ABSTRACT. Markov analysis was performed on a suite of stratigraphic sections from the Willwood Formation (lower Eocene) in the McCullough Peaks area of the Bighorn Basin (Wyoming) to test a current depositional model that links paleosol maturity to floodplain architecture. Under this model of alluvial aggradation, fine-grained sediments in alluvial systems are divided into two basic packages - true overbank deposits and avulsion deposits. True overbank deposits form during flooding events as the water level in a well-established channel exceeds the elevation of the levees and inundates the adjacent flood basin. These deposits are thought to be represented by relatively mature cumulative paleosols with minor amounts of intermixed sandstones and immature paleosols. Avulsion deposits are formed during the initial stages of channel reestablishment and are thought to be characterized by immature paleosols intermixed with ribbon and thin sheet sandstones. Predicted stacking patterns of floodplain lithologies under this model show abundant transitions within and between sandstones and low maturity paleosols (deposited during aggradation of the avulsion packages) grading upwards into higher maturity paleosols (as the new channel becomes established) and ending with an abrupt transition from highly mature paleosols back to a low maturity avulsion sequence (as another avulsion invades the low lying floodplain). Markov analysis of the stacking pattern of lithologies in the McCullough Peaks area indicates that the observed sequence of facies transitions is non-random and that the transitions that deviate most from random are consistent with the hypothesized relationship between paleosol maturity and avulsion.

INTRODUCTION

Alluvial sedimentary systems are often divided into coarse-grained channel-belt deposits and fine-grained floodplain deposits. These alluvial suites are commonly subdivided into component architectural elements in attempts to understand the spatio-temporal construction of the system as a whole (Miall, 1996). Traditionally, coarse channel-belt deposits have received more attention in attempts to reconstruct ancient alluvial systems due to their distinct and informative architectural elements (for example channel or gravel bar). More recently, workers have begun to focus on the finer grained floodplain suites as well, since they often represent the majority of sediment in alluvial systems. Advances in our understanding of two geological processes associated with floodplains, pedogenesis and avulsion, have been particularly important in this context. Pedogenesis causes significant geochemical and physical changes to fine-grained overbank deposits according to local environmental conditions. Resultant soils can be preserved in the geological record as paleosols and provide information related to climate, drainage, vegetation, and rates of sediment accumulation on the ancient floodplain, making them useful tools for evaluating basin evolution (Retallack, 1981; Fastovsky, 1987; Kraus and Aslan, 1993; Cerling and Quade, 1993; Kraus and Bown, 1993). Avulsion deposits have been shown to be important autocyclic components of some modern and Holocene floodplain deposits and thus could be informative in understanding alluvial aggradation over long time scales if they can be identified in ancient deposits (Smith and others, 1989; Smith and Pérez-Arlucea, 1994; Kraus, 1996; Pérez-Arlucea and Smith, 1999; Aslan and Blum, 1999; Makaske, 2001).

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The relationship between pedogenesis and avulsion, however, is not well understood and has only recently been investigated in ancient sedimentary systems (Kraus and Aslan, 1993; Kraus and Gwinn, 1997).

A recent depositional model of the Willwood Formation (lower Eocene) in the Bighorn Basin of Wyoming (fig. 1) suggests that this alluvial system was constructed largely through the aggradation of trunk channel, overbank, and avulsion deposits (Kraus, 1997; Kraus and Gwinn, 1997). The trunk channel deposits are characterized by large sheet sandstones (usually $\geq 3$ meters in thickness) and are thought to represent the main axial rivers in the system (fig. 2A). The overbank deposits are characterized by pedogenically modified mudstones that are thought to be deposited during flooding of the main trunk channels. Individual overbank deposits are often represented by a single well-developed paleosol profile that forms during subaerial exposure between major flooding events (fig. 2B). Assuming other variables are relatively constant (for example climate), the maturity of the paleosol is thought to be primarily controlled by its position on the ancient floodplain - more mature paleosols formed distal to the channel where short-term sediment accumulation rates were low, and less mature paleosols formed closer to the channel where short-term sediment accumulation rates were high (Bown and Kraus, 1981; Kraus and Bown, 1988). As opposed to the monolithic nature of the trunk channel and overbank deposits, the avulsion deposits are heterolithic and include ribbon sandstones, thin sheet sandstones, and mudstones that show weak paleosol development (Kraus and Aslan, 1993; Kraus, 1996; fig. 2B). The small ribbon sandstones are thought to be the feeder channels to the avulsion complex, the small sheet sandstones are thought to be the levees and crevasse splays from the feeder channels, and the paleosol mudstones which are usually vertically stacked in a single avulsion deposit, are thought to represent the fine-grained part of the avulsion complex. Study of Holocene avulsion belts suggest

