The Relationship Between Bedform and Log Orientation in a Paleogene Fluvial Channel, Weißelster Basin, Germany: Implications for the Use of Coarse Woody Debris for Paleocurrent Analysis

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PALAIOS, 2004, V. 19, p. 587–597

Isolated logs preserved in the Älterer Flußsande of the Weißelster basin, Germany, are examined relative to their subjacent bedform. Paleocurrent analyses conducted on both the log orientation and its underlying bedform are used to determine whether or not any relationship exists between these two structures. Two patterns emerge from this investigation. When the data set is taken collectively, the mean vector of the log orientation is in a subperpendicular relationship to the mean vector of their bedforms. This coarse woody detritus is not oriented preferentially parallel to paleocurrent direction as has been previously hypothesized. In addition, when individual log orientations are compared with their underlying bedforms, logs may be oriented parallel, subperpendicular, or perpendicular to the bedform. There is no statistical preference for any particular orientation in the data set. Comparison is made with an actualistic data set from the Lassa Distributary of the Rajang River delta where a similar trend is documented, and with previously published experimental and field data. This comparison indicates that there is no statistical preferred orientation of wood clasts in fluvial systems. Hence, these results caution against the use of woody phytoclasts as independent indicators of paleocurrent trends in fluvial systems.

INTRODUCTION

The use of fossilized wood as an aid in determining paleocurrent direction is equivocal, and it was recognized early that it was difficult to interpret such data sets (Potter and Pettijohn, 1977). Results from a literature survey conducted by Macdonald and Jefferson (1985) demonstrated that wood may be oriented either perpendicular to regional paleocurrent, parallel with flow conditions (as indicated by current structures within bedforms), or in a random arrangement (polymodal distribution). It becomes clear why such ambiguity exists when the literature is evaluated. First, there are very few published data sets available for comparison, and those that do exist originate from a wide variety of depositional settings, ranging from terrestrial alluvial-fan deposits to submarine turbidites. Data sets available outside of the geological sciences (e.g., forest ecology and ecosystem management) have not been considered to date. Second, most data sets are based on orientations of specimens that represent very small fragments of wood or charcoal because these are more common and numerous in outcrop (Table 1); few data sets are based upon large-diameter debris such as branches or logs. Third, wood-fragment orientations have been compared with paleocurrent trends of a local (a single cumulative data set) or regional (many cumulative data sets) character. Rarely do data exist concerning the orientation of the specimens in relation to the bedform on which they are preserved (e.g., Pelletier, 1958).

The Älterer Flußsande, an Upper Eocene fluvial sand complex exposed in Tagebau Schleenhain, in the Weißelster basin near Borna, Germany, preserves many isolated lignitized logs, providing the opportunity to assess the relationship of individual elements relative to their subjacent bedform. Orientation data based on isolated logs are preferable because there is the potential for reorientation of trees when amassed in any type of accumulation (Blair, 1997; Gastaldo and Degges, in press). Most Weißelster basin deposits are not lithified, making it possible to excavate the sand beneath individual logs, exposing the bedform upon which each log rests. Therefore, the exact relationship between log alignment and the paleocurrent orientation of its immediate subjacent bedform can be discerned. These data provide the 1:1 correlation most often missing in other data sets. The purpose of this contribution is to present the results of these bedform:log orientations and compare them to data from other recent fluvial settings to determine the usefulness of coarse woody detritus (CWD) as a proxy for paleocurrent.

TAGEBAU SCHLEENHAIN

Tagebau Schleenhain is an open-cast, brown-coal mine located in the central part of the Weißelster basin of northwest Saxony, south of Leipzig (Fig. 1). Few geological publications exist that describe or evaluate the basin (e.g., Eißmann, 1968; Bellman et al., 1982), mainly because mineralogical resource data were classified until German reunification. Only recently have concerted efforts been made to evaluate the fluvial character of the depositional systems preserved in the basin (Gastaldo et al., 1990; Halfar et al., 1998).

Tertiary strata in the basin essentially are horizontal. In Tagebau Schleenhain, a Middle Eocene coal (Flöz I) directly overlies an irregular surface of pre-Paleogene strata. This pre-Paleogene rock is kaolinized Buntsandstein (Eißmann, 1968). Flöz I thins and thickens over this erosional surface. The Upper Eocene coal, Flöz II, is separat-

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TABLE 1—Publications in which coarse woody detritus or woody phytoclasts have been used as paleocurrent indicators in Recent to ancient sedimentary environments.

AUTHOR	AGE	SETTING	WOOD	ORIENTATION
Krumbein (1942)	Recent	Canyon flood deposits	Logs	Random in horizontal and vertical/subvertical orientation within log jams associated with bends in the stream
Crowell (1955)	Paleogene	Flysch; turbidites	“Flecks” of cm-size	Parallel to flow
Dzulynskí and Radomski (1955)	Eocene	Flysch	Fragments	Found at ends of groove casts, therefore interpreted as parallel to flow
Pelletier (1958)	Carboniferous	Fluvial	< Fraction of an inch to 3–4“ fragments	Perpendicular (transverse) to regional paleocurrent
Colton and DeWitt (1959)	Devonian	Transitional marine	Linear fragments	Approximately parallel to regional trend
Gradzinski et al. (1959)	Pennsylvanian	Terrestrial	“Flakes” to trunks	No definitive relationship
Sullwold (1960)	Miocene	Turbidites-submarine fan	Charcoal fragments	Preferential orientation at 5 localities; 3 parallel, 2 perpendicular. Other localities randomly oriented
Sigafoos (1964)	Recent	Alluvial plain	Logs	Parallel to stream orientation
Diessal et al. (1967)	Triassic	Fluvial plain	Fragments	Parallel to paleocurrent trend in fine-grained laminites; perpendicular to trend in coarse-clastic deposits
Everett (1968)	Recent	Fluvial plain	Logs	Parallel to stream orientation
Macdonald and Tanner (1983)	Cretaceous	Turbidite	?? Fragments	Mainly parallel to current, although polymodal distribution reported
Macdonald and Jefferson (1985)	Recent	Experimental flume study	Fragments <20 cm in length	asymmetrical fragments current parallel; symmetrical fragments may be perpendicular, large organs may have a wide range of orientations
Wnuk and Pfefferkorn (1985)	Carboniferous	Terrestrial lake	Logs and aerial axes	Unidirectional orientation in response to wind storm
Blair (1987)	Recent	Alluvial fan	Logs	Parallel to slope at front of levees (non-cohesive gravity flow); random within boulder/log jams
Degges and Gastaldo (1989)	Carboniferous	Fluvial	Logs	Mainly perpendicular to channel orientation
Robison and Beschta (1990)	Recent	Coastal streams	Branches/logs (coarse woody debris)	<1/3 all debris oriented parallel to flow; > 1/3 debris oriented subperpendicular /perpendicular (80°–100°)
McKnight et al. (1990)	Jurassic	Fluvial	Logs	Polymodal
Fiorillo (1991)	Cretaceous	Fluvial	Incomplete logs (l = 15–60 cm; w = 3–75 cm)	No preferential orientation
Evans (1991)	Eocene	Alluvial fan	Wood casts/branches	Bimodal; principal mode is perpendicular, secondary mode is parallel to current lineations.
Gastaldo (1991)	Recent	Coastal plain	Trees	Tornado- (cyclone-) induced assemblage; unidirectional orientation in response to storm front (parallel to wind), but where cyclonic winds developed, trees oriented perpendicular to storm front.
Savrda and King (1993)	Cretaceous	Marine shelf	*Teredo*-bored logs, l:w ratio >3	Parallel to depositional strike, shore-parallel orientation
Fielding et al. (1997)	Recent	Fluvial	*In situ* inclined or reclined trunks	Parallel and subparallel orientation
Alexander et al. (1999)	Recent	Fluvial	Trees, logs, branches (CWD)	Polymodal (caught around obstacle), parallel, and subparallel orientation
Abbe and Montgomery (2003)	Recent	Fluvial	Trees and logs in jams (CWD)	Polymodal with orientation dependant upon the type of wood debris accumulation

