1993

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ABSTRACT

A new method uses alluvial paleosols to calculate sediment accumulation rates for thin (25 m) stratigraphic intervals and allows the reliable interpolation of ages for stratigraphic levels within a thick stratigraphic interval bounded by established dates. Sediment accumulation rates calculated for a 650 m composite section in the Eocene Willwood Formation of Wyoming span time intervals ranging from only 0.05 to 0.25 m.y. Important sedimentologic changes coincide with changes in accumulation rate and indicate close and direct relations between the history of basin subsidence and depositional patterns.

INTRODUCTION

Estimating sediment accumulation rates can improve understanding of sedimentary basin development. In foreland basins, the record of sediment accumulation can be used to determine spatial and temporal subsidence patterns of the basin, and these patterns provide information on thrusting history. Differential subsidence may also influence basinal facies patterns (e.g., Alexander and Leeder, 1987); therefore, resolving accumulation rates is also important to sedimentologic and stratigraphic analyses.

Sediment accumulation rates are commonly calculated by dividing the thickness of a stratigraphic section by its known or estimated time span. Because of compaction, this method yields rock accumulation rates. Sediment accumulation rates are readily calculated by decompacting a rock thickness to sediment thickness prior to burial (e.g., Baldwin and Butler, 1985). More difficult in most continental sequences is determining how much time is represented by the stratigraphic section of interest. With few exceptions (e.g., Johnson et al., 1988), the temporal resolution of paleomagnetic dating is still relatively coarse. Radiometric dates cannot commonly be obtained and, even where available, are generally widely spaced in time. Similarly, continental biostratigraphy produces relative dates that are poorly constrained or widely spaced in time. Consequently, these techniques usually yield accumulation rates that are poorly time averaged. Time-averaged rates are of value in large-scale studies; however, sediment accumulation rates calculated for short intervals are needed to detail the complexities of and interrelations between the structural and depositional histories of sedimentary basins. Despite some exceptions (e.g., Johnson et al., 1988), few studies have examined differential subsidence on a small scale and its influence on the sedimentary record.

This paper describes a new method to calculate sediment accumulation rates for thin stratigraphic intervals. The technique is based on alluvial paleosols and the recognition that paleosol maturity is inversely related to sediment accumulation rate. This paper builds upon a study (Bown and Kraus, 1993) in which we used paleosols to estimate the percent of total section time represented by subdivisions of a 650 m composite section in the Willwood Formation of Wyoming. Dating of the Willwood Formation since that study allows us here to calculate rock and sediment accumulation rates and changes in those rates over short time scales. Important sedimentologic events are correlated to the record of accumulation rates, and the factors that controlled the depositional changes are examined.

GEOLOGIC SETTING

The Eocene Willwood Formation in the southern part of the Bighorn basin (Fig. 1) contains ancient fluvial deposits with abundant paleosols (e.g., Bown and Kraus, 1987). Deposition of the Willwood Formation was coeval with Laramide structural development of the Bighorn basin, which is part of the Rocky Mountain foreland. The deep, westwardly asymmetric basin is adjacent to mountain ranges cored by Precambrian rocks (Fig. 1). To the north, in the subbasin termed the Clark's Fork basin, the Tertiary structural axis of the basin is overridden by the Beartooth Mountains. To the south, in the study area, the axis lies close to or is overridden by the Oregon basin fault (Stone, 1985; Parker and Jones, 1986). Subsurface data (Stone, 1985) show that this fault dips ~30° to the west-southwest. Maximum vertical offset is ~6000 m, and there is nearly 5 km of horizontal overhang at the basement level.