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**Fig. 1.** (A) Map showing the localities in the Bighorn Basin where sections were measured for this study (black dots). All sections fall within the Wa-3 faunal zone, which represents approximately 350,000 years of time during the early Eocene (Gingerich, 1991; Clyde, 2001). Gray area represents the lower Eocene Willwood Formation and stippled areas represent cores of surrounding Laramide mountain ranges.
that their lifespan is on the order of $10^2$ years implying there is insufficient time for significant pedogenesis (see for example Stouthamer and Berendsen, 2001). Although this depositional model for the Willwood (referred to here as the “Avulsion model”) is attractive in being consistent with studies of some modern alluvial systems that show the importance of both avulsion and overbank flooding in delivering fine to medium...
grained material to the floodplain (Pérez-Arlucea and Smith, 1999), there have been no quantitative tests of the model.

**Model Predictions**

Avulsion is the process by which an active channel is abandoned for a new channel, and it is commonly thought to occur when the active channel becomes superelevated with respect to the floodplain due to its higher rate of sediment accumulation (Heller and Paola, 1996; although see Smith and others, 1997, 1998; and Gibling and others, 1998 for other mechanisms). As the channel reaches some critical relief, the levee is breached and a series of crevasse-splay deposits form adjacent to the old channel, thus initiating the avulsion. Under the Avulsion model of alluvial aggradation, mature paleosols represent regions of lowest short-term sediment accumulation, which means aggrading channels will become most elevated with respect to these areas on the floodplain. Consequently, in a vertical stratigraphic section we would expect to see mature paleosols overlain abruptly by avulsion deposits (thin sandstones and low maturity paleosols) since avulsions should preferentially occur in the low lying areas of the floodplain where paleosols are most mature (fig. 3A and B). The model predicts a more gradual transition from avulsion package back into higher maturity paleosols as the new channel becomes established (fig. 3C). Statistically, this expected stacking pattern would translate into certain lithological transitions occurring more or less often than would be expected if transitions were completely independent of one another. For instance, the transition from mature paleosols to ribbon and thin sheet sandstones should be more common than predicted under a model of facies independence due to avulsion deposits inundating the low floodplain area where mature cumulative paleosols form. Similarly, (self) transitions between low

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Fig. 3. Simplified sketch of the Avulsion model of alluvial aggradation. The star marks the location of a hypothetical stratigraphic section that is being constructed on the floodplain. Paleosols are coded according to their maturity with higher stages (for example stage 3) representing greater pedogenic modification than lower stages (for example stage 1; see Bown and Kraus [1987] for coding scheme). During time A there is the development of a mature paleosol (for example stage 3) on distal floodplain mudstones where sediment accumulation rates are relatively low. During time B the channel avulses into the low lying distal floodplain depositing a heterolithic package of ribbon sandstones and immature paleosol mudstones on top of the mature paleosol from time A. Dashed line is abandoned channel. During time C the channel becomes reestablished and there is a gradual transition back to more mature paleosols. Flow is from the top of the figure.
maturity paleosols and thin sandstones should be more common due to the rapid aggradation and frequent lobe switching of avulsion packages. Conversely, gradual transitions from high maturity paleosols to lower maturity deposits should be less common than expected since the migration of channel belts toward the distal floodplain is thought to be controlled by episodic avulsion events rather than a more gradual process like meandering. In this paper, we test a prediction of the Avulsion model by quantitatively evaluating the stacking pattern of lithologies in a series of uncorrelated stratigraphic sections, which are often all that is available in ancient alluvial systems.

