

Mudrock-dominated fills formed in avulsion splay channels: examples from the Willwood Formation, Wyoming

MARY J. KRAUS* and K. SIAN DAVIES-VOLLUM†

**Department of Geological Sciences, University of Colorado, Boulder, CO 80309-0399, USA (E-mail: Mary.Kraus@colorado.edu)*

†*Interdisciplinary Arts and Sciences, University of Washington Tacoma, Box 358436, 1900 Commerce St., Tacoma, WA 98402, USA*

ABSTRACT

Mudrock-dominated channel fills are common features of the fluvial Palaeogene Willwood Formation of Wyoming. These fills are small, on average 30 m wide and 3 m deep, and they vary from simple plugs to more lithologically complex fills with internal scour surfaces. Some fills preserve plant material, and others show pedogenic modification. All fills are located within metre-thick intervals of weakly pedogenically modified mudstones that surround ribbon sandstones. The intervals have previously been attributed to channel avulsion; the fine-grained channel fills are interpreted as crevasse-splay feeder channels within these avulsion deposits. Variation in fill type, particularly the presence of pedogenic features, appears to be related to floodplain drainage. Possible factors that influenced drainage were basin position of the fills and Palaeogene climate fluctuations, although the role of either is not unequivocal. In general, channel fills with sombre colours and preserved plant detritus, indicating poorly drained conditions, dominate locations that were proximal to the Palaeogene basin axes. Fills that contain root traces, red and yellow-brown matrix colours and mottling, which indicate pedogenic modification and episodic subaerial exposure of the sediment, dominate locations that were more distal to the Palaeogene basin axes. Eocene climate fluctuations, particularly episodes of global warming, may have been a secondary control on the kind of fill that developed. Mudrock-dominated channel fills have not been described previously from ancient avulsion deposits. Their common presence in the Willwood Formation suggests that they are a typical component of avulsion belts and that similar channel fills in other stratigraphic units should be considered with regard to channel avulsion. The variety of fills observed in the Willwood Formation indicates that avulsion belt channels can experience very different fill histories. The descriptive details of fills provided here should help in their recognition elsewhere. In addition, the nature of the channel fill provides important information on ancient drainage conditions in the avulsion belt. Pedogenically modified channel fills have been recognized only rarely from the stratigraphic record. Their presence throughout the Willwood Formation suggests that they should exist in other alluvial successions and may have been overlooked previously. They indicate that periods of sediment exposure alternated with episodic influxes of water and sediment in an active avulsion belt.

Keywords Abandoned channel, avulsion, channel fills, palaeosol.

INTRODUCTION

Previous research on fluvial cut-and-fill structures at the channel scale has emphasized gravelly and/or sandy bedload fills (e.g. Allen, 1965; Miall, 1985; Mackey & Bridge, 1995). Work on fine-grained, suspended-load channel fills has focused on the formation of oxbow lakes in meandering river systems (e.g. Allen, 1970; Lewis & Lewin, 1983; Walker & Cant, 1984). Descriptions of fine-grained fills are uncommon, and most are in the context of channel abandonment in anastomosing river systems (e.g. Eberth & Miall, 1991; Kirschbaum & McCabe, 1992) or incision related to a drop in base level (Kraus & Bown, 1993). Only rarely have fine-grained channel fills been considered in the context of channel avulsions (e.g. Berendsen, 1982; Stouthammer, 2001).

This study describes mudrock-dominated channel fills from the Palaeogene Willwood Formation and documents their relationship to previously recognized avulsion deposits (Kraus & Wells, 1999; Davies-Vollum & Kraus, 2001). Although some fills consist only of carbonaceous shale, mudstone and siltstone, most fills also include some sandstone. Fifty-seven mudrock-filled channels have been studied, and these identify four types of fill that appear to be related to different palaeodrainage conditions. The geographic and stratigraphic distributions of the different types of channel fill are examined, and the factors that might have influenced these distributions are discussed.

This study indicates that mudrock-dominated channel fills should be present in other alluvial successions and that they might be examined in the context of channel avulsions. Kraus (1996) suggested that avulsion deposits may be relatively common in the stratigraphic record but misidentified. In particular, pedogenically modified fills, which are common in some parts of the Willwood section, may be an important tool for recognizing ancient avulsion belts in other alluvial basins. In addition, the nature of the channel fill provides important information on ancient drainage conditions on the floodplain.

GEOLOGICAL SETTING

The Willwood Formation consists of fluvial strata that accumulated during latest Palaeocene and early Eocene time in the Bighorn Basin and the Clark's Fork Basin, a small basin north of the

Bighorn Basin and separated from it by a NE-trending subsurface arch in the vicinity of the Shoshone River (Neasham & Vondra, 1972; Gingerich, 1983; Parker & Jones, 1986a; DeCelles *et al.*, 1991; Fig. 1A). The Bighorn, Beartooth and Owl Creek ranges, which formed during the Laramide orogeny, were the main source of sediments; however, most orogenic uplift of these ranges had ceased before Willwood deposition (Omar *et al.*, 1994). The basin is bounded to the west by the Absaroka volcanic complex, which formed after deposition of the Willwood Formation (Bown, 1980). The basin was open to the north.

The structural and depositional history of the Palaeogene deposits was controlled by several major thrust faults that dip to the west and have lateral and vertical offsets that can be measured in tens of kilometres (Fig. 1A). The faults are considered to have been the result of north-east-south-west compression related to the Laramide orogeny (Stone, 1985; Blackstone, 1986). These deep-seated faults cut the Precambrian basement and the sedimentary section older than the Willwood Formation; however, seismic data show that Willwood strata are not cut, and fault motion is believed to have terminated by the end of Palaeocene time (Stone, 1985; Parker & Jones, 1986a).

The Bighorn Basin and the position of its axis were influenced by the Oregon Basin fault, which is about 120 km long (Fig. 1A). Seismic data show that this west-dipping fault has a vertical offset of 6100 m and a horizontal offset of 4000 m (Stone, 1985). Uppermost Cretaceous and Palaeogene deposits thicken towards the Oregon Basin fault and indicate that there was an actively subsiding, north- to south-oriented depocentre just east of that fault (Parker & Jones, 1986a,b). The structural axis of the Clark's Fork Basin is offset from that of the main Bighorn Basin and, to the north, is overridden by the fault-bounded Beartooth Mountains (Foose *et al.*, 1961; Bonini & Kinard, 1983; Fig. 1A). A second major thrust fault – the Line Creek fault – influenced the Clark's Fork Basin (Fig. 1A). Earliest movement on that fault is believed to have been during early Palaeocene time and, because the Willwood Formation is not cut by the fault, fault motion had ended by latest Palaeocene time (Blackstone, 1986). The axis of the Clark's Fork Basin shifted westward during Palaeocene time, and Gingerich (1983) has shown that, by middle Late Palaeocene time, it was on the west side of the basin close to the Line Creek fault (Fig. 1A). That position is confirmed by isopach maps of the Palaeocene Fort Union Formation (Moore, 1961).

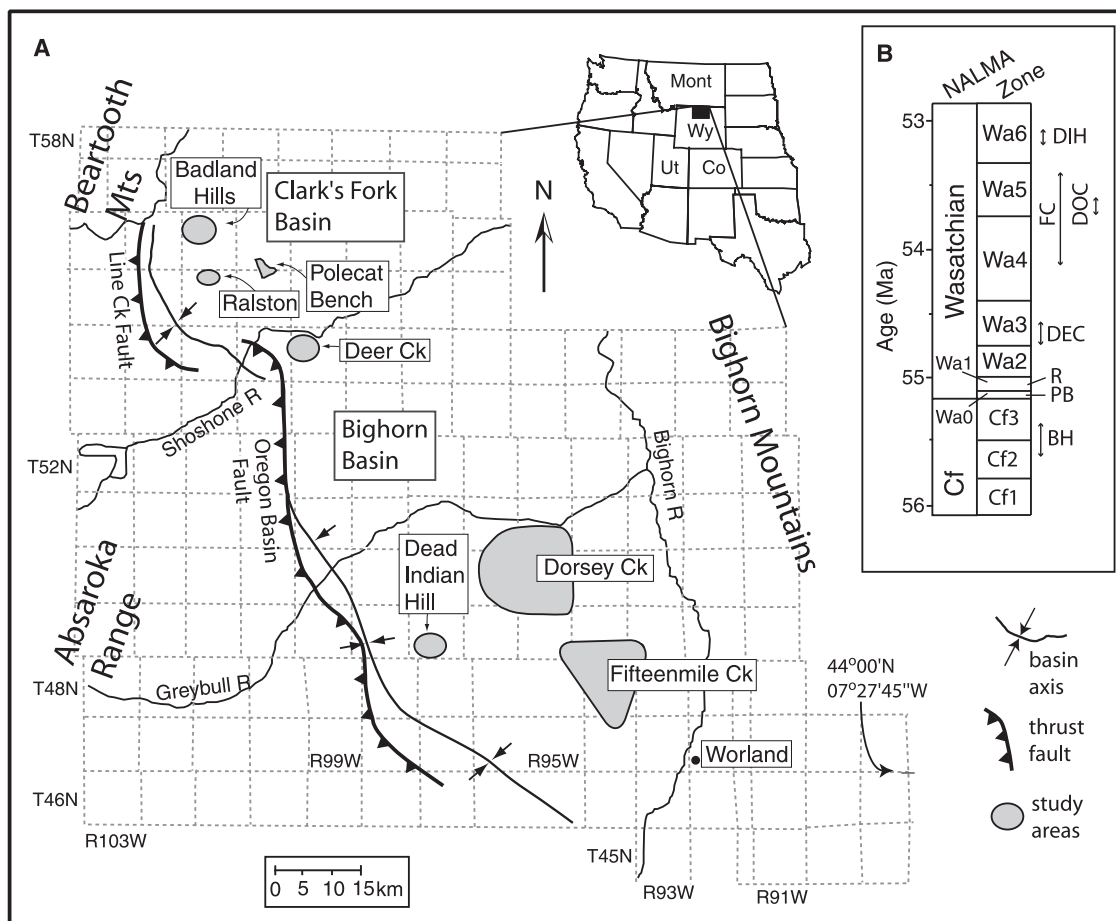


Fig. 1. (A) Map of the Bighorn and Clark's Fork basins showing the study areas and major structural features of the basins. Basin axes from Parker & Jones (1986a). (B) Diagram showing correlations of study sections in the Willwood Formation to biostratigraphic zones and North American Land Mammal Ages (NALMA). Radiometric age from Wing *et al.* (2000). BH, Badland Hills; PB, Polecat Bench; R, Ralston; DEC, Deer Creek; FC, Fifteenmile Creek; DOC, Dorsey Creek; DIH, Dead Indian Hill.