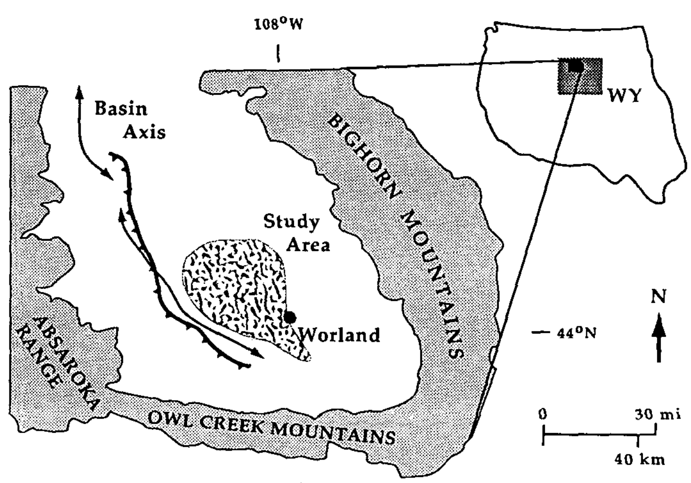

Figure 1. Map of Bighorn basin, Wyoming, showing major structural features and location of study area (shaded) in southern part of basin. Oregon basin fault is shown by heavy sawtoothed line.

TEMPORAL RESOLUTION IN THE WILLWOOD FORMATION

Temporal resolution of a stratigraphic sequence depends on reconstructing the amount of time represented by deposition, erosion, and nondeposition (e.g., Wheeler, 1958). We began time stratigraphic restoration of the Willwood Formation (Bown and Kraus, 1993), constructing a composite stratigraphic section extending from the base to the 650 m level of the formation from numerous measured sections. Willwood Formation paleosols record periods of deposition due to overbank floods and, more important in terms of total time, periods of nondeposition when pedogenesis modified alluvium. Paleosols vary in their degree of development or maturity. Maturity increases with longer periods of nondeposition (pedogenesis) and thus slower sediment accumulation. Paleosols have been eroded by channel sand bodies and by mud-rock–filled scours that are found in certain parts of the Willwood Formation. Both scour-and-fill features represent times of erosion, nondeposition, and deposition. To account for the total time represented by channel sand bodies and mud-rock–filled scours, we (Bown and Kraus, 1993) carefully substituted paleosols developed on laterally equivalent mud rocks for these features. In this way, the composite stratigraphic section was converted to a vertical sequence consisting entirely of paleosols.

Temporal reconstruction of the composite section is based on the relative maturities of the paleosols. We (Bown and Kraus, 1993) recognized seven stages of paleosol maturity and estimated their relative times of development on the basis of lateral relations among the seven stages. For example, laterally tracing paleosols showed that four vertically stacked stage 1 paleosols are laterally (and thus temporally) equivalent to a single stage 3 paleosol. Similarly, a stage 4 paleosol is laterally and temporally equal to two stage 3 paleosols.

The composite section was subdivided into 25-m-thick intervals, each of which consists of vertically stacked paleosols. The relative amount of time represented by each interval was estimated from the maturity of the included paleosols. Because the section is a composite, some of the 25-m-thick intervals are represented by several vertical sections measured in different locations. The number of paleosols examined per interval ranges from two to 82, and averages 24. Each paleosol was weighted according to its relative time of development (based on maturity), and those values were averaged for each interval to yield a maturation index. For example, the lowest 25 m interval contains eight paleosols ranging in maturity from stage 4 to stage 6 (very mature). On the basis of the relative times of development for those stages, the maturation index for the interval is 12.0, the highest for any interval in the Willwood Formation. Assuming that the 650 m section represents 100% time, we then estimated the percent of Willwood Formation time represented by each 25 m interval (Fig. 2). For example, dividing 12.0 by the sum of the maturation indices for the entire section (131.7) and multiplying by 100 indicates that the lowest 25 m interval occupied 9% of total Willwood time.

We emphasize that the paleosol weights are averaged not only over time but also over space, because the composite section was compiled from a number of different measured sections. The consequences of this spatial averaging are considered in a later section.

SEDIMENT ACCUMULATION RATES

New data have established lower and upper ages for the composite section and allowed us to quantitatively determine rock and sediment accumulation rates for each 25 m interval. A tuff at the 634 m level is 52.8 ±0.3 Ma, on the basis of $^{40}Ar/^{39}Ar$ dating of sanidine (Wing et al., 1991). Because the 625–650 m interval occupies such a small percentage of the total time represented by the composite section (Fig. 2), 52.8 Ma is a reasonable upper age for the section. A lower limit for the section is based on pollen correlation to the marine sedimentary record (Wing et al., 1991). Strata in the Fort Union Formation 35 m below its contact with the Willwood Formation correlate with the NP9-NP10 boundary, which has an interpolated age of ~55.7 Ma (see Obradovich, 1988). Because the Fort Union Formation had rapid rates of sediment accumulation relative to Willwood rocks (e.g., Gingerich, 1983), 55.7 Ma is a good approximation of the lower age limit for the composite section. Consequently, the time span calculated for the 650 m composite section is ~2.9 m.y.

