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Author(s): Catherine Badgley and Lisa Tauxe
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PALEOMAGNETIC STRATIGRAPHY AND TIME IN SEDIMENTS: STUDIES IN ALLUVIAL SIWALIK ROCKS OF PAKISTAN[1]

CATHERINE BADGLEY AND LISA TAUXE[2]
Museum of Paleontology, University of Michigan, Ann Arbor, MI 48109

ABSTRACT

Sediments may acquire magnetic remanence upon deposition and shortly after deposition. Hence, the paleomagnetic record of sedimentary rocks may provide a chronostratigraphic framework for rates and patterns of depositional and post-depositional processes over time scales intermediate between those of modern observation and those of the dated geologic record. Two applications of high-resolution magnetostratigraphy in Miocene, alluvial rocks of Pakistan illustrate this point. (1) Transition stratigraphy—the dense sampling of a magnetic reversal—of correlated sections in the Dhok Pathan Formation revealed high variability in sediment accumulation rates (over several thousand to 10,000 yr), time-transgressive strata representing a paleosol and a floodplain marsh, and a pervasive post-depositional record mainly from pedogenesis. (2) Lateral tracing of paleomagnetic reversal boundaries in the Chinji Formation revealed a secular change in sediment accumulation rate and evidence for increased accumulation rate associated with extensive sandstones and the time-transgressive nature of certain sandstone units. Both studies demonstrate the significant lateral component to accumulation of lithological units, indicating that individual strata may embody considerably greater time spans in their lateral extent than in any vertical transect. Hence, stratigraphic completeness should be evaluated in the lateral as well as the vertical dimension.

INTRODUCTION

Many problems of concern to stratigraphers, sedimentologists, and paleontologists revolve around an understanding of duration, rate, and chronology in strata. Specifying the relationship between sediment accumulation and time is fundamental to the precision of chronostratigraphic correlation, the reconstruction of systems of sedimentation, and the interpretation of biological change in paleontological samples. In principle, sediments record time-dependent processes during deposition—by vertical accumulation and lateral migration—and after deposition—by alteration of sedimentary fabric and mineralogy and incorporation of organic remains. Erosion may, of course, remove both of these components from the long-term record. The diachronous nature of sedimentation has been demonstrated repeatedly at both small and large scales (e.g., Shaw 1964; Schwarzacher 1975; Ager 1981). Recent approaches to the estimation of completeness of the stratigraphic record have emphasized the discrepancy between short-term sediment accumulation rates, as observed over time scales accessible to human observers, and long-term sediment accumulation rates, as measured in stratigraphic sections (e.g., Schindel 1980; Sadler 1981; Tipper 1983; McShea and Raup 1985). But emphasis on the vertical accumulation of sediment in stratigraphic sections misses a fundamental pattern of most sediment accumulation. If most strata accumulate by growing laterally, then the entire package of sediments should be considerably more complete than any vertical section through them. Here we review applications of paleomagnetic stratigraphy over relatively short time spans to document the lateral disposition of geologically isochronous markers in alluvial sedimentary rocks; in turn, these patterns are the basis for evaluating the contemporaneity of facies, variability in sediment accumulation rates, and the timing of post-depositional processes. Then we return to the issue of how time is recorded and consider the lateral dimension of stratigraphic completeness.

With few exceptions, elapsed time cannot be measured directly over most portions of stratigraphic sections. Horizons dated by radiometric methods or by paleomagnetic correlation provide estimates of absolute ages at arbitrary positions in a stratigraphic sequence. The precision or resolution of such age estimates is also somewhat arbitrary. Radiometric ages contain an error term such that the confidence interval about an age esti-

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[2] Scripps Institution of Oceanography, La Jolla, CA 92093.

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mate increases with the absolute age. The shortest resolved polarity interval in the magnetic polarity time scale (MPTS) is about 20,000 yr (Berggren et al. 1985). Estimates of the time represented by individual depositional units may be proposed with reference to sedimentation rates measured in analogous modern systems. Modern sedimentation rates can be measured over seconds to decades, but the step from modern observations to stratigraphic sequences requires information about deposition, erosion, and stasis in sediment accumulation. The interactions of these processes are more readily modeled (e.g., Schwarzacher 1975; Tipper 1983; Strauss and Sadler 1989; McRae 1990) than observed over time scales useful for stratigraphic interpretation. In particular, time scales intermediate between those of modern observations and records (10^{-4} to 10^2 yr) and those of the dated geologic record (10^5 to 10^9 yr) are difficult to investigate.

Recent applications of paleomagnetic stratigraphy have provided insights into historical patterns of sediment accumulation at these intermediate time scales. The applications include examining the record of paleomagnetic transitions themselves (transition stratigraphy) in densely sampled sections (e.g., Tauxe and Badgley 1988; McRae 1989), the lateral tracing of paleomagnetic reversal boundaries through multiple sections (e.g., Behrensmeyer and Tauxe 1982; Sheikh 1984), and quantification of variability in sediment accumulation rates as determined from the thickness of polarity intervals (e.g., Badgley et al. 1986; Johnson et al. 1988). In addition, analysis of properties of magnetic remanence provides information about depositional and post-depositional aspects of sediment history (e.g., Tauxe and Badgley 1984, 1988; Tauxe et al. 1990). Here we review and expand upon two studies in the alluvial Siwalik rocks of northern Pakistan: (1) transition stratigraphy as a means to demonstrate contemporaneous facies relationships and the timing of sediment accumulation and post-depositional processes and (2) the lateral tracing of reversal boundaries to investigate lateral and vertical variability in sediment accumulation rates.

In the following examples, we use the chron terminology of LaBrecque et al. (1983) and the time scale of Mankinen and Dalrymple (1979) for consistency with earlier studies, as well as the revised terminology and time scale of Berggren et al. (1985). The conclusions presented are not affected by the choice of time scale.

BACKGROUND

Geologic Setting.—The paleomagnetic stratigraphy and lithostratigraphy presented here occur in Miocene sediments of the Siwalik Group, a molassic sequence shed from the southern margin of the Himalayas. In the Potwar Plateau of northern Pakistan (fig. 1), Siwalik sediments are over 5000 m thick (Barry et al. 1980). This sequence is rich in vertebrate fossils, comprising the best documented record of the Neogene mammals of South Asia (Pilbeam et al. 1977, 1979; Barry et al. 1982, 1985, 1990). Paleomagnetic stratigraphy has provided the geochronological framework for Siwalik sediments and faunas of the Potwar Plateau and the means of correlation of stratigraphic sequences within the Potwar Plateau and with the Siwalik record of India (G. Johnson et al. 1983) and of Nepal (Munthe et al. 1983). In the Potwar Plateau, Siwalik formations are repetitive alternations of sandstone and silty-clayey rocks, with the relative proportions of coarse-grained and fine-grained units varying from one formation to another (Barry et al. 1980).

The field areas for the studies reviewed here occur on the northern and southern limbs of the Soan synclinorium, the major structural feature in the Siwalik sequence of the Potwar Plateau (fig. 1). Both areas contain exposures of Lower and Middle Siwalik rocks, with the Lower Siwalik sequence better exposed to the south and the Middle Siwalik sequence better exposed to the north. In both areas, long paleomagnetic columns provide the basis for correlation to the MPTS (e.g., Johnson et al. 1982, 1985; Tauxe and Opdyke 1982), and short sections have been measured through select intervals along strike for 15 to 30 km (e.g., Barndt et al. 1978; Johnson et al. 1988; McRae 1989, 1990). Brief facies descriptions are provided later in the paper.

Magnetic Remanence Acquisition.—Sediments may become magnetized by a variety of mechanisms during and after deposition, and some sediments may retain several components of magnetization that reflect dif-

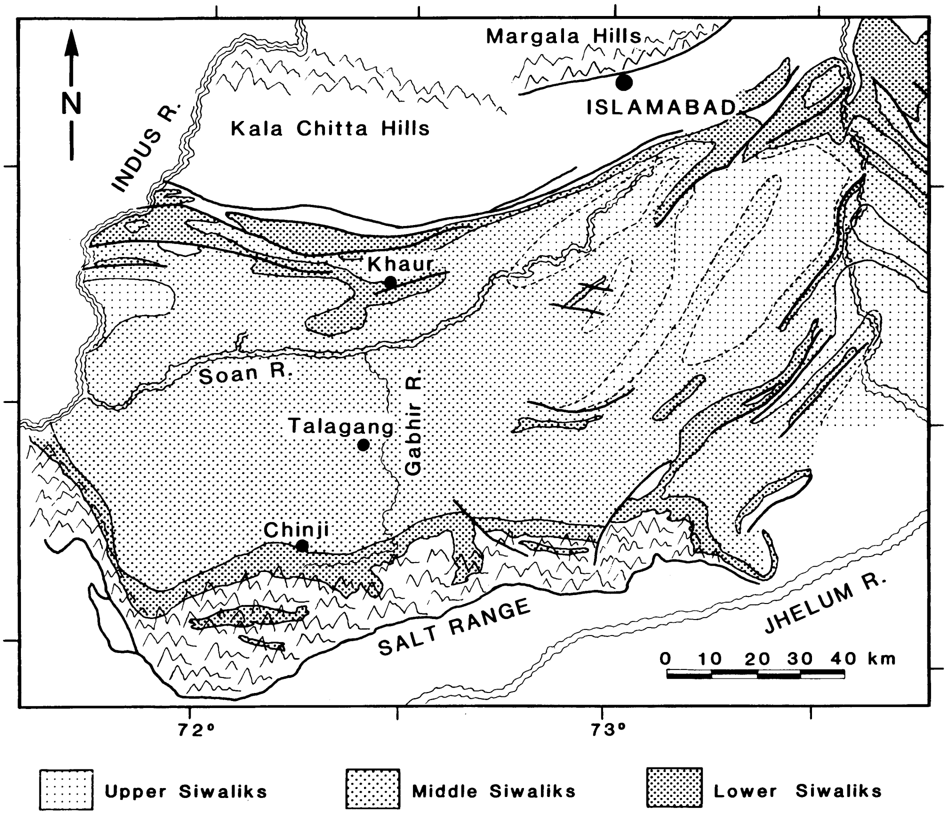

FIG. 1.—Map of Potwar Plateau, showing distribution of Lower, Middle, and Upper Siwalik sediments. Darkest lines are faults. Modified from Raza (1983).