The climate during deposition of the Willwood Formation was generally subtropical with seasonal rainfall; however, leaf margin analysis of Willwood palaeofloras shows that mean annual temperature (MAT) fluctuated significantly (Wing *et al.*, 1995; Bao *et al.*, 1999; Wing, 2000; Wing *et al.*, 2000). Over the last ≈ 1 million years of the Palaeocene, MAT rose from ≈ 13 °C to over 15 °C. MAT reached 18 °C during earliest Eocene time but then dropped to ≈ 11 °C during the first million years of the Eocene. This strong temperature decline was followed by a rapid increase to ≈ 22 °C by the end of Willwood deposition.

DEPOSITIONAL SETTING

Because the strata are nearly flat-lying, continuous stratigraphic sections of the Willwood

Formation are not available. Analysis of the Willwood fluvial system is based on relatively thin intervals (≈ 100 m or less) deposited at different times in different areas of the basin (e.g. Bown & Kraus, 1993; Kraus & Aslan, 1993; Kraus, 2002). Records of long-term depositional change are based on composite stratigraphic sections that have been compiled from a number of vertical sections in different areas. The composite sections have been constructed using the detailed biostratigraphy available for the Willwood Formation (Gingerich, 1983; Bown *et al.*, 1994; Clyde, 1997, 2001).

Everywhere it has been examined, the Willwood Formation is composed of relatively fine-grained alluvial successions, which have been divided into three major elements (Kraus & Aslan, 1993; Kraus, 1996, 2002). The first element – major sandstone bodies that are multistoreyed,

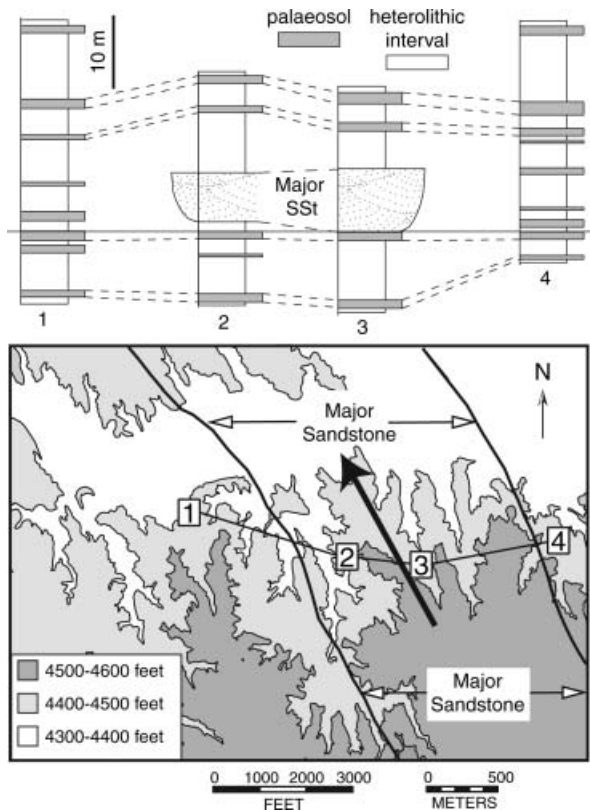


Fig. 2. Logged sections in the Dorsey Creek area (see Fig. 1 for location) showing the typical arrangement of facies in the Willwood Formation. Heterolithic intervals, which consist of small channel sandstones surrounded by mudrocks showing weak pedogenesis, are interpreted as avulsion deposits. Well-developed palaeosols can be traced laterally. A major channel sandstone, which is 1.5 km wide and 10 m thick, locally truncates both the palaeosols and the avulsion deposits. Locations of the stratigraphic sections are shown in the simple topographic map below. Large arrow shows summary palaeoflow direction of the channel sandstone (modified from Kraus, 2002).

10–30 m thick and up to 1.5 km wide – are interpreted as the deposits of major meandering channels (Kraus & Aslan, 1993; Kraus, 2002; Fig. 2). Palaeocurrents measured from these sandstone bodies show that the major drainage in the basin was from south-east to north-west, parallel to the basin axis (Neasham & Vondra, 1972; Kraus & Aslan, 1993; Kraus, 2002).

The second element comprises fine-grained deposits that show moderate to strong palaeosol development (Fig. 2). Characteristics indicative of palaeosol development include red, purple and yellow-brown mudrock colours, yellow-brown and purple mottles, iron oxide and carbonate nodules, slickensides, root traces and burrows (Kraus & Aslan, 1993; Kraus, 1996). Gradual

downward changes in grain size and geochemistry indicate that the parent material, which consisted of floodplain deposits, was homogenized by pedogenic processes (Kraus & Aslan, 1993). Individual palaeosol profiles can be several metres thick and have well-differentiated horizons. Although these fine-grained intervals may be cut by ribbon sandstones, those sandstones originate from and are temporally associated with heterolithic deposits overlying the palaeosol intervals.

The fine-grained intervals alternate vertically with the third element – heterolithic intervals that consist of fine-grained deposits, which show weak soil development, and ribbon and thin sheet sandstones, which show little or no pedogenic development (Kraus & Aslan, 1993; Kraus & Wells, 1999). These deposits are volumetrically significant in the Willwood Formation, making up $\approx 40\%$ of the strata (Kraus & Wells, 1999). The heterolithic intervals have a sheet-like geometry. They are generally 3–7 m thick and can be traced for distances up to 5 km, both transverse and parallel to the general palaeodrainage direction. Over those distances, they show no evidence of thinning, suggesting that they originally extended much further, although they are now either eroded or covered.

The fine-grained deposits show evidence of pedogenic modification including mottling, root traces and burrows; however, relict stratification is locally present and horizon development is weak. Where they can be delimited, palaeosol profiles are thin (< 1 m thick) and vertically stacked. These features are typical of palaeosols that are weakly developed.

Most of the ribbon sandstones in the heterolithic intervals are lenticular in cross-section, generally have width to thickness (W/T) ratios of less than 10 and range from 0.3 to 9 m in thickness. Larger ribbons are thicker than about 3 m and usually have two storeys separated by an erosion surface. Smaller ribbons (< 3 m thick) commonly have a single storey. Lateral accretion deposits are absent, and individual ribbons, where preserved, are straight to gently curved in plan view (Fig. 3). Palaeocurrents have been determined from large-scale cross-bedding and, in some cases, from the trends of laterally traceable ribbons. Larger ribbons generally show palaeoflow parallel to flow in major sheet sandstones that are present in the same area and the same part of the stratigraphic section (Kraus, 1996; Kraus & Gwinn, 1997; Kraus & Wells, 1999). Smaller ribbons have variable palaeocurrent

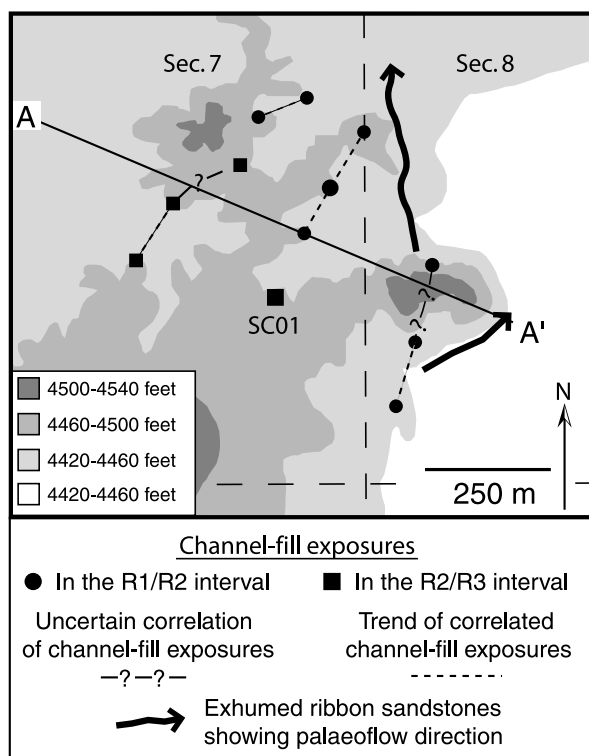


Fig. 3. Topographic map of the Badland Hills study area showing the locations of fine-grained channel fills at two stratigraphic levels. Arrows represent mapped distributions and directions of palaeoflow for two ribbon sandstones in the study area. Refer to Fig. 4 for line of section and Fig. 9 for stratigraphic section at SC01.

trends (Kraus & Wells, 1999; Davies-Vollum & Kraus, 2001).

The heterolithic intervals have been interpreted as ancient avulsion belt deposits formed as the trunk channels avulsed and became abandoned (Kraus & Aslan, 1993; Kraus, 1996; Kraus & Wells, 1999). They are analogous to modern deposits described from the Saskatchewan River (Smith *et al.*, 1989; Smith & Perez-Arlucea, 1994; Slingerland & Smith, 2004). In the abandonment process observed in that system, a network of splay channels takes up flow from the formerly dominant channel, and those networks spread water and sediment on to low parts of the adjacent floodplain. The deposits consist of ribbon sands, representing deposits of the splay channels, and fine-grained deposits representing flood-basin deposits associated with the splay channels. Soils formed on the fine-grained deposits are only weakly developed because deposition of the avulsion deposits was rapid (tens to hundreds of years; Smith *et al.*, 1989). The heterolithic avulsion deposits are laterally extensive (Figs 2 and 3), which is consistent with the

modern example described by Smith *et al.* (1989), covering roughly 500 km².

FINE-GRAINED CHANNEL-FILL DEPOSITS

Channels with fills that are dominated by fine-grained deposits are common in the Willwood Formation. The 57 fine-grained fills that have been studied are distributed throughout the Big Horn and Clark's Fork basins and at all stratigraphic levels of the Willwood Formation (Table 1). These sites can be broadly divided into seven areas: Badland Hills, Ralston, Polecat Bench, Deer Creek, Dorsey Creek, Fifteenmile Creek and Dead Indian Hill (Fig. 1). Based on the biostratigraphic studies of Gingerich (1983, 2001), Gingerich & Klitz (1985), Bown *et al.* (1994) and Clyde (1997, 2001), the fills can be assigned to different Palaeogene biozones. The fills studied in the Badland Hills area are located in strata assigned to the upper part of the Clarkforkian-2 (Cf-2) and lower part of the Clarkforkian-3 (Cf-3) biozones (Gingerich, 1983), making them the oldest fills in this study (Table 1; Fig. 1B). The fills studied at south Polecat Bench are located near the base of the Wasatchian-0 (Wa-0) biozone (e.g. Koch *et al.*, 1995; Gingerich, 2001), and those studied in the Ralston area formed during Wasatchian-1 (Wa-1) time. Willwood strata in the Deer Creek area have been assigned to the lower part of the Wa-3 biozone (Clyde, 1997, 2001). Fills in the Dorsey Creek area and fills from along Fifteenmile Creek are stratigraphically higher (Wa-4 to Wa-5; Bown *et al.*, 1994). Fills from Dead Indian Hill correspond to the middle of Wa-6 (Bown *et al.*, 1994).