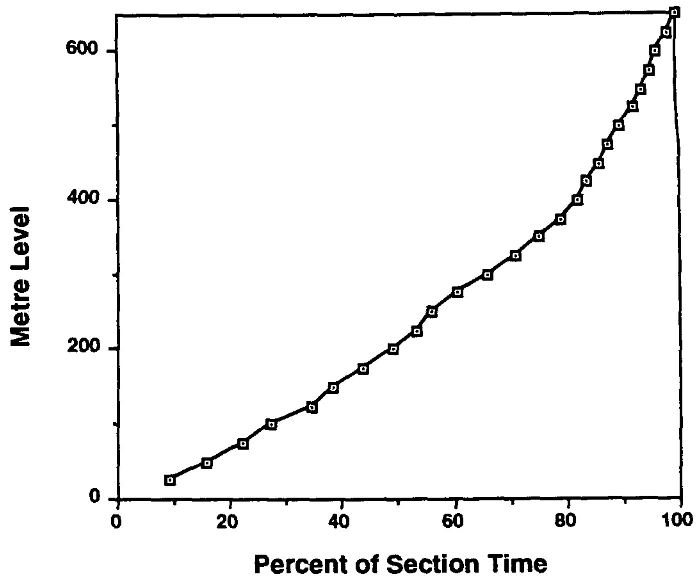

Figure 2. Plot of percent of section time vs. metre level for Willwood Formation composite section.

On the basis of a time span of 2.9 m.y. for the entire section and knowledge of the percentage of time represented by each 25 m interval, the rock accumulation rate was calculated and plotted against the midpoint of each interval (Fig. 3). Sediment accumulation rates were then calculated by decompacting the Willwood section following the methods of Baldwin and Butler (1985). On the basis of regional studies, the top of the Willwood Formation was probably buried to ~1000 m (e.g., Bown, 1982). Measured sections in different areas of the basin typically average ~75% mudstone and 25% sandstone. Those values were used for each 25 m increment, because the lithologies are relatively evenly dispersed. A plot of sediment accumulation rate against metre level shows trends similar to those in the rock accumulation rate plot (Fig. 3). The agreement between the plots probably reflects the fact that the section is only 650 m thick; thus, the difference in burial depth of the top and bottom of the section was insignificant. In addition, the lithology is relatively uniform.

The rate of sediment accumulation shows an overall increase upward through the composite stratigraphic section (Fig. 3). The value of the curve lies in the numerous fine subdivisions of Willwood Formation time shown. The longest 25 m interval represents 9% of formation time, or ~260 ka. The shortest interval spans only 53 ka. Thus, short-term fluctuations in accumulation rate can be identified and include (1) relatively steady, slow increase from 0 to 138 m with a slight decrease at 113 m; (2) steady accumulation followed by a rapid increase between 188 and 238 m; (3) a return to steady accumulation followed by a rapid increase between 338 and 413 m; (4) a decrease in accumulation rate from 413 to 513 m with a disruption at 438 m; and (5) an increase in accumulation rate.