ferent episodes of remanence acquisition. Such is the case for many Siwalik sediments. Sediments acquire a partial alignment of detrital magnetic particles just after deposition; this component is depositional detrital remanent magnetization. In Middle Siwalik sediments, this component is carried by detrital particles of hematite (Tauxe et al. 1980). During thermal demagnetization, this component is isolated at relatively high temperatures (650° to 685°C). After deposition, magnetic particles may become realigned by rotation of detrital grains within the sediment, a process enhanced by sediment disturbance, resulting in post-depositional detrital remanent magnetization. This component is also isolated at the high blocking temperature spectrum of 650° to 685°C, in specimens with disrupted magnetic fabrics. In alluvial sediments, acquisition of this component may be facilitated by physical disturbances—such as trampling or slickenside formation—of wet or dry sediments on floodplains and by processes of soil formation, including growth and leaching by roots and decomposing organisms. These processes may result in coherent realignment of detrital particles (but with the depositional magnetic fabric disrupted) or in randomization of alignment carried by the detrital phase; both patterns occur in Siwalik sediments. We have called the randomized pattern "misaligned remanent magnetization" (Tauxe and Badgley 1988). (Our usage of the term "coherent" in this context is "a well defined demagnetization trajectory, resolvable into one or more distinct components." "Incoherent" refers to trajectories with unresolvable components. We provide this explanation to distinguish our usage of these terms from their formal mathematical definitions in the field of signal-processing.) A third category of magnetization occurs as magnetic minerals grow in situ while sediment experiences surface weathering and diagenesis; this

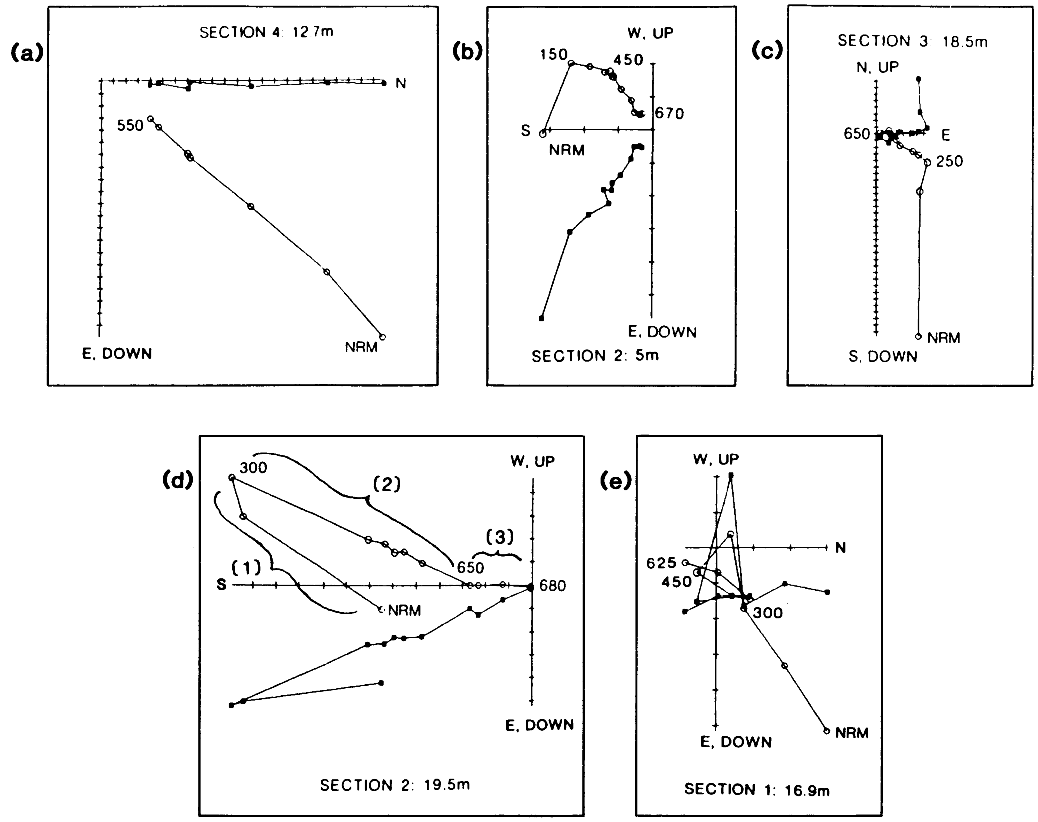

FIG. 2.—Vector endpoint diagrams of different patterns of magnetization. Each vector endpoint is depicted by a pair of points with solid points representing the horizontal plane and open circles representing the vertical plane. Each pair of points represents a step in thermal demagnetization. Modified from Tauxe and Badgley (1988). (*a*) Normally magnetized specimen with unidirectional decay of remanence. (*b*) Reversed magnetization and multi-component, coherent pattern. (*c*) Transitional direction, two components. (*d*) Reversed magnetization, three components isolated at different temperatures. (*e*) Randomized decay curve or spaghetti plot. Reproduced with permission of Blackwell Scientific Publications, Ltd.

component is chemical remanent magnetization. In Middle Siwalik sediments, this component is carried by pigmentary hematite and is isolated between 300° and 650°C during thermal demagnetization (Tauxe et al. 1980). In Siwalik sediments, analysis of different components of magnetization for paleomagnetic samples recording a polarity transition indicates that chemical remanent magnetization was acquired within hundreds to thousands of years after deposition (Tauxe and Badgley 1984). An additional component of magnetization, isolated at relatively low temperatures (up to 300°C) and presumably viscous in origin, is subparallel to the present geomagnetic field.

Middle Siwalik sediments exhibit several patterns of magnetization (Tauxe and Badgley 1988), illustrated in figure 2. Samples may be normal (as in fig. 2*a*), reversed (fig. 2*b*), or intermediate (fig. 2*c*) in the direction of magnetization. They may have single components of magnetization (fig. 2*a*), which may be attributed to detrital, post-depositional, or chemical remanent magnetization, depending upon the mineralogy and the temperature at which the component is isolated. Sediments may exhibit multi-component magnetization, with the different components isolated at different temperatures. Many Siwalik samples contain two or three components (fig. 2*b*–*d*). A three-component pattern (fig. 2*d*) may contain components representing (1) the present field, (2) chemical remanent magnetization, and (3) detrital or post-depositional detrital remanent magnetization. Another pattern is incoherent magnetization, in which the demagnetization trajectory changes many times in different directions, resulting in a "spaghetti plot" (fig. 2*e*). Different patterns of magnetization may be correlated with different lithofacies. For example, fine-grained sediments with abundant primary bedding structures generally display coherent demagnetization trajectories with one or more components, whereas fine-grained sediments with little primary bedding and pervasive pedogenic features have either coherent or random (incoherent) trajectories (also, see below). Thus, paleomagnetic remanence may record depositional and post-depositional sedimentary processes as well as global polarity.

The interpretation of the origin of remanence is facilitated by analysis of the anisotropy of magnetic susceptibility (Tauxe et al. 1990), a measure of the preferred alignment of magnetism with respect to crystallographic axes or bedding planes. Hematite grains bearing a detrital remanent magnetization exhibit a flattened, oblate ellipsoid with a near-vertical minor axis representing the anisotropy of magnetic susceptibility. Following deposition, detrital grains may rotate in the plane of the ellipsoid, resulting in a triaxial or prolate ellipsoid that accompanies post-depositional detrital remanent magnetization. If detrital particles become randomized or dissolve, leading to loss or randomization of the high-temperature component in the demagnetization trajectory, a spherical anisotropy ellipsoid results. Thus, the shape of the anisotropy ellipsoid indicates the origin of magnetic remanence. In Siwalik rocks, paleomagnetic specimens exhibiting coherent trajectories of demagnetization tend to have an oblate shape of the anisotropy ellipsoid and a subvertical axis of minimum susceptibility—the expected, primary depositional, magnetic fabric. In contrast, specimens with low coherency tend to have spherical or prolate anisotropy ellipsoids with randomly directed axes of minimum susceptibility, suggestive of substantial modification of the depositional magnetic fabric.