General characteristics

In the field, the channel fills described in this study are recognized as bodies of predominantly fine-grained, horizontally bedded sedimentary rocks that sit within U-shaped erosion surfaces that truncate other fine-grained deposits (Figs 4 and 5). The fills can be recognized in the field because they differ from the truncated, confining deposits in colour and, less strikingly, in lithology (Fig. 5). Some fills are entirely fine-grained with mudstones and siltstones and, in some examples, carbonaceous shales. Most fills also contain sandstone beds, generally at the base of the fill, and some contain a second sandstone bed higher within the fill (Fig. 6).

Locality	LMA zone	Total no. of fills	No. of fill types	W/T of fill
Badland Hills	Cf2–Cf3	14	Type 1: 3 Type 2: 2 Type 3 total: 3 3b: 2 3c: 1 Type 4: 6	Range: 5–55 Avg: 20
Polecat Bench	Wa0	6	Type 2: 1 Type 3 total: 5 3b: 1 3c: 4	Range: 4–54 Avg: 22
Ralston	Wa1	4	Type 1: 2 Type 2: 1 Type 4: 1	Range: 8–36 Avg: 19
Deer Creek	Wa3	8	Type 1: 2 Type 2: 3 Type 3 total: 3 3a: 1 3b: 1 3c: 1	Range: 5–41 Avg: 14.5
Dorsey Creek	Wa5	17	Type 2: 1 Type 3 total: 16 3a: 2 3b: 10 3c: 4	Range: 3–36 Avg: 17
Fifteenmile Creek	Wa4–Wa5	3	Type 3 total: 3 3c: 3	Range: 9.5–18 Avg: 13.8
Dead Indian Hill	Wa6	5	Type 3 total: 5 3b: 2 3c: 3	Range: 7.5–15.5 Avg: 11.4

Table 1. Survey of channel fills by area (57 fills analysed).

Although many channel fills are only partially preserved, those that can be measured range in depth from 0.5 to 10 m and average \approx 3 m. Maximum widths vary from 10 to 100 m but average less than 30 m. Width to thickness ratios for the channel-fill deposits are variable but average 20 m or less at most localities (Table 1).

More than two-thirds of the fills incise from a level of drab, heterolithic strata interpreted as avulsion deposits (Figs 4 and 5). The stratigraphic positions of the remaining fills cannot be determined because the sections above them are eroded. The channels commonly cut down through avulsion-associated heterolithic intervals, and some cut through the strongly developed palaeosol below an avulsion interval. For example, fill 'a' in Fig. 4 fills a 4.6 m deep channel that originates within a heterolithic interval between two red palaeosols (R3 and R4) and incises the lower palaeosol (R3).

The channel-fill exposures are generally isolated, and most cannot be connected along palaeoflow. However, rare examples of fills can be correlated between exposures because of the three-dimensional nature of the outcrops.

Correlation of these fills suggests that they represent parts of the same channel. For example, the Sand Coulee area contains at least 12 exposures of fine-grained channel fills that originate within two heterolithic intervals, either between palaeosols R1 and R2 or between palaeosols R3 and R4 (Figs 3 and 4), suggesting that the fills formed during two different episodes of channel erosion and filling. Figure 3 shows a map view of correlations among those exposures. These fills that can be laterally connected, indicating that they formed as part of the same channel, can be traced for distances of more than 250 m and show little variation in fill type or geometry over this distance. In plan view, the fills are relatively straight to moderately sinuous. The fills in this example generally trend NE–SW and parallel the trend of several exhumed ribbon sandstones that are at the same stratigraphic level (Fig. 3).

Interpretation

The channel-form shape of the fills in cross-section and the lateral continuity of the better preserved deposits suggest that they formed

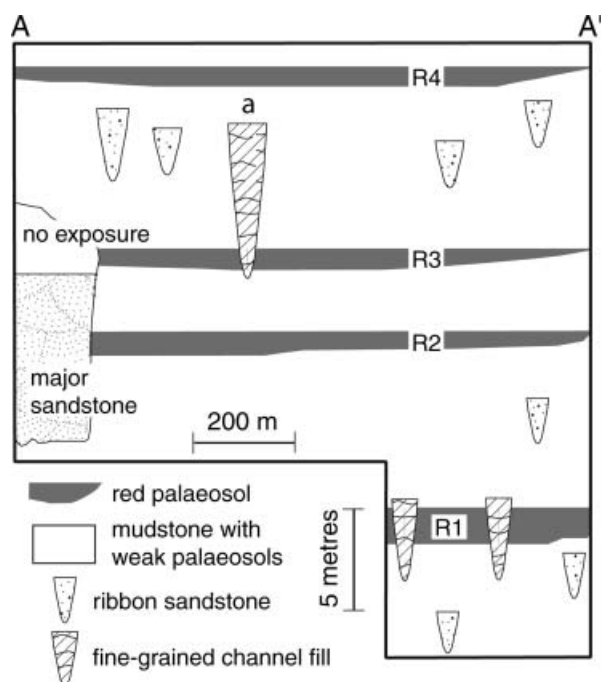


Fig. 4. Cross-section through deposits in the Badland Hills study area. Heterolithic deposits consist of fine-grained deposits (white) that show weak pedogenesis and ribbon sandstones. They are interbedded with red palaeosols (labelled R1 to R4). U-shaped scours filled dominantly by fine-grained deposits incise from the level of several heterolithic intervals. A major sandstone locally truncates both heterolithic intervals (avulsion deposits) and red palaeosols. Line of cross-section is shown in Fig. 3. R4 is used as datum for the section.

within small channels. The stratigraphic position of the channel fills within the heterolithic intervals, their cross-section widths and thicknesses and their plan view patterns are similar to those of the ribbon sandstones that are found in what have been interpreted as avulsion deposits. These similarities suggest that the fine-grained fills initiated as feeder channels in avulsion belts in a manner similar to the ribbon sandstones (Smith *et al.*, 1989; Kraus & Wells, 1999).

The grain size of sediment in the Willwood channel fills is thought to have been controlled by the proximity of the channel reach to the avulsion node on the trunk channel and by whether the splay channel was abandoned or remained active during filling (Fig. 7). The ribbon sandstones represent splay channels that remained active until they filled with sand and were abandoned. Most of the channel fills with sandstone in addition to fine-grained deposits are attributed to splay channels that were abandoned shortly after they formed and that later filled with mainly

fine-grained sediment. Newly abandoned channels may stay partly active but, as upstream filling continues in a particular channel reach, downstream flows become weaker, allowing only finer materials to accumulate from suspension in the abandoning reach. The Willwood channel fills that contain only fine-grained deposits and carbonaceous material are interpreted as downflow reaches of the splay channels that were too far from the avulsion node to receive bedload. The latter filled either when they were still active (rarely) or, more commonly, after they had been abandoned (Fig. 7). These interpretations are consistent with the observations of Smith & Perez-Arlucea (1994), who found that upflow reaches of splay channels fill with sand unless they are abandoned, whereas downflow reaches may fill with silt. They are also compatible with the observations of Berendsen (1982) and Stouthammer (2001), who recognized distal splay channels that filled with finer suspended sediment after they were abandoned.

TYPES OF MUDROCK-DOMINATED CHANNEL-FILL DEPOSITS

Four general types of mudrock-dominated fills are recognized: (1) type 1 – simple, low-chroma (greyish), mudrock fill; (2) type 2 – carbonaceous shale fill; (3) type 3 – pedogenically altered mudrock fill; (4) type 4 – complex fill with coarse-grained and fine-grained deposits. This section describes the four different fill types, and the following section explores how the different kinds of fill formed.

Type 1 fills

Type 1 fills (Fig. 5A) are composed mainly of low-chroma and green mudrock and sandy mudrock. The mudrock shows weak bedding and local bioturbation. Fossil plant material is rare and poorly preserved. Type 1 fills lack sedimentary structures that might indicate significant breaks in sedimentation during filling; they do contain single or, more rarely, multiple fining-upwards successions. Seven type 1 fills are recognized.

Interpretation

Type 1 fills were deposited relatively rapidly as indicated by fining-upward successions and the absence of internal scour surfaces. Relict bedding is present and pedogenic features are absent; this is attributed to rapid filling as well as to a high