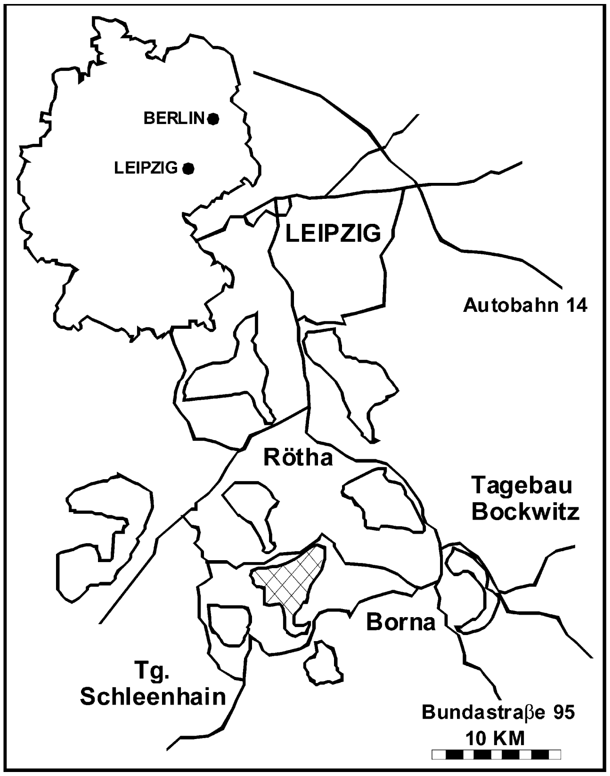

FIGURE 1—Generalized locality map of the Weißelster basin south of Leipzig, Germany. Open-cast, lignite mines (gray pattern) and Tagebau Schleenhain (cross-hatched pattern) are identified near the towns of Rötha and Borna. Locations of mining operations are as of 1991–1992.

ed from the Middle Eocene coal by the Mittlerer Basissand and the Luckenauer Ton. Flöz II is the main coal seam near Borna. Directly about the coal is a fining-upwards fluviatile sand sequence, the Älterer Flußsande, which has eroded locally into the underlying coal. This sequence is comprised of: (1) pebble to granule ($-0.8\ \phi$) matrix-supported conglomerate lenses; (2) coarse ($1\ \phi$) to fine ($2.1\ \phi$), angular to subangular, moderately well-sorted sand organized into small- and large-scale bedforms and bedform sets; (3) finely laminated medium silt; (4) clay- and organic-rich bedform drapes; and (5) a variety of medium- to dark-colored clay that may be found in contact with the sand bodies or the coals. Architectural fluvial elements have been identified following Miall (1985) and include: gravel bars and bedforms, sandy bedforms, downstream and lateral accretion deposits, overbank fines, and shallow-lake accumulations (Halfar et al., 1998; Fig. 2). This fluviatile sand separates Flöz II and Flöz III, the Thüringian Main Coal.

The Älterer Flußsande is fossiliferous. Autochthonous accumulations include rooted paleosols, as well as floating and submerged aquatic plants preserved in channel cutoff deposits. Parautochthonous leaf litters predominate abandoned channel fills and are typical of the Zeitz floralcomplex (Mai and Walther, 1991). These are identical in character to those reported by Gastaldo et al. (1996) for the Late Oligocene channel fills in Tagebau Bokwitz. Allochthonous leaves and lignitized logs are found upon and within, respectively, bedform structures.

An erosional disconformity exists above Flöz III, the result of emplacement of another fluviatile sand complex. At least the upper part of this complex is middle Oligocene in age, as dated by the presence of typical Haselbach floral components in abandoned channel fills (Mai and Walther, 1991). Overlying this middle Oligocene deposit is Flöz IV, also of middle Oligocene age.

LASSA RIVER, RAJANG DELTA, SARAWAK

The Rajang River delta is located in the East Malaysian state of Sarawak on the island of Borneo (Fig. 3). It is a tropical, peat-accumulating costal-plain system that occurs in an embayment formed by folded Mesozoic and Cenozoic strata of the Central Borneo Massif (Staub and Esterle, 1994; Staub and Gastaldo, 2003). The delta plain and river valley upstream cover approximately 6900 km^2 and include three physiographic regions—an alluvial valley; an abandoned, tidally flushed delta plain (Rajang River, Staub et al., 2000); and an actively accreting rectilinear delta plain.

The Lassa River is one of four active rivers in the delta debouching sediment into the South China Sea during both the wet and dry seasons (Staub et al., 2000). The Holocene delta received rainfall that exceeded 3.7 m/year with discharge normally ranging from 1000 to 6000 m^3/s, with approximately 24-million MT of sediment deposited in the delta front and prodelta regions annually. The delta is tidally influenced, and Spring tides range from 2.9 to 5.8 m in displacement in the costal zones, with the effects of these tides reaching as far inland as Kanowit.

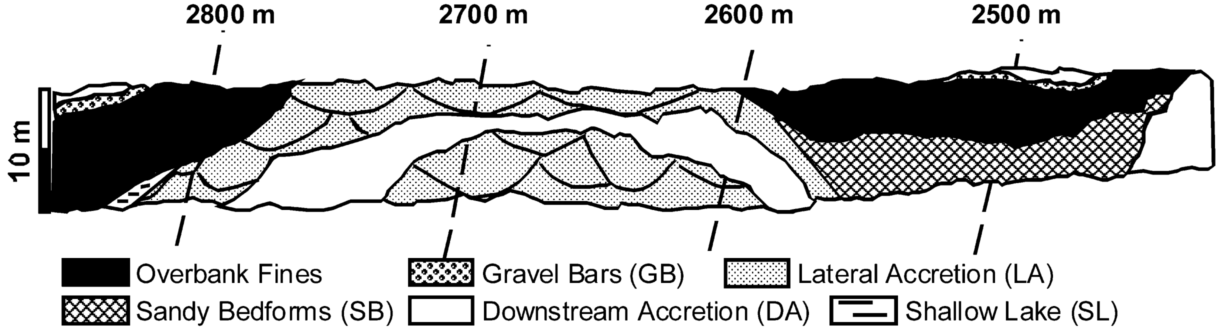

FIGURE 2—Graphic illustration of a lateral-profile photomosaic taken in Tagebau Schleenhain depicting the fluvial architectural elements over $>$ 400 m distance along the highwall (after Halfar et al., 1998).