METHODS

Data Collection

For this study we used 35 measured stratigraphic sections from the Willwood Formation in the McCullough Peaks area of the Bighorn Basin (fig. 1). All sections fall within the Wa-3 faunal zone (Gingerich, 1991), which is approximately 350,000 years in duration and has been recognized across the entire field area (Clyde, 2001). We restricted our observations to this limited stratigraphic window so that basin-scale changes in subsidence, sedimentation rate, and provenance would not confound the results. In order to eliminate any repetition of data, each section constitutes either a different interval in the McCullough Peaks composite section (Clyde and Gingerich, 1998; Clyde, 2001) or is several kilometers away from any of the other sections. Sections varied between 5 and 22 meters in thickness and were measured through places with 100 percent exposure.

At each locality, (1) a general reconnaissance of the locality was carried out in order to assess the lithological variation, (2) each sandstone body was marked with flagging tape, (3) photos of the locality were taken to provide a record of the site, and (4) a representative stratigraphic section was chosen, measured and described (fig. 4). Large channel sandstone bodies (>3 meters thickness; fig. 2A) were not included in representative sections since the avulsion-pedofacies model of Kraus addresses lithological associations in floodplain areas outside the main channel(s). The sandstone bodies in these sections are almost entirely of the ribbon and thin sheet type (<3 meters thick; fig. 2B) referred to in Kraus (1997). The thickness of individual beds and the entire section was measured using a Jacob staff and Brunton compass. Paleosols were coded according to the maturity scale of Bown and Kraus (1987).

Data Analysis

Sedimentological data were first analyzed using Markov analysis to test whether the observed ordering of lithologies is consistent with the ordering predicted under a random model. Markov chain analysis evaluates data sequences of mutually exclusive states to determine whether there is a tendency for one state to follow another (Davis, 1986). The observed distribution of lithological transitions is compared to the distribution of transitions expected for a hypothetical sequence with the same number of transitions but where each lithologic state is completely independent of the immediately preceding state. If the observed distribution is significantly different from the expected distribution (as determined by the chi-square statistic), particular facies in the observed sequence tend to follow other facies more or less often than would be expected under a null model of independence.

If a sequence is characterized by a significant Markov property, it is important to then identify which transitions contribute most to the deviation from random. The traditional approach of subtracting expected transition probabilities from observed transition probabilities and using the difference as an indication of significance has
been shown to be flawed when the facies distribution is skewed like it is here (Carr, 1982). Several analytical methods have been proposed to resolve this (for example Carr, 1982; Powers and Easterling, 1982); however we take a more straightforward computerized resampling approach (jacknifing) that does not rely on underlying statistical models (see Wilkinson and others, 1996 for a similar approach). We wrote a computer program that takes the observed number of lithological states and reshuffles them randomly, creating a new idealized sequence where facies occurrences are entirely independent of each other. The transition count matrix for this new randomized sequence is then recorded and the reshuffling procedure is repeated. By performing this reshuffling procedure 1000 times we generate a frequency distribution for each transition given the null model of facies independence. If an observed transition frequency lies outside the 95 percent confidence limit of the expected distribution generated from the reshuffling program, then that transition occurred either more or

Fig. 4. Simplified illustration of one of the 35 stratigraphic sections used in this analysis. The lower part of this section has a sequence of cumulative paleosols that are thought to represent true overbank deposition under the Avulsion model of alluvial aggradation. The upper part of the section has a sequence of immature paleosols and thin sandstones that are thought to represent avulsion deposition. Data for all 35 sections are available from (http://earth.unh.edu/clyde/data.html). Observed facies transitions are shown by horizontal lines.
less often than would be expected under a random stacking of the facies. For instance, we may observe a certain number of transitions between facies A and facies B but find that this many (or more) transitions between these facies occurred in less than 25 of our 1000 simulated sections. This would indicate that this particular transition is significantly more common than expected at the 95 percent confidence level. Once the significance of observed facies transitions is determined, the results are then compared to those expected under the Avulsion model to determine if any deviation from random is indeed consistent with this alternative model.