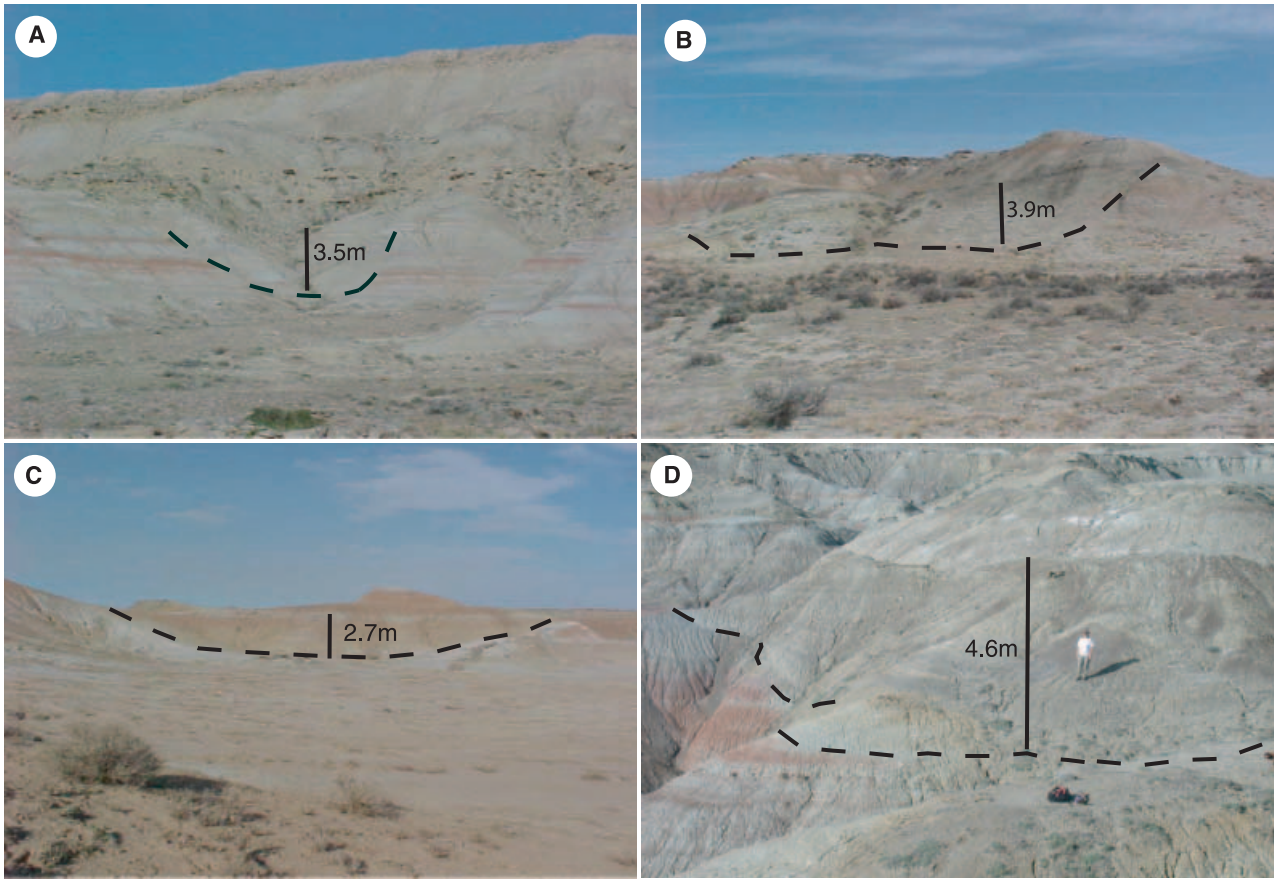


Fig. 5. Field photographs showing examples of each type of fine-grained channel fill. (A) Type 1 (simple) fill from Badland Hills; fill is 3.5 m thick. (B) Type 2 (carbonaceous shale) fill from Dorsey Creek; fill is 3.9 m thick. (C) Type 3b (pedogenically altered) fill from Dorsey Creek; fill is 2.7 m thick. (D) Type 4 (complex) fill from Badland Hills (SC01); fill is 4.6 m thick.

water table that prohibited pedogenic activity. A high water table is consistent with the low-chroma colours of the fill (e.g. Vepraskas, 1994). These fills are believed to represent the rapid filling of downflow reaches of crevasse channels either when those channels were still active or following abandonment (Fig. 7).

Type 2 fills

The presence of carbonaceous shale defines type 2 fills. The shales are brown, organic-rich and fissile, and they contain dense accumulations of fossil plant debris and leaf mats (defined as accumulations of overlapping leaves on a single bedding plane) as well as rare coaly lenses. Type 2 fills also contain organic-rich sandstone and mudrock (Figs 5B and 6). These fills are equivalent to the lenticular carbonaceous shales described by Wing (1984). Type 2 fills are commonly recognized by the presence of secondary gypsum and natrojarosite, which weather out of the shale

(Davies-Vollum & Wing, 1998). Eight fills were designated as type 2.

A representative type 2 channel fill from the Dorsey Creek area is shown in Fig. 6. The top of the scour is situated in a heterolithic interval (avulsion belt deposits), and the fill contains a mix of sandy siltstone, sandstone and mudstone arranged in two fining-upward successions. Carbonaceous shale is present towards the top of the second succession. The fill shows no evidence of rooting or mottling, and the colours are low chroma (≤ 2).

Interpretation

The presence of carbonaceous shale indicates that type 2 fills underwent relatively slow deposition with restricted sediment input for part of the time that they were filled. The lower part of the fill in Fig. 6 indicates either an initial period of channel activity followed by abandonment and reactivation or several pulses of sedimentation during one major flow event (e.g. Farrell, 2001). The upper,

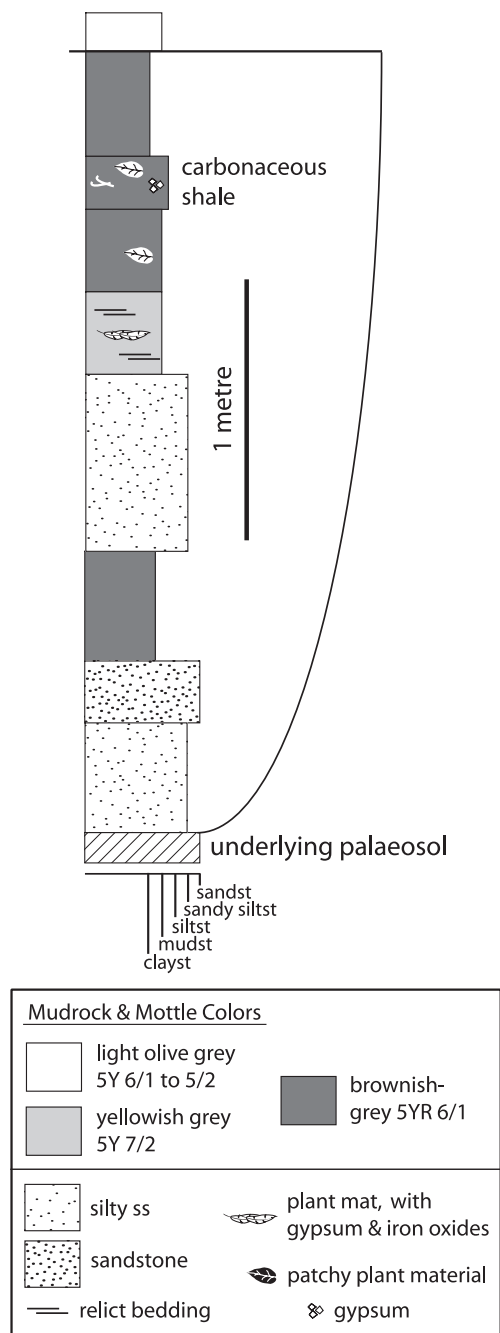


Fig. 6. Detailed measured section through a representative type 2 fill from the Dorsey Creek area. Shape of the scour surface is schematic.

organic-rich part of the fill is attributed to slow sedimentation following channel abandonment. The preservation of plant material was probably promoted by swampy, acidic and waterlogged conditions, which helped to prevent oxidation and biodegradation (Gastaldo & Staub, 1999). The presence of natrojarosite in these fills is consistent with very poorly drained conditions because it generally forms as an oxidation product of

pyrite (e.g. van Breeman, 1975, 1982). Pyrite precipitates under saturated conditions in the presence of organic matter.

Type 3 fills

Sixty per cent of the fills studied are of type 3, characterized by mudrocks that show evidence of pedogenic alteration, including colour mottling, root traces, small slickensides and local calcite accumulations (e.g. Fig. 5C). The pedogenically altered mudrocks of the fill are laterally confined by the scour surface, and none of them can be traced into interchannel areas. The mudrocks range in colour from grey to yellow-brown and, rarely, purple and red. Some type 3 fills have sandstone at their bases, and a few contain fossil plant material, although it is rarely well preserved. Type 3 fills commonly show single and multiple fining-upward and, more rarely, coarsening-upward successions. Type 3 fills can be divided into three subtypes based on the degree of pedogenesis of the fill and the presence of fossilized plant material.

Type 3a fill

This kind of fill contains a combination of carbonaceous shale and pedogenically altered mudrock. Only three fills were designated as type 3a. In two of these fills, carbonaceous shale is present at the base and is overlain by pedogenically altered mudrocks. Carbonaceous shale caps the other type 3a fill and overlies pedogenically altered mudrocks. The carbonaceous shales are similar to those found in type 2 fills. The mudrocks are characterized by low-chroma (grey) colours and yellow-brown mottles.

Type 3b fills

Sixteen of the 35 type 3 fills are designated as type 3b. Type 3b fills contain mudrock that was weakly modified by pedogenesis. Colours are of low chroma (grey colours) with orange mottling and, more rarely, red mottling that is commonly associated with grey root traces. The presence of relict bedding and faint horizon development indicate that pedogenesis was only weak. They commonly contain basal sandstone that was not pedogenically altered.

Type 3c fills

Type 3c fills contain mudrocks that show stronger pedogenic modification than the other type 3 fills; however, palaeosol development is still very weak as indicated by weak soil horizons and relict

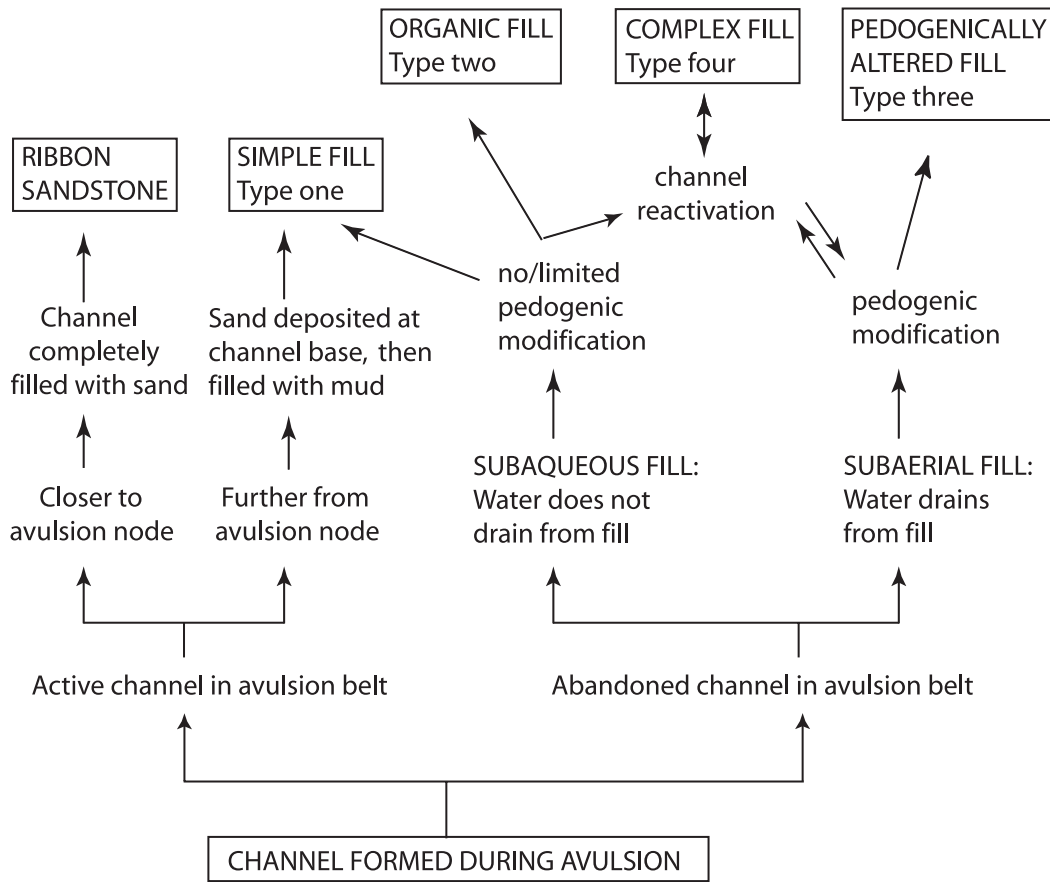


Fig. 7. Flow diagram illustrating formation of the four different fill types and ribbon sandstones.

bedding. Sixteen fills were designated as type 3c. A good example from the Fifteenmile Creek area is shown in Fig. 8. The top of the channel fill is positioned in the lower part of a thick heterolithic interval (avulsion belt deposit), and the basal erosion surface cuts through a well-developed palaeosol and into the heterolithic interval below.