TRANSITION STRATIGRAPHY

Magnetic polarity reversals are estimated to occur over 4,000 to 10,000 years (Opdyke et al. 1973). Hence, sampling of an interval with intermediate polarities conveys information about depositional and post-depositional processes over time spans of up to thousands of years. Tauxe and Opdyke (1982) documented a detailed transitional record in late Miocene sediments of the Middle Siwalik, Dhok Pathan Formation, in the northern part of the Potwar Plateau. The reversal boundary occurs in the upper part of the paleomagnetic subchron C4AR in the terminology of LaBrecque et al. (1983) and in Chron 9 in the terminology of Berggren et al. (1985). The age of this reversal is estimated at 8.41 Ma, according to the time scale of Berggren et al. (1985). We resampled this interval (fig. 3*a*) to examine lateral variability in lithological and paleomagnetic attributes of the transition in six correlated sections (figs. 3*b*, 4) over a distance of 8 km (Tauxe and Badgley 1988). From these data, we evaluated rates of sediment accumulation, the timing of post-depositional processes, and the position of the reversal in relation to lithological boundaries. The sampling density averaged one sample/m over about 25 to 30 m of section.

This portion of the Dhok Pathan Formation contains deposits of two interfingering fluvial systems (Behrensmeyer and Tauxe 1982). Sediments of the two fluvial systems are distinguished on the basis of color, mineralogy, outcrop pattern (thickness and lateral extent), sedimentary structures, and current directions of sandstone bodies, as well as facies characteristics of finer-grained units. The "blue-gray system" consists of thick (>10 m), laterally extensive sheets of blue-gray sandstone that thin and grade laterally into thinly bedded siltstones. The "buff system" consists of lenticular buff sandstones with associated buff, brown, and red-brown siltstones and silty claystones containing abundant pedogenic features. The C4AR transitional interval occurs in deposits of both systems. Three marker units of the blue-gray system—the Middle Gray unit, the Upper Gray unit, and the "U" sandstone—are the primary basis for lateral correlation among sections (figs. 3, 4). These units can be traced along strike for up to 30 km (Behrensmeyer and Tauxe 1982).

For the purposes of studying the transitional interval, we recognize three facies (fig. 4). Facies 1 includes the volumetrically domi-

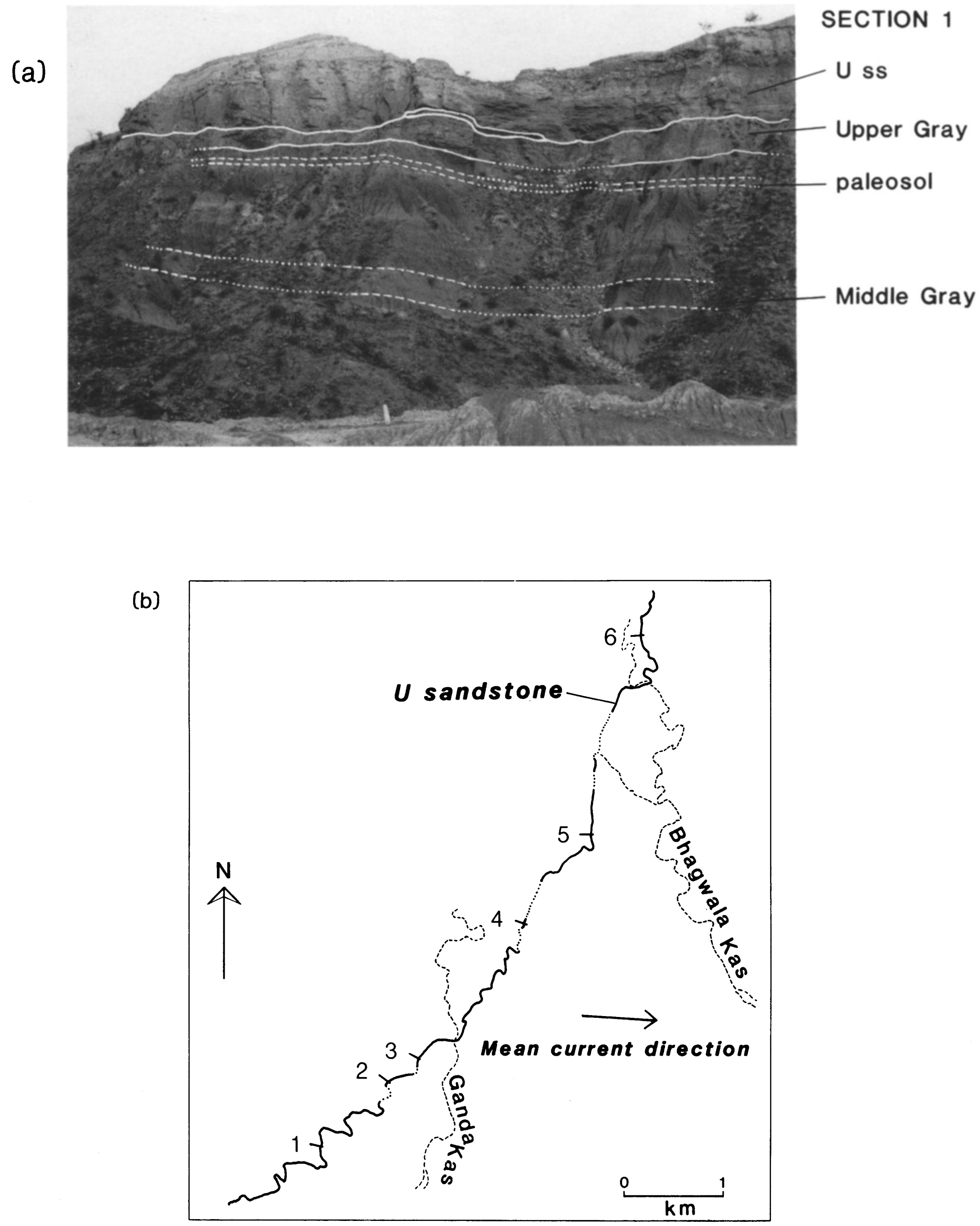

FIG. 3.—(*a*) Section 1, with four laterally persistent marker units indicated. In this view, the U sandstone locally cuts out much of the Upper Gray unit. (*b*) Extent of outcrop of the U sandstone through the study area to indicate the spacing of the six sections in figure 4. "Ganda Kas" and "Bhagwala Kas" are local valley names. The mean current direction of the U sandstone is from Behrensmeyer and Tauxe (1982).