Lithologies from the McCullough Peaks were generalized into four categories: sandstones, stage 1 paleosols, stage 2 paleosols, and stage 3 and 4 paleosols (fig. 4). Stage 3 and stage 4 paleosols were grouped together and treated as a single lithological “state” (a mature paleosol state) because there were only a few occurrences of stage 4 paleosols in the study area, and Markov analysis requires a minimum of 5 observations for each transition in order to be statistically robust. Willwood Formation paleosols tend to be composed of mudstone and siltstone whereas sheet and ribbon sandstones in this unit tend to be composed of fine to medium grained sand with minor amounts of intermixed silt. The lithological categories outlined above largely reflect transport mode on the one hand (suspension for mudstones versus bedload for sandstones) and degree of pedogenesis on the other. Other lithologies present in the Willwood Formation were not included in this analysis because either they were not observed in the study area (for example stage 5 paleosols) or because they are too rare (for example carbonaceous shales). Complete descriptions of the stratigraphic sections are available from http://earth.unh.edu/clyde/data.html or from the authors. Both self-transitions (occurrence of one lithology repeating itself) and non-self transitions (occurrence of one lithological state to another) were included in this Markov analysis. Self-transitions are easily identified in paleosol sequences due to internal horizonation (for example A horizons tend to separate different paleosols) and differences in hydromorphy. Self-transitions in sandstones are identified using erosional surfaces or abrupt changes in grain size.

RESULTS

The frequency distribution of facies from the sections used in this study is shown in figure 5 and the transition count matrix, which shows the observed distribution of facies transitions across all 35 sections, is shown in table 1. The distribution of facies is highly skewed with the majority of beds being stage 1 paleosols and sandstones. Statistical analysis of the transition count matrix shows that facies transitions in the Willwood Formation exhibit a significant Markov property, which means that the occurrence of each facies is at least partly dependent on the preceding facies. The chi-square statistic comparing the observed distribution of facies transitions to the expected distribution of transitions under a model of facies independence equals 99.1 (d.f. = 9), suggesting that we can reject the null hypothesis with a high degree of confidence (p << 0.01). Ten out of the 16 possible transitions deviate significantly (α = 0.05) from a model of facies independence when compared against distributions generated by random reshuffling of the facies (fig. 6). Four transitions (stage 3/4 paleosol to sandstone, stage 1 paleosol to stage 1 paleosol, stage 1 paleosol to sandstone, stage 2 paleosol to stage 2 paleosol) were observed to be significantly more common in the McCullough Peaks sections than in the simulated sequences (< 25 of 1000 simulations exhibited this many or more of the transition). Six of the transitions (stage 1 to stage 2, stage 1 to stage 3/4, stage 2 to stage 1, sandstone to sandstone, stage 3 to stage 1, and stage 2 to sandstone) were observed to be significantly less common than in the simulated sequences (< 25 of 1000 simulations exhibited this few or fewer of the transition). The other transitions were considerably more or less common than
expected but did not achieve statistical significance as determined by the reshuffling procedure.

DISCUSSION AND CONCLUSIONS

Markov analysis indicates that facies transitions in Willwood Formation exposures in the McCullough Peaks area are non-random ($\alpha = 0.05$). Given that the null model of facies independence can be ruled out for these sections, we can now turn our attention to determining if they are non-random in a way that is predicted under the

**Table 1**

*Transition frequency matrix showing distribution of transitions between lithologies for McCullough Peaks sections of the Willwood Formation. ss - sandstone, 1 - stage 1 paleosol, 2 - stage 2 paleosol, 3 or 4 - stage 3 or 4 paleosol*

<table>
<thead>
<tr>
<th>From:</th>
<th>ss</th>
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<td>18</td>
<td>79</td>
<td>26</td>
<td>13</td>
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<tr>
<td>1</td>
<td>103</td>
<td>219</td>
<td>22</td>
<td>8</td>
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<td>2</td>
<td>15</td>
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<td>3 or 4</td>
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Fig. 5. Frequency distribution of the different facies observed in this study. Low maturity paleosols (for example stage 1 paleosols) and thin sheet and ribbon sandstones (labeled here sandstones) dominate these sections suggesting that approximately 80 percent of deposition on the floodplain could occur during avulsions.
Avulsion model. As discussed earlier, the Avulsion model makes some key predictions in terms of stacking pattern, including: (1) common transitions between mature paleosols (stage 3/4) and sandstones due to avulsion into low lying parts of the floodplain where mature paleosols are thought to accumulate, and (2) common transitions between low maturity deposits (sandstones and stage 1 paleosols) due to rapid aggradation of the avulsion package just after the channel avulsed. The stacking patterns from the McCullough Peaks are generally consistent with both of these predictions.