The basal units of the fill shown in Fig. 8 are sandstone and sandy siltstone. Above these, the succession is abruptly finer (claystones), but then gradually coarsens upwards to mudstones and siltstones. A key feature of the finer grained strata is that they show pedogenic features including yellow-brown and light-brown matrix colours, local slickensides and mottles. Grey root mottles, some with red rims, and yellow-brown mottles are common, and red mottles are locally present, although sparse. Meagre calcite accumulations are also present in the form of filaments locally present within root traces (Fig. 8).

Interpretation

The thin sandstones found at the base of most type 3 fills mark the period when the channel was

actively transporting bedload; the overlying finer grained deposits record channel abandonment and filling with suspended sediment. The evidence of pedogenic modification in all type 3 fills indicates that, during the abandonment phase, periods of sedimentation alternated with periods of subaerial exposure during which soil formation took place (Fig. 7). The absence of distinct soil horizons and the local presence of relict bedding (Fig. 8) indicate that none of the fills shows more than weak soil development, suggesting that sedimentation was slow enough to permit pedogenesis but sufficiently rapid that soil development was only weak. Carbonaceous shale in type 3a fills indicates a period of channel abandonment during which plant material was able to accumulate.

Differences among the three kinds of type 3 fill are attributed to different degrees of fill drainage and different durations of subaerial exposure. Pedogenesis affected the entire thickness of type 3b and 3c fills but did not affect the entire thickness of the rare type 3a fills, as evidenced by the presence of carbonaceous shale. Formation of

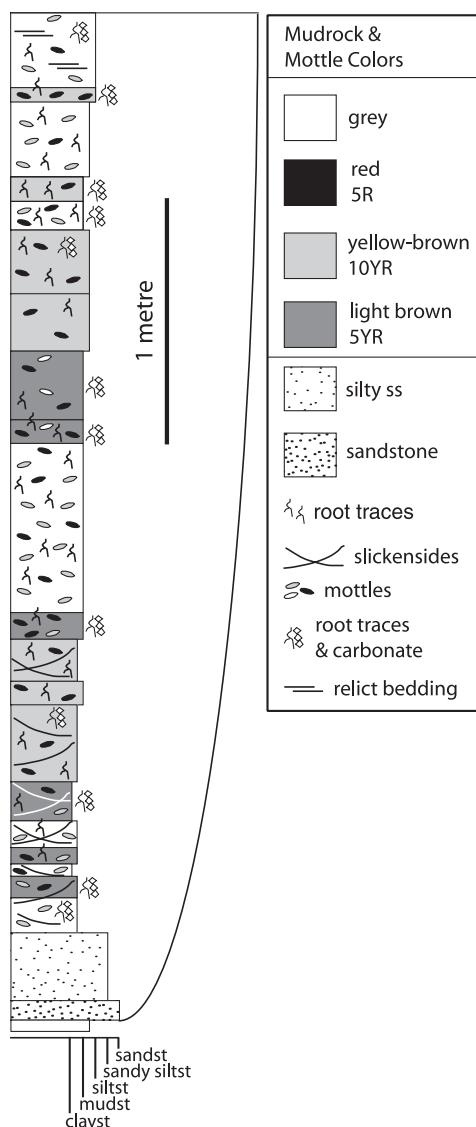


Fig. 8. Detailed measured section of a representative type 3c fill from Fifteenmile Creek. Shape of the scour surface is schematic.

carbonaceous shale requires minimal clastic influx and waterlogging to limit biodegradation of organic material, whereas pedogenically modified mudrocks require better drainage and greater clastic influx. The association of both carbonaceous shale and pedogenically modified strata, although rare, in a single fill indicates that local drainage conditions and the amount of clastic input changed significantly during the abandonment phase of the channel.

The low-chroma matrix colours in the type 3b fills indicate poorly drained conditions; however, the yellow-brown and red mottles reflect episodic drying of the sediment (Vepraskas, 1994). The presence of yellow-brown and brown matrix

colours, red rims on grey root traces and sparse calcite indicate that the soils of type 3c fills were moderately drained (Fanning & Fanning, 1989; PiPujol & Buurman, 1994, 1997). The various mottles are redoximorphic features that resulted from the reduction, movement and reprecipitation of iron. The mottles as well as the slickensides and calcite accumulations indicate that the palaeosols underwent alternate wetting and drying, probably on a seasonal basis (Wilding & Tessier, 1988; Vepraskas, 1994; PiPujol & Buurman, 1997).

Type 4 fills

Type 4 fills (e.g. Fig. 5D) consist mainly of interbedded mudstone and siltstone; some have sandstone beds and conglomerates. The conglomerates contain carbonate nodules, mudstone clasts, freshwater molluscan shells and plant debris in a sandstone matrix (Fig. 9). Beds that are 2–3 cm thick and consist of sandstone overlain by mudstone are common. These are separated from one another by sharp to scoured contacts. Also common are relict bedding and well-preserved fossil plant material. Many type 4 fills are complex in that they are partitioned by bounding surfaces and have multiple fining-upward successions. Seven fills are recognized as type 4.

Interpretation

Basal conglomerates in some type 4 fills indicate that bedload was transported and deposited at the base of the channel after incision but that the source of coarse sediment was rapidly cut off or that flow strength diminished and fine-grained sediment dominated (Fig. 9). The presence of mostly silt- and clay-rich beds at the base of other type 4 fills suggests that initial cutting was not always followed by the deposition of coarse-grained material. Internal erosion surfaces and small-scale variations in grain size reflect multiple reactivations of the channel fills (Fig. 7). Each thin sandstone/mudstone bed records a single pulse of sediment and water into the fill when the channel was briefly active. The coarser layer was deposited as bedload during active flow in the channel, and the upper, fine-grained bed was deposited later as the current waned.

FORMATION OF MUDROCK-DOMINATED CHANNEL-FILL DEPOSITS

The different kinds of channel-fill deposits are interpreted as the fills of abandoned crevasse-splay

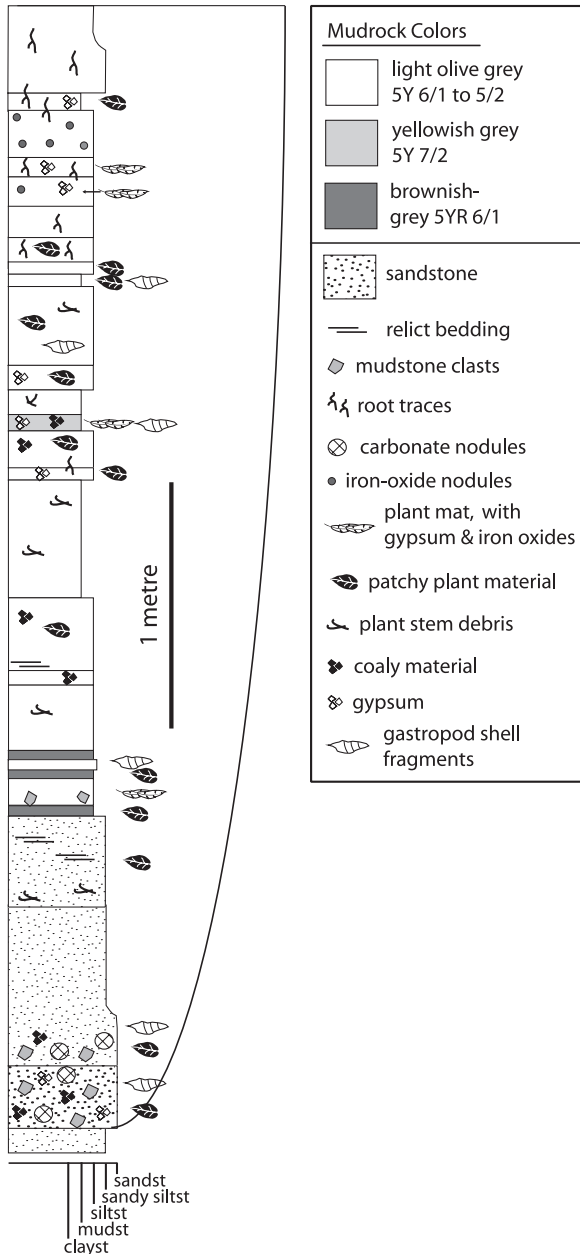


Fig. 9. Detailed measured section of a representative type 4 fill (SC01 from the Badland Hills). Refer to Fig. 4 for location of section.

channels that varied in terms of (1) the rate of filling and (2) the drainage of the fill sediments. Type 1 fills were generated by one or two episodes of rapid sedimentation before the channel was abandoned (Fig. 7). Of the four fill types described, type 1 fills are the only type that was predominantly deposited while the channel was active. Both pedogenically altered fills, where organic material is absent or has been degraded (types 3b and 3c), and fills that preserve plant fossils and concentrations of organic material (types 2, 3a and 4) were produced

by multiple episodes of sedimentation after the channel was abandoned (Fig. 7). Internal scour surfaces and sandstone/mudstone beds in type 4 fills and stacked soil sequences in type 3 fills record episodic filling. Episodic filling was probably related to flood events, which periodically redirected water and sediment to abandoned splay channels during an avulsion.

The difference between fills that are pedogenically altered and those that preserve fossil plant material is attributed to different drainage conditions following channel abandonment. The water table needed to remain high in the channels in which organic material accumulated and was preserved (types 2, 3a and 4). In contrast, the pedogenically altered fills that lack concentrations of organic material (types 3b and 3c) required periods of post-depositional emergence of the sediment.

Comparison with other fills

In their work on anastomosing systems of the Late Palaeozoic Cutler Formation, Eberth & Miall (1991) described 'U-shaped mixed fills' that are 1–10 m thick and that, in their middle to upper parts, contain shale and marls together with the remains of plants and vertebrates. They suggested that the fills accumulated under generally low-energy conditions in deep crevasse channels and that various features indicated standing water in the later stages of filling. In the Cretaceous Dakota Formation, Kirschbaum & McCabe (1992) observed 1–9 m thick ribbon bodies with heterolithic fills of sandstone, siltstone and mudstone and rare mudstone fills. They interpreted these as the fills of abandoned or partly abandoned channels from an anastomosing river system. The heterolithic fills contained preserved plant material; mudstones were either laminated or rooted. Pelzer *et al.* (1992) described ribbon-shaped bodies with W/T ratios <10 that consisted dominantly of mudstones, especially laminated grey mudstones, containing locally well-preserved plant remains. These fills were attributed to deposition in active anastomosed channels. Hornung & Aigner (1999) described channels filled with fine-grained deposits that ranged in thickness from 1 to 10 m and with widths between 10 and 100 m. These fine-grained channel fills were surrounded by fine-grained floodplain deposits.