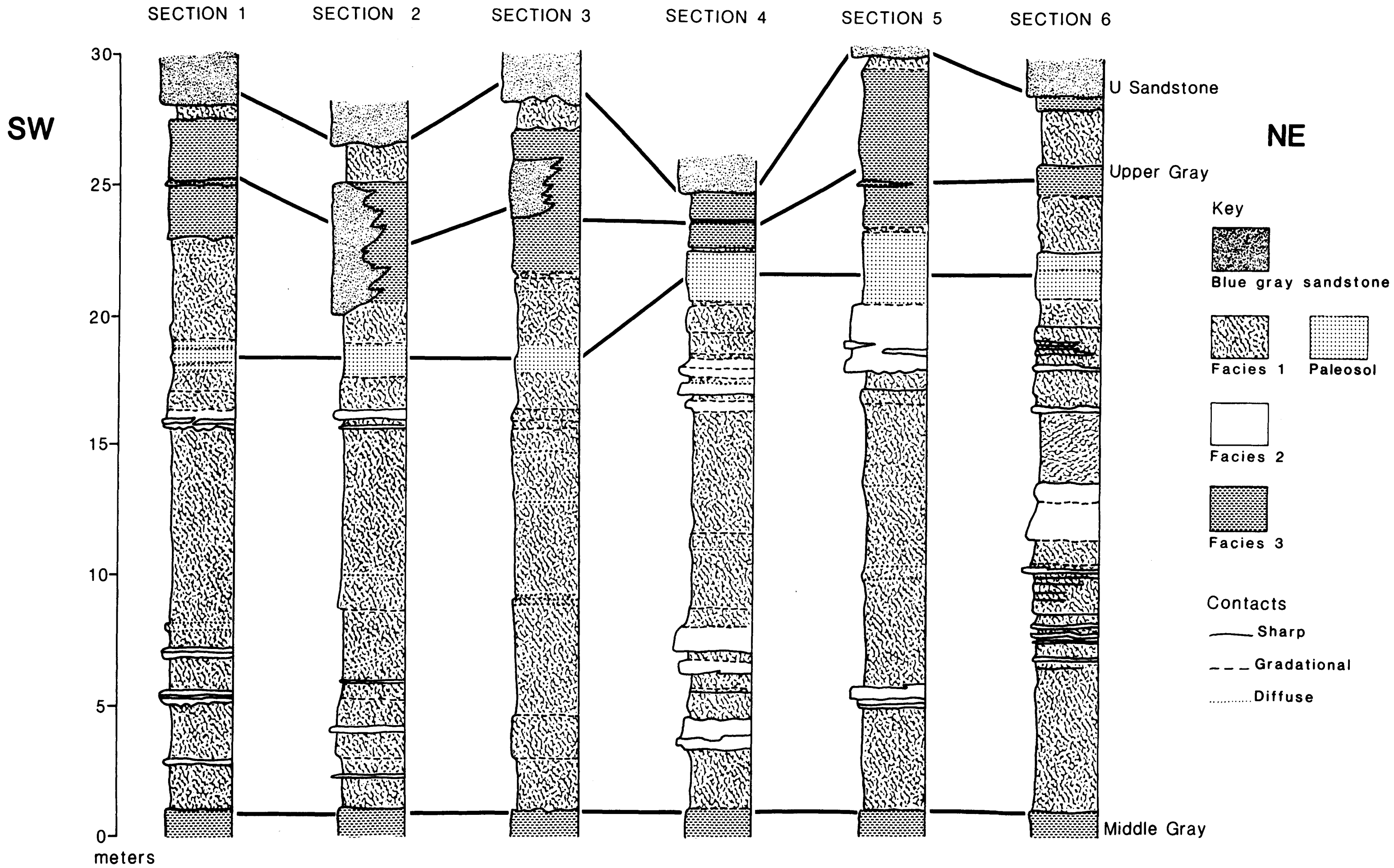

FIG. 4.—Lithostratigraphy of the transitional interval below the U sandstone in the Dhok Pathan Formation. Facies 1 is bioturbated siltstones and claystones. A laterally persistent paleosol unit is highlighted and is also shown in figure 6. Facies 2 is buff sandstones. Facies 3 is blue-gray siltstones and sandstones. See text for facies descriptions. Modified from Tauxe and Badgley (1988).

nant, poorly sorted siltstones and claystones with abundant post-depositional structures. Colors range from buff to medium brown to red-brown. Individual units range from 0.15 to 7.5 m thick with mainly gradational contacts. While some units can be traced laterally for several kilometers, others cannot be traced even between neighboring sections, indicating considerable lateral variation in this facies. (One laterally persistent paleosol is indicated in fig. 3*a* and the six sections of fig. 4.) While primary bedding structures are rare, secondary structures are common, including disrupted bedding, root and burrow casts, slickensides, nodules, and mottling. These secondary features are considered to result from pedogenic processes (Behrensmeyer and Tauxe 1982; Retallack 1988). Facies 2 consists of sandstones and silty sandstones, with minor lenses and bands of siltstone and infrequent lenses of intraformational conglomerate. Colors range from buff to red-brown. Individual units range from 0.2 to several meters thick. Contacts are sharp at the base and either fine upward or are sharp on top. The sandstones often contain laminated bedding or small-scale, trough cross-bedding. Secondary structures include mottling and root/burrow casts. Facies 1 and 2 belong to the buff fluvial system. Facies 3, represented by the Middle Gray and Upper Gray units (figs. 3, 4), contains interbedded siltstone, fine sandstone, and silty claystone. Colors include pale blue-gray, olive-gray, yellow-gray, and gray-brown. Bedding ranges from massive to finely laminated, with occasional small ripples. Mottling, burrow/root casts, and locally contorted bedding are moderately common, and some beds are calcareous (marls). The base of the Upper Gray unit ranges from sharp to diffuse; the top of both units is generally sharp. Facies 3 belongs to the blue-gray fluvial system. Facies 1 is considered the floodplain paleosols of the buff system, Facies 2 the channels and crevasse splays of the buff system, and Facies 3 the swamps, shallow floodplain ponds, and crevasse splays of the blue-gray system. These facies are described in greater detail in Behrensmeyer and Tauxe (1982) and in Tauxe and Badgley (1988).

Paleomagnetic samples were collected as described in Johnson et al. (1975) and processed as described in Tauxe and Badgley (1988). We collected four specimens at each site. For most sites, at least one specimen was subjected to stepwise thermal demagnetization. Two additional specimens were subjected to blanket thermal demagnetization. The fourth sample was saved for studies of petrology and anisotropy of magnetic susceptibility (Tauxe et al. 1990). The direction of magnetization at each site was measured in two ways: (1) the best-fit line (BFL) calculated from a least squares fit for three or more consecutive demagnetization steps for specimens subjected to stepwise thermal demagnetization (Kirschvink 1980) and (2) the vector mean of directions from three specimens after demagnetization at a single temperature step (Fisher 1953). Both methods yielded similar transition records (fig. 5). We defined a transitional site as one in which the direction is more than 45° away from the expected normal and reversed directions for this area in the late Miocene and which lies (by itself or in a sequence) between sites of normal polarity below and reversed polarity above (in this case). In addition, we measured two magnetic parameters that express the coherency of magnetization: (1) the maximum angle of deviation (MAD; Kirschvink 1980) calculated from the variance about the best-fit line (hence, measured on a single specimen) and (2) the circular standard deviation (CSD) of directions about the vector mean for three specimens from a site (Fisher 1953). We considered magnetization to be coherent for a single specimen if the MAD was $<15°$ and for a site if the CSD was $<35°$.

All six sections contain some record of the transition (figs. 5 and 6, table 1), as defined above. Since the exact behavior of the earth's magnetic field during any particular transition is poorly known, it is premature to evaluate what part of the transition is recorded in a transitional sequence. Hence, we have refrained from recognizing the early part of the transition in one record and the middle or late part in another. Lateral variability in the transitional interval is illustrated in figure 6 and table 1. By the criteria given above, the transition occupies from one to five sites in stratigraphic intervals ranging from that represented by one site (about 0.5 m) in Sections 1, 5, and 6, to 2.7 m in Section 3. The thickness of the transitional interval does not appear to be correlated with lithofacies;

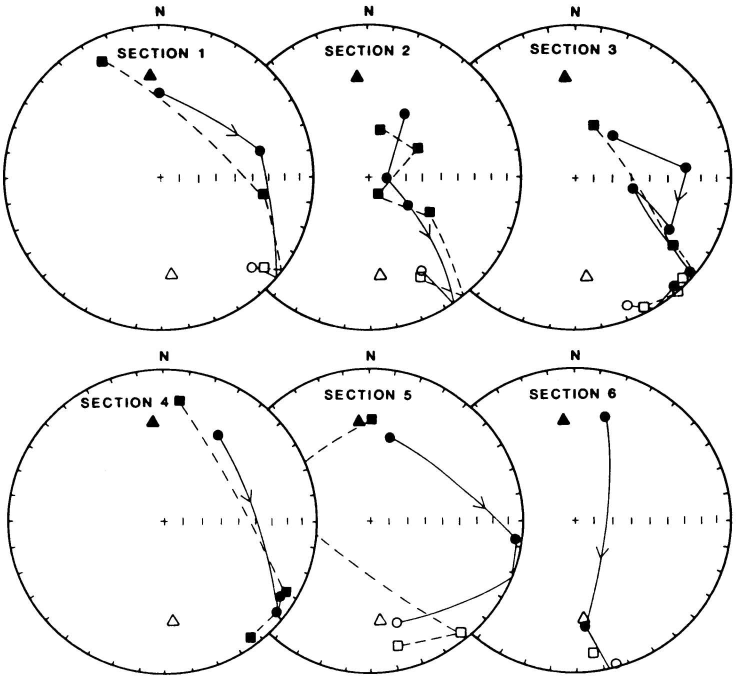

FIG. 5.—Equal-area projections of paleomagnetic directions through the transitional interval from two demagnetization techniques: (1) best-fit lines through stepwise demagnetization data (circles) and (2) site means from a single temperature step (squares). Solid symbols are on the lower hemisphere, open symbols on the upper hemisphere. The points shown are the bounding normal and reversed sites and the intervening transitional sites as defined in the text. Triangles represent expected normal and reversed directions for this area in the late Miocene. From Tauxe and Badgley (1988); reproduced with permission of Blackwell Scientific Publications, Ltd.

thicker and thinner transitional intervals occur in both Facies 1 and 3. In the study area, the transitional interval crosses the facies boundary between the paleosols of Facies 1 and the Upper Gray unit of Facies 3. The Upper Gray unit became established in the region of Sections 3, 4, and 5 before moving into the areas of Sections 1, 2, and 6. Also, the transitional interval occurs in the highlighted paleosol in Sections 1 and 2 and then lies above this paleosol in the remaining sections to the northeast.