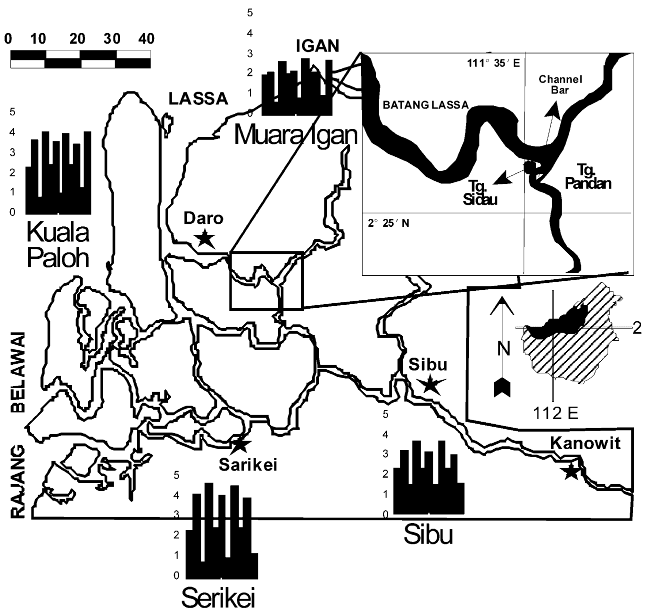

FIGURE 3—Locality map of the Rajang River delta, Sarawak, East Malaysia. The lateral channel bar exposed at low tide on which Coarse Woody Debris (CWD) was analyzed occurs east of Tandjung Sidau, adjacent to Tg. Pandan (insert). Tidal-range data for October 18th and 20th, 1992, the days before and after the sampling date, are shaded in gray; tidal ranges for the date of sampling, October 19th, are indicated in black for tidal gauges at Kuala Paloh, Muara Igan, and the towns of Serikei and Sibu.

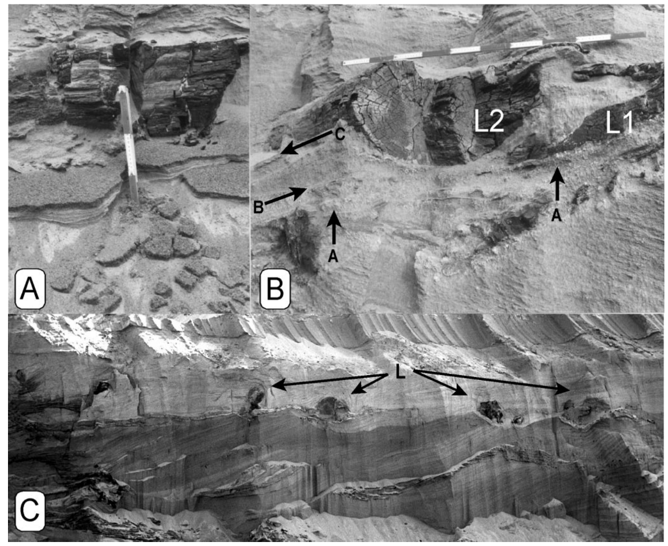

FIGURE 5—Examples of logs (CWD) in outcrop along the highwall of Tagebau Schleenhain. (A) Photograph of CWD overlying the bedform upon which it was emplaced. Only 34 logs displaying this arrangement were accessible in Tagebau Schleenhain and used in the present study. Scale is in decimeters. (B) Photograph of CWD not used in the present study, although, on first inspection, it would appear to be a valid datum. Note that log L1 was emplaced upon the foreset bed (A) and acted as a baffle, resulting in the deposition of crossbed (B). Log L2 rests 3 cm above crossbed (B) on a partially eroded bedform that is evident between L1 and L2. Crossbeds (C) were produced on the downstream side of L2 in response to sediment flow over the log. Scale in dm. (C) Photograph of highwall exposure in which several logs (L) lie on the contact between two different architectural elements. Note the scour-and-fill structures that are evident beneath most CWD.

METHODOLOGY

Lignitized logs, ranging from 8 to 130 cm in diameter and greater than 2 m in length (minimum estimate based on excavation and exposure in the highwall), were identified in the Älterer Flußsande complex separating Flöz II and Flöz III (Fig. 4). Each accessible log along the highwall was examined *in situ* to determine whether it was associated directly with an undisturbed underlying bedform, or if there had been some influence to, or alteration of, the bedform associated with the log subsequent to its emplacement (Fig. 5A). In some cases, woody roots were found attached to logs, allowing for the recognition of the original apical direction; in most cases, though, this information was unavailable. Where roots were encountered, these structures had held the basal part of the log above the sediment-water interface for some time following emplacement and during sedimentation. This interpretation is supported by the fact small-scale undulatory and distorted bedforms occur isolated beneath such samples. In other instances, it was obvious that scouring beneath a log followed its emplacement (Fig. 5C). Such a log rested unconformably upon the bedform, and it was seen that the top of the bedform had been eroded. Where scouring occurred beneath a log, the scour fill consisted of a small, lenticular sand body of similar grain size, or one composed of coarser sediment. Logs that were found to have had some influence on the bedform upon which they rested were not used in the study (Fig. 5B). It was assumed that the original orientation of these logs at the time of emplacement had been

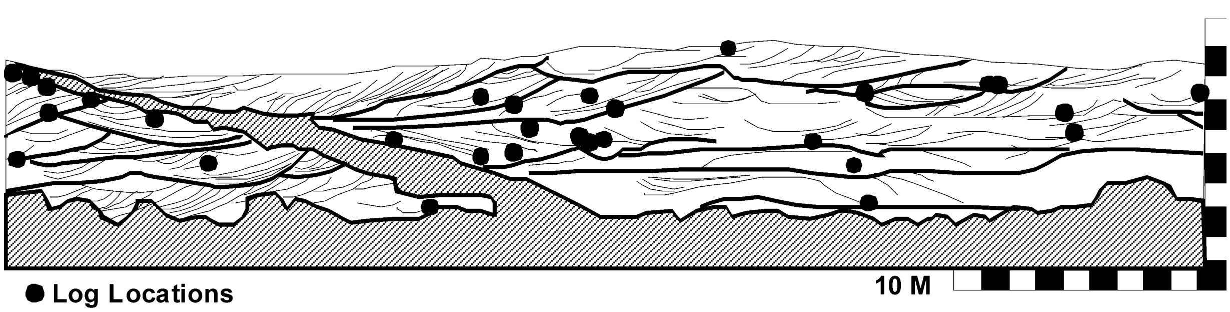

FIGURE 4—A 40-m lateral section of the Älterer Flußsande exposed along the highwall of Tagebau Schleenhain as illustrated from a photomosaic taken August 20, 1992. The positions of isolated logs within bedforms are indicated as closed circles. The diagonal pattern at the base represents covered highwall.