Our results indicate that mature paleosols transition to sandstones more often than would be expected under a model of facies independence suggesting that sandstones were preferentially deposited in areas where mature paleosols had previously formed (fig. 6). Studies of the modern Saskatchewan River have shown that channels avulse to the topographically low-lying wetland areas of a floodplain (Smith and others, 1989). Typically, the areas of lower elevation are characterized by lower short-term accumulation rates and therefore would correspond to areas of mature pedogenesis in the pedofacies model (Bown and Kraus, 1987). Furthermore, within the Willwood Formation, carbonaceous shale beds are often found directly underneath ribbon and small sheet sandstone bodies (Davies-Vollum and Wing, 1998; Davies-Vollum and Kraus, 2001), although there were too few of these to be included.
in this analysis. Carbonaceous shales likely represent low-lying swampy environments on the ancient floodplain (Wing, 1984; Davies-Vollum and Wing, 1998), and their vertical association with these small sandstone bodies also supports an avulsion interpretation. Carr (1982) re-analyzed the data from Gingerich (1969) for the underlying Fort Union Formation, and found that the carbonaceous shale (lignite) to sandstone transition was the only facies transition significantly more common than would be expected under a random model. It seems that the Willwood Formation is characterized by a similar aggradational style as the preceding Fort Union Formation, although the poorly drained carbonaceous shales of the Fort Union are largely replaced by better drained mature paleosols in the Willwood.

Low maturity paleosols also seem to group together more often than would be expected under a random model (fig. 6). Two of the three transitions expected to be particularly common during aggradation of avulsion packages (sandstone to stage 1, stage 1 to stage 1, stage 1 to sandstone) are found to be significantly more common than expected, with self-transitions between stage 1 paleosols being one of the most anomalously common facies transition in the whole study (fig. 6). It is also important to note that the transitions associated with decreases in paleosol maturity (for example stage 2 to stage 1, stage 3 to stage 1) are observed to be significantly uncommon which supports an aggradational mode where maturity decrease occurs episodically (for example during avulsion) rather than gradually (for example during meandering) or randomly. Also, self-transitions within paleosols are particularly common which could indicate lateral stability of the main channel between avulsion events.

Although these results do not necessarily rule out alternative depositional models, they are generally less consistent with them compared to the Avulsion model. A random model of deposition is argued against by the statistically significant ordering in the facies stacking. A model where facies are controlled by stream meandering is argued against by a lack of gradual decreases in paleosol maturity that would be expected as the main channel migrates across the floodplain. A crevasse splay model would predict many of the same transitions observed here (for example stage 1 paleosol to sandstone) however the scale of the low maturity heterolithic packages observed here (~5 to 10 meters) is considerably larger than that of typical crevasse splay deposits. In fact, many of the ribbon and thin sheet sandstones in this study are clearly crevasse splay deposits but they represent only one bed in a sequence of lithologies that make up one of the heterolithic packages that are interpreted to be avulsion deposits. Studies of lateral facies relationships have shown that crevasse splay deposits are likely an important component of these heterolithic sequences but they do not explain their entire deposition (see for example Kraus and Gwinn, 1997).

Detailed descriptive field studies (for example Kraus, 1996, 1997) and the results presented here suggest that the Willwood Formation is characterized by coherent heterolithic intervals of thin sandstones and low maturity paleosols (interpreted to be the product of avulsions) that are separated by more mature paleosols (interpreted to be the low lying areas on the floodplain). The thin sandstones and low maturity paleosols represent almost 80 percent of the sediment in the McCullough Peaks sections which means that if the Avulsion model is valid, avulsions were a very important aggradational process in this sedimentary system (fig. 5). The Willwood Formation represents one of the only ancient sedimentary units for which avulsion deposits have been identified; yet these deposits seem to represent the majority of floodplain deposition. If this new model is supported by further analyses like the one presented here, it will necessitate the reevaluation of many other units that preserve floodplain sediments.
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