As mentioned above, different facies exhibit different patterns of demagnetization

TABLE 1

STRATIGRAPHIC AND PALEOMAGNETIC DATA FOR THE TRANSITIONAL INTERVAL

Section	No. of transitional sites from BFL data	Stratigraphic position of transition (m)	Stratigraphic span: Transitional sites (m)	Stratigraphic span: Incoherent sites (m)	Facies of transitional interval
1	1	18.7	1 site	3.2	1
2	2	15.0–16.5	1.5	1 site	1
3	5	19.5–22.2	2.7	1 site	1+3
4	2(+)	23.3–24.5	1.2(+)	4.7	3
5	1	24.2	1 site	5.0	3
6	1	23.9	1 site	4.7	1

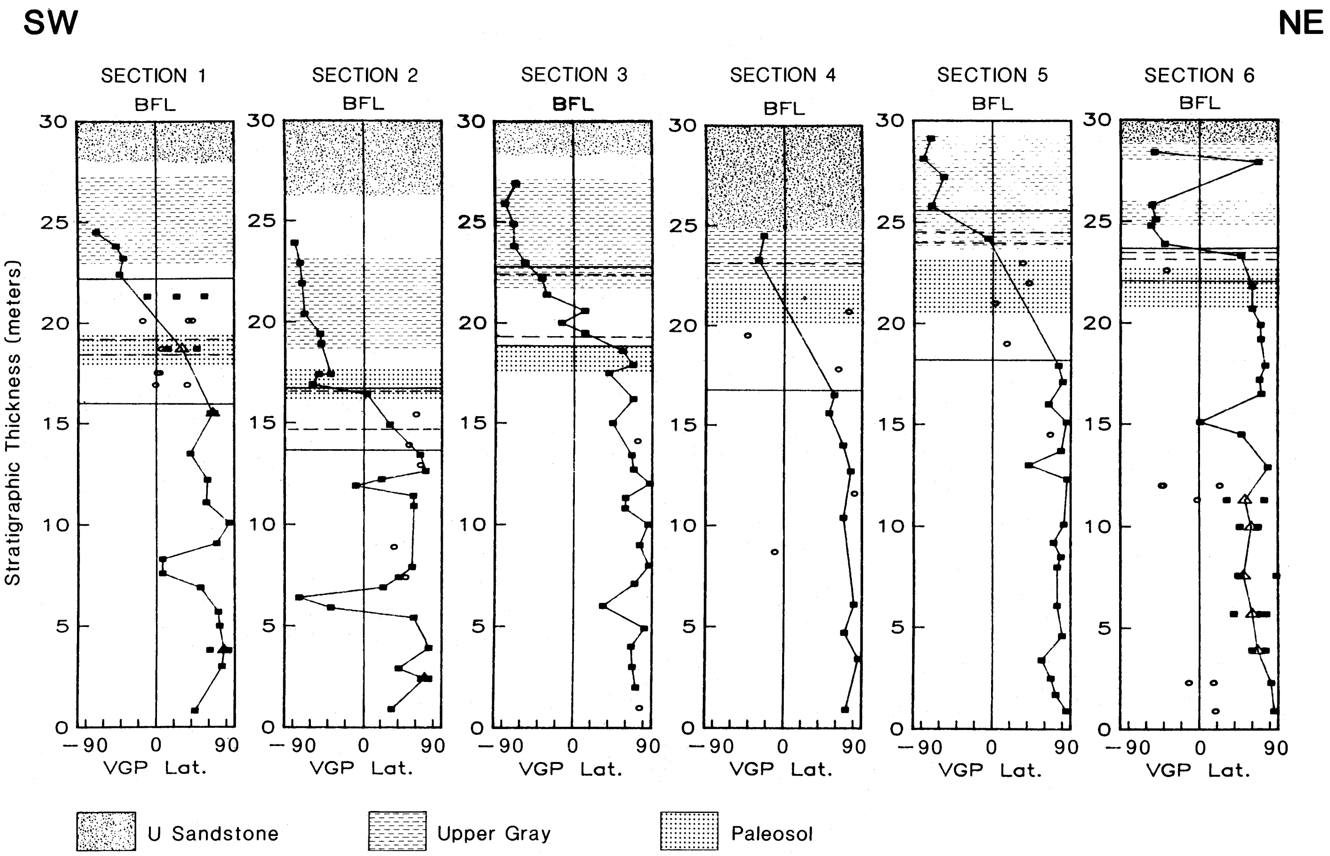

FIG. 6.—Paleomagnetic data for the six sections of figure 4, based on Tauxe and Badgley (1988). Each column contains virtual geomagnetic pole (VGP) latitudes of best-fit lines (BFL) from stepwise thermal demagnetization of specimens. Open symbols have MAD's greater than 15°, indicating incoherency within specimens. Sites with multiple specimens having statistically significant site means are plotted as triangles. Transitional specimens are defined as those in which the direction is more than 45° away from expected normal or reversed directions (hence VGP positions between ±45°), and bracketed by sites of normal polarity below and reversed polarity above. Minimum (dashed line) and maximum (solid line) stratigraphic spans of the transitional interval (from table 1) are indicated. Discussion of the transitional interval in the text is based on the minimum interval. The U sandstone, the Upper Gray unit, and the highlighted paleosol of figure 4 are indicated to illustrate the time transgressive nature of these units.

behavior. Samples from Facies 3, the Middle and Upper Gray units, generally contain coherent, multi-component demagnetization trajectories as in figure 2*d*. Hence, these sediments retain a detrital (probably depositional) remanent magnetization and have also acquired a chemical remanent magnetization. Samples from Facies 1 contain both coherent and random demagnetization trajectories (e.g., figs. 2*c* and *e*). Many coherently magnetized specimens retain the high-temperature component. Petrographic analysis of this facies reveals specular hematite concentrated in cracks that presumably opened up during pedogenesis. The high-temperature component in this facies is probably a post-depositional detrital remanence. The high MAD's for these specimens indicate misaligned remanent magnetization, resulting probably from inhomogeneous remagnetization on a scale smaller than the size of a paleomagnetic sample. Such random behavior is especially common in paleomagnetic sites below the polarity transition (Tauxe and Badgley 1988). Furthermore, the thickness of the coherently magnetized transitional interval is inversely correlated with the thickness of incoherently magnetized sites (table 1), as indicated by high values of MAD and CSD.

These stratigraphic and paleomagnetic data from the transitional interval and below permit inferences about the timing of depositional and post-depositional processes. (1) The stratigraphic span of the transitional interval (table 1, fig. 6), an estimate of minimum thickness, varies over five-fold among sections, from about 0.5 m (one site) to 2.7 m. These values do not account for compaction of original sediment thickness, so original values would have been higher, but similar variability would probably remain. Also, the transitional interval may have been truncated in more than one section (there is clear evidence for truncation in Section 4 where the U sandstone cuts into the Upper Gray unit in the transitional interval). On the basis of minimum thickness of the transitional interval, relative rates of sediment accumulation varied by a factor of five over some thousands of years in this part of the Siwalik fluvial system. (2) The Upper Gray unit and the paleosol below it are both time transgressive with respect to the transitional interval. The six sections form a curvilinear band nearly perpendicular to reconstructed flow directions for the blue-gray and buff fluvial systems (fig. 3*b*). The position of the transitional interval in figure 6 indicates that the six sections sampled only irregularly the gradient of lateral growth of the time transgressive units. The Upper Gray unit is diachronous on the order of thousands of years, since the transitional interval is below it in Sections 1, 2, and 6 and is included in the lower part of this unit in Sections 3, 4, and 5. The paleosol appears to have grown laterally from northeast (Sections 4, 5, and 6) to southwest (Sections 1 and 2), within the study area. (3) The development of pedogenic features was substantially faster than the duration of the transition, as indicated by the pattern of the transition in Section 3 (figs. 4 and 6). There the polarity transition began in Facies 1 and passed upward gradationally into Facies 3. Facies characteristics indicate that Facies 3 was predominantly an aquatic habitat, while Facies 1 was predominantly subaerial. Hence, we infer that the pedogenic features of Facies 1 had been acquired before Facies 3 became fully established. This interpretation is supported by data indicating that chemical remanent magnetization records only a slightly later directional signal than detrital depositional remanent magnetization in specimens from the transition (Tauxe and Badgley 1984).

Incoherently magnetized specimens occur with notable frequency at or below the transitional interval. Such specimens indicate a complex history of magnetization and are not straightforward indicators of the behavior of the geomagnetic field. Often such data are excluded from traditional studies of paleomagnetic stratigraphy. However, the causes of random patterns are post-depositional processes that are themselves of interest in relation to facies analysis. We interpreted the zone of incoherent magnetization below some transitional intervals as a zone of remagnetization. Presumably zones of remagnetization are common but are not readily detectable unless the geomagnetic field is changing at the time of remagnetization—hence the strong association of randomly magnetized sites with the transitional interval. The inverse correlation between the thickness of the transitional interval and the zone of remagnetization (table 1) suggests that low rates of sediment accumulation enhanced pervasive remagnetization. Where higher rates of sediment accumulation occurred, as in Sections 2 and 3, little incoherent magnetization occurred below the transitional interval. While the transitional interval always occurs in or just above the pedogenic facies (Facies 1), this facies does not always contain a thick zone of remagnetization. The specific causes of this pattern are not clear; the processes that randomize magnetization operated quite successfully in areas of low sediment accumulation and less successfully in areas of high sediment accumulation.

Since polarity transitions occur over thousands of years, detailed transitional records provide opportunities to investigate processes over geologically short time scales often inaccessible to geologists and paleontologists. The study described above shows that the polarity transition left both a depositional and a post-depositional record; that the transition record differed in patterns of remanence acquisition between the two major facies; that sediment accumulation rates varied five-fold over a relatively small lateral transect; that facies boundaries are diachronous over thousands of years in the study interval; and that pedogenic features were probably acquired within a fraction of the time span of the polarity transition. Other potential uses of transition stratigraphy include: (1) evaluation of the time span of accumulation of fossil assemblages in particular facies, such as paleosols; (2) comparison of sediment accumulation rates and patterns of remanence acquisition in different facies within the same sedimentation system; and (3) comparison of sediment accumulation rates and patterns of remanence acquisition in contemporaneous, laterally adjacent sedimentation systems, such as fluvial and lacustrine systems. Of course, this approach is limited arbitrarily to intervals in which polarity transitions occur; but there are many such choices in long stratigraphic sections.

