member and Tidwell unit of the Morrison Formation in the Henry and Kaiparowits basins, Utah. In: Picard, M.D (Ed.), Henry Mountains Symposium Utah Geological Association Publication. Utah Geological Association, Salt Lake City, Utah, vol. 8, pp. 305–322.

Peterson, F., 1984. Fluvial sedimentation on a quivering craton: influence of slight crustal movements on fluvial processes, Upper Jurassic Morrison Formation, western Colorado Plateau. Sedimentary Geology. American Association of Petroleum Geologists, Tulsa, Oklahoma, vol. 38, pp. 21–49.

Peterson, F., 1986. Jurassic paleotectonics in the west-central part of the Colorado Plateau, Utah and Arizona. In: Peterson, J.A. (Ed.), Paleotectonics and Sedimentation in the Rocky Mountain Region, United States American Association of Petroleum Geologists Memoir, vol. 41, pp. 563–593.

Peterson, F., 1988. Stratigraphy and nomenclature of Middle and Upper Jurassic rocks, western Colorado Plateau, Utah and Arizona. U.S. Geological Survey Bulletin 1633B, 17–56.

Peterson, F., 1994. Sand dunes, sabkhas, streams, and shallow seas: Jurassic paleogeography in the southern part of the Western Interior Basin. In: Caputo, M.V., Peterson, J.A., Franczyk, K.J. (Eds.), Mesozoic Systems of the Rocky Mountain Region, U.S.A. SEPM Rocky Mountain Section. Society for Sedimentary Geology, Tulsa, Oklahoma, pp. 233–272.

Pipiringos, G.N., O'Sullivan, R.B., 1978. Principal unconformities in Triassic and Jurassic rocks, Western Interior United States—a preliminary survey. U.S. Geological Survey Professional Paper 1035-A (29 pp.).

Retallack, G.J., 1991. Untangling the effects of burial alteration and ancient soil formation. Annual Review of Earth and Planetary Sciences 19, 183–206.

Retallack, G.J., 1997. Dinosaurs and dirt. In: Wolberg, D.L, Stump, E. (Eds.), Dinofest International Proceedings. Dinofest (TM), pp. 345–359.

Robinson, J.W., McCabe, P.J., 1997. Sandstone-body and shale-body dimensions in a braided fluvial system: salt wash sandstone member (Morrison Formation), Garfield County, Utah. AAPG Bulletin 81, 1267–1291.

Robinson, J.W., McCabe, P.J., 1998. Evolution of a braided river system: the salt wash member of the Morrison formation (Jurassic) in southern Utah. In: Shanley, K.W., McCabe, P.J. (Eds.), Relative Role of Eustacy, Climate, and Tectonism in Continental Rocks. SEPM Special Publication. Sedimentary Geology, Tulsa, Oklahoma, vol. 59, pp. 93–107.

Royse, F., 1993. Case of the phantom foredeep; Early Cretaceous in west-central Utah. Geology 21, 133–136.

Taylor, W.J., Bartley, J.M., Martin, M.W., Geissman, J.W., Walker, J.D., Armstrong, P.A., Fryxell, J.E., 2000. Relations between hinterland and foreland shortening; Sevier Orogeny, central North American Cordillera. Tectonics 19, 1124–1143.

Turner, C.E., Fishman, N.S., 1991. Jurassic Lake T'oo'dichi': a large alkaline, saline lake, Morrison Formation, eastern Colorado Plateau. Geological Society of America Bulletin 103, 538–558.

Turner-Peterson, C.E., 1986. Fluvial sedimentology of a major uranium-bearing sandstone—a study of the Westwater Canyon Member of the Morrison Formation, San Juan basin, New Mexico. In: Turner-Peterson, C.E., Santos, E.S., Fishman, N.S. (Eds.), A Basin Analysis Case Study: the Morrison Formation, Grants Uranium Region, New Mexico. American Association of Petroleum Geologists Studies in Geology. American Association of Petroleum Geologists, Tulsa, Oklahoma, vol. 22, pp. 47–75.

Tyler, N., Ethridge, F.G., 1983a. Depositional setting of the Salt Wash Member of the Morrison Formation, southwest Colorado. Journal of Sedimentary Petrology 53, 67–82.

Tyler, N., Ethridge, F.G., 1983b. Fluvial architecture of Jurassic uranium-bearing sandstones, Colorado Plateau, western United States. In: Collinson, J.D., Lewin, J. (Eds.), Modern and Ancient Fluvial Systems. International Association of Sedimentologists Special Publication. Blackwell, Oxford, vol. 6, pp. 533–547.

Vepraskas, M.J., 1994. Redoximorphic features for identifying aquic conditions. North Carolina Agricultural Resource Services Technical Bulletin 301.

Wood, H.B., 1956. Relations of the origin of the host rocks to uranium deposits and ore production in the western United States. U.S. Geological Survey Professional Paper 300, 533–541.