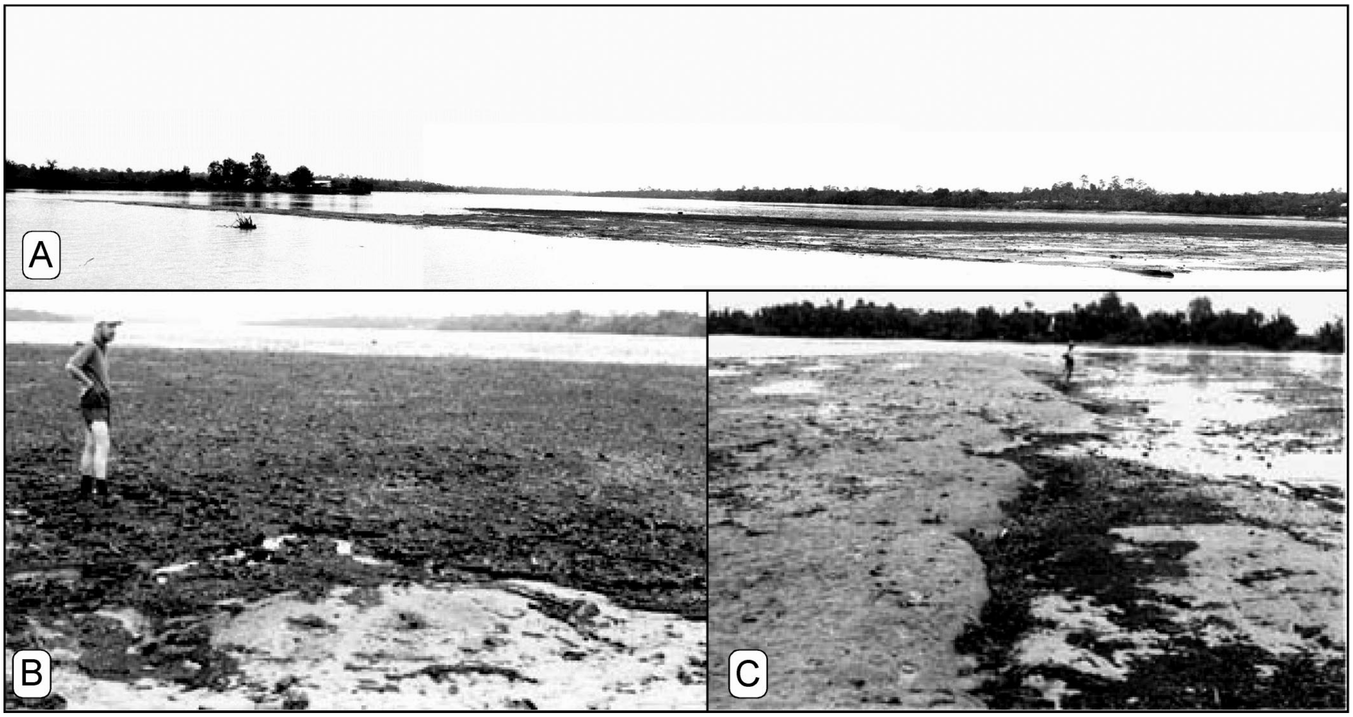

FIGURE 6—Exposed lateral channel barform in the Lassa River, Rajang River delta, Sarawak. (A) Photomosaic of the exposed barform on October 19, 1992, with CWD concentrated in the dune troughs. Tandjung Sidau is the forested area in the upper left; photograph looking North. (B) Coarse woody detritus and leaves concentrated in troughs of the channel bar. Photograph taken looking North; Jerome Ward for scale. (C) Photograph taken directed westward showing the foreset and topset beds of a migrating sand wave across the top of the lateral channel barform, with concentrated CWD in the trough between the dune crests; Jerome Ward for scale.

altered by subsequent physical processes. Hence, data taken from these samples would not directly reflect their orientation in relation to the fluvial processes operating at the time of movement from suspension load to the riverbed. The logs used in this study conform to the loose flotsam type of Abbe and Montgomery (1996). Only those logs found to be in direct contact with an underlying undisturbed bedform were used to collect the data set (Fig. 5A).

Wood orientation was measured parallel to the axis of the log. Due to the limited exposure of each log along the highwall, it was impossible to discern if the orientation was in an apical (towards the crown) or basal (towards the root stock) direction. Thirty-four logs that met the criteria for measurement were found along the 400-m stretch of highwall. Sediment covering the bedform directly underlying each log was excavated to the top of that bedform. Paleocurrent measurements on these beds were acquired according to standard accepted procedure.

Rajang River Delta

During an unusually low tide of a King tidal cycle on October 19, 1992, the top of a lateral channel bar near Tg. Sidau was uncovered, exposing a dune field in which CWD and leaves were concentrated in the troughs (Fig. 6). A 0.5-m^2 quadrat was placed randomly within one exposed trough, and measurements were taken on all woody detritus therein. A supplemental data set was collected outside the quadrat and consists of 34 phytoclasts; the number limited only by the rising tide. Each clast was measured for its total length, whereas clast orientations were taken towards the growing end of the limb, which was determined by evaluating taper. The orientation of the macroform crest immediately adjacent to the sample quadrat also was recorded.

Analytical Methods

Paleocurrent orientations, as determined from bedform analysis and log orientation, were plotted in rose diagrams and analyzed using Oriana (v. 1.06, Kovach Computing). Analyses included Rayleigh's uniformity test (test of the null hypothesis that the data are distributed in a uniform manner), the calculation of the mean angle and length (r), circular variance, and standard deviation of each data set. Bedform orientations were compared to log orientations using Watson's F-test (comparison of the mean vectors for each sample with the pooled data of the two sets). Each individual paleocurrent:log orientation in the Tg. Schleenhain data set was graphed to determine the divergence of the log orientation from the bedform datum. These results also were plotted in a rose diagram, standardizing the bedform orientation to North, to determine the variance of log orientation around the bedform. Divergence data for log orientations were grouped into sets of 15° and 30° intervals (conventional practice; see Macdonald and Jefferson, 1985), and plotted, again using the axis of the bedform as the central datum. χ^2 tests were conducted to determine if any statistical variance existed over the range of observed log divergence.