LATERAL TRACING OF PALEOMAGNETIC REVERSAL BOUNDARIES

While transition stratigraphy reveals patterns of sediment accumulation over some thousands of years, the lateral tracing of reversal boundaries through "busy" portions of the paleomagnetic record provides a chronological framework for sediment accumulation at time scales of 10^4 to 10^6 years. (In some studies, reversal boundaries have been called "isochrons," but this term implies the absence of gaps—resulting from erosion or non-deposition—at reversal boundaries. This implication is not safe in many stratigraphic sequences, nor is it necessary to many of the potential applications of this approach.) The lateral tracing of reversal boundaries is typically accomplished by sampling and correlating multiple sections in parallel through the sequence of interest. Sections may be short or long depending on the scale of the investigation; if short sections (i.e., spanning only a few reversal boundaries) are measured, then they may be tied into a long section that can be satisfactorily correlated to the MPTS. The paleomagnetic records, their correlation to each other, and their correlation to the MPTS are all sensitive to sampling density. (Johnson and McGee [1983] designed a probabilistic method of estimating the expected frequency of reversals and the expected recovery of the reversal record at a given sampling density.) With this caveat in mind, the approach provides a two- to three-dimensional depiction of sediment accumulation in a stratigraphic sequence.

The detailed chronostratigraphic correlation made possible by lateral tracing of paleomagnetic reversal boundaries, tied into a long reference section, has facilitated geological and paleontological studies at several scales in the Siwalik rocks of Pakistan. Barndt et al. (1978) documented magnetic polarity stratigraphy of Middle Siwalik strata (Nagri and Dhok Pathan Formations) in the northern Potwar Plateau in one long and five shorter stratigraphic sections. Along with biostratigraphic information, the magnetic polarity stratigraphy provided the first correlation to the MPTS. The magnetostratigraphy in this area and its correlation to the MPTS were refined by Tauxe (1979) and Tauxe and Opdyke (1982). Behrensmeyer and Tauxe (1982) traced several reversal boundaries laterally for almost 30 km in the Dhok Pathan Formation to examine the disposition of contemporaneous fluvial systems (see Flynn et al. 1990). Johnson et al. (1982) documented the magnetostratigraphy of six regions of the Potwar Plateau, providing chronostratigraphic and lithostratigraphic correlations among widely separated field areas. Sediment accumulation rates were compared over one long polarity interval present in the six regions. At Khaur, the area closest to the inferred sediment source (Himalayan ranges north of the Potwar Plateau), the sediment accumulation rate was approximately twice those in four areas on the north side of the Salt Range (fig. 1). The sixth region, also north of the Salt Range, had an intermediate rate. Sheikh (1984), Kappelman (1986), Johnson et al. (1988), and McRae (1989, 1990) traced reversal boundaries laterally for selected intervals from the magnetostratigraphy of the Chinji Formation; the high-resolution magnetostratigraphies are the basis for evaluating rates and patterns of sediment accumulation (see below). Barry et al. (1990) used the Siwalik paleomagnetic chronostratigraphy as the temporal framework for analyzing rates and patterns of mammalian faunal change.

Lateral tracing of paleomagnetic reversal boundaries has demonstrated the time-transgressive nature of facies boundaries at the scale of both formations and major lithological units within formations. In the northern Potwar Plateau, between the towns of Khaur and Dhok Pathan (fig. 1), the boundary between the older Nagri and the younger Dhok Pathan formations is time transgressive with respect to paleomagnetic reversal boundaries by about 1.5 m.y. over a distance of about 40 km (Barry et al. 1980). In the southern Potwar Plateau, the boundary between the older Chinji Formation and the younger Nagri Formation is time transgressive by about 0.8 m.y. over a distance of about 15 km (Johnson et al. 1988). These time transgressive boundaries mark lateral shifts in the domains of adjacent fluvial systems. On a much smaller scale, lateral tracing of a single reversal boundary (Behrensmeyer and Tauxe 1982; Tauxe and Badgley 1988) indicated that the base of a major lithological unit within the Dhok Pathan Formation (the Upper Gray unit of fig. 4) is diachronous, probably on the order of thousands of years.

Based on refinement of Sheikh (1984), Johnson et al. (1988) compared the vertical and lateral variability in sediment accumulation rates from laterally traced reversal boundaries in the lower Chinji Formation (see fig. 7). Vertical variability was measured by two standard deviations (2*s*) about the mean of sediment accumulation rate of four polarity intervals in each of nine sections. An error term for sample spacing was subtracted and then the adjusted 2*s* values were averaged for all nine sections. By this method, Johnson et al. (1988) found a vertical variability in sediment accumulation rates (unsteadiness) of 41%. Lateral variability was determined as 2*s* about the mean of sediment accumulation rates of individual polarity intervals as represented in the nine correlated sections. Likewise, an error term for sample spacing was subtracted and the adjusted 2*s* values averaged for all polarity intervals; the average lateral variability (nonuniformity) was 28%. Johnson et al. (1988) proposed that these estimates of lateral and vertical fluctuations in sediment accumulation characterize the fluvial system that deposited the lower Chinji sequence.

We have taken an alternate approach to analyzing these data with an analysis of variance (ANOVA). Johnson et al. (1988) determined variability in sediment accumulation rates from the sections of figure 7*a* by pooling the sediment accumulation rate for each of the four individual polarity intervals and all possible composites of them in each section, for a total of 10 measures of sediment accumulation rate. Only four of these measures are independent observations in each section; moreover, combining the independent observations with the composite intervals obscures interesting patterns in the original data (see below). Also, the statistical analysis of variability seems rather indirect and is missing a test of whether the estimates of lateral and vertical variability in sediment accumulation rates are significantly different. We used a two-way, mixed model ANOVA (Snedecor and Cochran 1980, Sokal and Rohlf 1981) for the sediment accumulation rates depicted in Figure 7*a*, with time in the form of polarity intervals as a fixed factor (rows) and space in the form of stratigraphic sections sampling different locations in the fluvial system as the other, random factor (columns). The two-way ANOVA tests for differences in means among multiple samples and in the present context addresses the question: do time or location contribute significantly to the observed variability in sediment accumulation

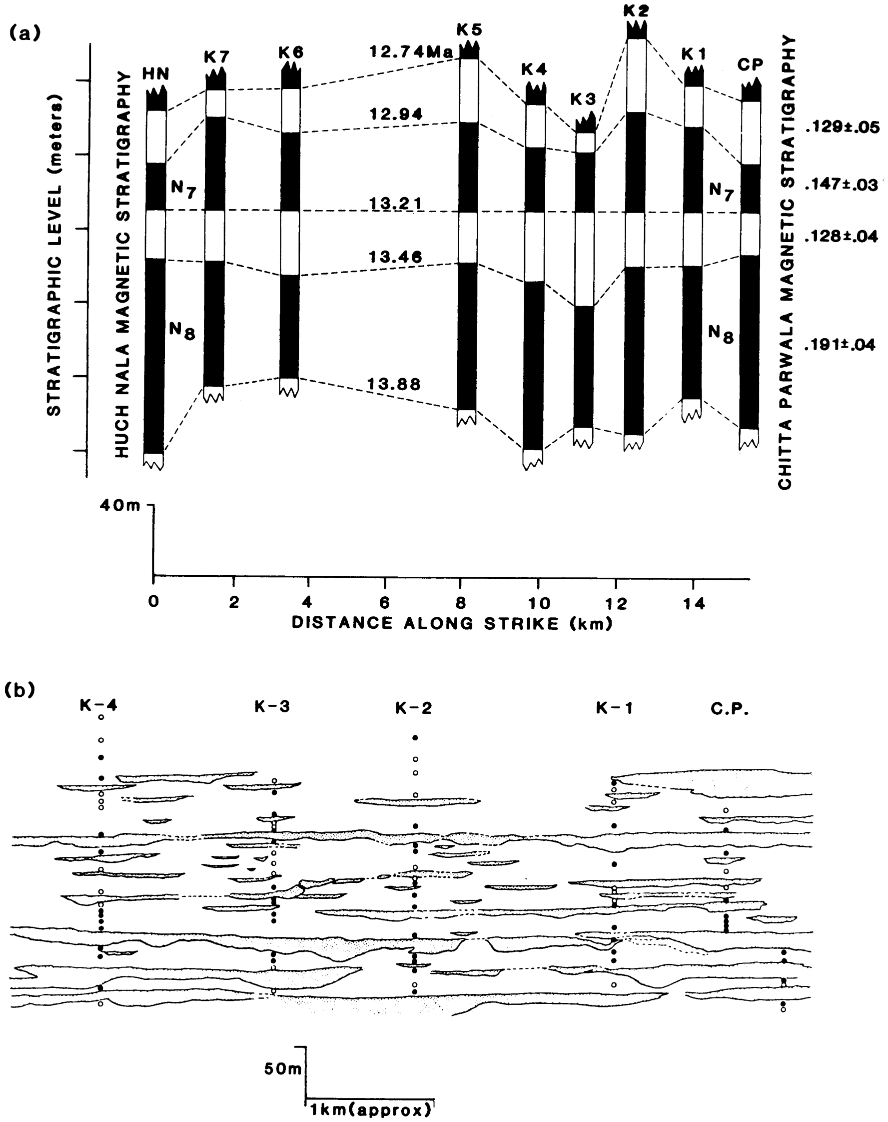

FIG. 7.—Lateral tracing of reversal boundaries from the Lower Chinji Formation, south of Chinji village (fig. 1). (*a*) Nine correlated sections. Huch Nala and Chitta Parwala are local valley names. Complete descriptions of paleomagnetic sampling and demagnetization are given in Sheikh (1984). In each section, the position of each magnetic reversal is placed midway between adjacent sites of opposite magnetic polarity, from Johnson et al. (1988). Numbers at the right are mean and 1 s.d. of sediment accumulation rate for each polarity interval, calculated from data in Johnson et al. (1988). (b) Distribution of paleomagnetic samples in relation to major sandstone units in five correlated sections. Note that sandstones at the base cross reversal boundaries. Modified from Johnson et al. (1988) and Sheikh (1984).

rates? Hence, this approach does compare lateral and vertical variation.