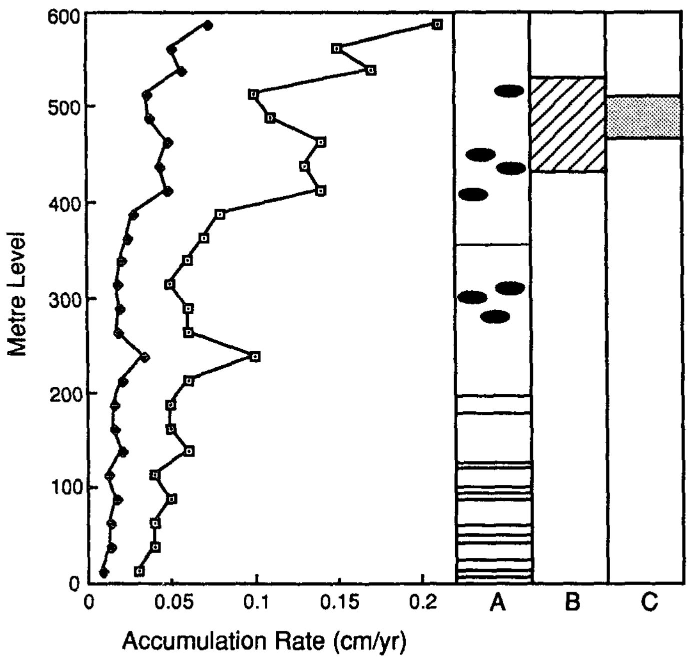

Figure 3. Plot of rock accumulation rate (black diamonds) and sediment (decompacted rock) accumulation rate (open squares) vs. metre level in composite section of Willwood Formation. Column A shows stratigraphic locations of tabular (straight lines) and lenticular carbonaceous shales. Column B shows stratigraphic location of mud-rock–filled scours, and column C shows position of thick and laterally extensive sheet sand-body complex.

To some degree, the overall increase in accumulation rate reflects change in location rather than an increase at a single locality. The oldest Willwood Formation exposures are in the eastern part of the study area. Progressively younger deposits are exposed toward the Oregon basin fault, in the direction of sediment thickening (Parker and Jones, 1986). Whereas the overall increase may be an artifact of the space-averaged nature of the data, the smaller scale perturbations are interpreted as actual temporal changes. The smaller changes listed above occur over relatively short stratigraphic intervals, and they generally record change within individual vertical sections within the composite section.

SEDIMENTOLOGIC EVENTS

Sedimentologic events can be correlated with the sediment accumulation rate curve (Fig. 3) to provide a more synthetic view of the early Eocene history of the Willwood Formation and to show how the structural development of the basin influenced depositional patterns. Similarly, major mammalian disappearances and appearances have been correlated to the upward changes in paleosol maturity (Bown and Kraus, 1993). The principal sedimentologic features include carbonaceous units, large sheet sand bodies, and extensive scour-and-fill structures.

The 0 to 138 m interval contains unusually abundant drab siltstones and shales that are carbonaceous and contain abundant plant-compression fossils (Wing, 1984). Although carbonaceous units typically constitute only 2% of the Willwood section, they make up as much as 20% of the lowest 100 m (Wing, 1984). The carbonaceous units in this part of the section are generally tabular, and their lateral extent and megafloral content indicate accumulation on broad, poorly drained flood plains (Wing, 1984). Wing (1984) attributed their development to comparatively low rates of basin subsidence and sediment accumulation, consistent with the slow accumulation rates calculated for the 0 to 138 m interval.

At about the 300 m level, carbonaceous units change from tabular to dominantly lenticular (Wing, 1984). This change just preceded the sharp increase in accumulation rates that characterizes the 238 to 413 m interval. Wing (1984) concluded that lenticular units formed in abandoned channels and indicate rapid rates of flood-plain aggradation as compared to the tabular units. Lenticular carbonaceous units in the upper part of the section are consistent with that interpretation.

The 413–513 m interval is notable for scour-and-fill structures filled predominantly by mud rocks on which immature paleosols developed. The scours are up to tens of metres deep and dissect sediments upon which older, better developed paleosols formed. The mud-rock–filled scours are found principally between the 430 and 530 m levels of the composite section and thus conform closely to the one significant period in Willwood Formation time when sediment accumulation rates declined (Fig. 3). The upper half of the 413 to 513 m interval also has an unusually thick and laterally extensive sand-body complex. This 40-m-thick complex contains four sand bodies separated by a total thickness of only 10 m of mud rocks. Numerous mudstone-filled scours are associated with the sandstone zone. The close stratigraphic spacing of the sand bodies and the associated scours indicate that overbank deposits were intensively eroded and reworked by channel systems (e.g., Bridge and Leeder, 1979).