These examples are similar to the channel-shaped bodies in the Willwood Formation in terms of thickness, W/T ratio and lithology (Table 1); they also resemble the Willwood fills

in that the U-shaped bodies are commonly situated within other fine-grained deposits. A key way in which the four ancient examples described above differ from channel fills in the Willwood Formation is that, other than the rooting described by Kirschbaum & McCabe (1992), pedogenic modification has not been recognized in them.

Fine-grained fills that are pedogenically modified have been described at a larger scale (kilometres wide and tens of metres deep) in a small number of alluvial successions. For example, Kraus & Middleton (1987) described a Triassic scour system that could be traced for several kilometres and was up to 30 m deep. The scour could be recognized because it truncated strongly developed palaeosols that differed in colour from weakly developed palaeosols filling the scour. Bestland (1997) described similar features in Oligocene strata. These examples differ from the Willwood fine-grained channel fills not only in terms of their larger scale but also because they have erosional bases that consist of multiple, stepped surfaces rather than a simple U-shaped surface. In addition, these larger scour systems have been attributed to base-level fluctuations resulting from climate change or tectonic activity, whereas the Willwood channel fills are attributed to autogenic fluvial processes.

The following section examines the factors that might have controlled the pedogenic modification of some fills and the preservation of plant material in other fills in the Willwood Formation.

Possible controls on fill type

The geographic and stratigraphic locations of the two major kinds of channel fill in the Willwood Formation (poorly drained with preserved plant debris and pedogenically modified) are shown in Fig. 10. This figure also shows mean annual temperatures (MAT) calculated for the Willwood Formation from leaf margin analysis (Wing, 2000). The channel-fill data currently available are sparse: the number of localities for such a large basin is few, and the number of fills at each locality is relatively small. Based on these limited data, the sections below explore how basin position and climate might have influenced the type of fine-grained channel fill that accumulated.

Basin position

Two basinal factors that could have influenced the distribution of different kinds of fills are: (1) lateral tilting of the floodplain related to tectonic

activity; and (2) palaeoslopes within the basin. In general, locations that were proximal to the Palaeogene axes of the Bighorn and Clark's Fork basins: (Badland Hills, Ralston and Deer Creek) are dominated by poorly drained channel fills (Fig. 10). None of the fills at Ralston and less than 40% of fills at Deer Creek and Badland Hills show evidence of pedogenesis. Locations that are dominated by pedogenically modified fills are more likely to be further from the axes of the two basins (Fig. 10).

Various studies indicate that lateral tilting of the floodplain in response to tectonic activity causes trunk channels to migrate in the direction of tilting (e.g. Alexander & Leeder, 1987; Peakall, 1998; Holbrook & Schumm, 1999). In the case of normal faults, channels preferentially relocate towards the fault that causes the tilting, as a result of either avulsion or lateral migration of the channel (Peakall *et al.*, 2000). Lateral tilting of the floodplain can also be produced by flexure associated with thrust loading and by epeirogenic warping (e.g. Holbrook & Schumm, 1999).

Although evidence shows that movement along the major thrust faults had ceased by the time the Willwood Formation was deposited, Palaeogene deposits thicken towards those faults (Gingerich, 1983; Parker & Jones, 1986a), indicating that subsidence rates increased westwards as a result of tectonic loading by the thrusts. If channels were more common through time close to the basin axes because of more rapid basin subsidence, areas close to the axes may have been more prone to higher water tables and have been flooded more frequently than areas more distal to the basin axis. Unfortunately, exposures across the axial parts of the basins do not allow lateral variations in channel density to be constrained.

The Dead Indian Hill site is an apparent anomaly to this possible link between proximity to the basin axis and drainage in the channel fills. Despite its position close to the basin axis, the site is dominated by pedogenically modified fills, and most of those are the better drained type 3c fill. As described below, the fill type at Dead Indian Hill may be related to climate.

Alternatively, variations in drainage were influenced by the regional palaeoslope along the Bighorn and Clark's Fork basins. Figure 10A shows that locations in the southern part of the study area are dominated by pedogenically modified fills, and locations in the north are dominated by poorly drained channel fills. Based on palaeocurrent data showing north-west drainage during early Eocene time (Neasham & Vondra, 1972;

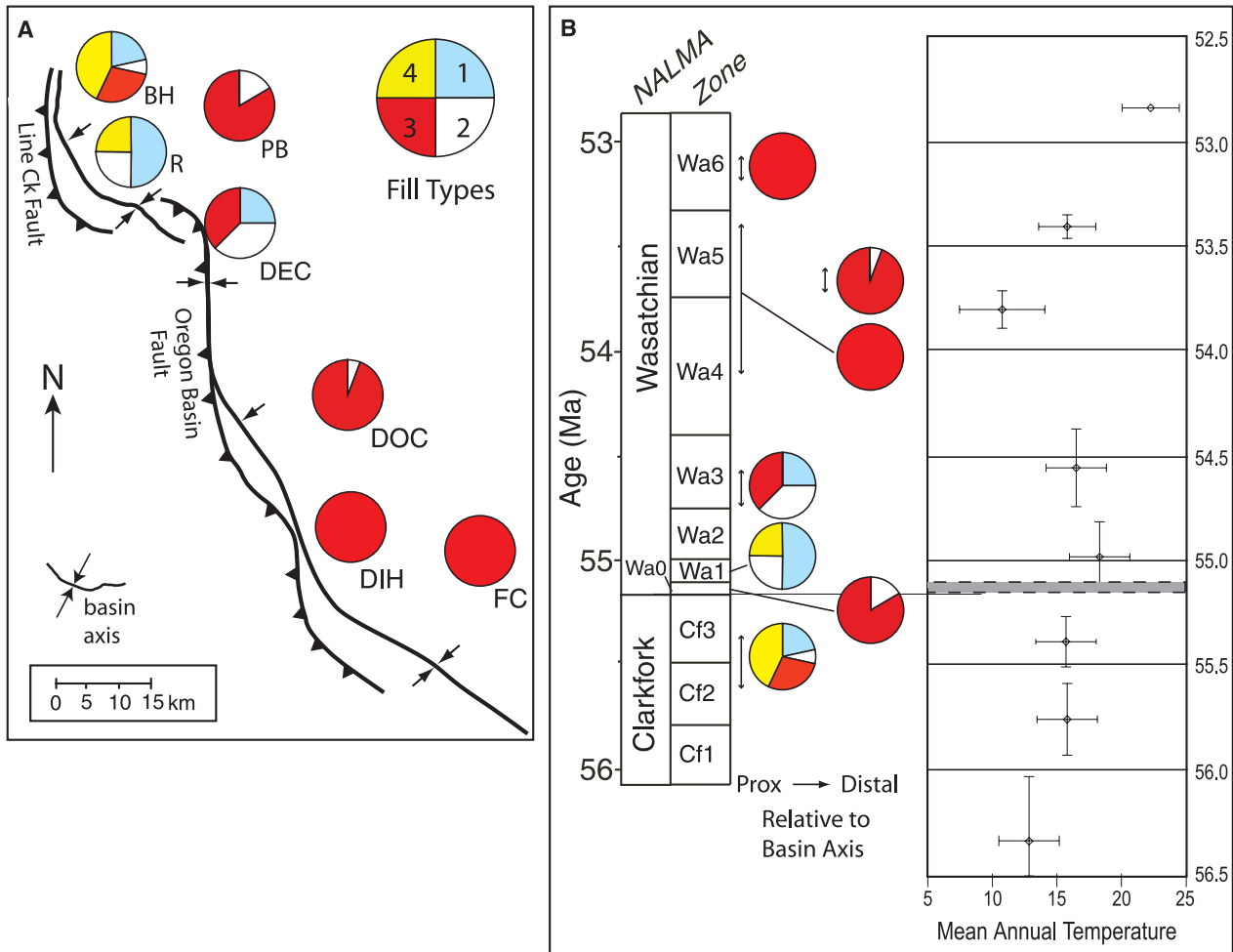


Fig. 10. (A) Schematic diagram of part of the Bighorn and Clark's Fork basins showing the geographic distribution of fill types relative to the Palaeogene structural axes of the basins and to major thrust faults. Fault locations and basin axes from Parker & Jones (1986b). See text for details. (B) Stratigraphic distribution of fill types relative to changes in mean annual temperature (MAT) in the Bighorn Basin and to location proximal or distal to the Palaeogene axis of the Bighorn Basin. Pie charts show proportion of fill types at each of the seven study sites. MAT values from Wing *et al.* (2000); error bars represent $\pm 1\sigma$ for leaf margin data.

Kraus, 2002), the more poorly drained channel fills were down palaeoslope from the pedogenically modified fills. Several studies have observed that palaeosols are more poorly drained down palaeoslope, a variation that has been attributed to a decrease in topographic relief (Atkinson, 1986; Platt & Keller, 1992). The exception to this north–south trend is Polecat Bench; however, as described below, the section there was deposited under exceptional climatic conditions.

Climate

Oxygen isotope studies of the marine record show a global warming trend from about 59 to 50 million years ago. Plant fossils record this warming trend in the Bighorn Basin and provide mean annual temperature (MAT) estimates (Wing *et al.*,

2000; Fig. 10B). A dramatic but transient global warming event – the Palaeocene–Eocene thermal maximum or PETM – occurred at the Palaeocene–Eocene boundary (Koch *et al.*, 1992, 1995; Zachos *et al.*, 1993). Although plant fossils have not been found in this interval, isotopic analyses of fossil vertebrates suggest that MAT increased by 4 °C in the Wyoming region at this time (Fricke *et al.*, 1998).

The PETM interval is preserved in the Bighorn Basin and is characterized by distinctive palaeosols that show evidence of unusually well-drained conditions compared with other Willwood palaeosols (Kraus & Riggins, 2002). The PETM interval has been best studied at Polecat Bench. The palaeosols there have unusually abundant carbonate nodules and brick red

colours indicating well-drained soil conditions (e.g. Torrent *et al.*, 1980). Purple and yellow-brown, colours that indicate less-well drained conditions, are uncommon (Wright *et al.*, 2000; Kraus, 2002). These features have been attributed to climatic drying that accompanied the dramatic warming of the PETM (Kraus & Riggins, 2002). The presence of pedogenically modified channel fills at Polecat Bench is consistent with the dry conditions indicated by the PETM palaeosols (Fig. 10). Thus, climatic drying may have been the primary reason why pedogenically modified fills formed at Polecat Bench.