Table 2, based on the data in Johnson et al. (1988) presents the results of the analysis. In the first ANOVA, the variance component (represented by the mean-square) among polarity intervals is more than eight times greater than the variance component for location of stratigraphic sections. Only the factor corresponding to time is significant. Since the ANOVA assumes that residuals follow a normal distribution, we determined the maximum normed residuals among the data to identify outliers (Snedecor and Cochran

TABLE 2

TWO-WAY ANOVA OF SEDIMENT ACCUMULATION RATES IN M/10^3 YR, LOWER CHINJE FORMATION

Source of Variation	df	Sum of Squares	Mean Square	F
Original data:				
Polarity intervals (rows)	3	.0233	.0078	4.33[b]
Section locations (cols.)	8	.0069	.0009	.50[c]
Deviations	24	.0426	.0018	
Total	35	.0728		
Outlier (.204) replaced by least squares estimate (.67):				
Polarity intervals (rows)	3	.0306	.0102 (.0097)[a]	7.46[d]
Section locations (cols.)	8	.0161	.002	1.54[e]
Deviations	23	.0301	.0013	
Total	34	.0768		

NOTE.—Data is from four polarity intervals measured over nine sections; for data, see Johnson et al. (1988).

[a] To test whether the mean squares are significantly different (variance among polarity intervals is greater than variance among locations of sections), the F ratio is .0098/.002 = 4.85. For a one-tailed test, at p = .05 the critical value is 4.07; at p = .01, the critical value is 7.59.

[b] At the 5% probability level (df = 3/24) the critical F value is 3.01.

[c] At the 5% probability level (df = 8/24) the critical F value is 2.36.

[d] At the 5% probability level (df = 3/23) the critical F value is 3.03.

[e] At the 5% probability level (df = 8/23) the critical F value is 2.38.

1980). This test revealed one outlier in the original data—the value .204 from Section K3. Since we were not in a position to check on possible errors contributing to this datum, we removed this value and substituted the least squares estimate—the value .067. In the second ANOVA with the substitute value, the results are qualitatively similar. The variance component among polarity intervals is almost five times greater than the variance component for location; only the time factor is significant. The modified data set has no outliers by the test of maximum normed residuals. An F test for homogeneity of variances (table 2) indicates that the variances of the two factors are barely significantly different at the 5% level. By this approach then, the lateral and vertical variabilities in sediment accumulation rate differ marginally, and accumulation rate changes significantly over time but not across the floodplain.

The variance of mean rate is consistently higher for the individual polarity intervals than for the composite sections. The nine long sections of figure 7*a* exhibit a mean sediment accumulation rate over 1.14 m.y. of 0.156 m/10^3 yr with $s = 0.017$ m/10^3 yr. The mean sediment accumulation rate for each polarity interval over all nine sections ranges from 0.128 (possibly lower if the outlier mentioned above represents an error) to 0.191 m/10^3 yr (fig. 7*a*), with apparent secular changes in sediment accumulation rate over time. The oldest interval (N_8 in fig. 7*a*) has a higher sediment accumulation rate (0.191 m/10^3 yr) than any of the succeeding three intervals. This pattern could explain why the net sediment accumulation rate is higher than the mean sediment accumulation rates over the three shorter polarity intervals.

Secular changes in sediment accumulation rate appear to be correlated with facies. The mean sediment accumulation rates (based on lateral variation) are lower for the intervals of reversed polarity in figure 7*a*. Intervals of normal polarity contain one or more laterally extensive sandstones (fig. 7*b*), while the intervals of reversed polarity above and below N_7 contain lenticular sandstones of limited lateral extent. This pattern suggests that the dominant sandstone complexes contribute to higher sediment accumulation rates in the intervals where they occur. If rates were higher during sand-dominated intervals, then the major channelling episodes probably did not condense the section significantly through erosion.

Finally, two sandstone units at the base of Sections K-4 and K-3 (fig. 7*b*) appear to cross reversal boundaries. The lowest sandstone has a normally magnetized site above it in Section K-4, a reversely magnetized site above it in Section K-3, and another normally magnetized site above it in Section K-2. Hence, either the top of the sandstone or the overlying floodplain units are time transgressive. A similar pattern holds for the superjacent sandstone in Sections K-4 and K-3. Another possibility is that these discrepancies represent minor magnetic anomalies that are found inconsistently at the sampling density in these sections. A higher sampling density along with lateral facies mapping would resolve this issue.

This study illustrates some of the potential uses of tracing paleomagnetic reversal boundaries laterally through a stratigraphic sequence. The disposition of reversal boundaries in two or three dimensions may indicate the nature of contemporaneous topography (along with facies analysis) and identify diachronous facies. Also, this approach permits statistical analysis of variability in sediment accumulation rates over 10^4–10^6 yr and ideally, evaluation of sediment accumulation rates in relation to facies. These applications offer ways to characterize processes of sediment deposition and removal in stratigraphic sequences and changes in these processes with time and position and in different environments.

DISCUSSION

The application of high-resolution paleomagnetic stratigraphy to portions of the Siwalik sequence illustrates three general features of alluvial stratigraphy. First, the study of both transition stratigraphy in the Dhok Pathan Formation and lateral tracing of reversal boundaries in the Chinji Formation demonstrated the diachronous nature of certain lithostratigraphic units, since chronostratigraphic markers crossed the lower or upper boundaries of these units. Boundaries are diachronous when lithostratigraphic units grow laterally. The lateral accumulation of sediment occurs over a wide range of scales, arising from both the lateral transport of sediment on the small scale and from the lateral migration of fluvial systems on the large scale. Figure 8 illustrates several common patterns of lateral accumulation.

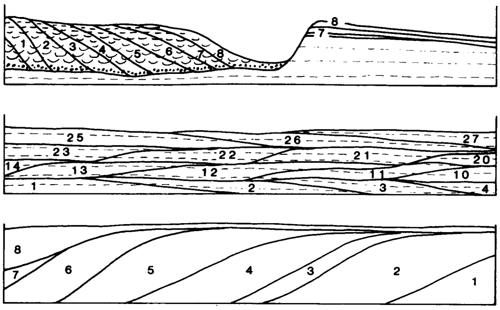

FIG. 8.—Diagram of hypothetical patterns of sediment accumulation with equal intervals of time indicated by dark lines to illustrate the lateral migration of strata and the consequences for evaluating completeness of record. The lowest panel illustrates a pattern similar to that of cross-bedding in channel sandstones. The middle and upper panels contain both time lines (dark, solid) and bedding planes (light, dashed). The middle panel represents accumulation of floodplain strata with some time periods missing due to erosion and deposition in other parts of the system; at the top of the panel, three units, representing different soil types are active simultaneously. The upper panel contains a cross section through an idealized meandering channel, cutting into earlier floodplain deposits. In any of these panels, a vertical section contains only a fraction of the time represented in the panel as a whole.

While this pattern has been recognized as fundamental by many sedimentary geologists, its significance for evaluating the amount of time in the stratigraphic record has not been fully appreciated. Walther (as summarized in Fraser (1989)) emphasized the lateral migration of facies in the creation of stratigraphic sequences; "Walther showed that the law of superposition must be applied with care because time lines cross facies boundaries" (Fraser 1989, p. 23). Shaw (1964), in developing his approach to chronostratigraphic correlation based on the vertical succession of fossils, argued that lithostratigraphic units are the products of laterally migrating environments and that consequently, chronostratigraphic correlation should not be confounded with lithostratigraphic correlation. "Whenever rock correlations (other than volcanic ash) are used as the basis for paleogeographic maps, the order of geologic events will be reversed and the pattern of 'paleotopographic' development will be inverted" (Shaw 1964, p. 60). Ager (1981) contrasted two concepts of sedimentation—"the gentle rain from heaven" by which all contemporaneous environments are being recorded simultaneously and "the moving finger writes" by which sedimentation starts in one area and migrates laterally. Ager argued persuasively that the "moving finger" writes most of the stratigraphic record: "in other words, all bedding is likely to be cross-bedding, though often on so gentle a scale as not to be recognizable in the field" (Ager 1981, p. 59). Considering time on the scale of transport processes, Schwarzacher (1975) stated, "whenever lateral transport of sediment takes place, horizontal surfaces must be of composite age" (p. 24). If this view of sedimentation is correct, then the completeness of any stratigraphic record should be evaluated laterally as well as vertically. We return to this subject below.