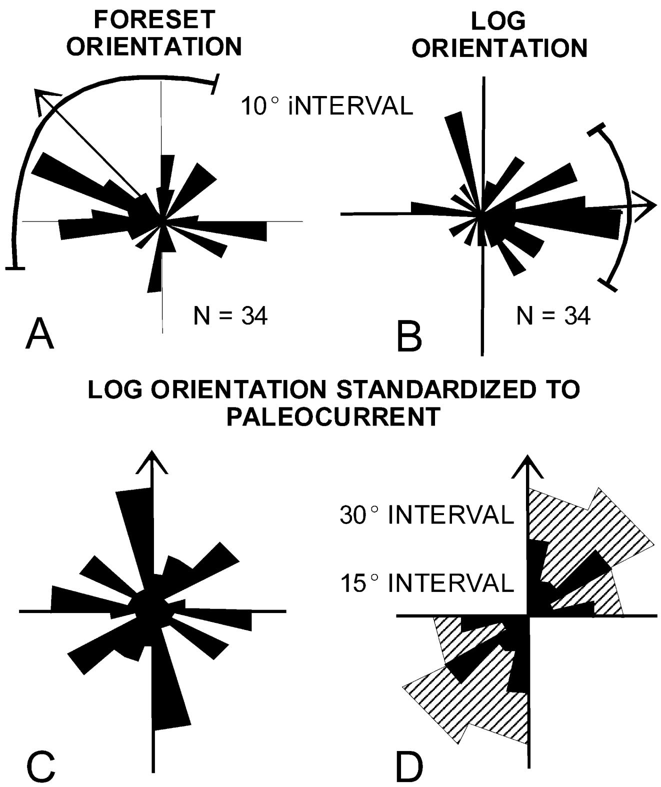

FIGURE 7—Plots of Tagebau Schleenhain data. (A) Rose diagram of cross-bed forset orientations (n = 34) with a mean foreset vector of 322°. Confidence intervals (95%) of the data set also are plotted. (B) Orientations of logs overlying cross beds (n = 34) with a mean CWD vector of 72°. Confidence intervals (95%) are plotted. There is no preferential orientation of either data set when quadrants are compared using the χ^2 statistic. Note that the confidence intervals for each data set are non-overlapping. (C) Rose diagram of log orientations after each measurement was standardized to an arbitrary bedform paleocurrent direction of North. There is no preferential log orientation relative to the underlying bedform. (D) Log orientations plotted relative to the underlying bedform compiled into 15° and 30, intervals. Again, no preferential orientation can be noted. This is verified by the χ^2 statistic.

RESULTS

Älterer Flußsande

Halfar et al. (1998) interpreted sandy bedform architectural elements as subaqueous dunes, sandwaves, transverse bars, and ripple-laminated sands. These bodies are characterized by tabular, wedge-shaped, and trough-shaped cross bedding. Cross-bed sets are thickly to very thickly bedded, with bed-set contacts most often erosional. Logs are primarily found within trough cross beds.

Paleocurrent direction, as determined from the bedforms beneath logs, appears polymodal, with predominant east, west, and northwest directions (Fig. 7A), with a mean vector of 322° (Table 2). Paleocurrent, as determined by log orientation, is random, with no preferential log alignment ($\chi^2 = 1.06; p = 0.5$; df = 3). The mean vector for this data set is 72°, reflecting an overall subperpendicular orientation of coarse woody detritus to observed bedforms, and results of Watson's F-test indicate that the two means are different (F = 13.8; $p = 0.00$; df = 66). When log-orientation data are standardized around a single bedform datum (arbitrarily chosen as North; Fig. 7C), it is seen that there is no preferred wood orientation relative to the underlying bedform. The assemblage of log data into 15° and 30° intervals also shows that there is no preferential orientation (Fig. 7D). χ^2 analyses of these data indicate that logs are equally distributed in all categories (15° intervals: $\chi^2 = 6.05$; $p = 0.5$, df = 5; and 30° intervals: $\chi^2 = 0.76$, $p = 0.5$, df = 2).

Rajang River Delta

All data sets fail the Raleigh test for uniformity, which means that each data set displays a unimodal distribution (Table 2). When all wood clasts in the sample quadrat are analyzed, the mean vector for the data set is 328°, with a narrowly defined 95% CI (Fig. 8A). The mean vector is oriented subperpendicular to flow in the Lassa (dune crest strike = 315°; dune migration vector = 45°), but a wide dispersion in orientation of individual clasts is evident. When individual subsets based on clast size are assessed, all demonstrate a mean vector that tends to be subperpendicular in orientation to that of dune migration (Fig. 8B–F). When the 95% CIs of individual subsets are compared against each other, most CIs overlap, with only two exceptions. The data set from within the 0.5-m² quadrat with the 11–12-cm clast subset, and the 11–12-cm subset with the enlarged >11-cm data set, are non-overlapping (Fig. 8A, E, F), indicating statistically different vectors, verified by pair-wise analysis using the Watson's F-test (quadrat versus 11–12 cm: F = 6.73, $p = 0.01$, df = 78; 11–12 cm versus >11 cm: F = 7.16, $p = 0.02$, df = 17).

TABLE 2—Results of circular statistics on data sets from the Älterer Flußsande and lateral channel bar in the Lassa River, Sarawak.

Sample	Schleenhain Bedform	Schleenhain Log Orientation	Rajang 0.5-m Quadrat	Rajang 6–7-cm clasts	Rajang 8–10-cm clasts	Rajang 11–12-cm clasts	Rajang >11-cm clasts	Rajang 6–16-cm clasts
Observations	34	34	72	41	23	8	11	80
Mean vector (μ)	316°	85°	328°	304°	304°	282°	339°	306°
Length of mean vector (r)	0.20	0.41	0.70	0.78	0.81	0.89	0.69	0.76
Circular variance	0.80	0.59	0.30	0.22	0.19	0.11	0.31	0.24
Circular standard deviation	102°	77°	48°	40°	37°	28°	49·	42°
Standard error of mean	34°	16°	6°	6°	8°	12°	15°	5°
95% confidence interval (±) for μ	249°	53°	317°	292°	289°	259·	310°	297°
	22°	117°	339°	316°	320°	306°	9°	315°
Raleigh test of uniformity (p)	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00