As stated above, despite its proximity to the Palaeogene basin axis, the Dead Indian Hill site is dominated by pedogenically modified channel fills. The Willwood Formation here formed as MAT was approaching its early Eocene peak of ≈ 22 °C during Wa6 (Fig. 10A). The better drained character of those channel fills may reflect drier conditions related to the unusually high MAT. Climatic drying is also indicated by analysis of the more strongly developed palaeosols in the southern two-thirds of the basin (Bown & Kraus, 1993). Palaeosols in the upper part of the Willwood section show a marked decrease in soil hydromorphy relative to older palaeosols.

Despite the possible influence of climate on fine-grained channel fills at Polecat Bench and Dead Indian Hill, the link between climate and fill type is uncertain because it does not appear to be systematic. Although pedogenically modified fills are found at Polecat Bench and Dead Indian Hill at times of high MAT, pedogenically modified channel fills also dominate in the Dorsey Creek area even though they formed during a significant cooling trend (Fig. 10A). It is difficult to test a possible relationship between climate and fill type: trends in palaeoprecipitation did not necessarily track trends in palaeotemperature during early Eocene time (Bice & Marotzke, 2002), and reliable data on palaeoprecipitation are not currently available for most of the Willwood strata.

CONCLUSIONS

Fine-grained and heterolithic deposits filling channels in Palaeogene alluvial strata of the Bighorn Basin, Wyoming, are interpreted as the fills of abandoned splay channels associated with avulsion belts. The type of fill that accumulated appears to have been influenced by the proximity of the avulsion belt to the basin axis. Channel fills

close to the basin axis generally show limited pedogenic modification and contain strata that reflect poor drainage. Fills further from the basin axis are pedogenically modified, reflecting more distal, better drained areas of the basin that received influxes of floodwaters and sediment less frequently than areas that were closer to the axis. This difference is attributed to floodplain tilting towards major thrust faults in the basin. Locations close to the faults had higher water tables and underwent more frequent flooding than locations more distal to the faults. Alternatively, variations in drainage represented by the different kinds of fills were influenced by the palaeoslope of the Bighorn and Clark's Fork basins. Unusually warm climates may also have influenced the kinds of fill that formed in the upper part of the Willwood Formation. This suggests that climate also plays a role; however, it appears to be secondary to the tectonic control on the kind of channel fill that developed.

This study has implications for understanding the fine-grained facies of other fluvial successions. Pedogenically modified channel fills have only rarely been recognized in the stratigraphic record (Bown & Kraus, 1993). Unless there are obvious colour differences between the palaeosols that are scoured and the palaeosols that form the channel fill, these features may be very difficult to identify. Yet, their presence in numerous Willwood avulsion deposits suggests that they represent a typical component of avulsion belt deposits, but one that, until now, has not been recognized (Kraus & Wells, 1999). In addition, the nature of the channel fill provides important information on ancient drainage conditions in the avulsion belt.

Their presence within avulsion sequences of the Willwood Formation also indicates that mudrock-dominated channel fills could be an important tool for recognizing ancient avulsion belts in other alluvial successions. In view of this study, it is suggested that mudrock-dominated channel fills that have been described previously in terms of anastomosing river systems might warrant further consideration in the context of avulsions.

ACKNOWLEDGEMENTS

M.J.K. acknowledges support from National Science Foundation grant EAR-0000616. K.S.D.V. acknowledges support from a Smithsonian Institution Scholarly Studies Grant and Delaney Funds from the Pomona College Geology

Department. We thank Susan Riggins and Hannah Wanebo for field assistance in 2001 and 2002, respectively, students interning with the Paleobiology Department at the National Museum of Natural History during the summer of 2000 and undergraduate students from Pomona College in the summer of 2002.

REFERENCES

- Alexander, J.** and **Leeder, M.R.** (1987) Active tectonic control on alluvial architecture. In: *Recent Developments in Fluvial Sedimentology* (Eds F.G. Ethridge, R.M. Flores and M.D. Harvey), *SEPM Spec. Publ.*, **39**, 243–252.
- Allen, J.R.L.** (1965) A review of the origin and characteristics of recent alluvial sediments. *Sedimentology*, **5**, 89–191.
- Allen, J.R.L.** (1970) A quantitative model of grain size and sedimentary structures in lateral deposits. *Geol. J.*, **7**, 129–146.
- Atkinson, C.D.** (1986) Tectonic control on alluvial sedimentation as revealed by an ancient catena in the Capella Formation (Eocene) of northern Spain. In: *Paleosols: Their Recognition and Interpretation* (Ed. V.P. Wright), pp. 139–179. Blackwell Scientific Publications, Cambridge.
- Bao, H., Koch, P.L.** and **Rumble, D., III** (1999) Paleocene–Eocene climatic variation in western North America: evidence from the $\delta^{18}\text{O}$ of pedogenic hematite. *Geol. Soc. Am. Bull.*, **111**, 1405–1415.
- Berendsen, H.J.A.** (1982) *De genese van het landschap in het zuiden van de provincie Utrecht, een fysisch-geografische studie*. PhD Thesis, Utrecht University, 256 pp.
- Bestland, E.A.** (1997) Alluvial terraces and paleosols as indicators of early Oligocene climate change (John Day Formation, Oregon). *J. Sed. Res.*, **67**, 840–855.
- Bice, K.L.** and **Marotzke, J.** (2002) Could changing ocean circulation have destabilized methane hydrate at the Paleocene/Eocene boundary? *Paleoceanography*, **17**. DOI: 10.1029/2001PA000678.
- Blackstone, D.L.** (1986) Foreland compressional tectonics: southern Bighorn Basin and adjacent areas. *Wyoming Geol. Surv. Rept. Invest.*, **34**, 32 pp.
- Bonini, W.E.** and **Kinard, R.E.** (1983) Gravity anomalies along the Beartooth front, Montana. *Guidebook of the Wyoming Geol. Assoc., 34th Annual Field Conference*, pp. 89–95.
- Bown, T.M.** (1980) Summary of latest Cretaceous and Cenozoic sedimentary, tectonic, and erosional events, Bighorn Basin, Wyoming. In: *Early Cenozoic Paleontology and Stratigraphy of the Bighorn Basin, Wyoming* (Ed. P.D. Gingerich), *Univ. Mich. Paper Paleont.*, **24**, 5–32.
- Bown, T.M.** and **Kraus, M.J.** (1993) Time-stratigraphic reconstruction and integration of paleopedologic, sedimentologic, and biotic events (Willwood Formation, Lower Eocene, northwest Wyoming, USA). *Palaios*, **8**, 68–80.
- Bown, T.M., Rose, K.D., Simons, E.L.** and **Wing, S.L.** (1994) Distribution and stratigraphic correlation of fossil mammal and plant localities of the Fort Union, Willwood, and Tattman formations (Upper Paleocene–Lower Eocene), central and southern Bighorn Basin, Wyoming. *US Geol. Surv. Prof. Paper*, **1540**, 103 pp.
- van Breeman, N.** (1975) Acidification and deacidification of coastal plain soils as a result of periodic flooding. *Soil Sci. Soc. Am. Proc.*, **39**, 1153–1157.
- van Breeman, N.** (1982) Genesis, morphology, and classification of acid sulfate soils in coastal plains. In: *Acid Sulfate Weathering* (Eds J.A. Kittrick, D.S. Fanning and L.R. Hossner), *Soil Sci. Soc. Am. Spec. Publ.*, **10**, 95–108.
- Clyde, W.C.** (1997) *Stratigraphy and mammalian paleontology of the McCullough Peaks, northern Bighorn Basin, Wyoming: implications for biochronology, basin development, and community reorganization across the Paleocene–Eocene boundary*. PhD Thesis, University of Michigan, Ann Arbor, MI, 271 pp.
- Clyde, W.C.** (2001) Mammalian biostratigraphy of the McCullough Peaks area in the northern Bighorn Basin. In: *Paleocene–Eocene Stratigraphy and Biotic Change in the Bighorn and Clark's Fork Basins, Wyoming* (Ed. P.D. Gingerich), *Univ. Mich. Paper Paleontol.*, **33**, 109–126.
- Davies-Vollum, K.S.** and **Kraus, M.J.** (2001) A relationship between alluvial backswamps and avulsion cycles: an example from the Willwood Formation of the Bighorn Basin, Wyoming. *Sed. Geol.*, **140**, 235–249.
- Davies-Vollum, K.S.** and **Wing, S.L.** (1998) Sedimentological, taphonomic, and climatic aspects of Eocene swamp deposits (Willwood Formation, Bighorn Basin, Wyoming). *Palaios*, **13**, 28–40.
- DeCelles, P.G., Gray, M.B., Ridgway, K.D., Cole, R.B., Srivastava, P., Pequera, N.** and **Pivnik, D.A.** (1991) Kinematic history of a foreland uplift from Paleocene synorogenic conglomerate, Beartooth Range, Wyoming and Montana. *Bull. Geol. Soc. Am.*, **103**, 1458–1475.
- Eberth, D.A.** and **Miall, A.D.** (1991) Stratigraphy, sedimentology and evolution of a vertebrate-bearing braided to anastomosed fluvial system, Cutler Formation (Permian–Pennsylvanian), north-central New Mexico. *Sed. Geol.*, **72**, 225–252.
- Fanning, D.S.** and **Fanning, M.C.B.** (1989) *Soil: Morphology, Genesis, and Classification*. Wiley & Sons, New York, 395 pp.
- Farrell, K.M.** (2001) Geomorphology, facies architecture, and high-resolution, non-marine sequence stratigraphy in avulsion deposits, Cumberland Marshes, Saskatchewan. *Sed. Geol.*, **139**, 93–150.
- Foose, R.M., Wise, D.U.** and **Garbarini, G.S.** (1961) Structural geology of the Beartooth Mountains, Montana and Wyoming. *Bull. Geol. Soc. Am.*, **72**, 1143–1172.
- Fricke, H.C., Clyde, W.C., O'Neil, J.R.** and **Gingerich, P.D.** (1998) Evidence for rapid climate change in North America during the latest Paleocene thermal maximum: oxygen isotope compositions of biogenic phosphate from the Bighorn Basin (Wyoming). *Earth Planet. Sci. Lett.*, **160**, 193–208.
- Gastaldo, R.A.** and **Staub, J.R.** (1999) A mechanism to explain the preservation of leaf litter in coals derived from raised mires. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **149**, 1–14.
- Gingerich, P.D.** (1983) Paleocene–Eocene faunal zones and preliminary analysis of Laramide structure deformation in the Clark's Fork Basin, Wyoming. *Guidebook of the Wyoming Geol. Assoc., 34th Annual Field Conference*, pp. 185–195.
- Gingerich, P.D.** (2001) Biostratigraphy of the continental Paleocene–Eocene boundary interval on Polecat Bench in the northern Bighorn Basin. In: *Paleocene–Eocene Stratigraphy and Biotic Change in the Bighorn and Clark's Fork Basins, Wyoming* (Ed. P.D. Gingerich), *Univ. Mich. Paper Paleontol.*, **33**, 37–71.
- Gingerich, P.D.** and **Klitz, K.** (1985) University of Michigan Paleocene and Eocene fossil localities in the Fort Union and Willwood Formations, Clark's Fork Basin, Wyoming.