CONTROLS

Flexural modeling indicates that structural subsidence of Laramide-style basins resulted from loading by basin-margin uplifts (Hagen et al., 1985). The structural development and depositional history of the southern two-thirds of the Bighorn basin were controlled principally by the Oregon basin fault. The latest Cretaceous Lance Formation and the combined Fort Union (Paleocene) and Willwood formations thicken toward the fault and indicate that a north-trending structural trough had formed just east of the fault due to tectonic loading (Parker and Jones, 1986). The fault cuts the Fort Union Formation but not the Willwood Formation (Stone, 1985), suggesting to Parker and Jones (1986) that fault motion had ceased by the end of Paleocene time. Paleosol maturity also increases dramatically from the Fort Union into the Willwood Formation, indicating a decline in accumulation rates and confirming that thrusting had ended.

The sediment accumulation curve for the Willwood Formation (Fig. 2) reflects infilling of space created both by earlier thrusting along the Oregon basin fault and by subsidence resulting from redistribution of the tectonic load due to Eocene erosion and deposition. Modeling predicts that, as the balance between those processes changes when thrusting is episodic, the depositional history in the basin varies over time and space (Flemings and Jordan, 1990). The spatial variability is especially important to note when interpreting the accumulation curve for the Willwood Formation, which is based on a composite stratigraphic section. As mentioned above, the overall increase in sediment accumulation rate upward through the section probably reflects the fact that progressively younger deposits are exposed toward the Oregon basin fault, in the direction of sediment thickening (Parker and Jones, 1986). Temporal variability is seen in the smaller scale fluctuations of the accumulation rate curve. What controlled these changes in accumulation rate over comparatively small time periods is not clear.

Mud-filled scours and an unusually thick and extensive sheet sand-body complex indicate that erosion was a more important process at this time than during the rest of Willwood Formation deposition, consistent with the declining accumulation rates. Although we (Bown and Kraus, 1993) hypothesized that tectonic activity in the Owl Creek Mountains may have led to the interval of downcutting, we now believe that the Oregon basin fault was a more important control. With the cessation of thrusting, presumably at the end of the Paleocene (Parker and Jones, 1986), continued development and infilling of the basin was influenced by erosion and redistribution of the mountain belt. Because denudation of a mountain belt declines without sustained uplift and relief (e.g., Flemings and Jordan, 1990), a decrease in the sediment supply beyond some threshold may have led to downcutting in the basin.

SUMMARY AND CONCLUSIONS

The method presented here uses variations in paleosol maturity to calculate sediment accumulation rates for geologically short time intervals. In the absence of absolute age information, this method yields relative rates of sediment accumulation.

The paleosol approach also allows the reliable interpolation of ages for stratigraphic levels within a larger stratigraphic interval bounded by established dates. For example, the age of successive 25 m levels in the Willwood Formation can be determined when the percentage of total formation time represented by each interval and the two ages bounding the section are known. Such information can be critical for finely correlating geologic and biological events within and between basins. It may also be valuable for correlating facies in the distal parts of a basin to deposits and events along the basin margin. Although changes in the rates of accumulation and the facies of distal deposits are used regularly to interpret the timing of orogenic activity, the actual influence of deformation on those distal deposits is not clear. For example, Flemings and Jordan (1990) concluded that, in distal parts of the basin, changes in sediment accumulation may be out of phase with tectonic activity, and there is some dispute over the facies deposited in distal areas during orogenesis (e.g., Heller et al., 1988; Burbank et al., 1988). If distal deposits could be correlated more confidently to their proximal counterparts, which more commonly show the direct effects of orogenic activity, these models could be tested and the effects of tectonic activity on distal deposits clarified. Because paleosols are commonly developed on alluvial deposits in distal areas, the method described here is potentially useful.

ACKNOWLEDGMENTS

Partially supported by National Science Foundation grant EAR-8608152 to Kraus. Collection of paleosol maturity data was funded by National Geographic Society grant 3985-89 to Bown.

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Manuscript received January 29, 1993
Revised manuscript received April 26, 1993
Manuscript accepted May 3, 1993

Reviewer's comment

A clever and innovative method for deriving temporal resolution in continental sediments.

Paul Koch