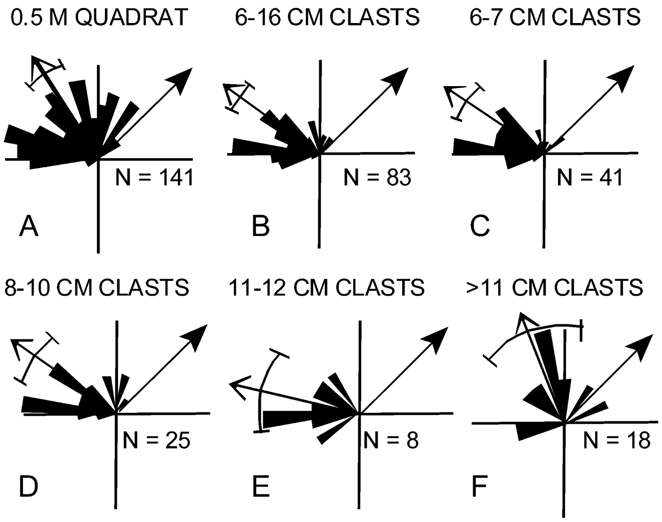

FIGURE 8—Rose diagram plots of all CWD measured in dune troughs of a lateral channel bar in the Lassa River, Sarawak. (A) Plot with mean vector and 95% confidence intervals for all CWD measured in a 0.5-m^2 sample quadrat; arrow indicates the direction of dune migration. (B) Plot of woody clasts only 6 to 16 cm in overall length. Sample number includes a subset of clasts from the 0.5-m^2 quadrat supplemented by measurements of other CWD in the trough. Clast-size distribution is the same as that used in experiments by Macdonald and Jefferson (1985). (C) Plot of clasts 6–7 cm in length, sample composition similar to above. (D) Plot of clasts 8–10 cm in length, sample composition similar to above. (E) Plot of clasts 11–12 cm in length, sample composition similar to above. (F) Plot of clasts >11 cm in length, sample composition similar to above.

TABLE 3—Results of Chi-square analyses on experimental data presented by Macdonald and Jefferson (1985, fig. 2), who plotted their data in 30° class intervals relative to flow in the flume. An evaluation of their rose diagrams indicated that the following class intervals were plotted: 345–15, 15–45, 45–75, 75–105, 105–135, 135–165; these are used in the present analyses. The number of observations from each velocity run (0–15 cm/sec., 15–30 cm/sec., and >30 cm/sec.) were compared against each other for each 30° class interval.

30° class interval	χ^2	P (df = 2)
345°–15°	3.21	0.20
15°–45°	2.73	0.25
45°–75°	16.59	0.00
75°–105°	1.40	0.49
105°–135°	3.48	0.17
135°–165°	5.57	0.06

DISCUSSION

The use of fossil material as an aid in the analysis of local and regional paleocurrents has been advocated since Ruedemann (1897). There have been numerous studies on current direction in marine settings as derived from macroinvertebrate orientation, particularly as inferred from conical shells (see Wendt, 1995). The geometrical similarity between conical shells and cylindrical woody detritus has led to the application of this technique to phytoclasts in a variety of terrestrial, transitional, open-marine, and bathyal settings (Table 1), with varying success. The degree of success appears to be related to several factors that include the physical dimensions of the material studied, the environment of deposition, and the actual sample size used in the analysis. The smaller the size of the phytoclasts and the fewer the number in the data set, the more positive a correlation with paleocurrent has been made.

In an effort to study the factors controlling wood orientation under unidirectional flow conditions, Macdonald and Jefferson (1985) conducted limited flume experiments. These consisted of using one clast of <5 cm, two clasts 5–7 cm, three clasts 8–10 cm, four clasts 11–16 cm, and one clast 19 cm in length. They found that asymmetrical fragments (<20 cm in length) were oriented parallel to flow (5 of 11 samples) at moderate (15–30 cm/sec.) to high (>30 cm/sec.) rates, but there was a wide variance that included subparallel to perpendicular orientations (Macdonald and Jefferson, 1985; fig. 2). Although no statistical analyses were conducted on the data, their conclusion was that although the data set was equivocal, asymmetrical wood fragments tend to adopt current-parallel orientations, and this preference is controlled by flow velocity. Subjecting Macdonald and Jefferson's (1985) data to a χ^2 analysis demonstrates that there is no statistical preference for orientation of the experimentally derived data in most of the plotted 30° intervals (Table 3). That is, there is no difference in the number of observations within each 30° interval (except the 45°–75° class) when the data from all experiments are compared. Macdonald and Jefferson (1985) acknowledged that a greater directional variance and, hence, a decrease in the utility of wood in the analysis of paleocurrent, can be adopted by larger wood fragments than those used in their experiment. This latter assertion is the case as demonstrated in the Älterer Flußsande data, but also applies to the size of CWD as used in their experiments and exemplified by the Lassa river data. The majority of coarse woody clasts adopt an orientation subperpendicular to flow direction.

Ecological studies have focused on wood orientation and aggregation in river systems to understand the role that coarse woody detritus plays on geomorphological and ecological relationships (e.g., Robison and Beschta, 1990). These data generally are presented relative to the linear trend of the stream, providing a generalized aspect of the wood assemblage and flow direction. Robison and Beschta (1990) assessed CWD along five low gradient, 2nd-, 3rd-, and 4th-order streams in Alaska (Fig. 9), restricting their analysis to clasts >0.2 m in diameter and at least 1.5 m in length. They defined a log as demonstrating a 0° orientation relative to flow if the tree base was upstream, perpendicular if the base was 90° to flow direction, and 180° when bases were oriented downstream. Their data set consists of nearly 1500 observations. Re-plotting their data demonstrates the same perpendicular to subperpendicular orientation (Fig. 9), and circular statistical analyses verify this relationship, with the exception of the 4th-order stream—Kadashan River (Table 4). Here, orientation data pass the Raleigh test for uniformity, indicating a uniform distribution of logs in this larger river channel. Hence, CWD greater than 1.5 m in length generally adopt a unimodal orientation that essentially is perpendicular to flow, except when the river system becomes a trunk channel. Then, logs are uniformly distributed in their orientation, potentially making this relationship—uniform distribution equates to large, trunk channel—the only proxy