- University of Michigan Museum of Paleontology, map, 1 sheet, scale approx. 1:62,500.
- Holbrook, J.** and **Schumm, S.A.** (1999) Geomorphic and sedimentary response of rivers to tectonic deformation: a brief review and critique of a tool for recognizing subtle epirogenic deformation in modern and ancient settings. *Tectonophysics*, **305**, 287–306.
- Hornung, J.A.** and **Aigner, T.** (1999) Reservoir and aquifer characterization of fluvial architectural elements: Stubensandstein, Upper Triassic, southwest Germany. *Sed. Geol.*, **129**, 215–280.
- Kirschbaum, M.A.** and **McCabe, P.J.** (1992) Controls on the accumulation of coal and on the development of anastomosed fluvial systems in the Cretaceous Dakota Formation of southern Utah. *Sedimentology*, **39**, 581–598.
- Koch, P.L., Zachos, J.C.** and **Gingerich, P.D.** (1992) Correlation between isotope records in marine and continental carbon reservoirs near the Paleocene/Eocene boundary. *Nature*, **358**, 319–322.
- Koch, P.L., Zachos, J.C.** and **Dettmann, D.L.** (1995) Stable isotope stratigraphy and paleoclimatology of the Paleogene Bighorn Basin (Wyoming, USA). *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **115**, 61–89.
- Kraus, M.J.** (1996) Avulsion deposits in lower Eocene alluvial rocks, Bighorn Basin, Wyoming. *J. Sed. Res.*, **66**, 354–363.
- Kraus, M.J.** (2002) Basin-scale changes in floodplain paleosols: implications for interpreting alluvial architecture. *J. Sed. Res.*, **72**, 500–509.
- Kraus, M.J.** and **Aslan, A.** (1993) Eocene hydromorphic paleosols: significance for interpreting ancient floodplain processes. *J. Sed. Petrol.*, **63**, 453–463.
- Kraus, M.J.** and **Bown, T.M.** (1993) Short-term sediment accumulation rates determined from Eocene alluvial paleosols. *Geology*, **21**, 743–746.
- Kraus, M.J.** and **Gwinn, B.M.** (1997) Controls on the development of early Eocene avulsion deposits and floodplain paleosols, Willwood Formation, Bighorn Basin. *Sed. Geol.*, **114**, 33–54.
- Kraus, M.J.** and **Middleton, L.T.** (1987) Dissected paleotopography and base-level changes in a Triassic fluvial sequence. *Geology*, **15**, 18–21.
- Kraus, M.J.** and **Riggins, S.** (2002) Effects of the PETM on continental weathering: analysis of alluvial paleosols, Bighorn Basin, Wyoming. *Geol. Soc. Am. Abstract Prog.* **34**, 535.
- Kraus, M.J.** and **Wells, T.M.** (1999) Recognizing avulsion deposits in the ancient stratigraphical record. In: *Fluvial Sedimentology VI* (Eds N.D. Smith and J. Rogers), *IAS Spec. Publ.*, **28**, 251–268.
- Lewis, G.W.** and **Lewin, J.** (1983) Alluvial cutoffs in Wales and Borderlands. In: *Modern and Ancient Fluvial Systems* (Eds J.D. Collinson and J. Lewin), *IAS Spec. Publ.*, **6**, 145–154.
- Mackey, S.D.** and **Bridge, J.S.** (1995) Three-dimensional model of alluvial stratigraphy: theory and application. *J. Sed. Res.*, **65B**, 7–31.
- Miall, A.D.** (1985) Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. *Earth Sci. Rev.*, **22**, 261–308.
- Moore, D.A.** (1961) Isopachous map Fort Union Formation, Bighorn Basin. *Guidebook of the Wyoming Geol. Assoc., 16th Annual Field Conference*, pp. 200–203.
- Neasham, J.W.** and **Vondra, C.F.** (1972) Stratigraphy and petrology of the lower Eocene Willwood Formation, Bighorn Basin, Wyoming. *Bull. Geol. Soc. Am.*, **83**, 2167–2180.
- Omar, G.I., Lutz, T.M.** and **Giegengack, R.** (1994) Apatite fission-track evidence for Laramide and post-Laramide uplift and anomalous thermal regime at the Beartooth overthrust, Montana-Wyoming. *Bull. Geol. Soc. Am.*, **106**, 74–85.
- Parker, S.E.** and **Jones, R.W.** (1986a) Influence of faulting on Upper Cretaceous-lower Tertiary deposition, Bighorn basin, Wyoming. *Montana Geol. Soc. and Yellowstone Bighorn Res. Assoc., 50th Annual Field Conference, Guidebook*, pp. 137–144.
- Parker, S.E.** and **Jones, R.W.** (1986b) Isopachous map of Tertiary overburden above latest Cretaceous Lance Formation, Bighorn Basin, Wyoming. *Geol. Survey Wyoming Open File Report*, **86-8**.
- Peakall, J.** (1998) Axial river evolution in response to half-graben faulting: Carson River, Nevada, USA. *J. Sed. Res.*, **68**, 788–799.
- Peakall, J., Leeder, M., Best, J.** and **Ashworth, P.** (2000) River response to lateral ground tilting: a synthesis and some implications for the modelling of alluvial architecture in extensional basins. *Basin Res.*, **12**, 413–424.
- Pelzer, G., Riegel, W.** and **Wilde, V.** (1992) Depositional controls on the Lower Cretaceous Wealden coals of northwest Germany. In: *Controls on the Distribution and Quality of Cretaceous Coals* (Eds P.J. McCabe and J.T. Parrish), *Geol. Soc. Am. Spec. Paper*, **267**, 227–244.
- PiPujol, M.D.** and **Buurman, P.** (1994) The distinction between ground-water gley and surface-water gley phenomena in Tertiary Paleosols of the Ebro Basin, NE Spain. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **110**, 103–113.
- PiPujol, M.D.** and **Buurman, P.** (1997) Dynamics of iron and calcium carbonate redistribution and palaeohydrology in middle Eocene alluvial paleosols of the southeast Ebro Basin margin (Catalonia, northeast Spain). *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **134**, 87–107.
- Platt, N.H.** and **Keller, B.** (1992) Distal alluvial deposits in a foreland basin setting – the Lower freshwater Molasse (lower Miocene), Switzerland: sedimentology, architecture and palaeosols. *Sedimentology*, **39**, 545–565.
- Slingerland, R.** and **Smith, N.D.** (2004) River avulsions and their deposits. *Annu. Rev. Earth Planet. Sci.*, **32**, 257–285.
- Smith, N.D.** and **Perez-Arlucea, M.** (1994) Fine-grained splay deposition in the avulsion belt of the Lower Saskatchewan River, Canada. *J. Sed. Res.*, **B64**, 159–168.
- Smith, N.D., Cross, T.A., Dufficy, J.P.** and **Clough, S.R.** (1989) Anatomy of an avulsion. *Sedimentology*, **36**, 1–23.
- Stone, D.S.** (1985) Geologic interpretation of seismic profiles, Bighorn Basin, Wyoming, Part II: West flank. In: *Seismic Exploration of the Rocky Mountain Region: Denver, Colorado* (Eds R.R. Gries and R.C. Dyer), pp. 175–186. Rocky Mountain Association of Geologists and Denver Geophysical Society.
- Stouthammer, E.** (2001) Sedimentary products of avulsion in the Rhine–Meuse Delta, The Netherlands. *Sed. Geol.*, **145**, 73–92.
- Torrent, J., Schwertmann, U.** and **Schulze, D.G.** (1980) Iron oxide mineralogy of some soils of two river terrace sequences in Spain. *Geoderma*, **23**, 191–208.
- Vepraskas, M.J.** (1994) Redoximorphic features for identifying aquic conditions. *North Carolina Agric. Res. Serv. Tech. Bull.*, **301**, 33 pp.
- Walker, R.G.** and **Cant, D.J.** (1984) Sandy fluvial systems. In: *Facies Models* (Ed. R.G. Walker), *Geoscience Canada Reprint Series*, **1**, 71–90.
- Wilding, L.P.** and **Tessier, D.** (1988) Genesis of Vertisols: shrink-swell phenomena. In: *Vertisols: Their Distribution,*

- Properties, Classification and Management*. (Eds L.P. Wilding and R. Puentes), *Technical Monograph*, **18**, pp. 55–96. Texas A&M University, College Station, TX.
- Wing, S.L.** (1984) Relation of paleovegetation to geometry and cyclicity of some fluvial carbonaceous deposits. *J. Sed. Petrol.*, **54**, 52–66.
- Wing, S.L.** (2000) Cool, warm, cool, warm – climate oscillation and floral change during the Paleocene/Eocene boundary interval. In: *Early Paleogene Warm Climates and Biosphere Dynamics* (Eds B. Schmitz, B. Sundquist and F.P. Andreasson), *Geol. Fören. Förh.*, **122**, 57–59.
- Wing, S.L., Alroy, J. and Hickey, L.J.** (1995) Plant and mammal diversity in the Paleocene to Early Eocene of the Big-horn Basin. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **115**, 117–155.
- Wing, S.L., Bao, H. and Koch, P.L.** (2000) An early Eocene cool period? Evidence for continental cooling during the warmest part of the Cenozoic. In: *Warm Climates in Earth History* (Eds B.T. Huber, K.G. Macleod and S.L. Wing), pp. 197–237. Cambridge University Press, Cambridge.
- Wright, V.P., Taylor, K.G. and Beck, V.H.** (2000) The paleo-hydrology of Lower Cretaceous seasonal wetlands, Isle of Wight, southern England. *J. Sed. Res.*, **70**, 619–632.
- Zachos, J.C., Lohmann, K.C., Walker, J.C.G. and Wise, S.W.** (1993) Abrupt climate change and transient climates during the Paleogene: a marine perspective. *J. Geol.*, **101**, 191–213.

Manuscript received 5 November 2002; revision accepted 15 June 2004.