Second, the study of transition stratigraphy demonstrates the considerable representation of post-depositional time in the finer-grained sediments of the Dhok Pathan Formation, or in the vernacular of Murphy's Laws—"everything takes longer than it takes." The zones of remagnetization (fig. 6), the multiple components of paleomagnetism (fig. 2) in many Siwalik samples, and the post-depositional features of Facies 1 and 3 all attest to active recording in the geologic system after deposition of sediment. In Siwalik sediments, three kinds of ancient paleomagnetic remanence are acquired fairly soon after deposition: (1) post-depositional, detrital remanent magnetization, (2) chemical remanent magnetization, and (3) misaligned remanent magnetization. These components develop as a consequence of mechanical and chemical changes in sediment. Potential agents of these changes include wetting and drying of sediment, trampling and burrowing by animals, leaching by roots and decomposing organisms, and surface weathering of sediment. In addition to paleomagnetic remanence, the development of paleosols is post-depositional, sometimes signalling local or basinal stasis in deposition. Also, significant components of the fossil record may be incorporated into sedimentary substrate after deposition of the sediment itself; examples include vertebrate remains in paleosols and benthic infaunal assemblages in marine environments. On the basis of the substantial record of paleosols and their included fossils in alluvial sequences, Kraus and Bown (1986) proposed the distinction between lithostratigraphic completeness and biostratigraphic completeness in paleosols, arguing that "the only time that is 'missing' (not represented) is that time elapsed during erosion and that time lost from the rocks and paleosols that were removed by erosion" (p. 197). It would be difficult, however, to assess completeness within paleosols at finer time scales.

Third, variability of sediment accumulation rates is greater over shorter time spans. In the lower Chinji Formation, the coefficients of variation of sediment thickness (n = 9) over four time spans (polarity intervals from 2.0 to 4.2×10^5 yr in duration; fig. 7*a*) range from 0.20 to 0.36, while the coefficient of variation for the nine long sections is 0.11. In the transitional interval of the Dhok Pathan Formation, sediment thickness varied fivefold in six sections. Both (admittedly small) data sets express lateral variation in sediment accumulation along a small transect across an extensive floodplain. Nonetheless, it is tempting to consider this relationship a general one, reflecting high and variable instantaneous sedimentation rates, the lateral growth of strata (hence variable vertical accumulation in any one place), and contemporaneous erosion. The controlling factors would be seasonal and climatic cycles and crevassing and avulsion of channels about the floodplain. (For an extensive examination of controlling factors in relation to variability in sediment accumulation rates, see McRae [1989, 1990]). Over longer time spans ($>10^6$ yr), sediment accumulation rates would be determined by the balance between accumulation and erosion imposed by tectonics. Hence, both autocyclic and allocyclic controls on sediment accumulation rates are important, but they operate over different time spans (Schumm 1977; Fraser 1989). Alluvial systems may not have a single characteristic relationship between sediment accumulation rate and time span. Rather, the magnitude and variability in accumulation rate should vary with geographic position on the floodplain, along the longitudinal profile of the fluvial system, and with changes in the rate of subsidence. The analysis of variance—as exemplified above—should prove a useful analytical approach to quantifying the relative importance of different local geomorphic gradients or geomorphic and temporal gradients on sediment accumulation rates and their variability.

Completeness.—The traditional approach to evaluating stratigraphic completeness has been to compare long-term and short-term rates of vertical sediment accumulation (e.g., Sadler 1981) as determined from stratigraphic sections. Stratigraphic sections record the vertical accumulation of sediment. If deposition produced predominantly vertical accretion, then the vertical profile of stratigraphic sections would contain a useful and representative record of depositional time. But if "the moving finger writes" (Ager 1981), then any localized portion of a stratigraphic unit (as in the outcrop area measured in a stratigraphic section) must represent only a limited period in the growth of the unit. To whatever degree lateral accumulation dominates vertical accumulation, the time represented by a stratum will be underestimated by vertical accumulation rate. No criticism of the practice of measuring vertical sections is intended, rather a reminder that the vertical profile probably does not follow depositional processes any better than a single column of letters on a page represents the writing of text.

If sediment accumulation is predominantly lateral, then individual strata must embody greater time spans in their lateral directions than in any vertical transect. For this reason, it is useful to think of stratigraphic completeness in the context of the entire depositional system, rather than in one or more vertical profiles. A vertical section can only contain a small fraction of the elapsed time contained in a laterally growing unit (e.g., fig. 8). But stratigraphic sequences in their geographic entirety may represent geologically significant time spans with considerable continuity. Of course, erosion acts both laterally and vertically, and the importance of its fundamental role in reducing completeness of the record is unchanged by the present arguments. One approach to recognizing and documenting the vertical and lateral components of sediment accumulation in a stratigraphic sequence is to measure multiple long sections with broad geographic coverage, correlate them with chronostratigraphic, lithofacies, and biostratigraphic data, and then add detailed studies at much higher resolution (such as the studies described above) for selected intervals. In this manner, time transgression can be documented at coarse and fine scales.

While the diachronous nature of most stratigraphic units has been demonstrated repeatedly, the consequences of this property for estimates of completeness have been overlooked. For example, Anders et al. (1987) have revised Sadler's (1981) approach to stratigraphic completeness with an analysis of spurious trends in accumulation rate diagrams and corrections for bioturbation, compaction, and spurious increases in median rates. While qualifiers have been carefully laid out, the revised approach still involves the graphical comparison of accumulation rates over different time spans, as determined from vertical sections. Their revised analysis of sediment accumulation rates for pelagic environments concludes that the calcareous oozes of pelagic sequences have high completeness values, which still decrease with absolute age. Interestingly, this environment is the major exception to the generality of the dominance of lateral over vertical sediment accumulation (Ager 1981). Stochastic models of sediment accumulation (e.g., Tipper 1983; Strauss and Sadler 1989), while clarifying relationships between completeness and time span, thickness, and the joint interaction of accumulation and erosion, have not addressed the distinction between vertical and lateral growth of strata.

CONCLUSION

High-resolution magnetostratigraphy can provide the chronostratigraphic framework for evaluating rates and patterns of depositional and post-depositional processes in alluvial sequences over time scales that are otherwise difficult to probe. Transition stratigraphy, the detailed sampling of a reversal of the geomagnetic field in relation to facies, presents the opportunity to examine sediment accumulation and post-depositional modification over several thousand to ten thousand years. The study of transition stratigraphy in six laterally correlated sections from the Dhok Pathan Formation of northern Pakistan indicated high variability in sediment accumulation rates, the time-transgressive nature of strata representing a paleosol and a floodplain marsh, and the extensive post-depositional record in the finer grained facies. The lateral tracing of reversal boundaries presents the opportunity to measure and depict contemporaneous variation in rates and patterns of sediment accumulation over tens to hundreds of thousands of years. The study from the Chinji Formation suggested the time-transgressive nature of certain sandstone units (although short magnetic anomalies sampled irregularly is an alternative explanation), a secular change in sediment accumulation rate, and evidence for increased accumulation rate associated with extensive sandstone units.

Both studies indicated a significant lateral component to the accumulation of lithological units. There is a long tradition in the stratigraphic literature for considering this pattern a fundamental one. If vertical sequences grow predominantly by lateral accumulation, then the assessment of stratigraphic completeness must take into account lateral as well as vertical sediment accumulation. Emphasis on the lateral dimension of completeness should lead to greater effort in tracing chronostratigraphic markers laterally through a stratigraphic sequence. Such markers include volcanic ash units, some biostratigraphic indicators, and paleomagnetic reversals.

A final point to consider is whether the importance of lateral accumulation, stressed here for alluvial sediments, applies to other kinds of sequences as well. For clastic depositional sequences, bed-load transport should produce laterally growing units, while the suspended load may settle more like a blanket. But the short-term reworking of sediment in subaerial or shallow subaqueous environments prevents most units from being preserved in their entirety. For carbonate sequences, in which sediment accumulation is strongly influenced by biological and chemical components of the environment, there are strong environmental gradients that shift laterally over seasonal to eustatic cycles. Hence, carbonate facies should be predominantly time transgressive also, with the exception of abyssal oozes, in which the dominant mode of accumulation is vertical. In sum, those regions in which sediment accumulates through the settling of suspended material in relatively long-lived aquatic environments (deep lakes and deep ocean basins) will have dominantly vertical accumulation. While significant in terms of geographic cover, these environments make a volumetrically small contribution to the rock record. Thus, we follow Shaw (1964) and Ager (1981) in considering lateral accumulation to be the dominant trend in the growth of strata. If this view is wrong, it will probably be disproved through the lateral tracing of paleomagnetic reversals in stratigraphic sequences.

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