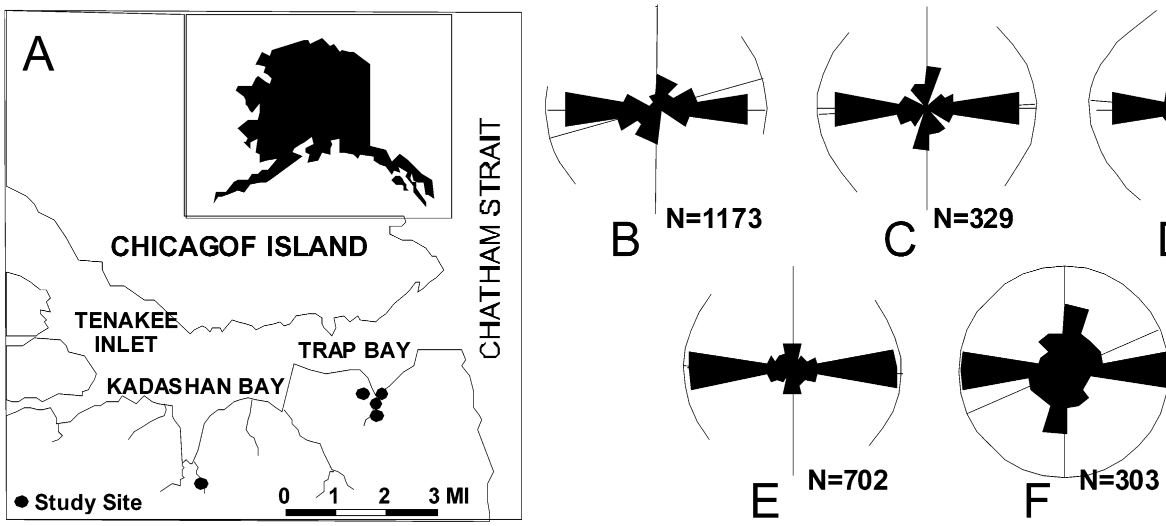

FIGURE 9—Replots of data presented for CWD in rivers evaluated on Chicagof Island, Alaska. (A) Locality map from Robison and Beschta (1990). (B) Rose diagram of all CWD orientations from all sample sites, with mean vector and 95% confidence intervals plotted. (C) Rose diagram of all CWD >1.8 m³ from all sample sites (D) Plot of CWD from Bambi Creek, a 2nd-order stream. (E) Plot of CWD from Trap Creek, a 3rd-order stream. (F) Plot of CWD from the Kadashan River, a 4th-order stream.

that may be derived from CWD orientation in fluvial deposits.

Two generalized patterns can be deduced from the Weißelster basin and the Lassa River data. The first is based on the collective data set of isolated logs in which the average mean vector of CWD is subperpendicular to the average mean trend of their associated bedforms. This observation conforms to data from Recent and experimental investigations (Robison and Beschta, 1990; Macdonald and Jefferson, 1985), although comparison with some Recent data must be cautioned. This caveat is necessary because of the differences in the scale of the Weißelster basin river systems and the 1st-, 2nd- and 3rd-order streams studied in northwestern North America where comparative data exist (e.g., Bibly, 1985; Hogan, 1987; Andrus et al., 1988; Abbe and Montgomery, 2003), as well as the differences between fine- and coarse-grained clastic regimes (e.g., Alexander et al., 1999). The large-scale bedforms and bedsets in the Oligocene river system indicate a coarse- to medium-grained, broad (>350 m), and deep (>20 m) meandering fluvial system (Halfar et al., 1998) in which individual allochthonous logs were deposited and buried (no log jams have been identified to date within these river channels). A similar scale of distributary channels exists in the Rajang River delta (Staub and Esterle, 1994; Staub et al., 2000). Recent streams from which CWD data have been collected generally average less than 1 m at low-flow depth, and, at bankfull stage, have a width of less than 25 m. Additionally, many of these streams are in mountainous terranes (e.g., Abbe and Montgomery, 2003), rather than in lowland fluvial systems or coastal-plain settings. Coarse woody debris investigated in these streams is generally parautochthonous, having originated from bank undercutting and erosion (Robison and Beschta, 1990), although a recent classification scheme proposed by Abbe and Montgomery (2003) recognizes three mechanisms—autochthonous, allochthonous, and combination—responsible for the emplacement of key members that act to entrap loose debris. In autochthonous jams (Abbe and Montgomery, 2003), tree bases and roots commonly are found remaining on the bank, with only the stem and crown of the fallen tree submerged. Additionally, because this wood is always buried, there is always the possibility that it will be re-suspended and transported downstream (or to a higher-order tributary), where is will acquire a different final orientation during high-discharge events, if not entrapped in another wood-accumulation type. If the re-entrained CWD becomes racked further downstream, it may come to rest at any number of various orientations depen-

TABLE 4—Results of circular statistics on data presented as histograms by Robison and Beschta (1990) for CWD in 1st-, 2nd-, 3rd-, and 4th-order streams in Alaska. Asterisks (*) indicate that these results may be unreliable due to the statistically uniform distribution of data.

Sample Label	All	>1.8 m³	Bambi Creek	Trap Creek	Kadashan River
Mean vector (μ)	75°	87°	95°	92°	67°
Length of mean vector (r)	0.35	0.23	0.16	0.33	0.10
Circular variance	0.65	0.77	0.84	0.67	0.90
Circular standard deviation	83°	98°	109°	85°	123°
Standard error of mean	14°	24°	31°*	22°	72°*
95% confidence interval (±) for μ	48°	40°	33°*	50°	286°*
	102°	134°	156°*	135°	208°*
Raleigh test of uniformity (p)	0	0.06	0.19	0.03	0.73

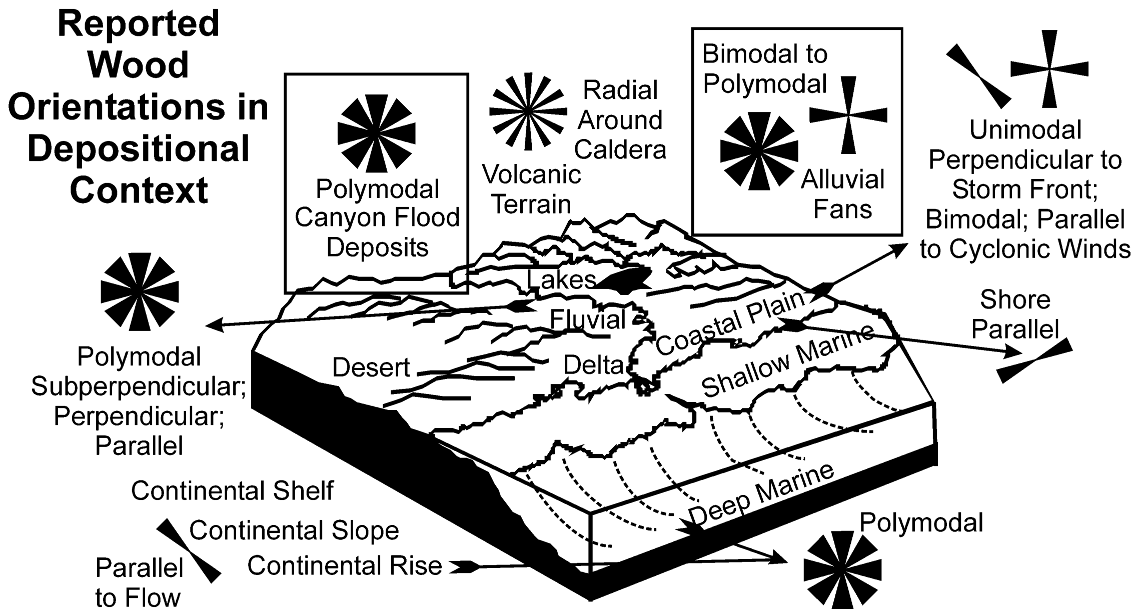

FIGURE 10—A generalized model depicting the probable orientation of coarse woody detritus and phytoclasts in continental, transitional, and basinal setting. Data from Table 1 and the present paper.

dant upon the resultant jam type, and may no longer be considered as isolated flotsam.

The results of the cumulative wood- and subjacent bedform-orientation data sets do not support the contention of Macdonald and Jefferson (1985) that the majority of eccentric-shaped woods tend to adopt current-parallel orientation. Rather, there is an overall subperpendicular orientation to the assemblage of this coarse woody debris. This condition probably is due to physical constraints of bedform size and shape, and the orientation at which the log material can be stabilized within the bedform under varying flow conditions.

The second trend in the data reflects a wide variance between the log and the strike of the underlying bedform. When log orientation is compared to a normalized bedform current direction, it can be seen that logs may be oriented parallel, perpendicular, or subperpendicular to flow (Fig. 7C); the same holds for smaller CWD, as exemplified in the Rajang delta (Fig. 8A). This agrees with one of Macdonald and Jefferson's (1985) conclusions about the orientation of large specimens (in their case, <20 cm long) over a wide range of current velocities, a condition inherent in the Älterer Flußsande as reflected by the diversity of primary sedimentary structures, bedforms, and bedsets (Halfar et al., 1998). This fact alone should prevent the use of individual isolated trees, or even a small number of isolated logs, as a proxy for local or regional paleocurrent directional indicators in fluvial systems.

Although there is a limited amount of published data concerning wood orientation in the stratigraphic column, it is possible to depict the expected behavior of isolated woody clasts within depositional context in terrestrial, transitional, and marine environments (Fig. 10). A variety of wood assemblages are preserved in volcaniclastic terrains, and generally are the result of explosive volcanism. Autochthonous tree assemblages preserved around a caldera are arranged radially (Froggart et al., 1981), reflecting collapse of the eruptive column. These trees may or may not have their root bases intact, depending on their relative distance from the blast site. Allochthonous logs transported away from the blast site by laminar flow events (mudflows) generally are prostrate, and aligned parallel to the valley axes (Fritz and Harrison, 1985; Karowe and Jefferson, 1987). Where erect tree stumps have been moved downslope, physical characteristics attributed to uprooting and transport can be used to differentiate them from *in situ* vegetation (Fritz, 1980; Fritz and Harrison, 1985). The ultimate orientation of logs transported *en mass* within the confines of channel systems draining the area is similar to other log accumulations that have resulted from high-discharge events (Krumbein, 1942). These assemblages exhibit a polymodal distribution, with axes oriented parallel, perpendicular, or subperpendicular to paleocurrent direction (Abbe and Montgomery, 2003).

A bimodal to polymodal orientation is characteristic of logs preserved in alluvial-fan deposits (Blair, 1987; Evans, 1991). Individual logs at the foot of the fan slope tend to be oriented parallel to the slope, while those aggregated within the log accumulations exhibit a polymodal distribution. A bimodal distribution of logs also is reported where most logs are oriented perpendicular to depositional strike, while some CWD parallels current lineations. Such a bimodal distribution appears to be characteristic of alluvial and coastal-plain forests that have been subjected to cyclonic wind shears (Gastaldo, 1991), but where storm fronts have passed through forested areas, the resultant blowdowns are generally unimodal in orientation (Wnuk and Pfefferkorn, 1987).

Coarse woody detritus preserved in fluvial channels (from 1st-order tributaries to deltaic distributaries) may be oriented parallel, perpendicular, or subperpendicular to flow regime (Table 1). The disposition of any individual log is dependent upon many interrelated variables operating within the channel (Abbe and Montgomery, 2003). Logs that are transported into the nearshore marine environment generally are trapped in this setting (exceptions do occur, see Darwin, 1906, p. 444). Logs emplaced on the innermost shelf adopt a shore-parallel orientation that reflects their periodic reworking and alignment by bottom currents. Current reworking and reorientation can be determined using ichnological features of these xylic substrates (Savrda and King, 1993). Mechanical fragmentation of, and bioturbation within these woods may result in significant size reduction of the original log.

The occurrence of terrestrial woody phytoclasts in continental-slope/-rise settings may be a function of the proximity of these settings to active tectonic margins (flysch) or sea-level lowstands (Damuth and Kumar, 1975; Damuth, 1977; Caratini, 1994). In turbidites of continental-slope and -rise settings, eccentric clasts have been reported to be oriented parallel to flow in channel deposits (e.g., Crowell, 1955; McDonald and Tanner, 1983), while in other studies, a polymodal distribution has been recognized.

CONCLUSIONS

Extreme caution should be used when logs and woody phytoclasts are employed as independent indicators of paleocurrent in the rock record. This detritus can adopt a wide variety of orientations prior to burial and preservation, depending on environmental context. In most cases, coarse woody detritus is not a direct indicator of either local or regional paleocurrents, and should not be used as such.

Results obtained from an analysis of isolated logs and their subjacent bedforms within a Paleogene fluvial system indicate that individual clasts can be oriented variously (parallel, subperpendicular, or perpendicular) to the bedform, with the mean vector adopting a subperpendicular orientation. Hence, no direct relationship exists between the paleocurrent direction of the bedform and the overlying CWD. In fact, the woody clasts have an equal probability of any one of the three principal orientations. These data do not support the conclusions drawn by Macdonald and Jefferson (1985) from experiments using woody clasts, where the assertion is made that isolated eccentric clasts preferentially adopt a current-parallel orientation. A comparison of a Recent data set from the Lassa River in East Malaysia, comprised of similar-sized clasts as those used by Macdonald and Jefferson (1985), also does not support the current-parallel conclusion. When the data are taken collectively, a pattern emerges reflecting a subperpendicular orientation of the CWD to prevailing paleocurrent directions in these fine-grained regimes. This observation may be helpful in assessing local paleocurrent trends if enough coarse woody material is present for analysis.

ACKNOWLEDGEMENTS

The author would like to thank MIBRAG (Mitteldeutschen Braunkohlen AG) for access and logistical support in Tagebau Schleehain. Dr. Jochen Halfar is acknowledged for his assistance and efforts to discern the fluvial architecture in the Älterer Flußsande as part of his DiplomArbeit. The author is particularly indebted to Dr. H. Walther (Dresden) and Dr. W. Riegel (Göttingen) for their cooperation, friendship, and encouragement during the time that this research was conducted in the Weißelster basin under a Forschungpreis, awarded by the Alexander von Humboldt-Stiftung, Bonn, during 1991–1992. The author is indebted to the personnel of the Geological Survey of Malaysia, Sarawak, and the Soils Division, Department of Agriculture, Sarawak; H. Among, H. Rosli bin Sahari, J.R. Staub, and J. Ward are acknowledged for their collaboration in the Rajang River delta, supported by NSF EAR 9111842 (RAG) and EAR 9104945 (JRS) in 1991–1992.

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ACCEPTED APRIL 28, 2004