PRELIMINARY EVALUATION OF PALEOSOLS AND IMPLICATIONS FOR INTERPRETING VERTEBRATE FOSSIL ASSEMBLAGES, KULDANA FORMATION, NORTHERN PAKISTAN

by

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ABSTRACT

Paleosols and the taphonomy of vertebrate fossils in the Eocene Kuldana Formation of northern Pakistan provide important information on the preservation and time-averaging of fossil assemblages. Morphologic, mineralogic, and chemical data as well as comparisons with Quaternary soils suggest that Kuldana paleosols formed under generally dry and oxidizing conditions over time intervals of less than 10^5 years and perhaps as short as 10^3 years. The distribution of carbonate in Kuldana paleosols further indicates that the upper half of the profiles were acidic whereas the lower halves were alkaline. Vertebrate fossils are rare in Kuldana paleosols and occur primarily in well-cemented sandstones and conglomerates with abundant micritic and iron-stained nodules that were reworked from floodplain soils. The scarcity of vertebrate remains in Kuldana paleosols probably reflects a combination of acidic, dry, and oxidizing conditions in the upper half of the profiles and rapid floodplain sedimentation.

Comparisons between the taphonomic characteristics of Kuldana channel fossil assemblages and bone accumulations in modern rivers provide a basis for estimating the length of time represented by Kuldana fossils from several important localities. Vertebrate fossil assemblages from Barbora Banda are characterized by a low-diversity paleofauna, partially articulated skeletons, and bones that are sorted by size and shape. Comparison with bone accumulations in modern rivers suggests that the fossils from Barbora Banda accumulated in 1 to 10 years. Vertebrate fossils from the Lower Kuldana in the Kala Chitta Hills region, typified by locality H-GSP 62, are characterized by a high-diversity paleofauna and generally random and unsorted fossil bone distributions, which suggest that the fossils from these localities represent longer time intervals than the Barbora Banda fossils. Based on the time estimates for Kuldana paleosol development, fossil assemblages in Kuldana channel deposits in the Kala Chitta Hills region probably represent time intervals of about 10^3 years.

RESUME

Les paléosols et la taphonomie des vertébrés fossiles de la Formation Kuldana (nord du Pakistan) fournissent des informations importantes sur la préservation et la durée de dépôt des assemblages fossiles. Des données morphologiques, minéralogiques et chimiques, ainsi que des comparaisons avec des sols quaternaires suggèrent que les paléosols de la Formation Kuldana se sont formés dans des conditions oxydantes et sèches dans des intervalles de temps inférieurs à 10^5 années et peut-être aussi courts que 10^3 années. De plus, la distribution des carbonates dans les paléosols de Kuldana indiquent que la moitié supérieure des profils était acide, alors que les parties inférieures étaient alcalines. Les vertébrés fossiles sont rares dans les paléosols de la Formation Kuldana et se trouvent principalement dans des grés bien cimentés et dans des conglomérats renfermant de nombreux nodules de micrite, ferrugineux, remaniés de sols de plaine inondable. La rareté des restes de vertébrés dans ces paléosols reflète probablement la combinaison de conditions paléopédologiques acide, sèches, et oxydantes dans la moitié supérieure des profils et d'une sédimentation rapide de plaine inondable.

La comparaison entre les caractéristicques taphonomiques des assemblages fossiles de chenaux et des accumulations d'ossements de la Formation Kuldana avec celles de fleuves actuels fournit une base pour estimer la durée représentée par les fossiles de plusieurs localités importantes. Les assemblages de vertébrés fossiles de Barbora Banda sont caractérisés par une paléofaune de faible diversité, des squelettes partiellement en connexion, et des ossements triés selon leur taille et leur forme. La comparaison avec des accumulations d'os dans des fleuves actuels suggère que les fossiles de Barbora Banda se sont accumulés en 1 à 10 ans. Les vertébrés fossiles de la partie inférieure de la Formation Kuldana dans la région des Kala Chitta Hills, typiquement représentés par la localité H-GSP 62, sont caractérisés par une paléofaune de grande diversité et des ossements généralement non triés et distribués au hasard. Ceci suggère que les fossiles de ces gisements représentent des intervailles de temps plus longs que ceux de Barbora Banda. En

se basant sur les estimations de temps pour le développement des paléosols de la Formation Kuldana, les assemblages fossiles de chenaux de la région de Kala Chitta Hills représentent probablement des intervaillede temps de mille ans.

INTRODUCTION

Paleosols represent a relatively new and useful tool for studying a variety of topics including paleoclimates (Cerling *et al.* 1989, Quade *et al.* 1989, Cerling 1991, Mora *et al.* 1991, Driese & Foreman 1992, Driese *et al.* 1992), relative sea level changes (Joeckel 1991), sediment accumulation rates (Retallack 1984, Kraus & Bown 1986, 1993), and mammalian evolution and paleoecology (Gingerich 1989, Bown & Beard 1990). In studies of vertebrate fossils, paleosols also provide insight on processes of fossil preservation as well as on the amount of time represented by fossil assemblages (Retallack 1984). Temporal inferences are important for interpreting fossil assemblages and their evolutionary relationships (Gingerich 1980, 1989, Behrensmeyer 1982, Bown & Rose 1987, Thewissen 1992).

In this paper, we integrate information on the taphonomic context of vertebrate remains from the Kuldana Formation in the Kala Chitta Hills region of northern Pakistan with preliminary data on paleosols from the same area. Conditions of Kuldana paleosol development provide insight on vertebrate fossil preservation in the Kuldana Formation. In addition, taphonomic characteristics of Kuldana channel bone assemblages are compared with studies of bone accumulation in modern rivers to develop broad estimates for the amount of time represented by several important Kuldana fossil assemblages.

STUDY AREA AND METHODS

The Eocene Kuldana Formation in the Kala Chitta Hills region of northern Pakistan is approximately 150 m thick and consists of red mudstones and lesser quantities of limestones, sandstones, and conglomerates (Hussain *et al.* 1978, West & Lukacs 1979, Wells 1983, 1984). Previous studies have suggested that Kuldana sediments accumulated within a low-lying alluvial plain characterized by small and perhaps ephemeral streams (Wells 1983, 1984). Kuldana paleosols, however, have received little attention.

In the study area, the lower half of the Kuldana Formation is subdivided into numerous vertically-stacked lithofacies sequences that are typically 2 to 5 m thick. The base of each sequence is represented by lenticular sandstones or conglomerates, which are overlain by laterally-persistent purple and red mudstones (Fig. 1). The sandstones

and conglomerates frequently contain vertebrate remains and most fossil localities in the Kuldana Formation are associated with this lithofacies (West & Lukacs 1979, Wells 1983, 1984). Overlying the purple and red mudstones and capping the sequences are thin (< 1 m thick) grey limestones with common ostracod shell fragments.

Kuldana paleosols were studied using a combination of field and petrographic observations as well as by mineralogic and geochemical analyses. The mineralogy of the clay-sized fraction of paleosol samples was determined using a Scintag X-ray diffractometer with a Cu target. Oriented clay samples were analyzed following air-drying (untreated), glycolation, and heating to 550° C. Major oxide chemistry of paleosol samples was analyzed by X-ray fluorescence spectrometry. Total oxidizable carbon was measured using the Walkley-Black method (Janitzky 1986). Paleosol colors were described using Munsell notation.

KULDANA PALEOSOLS

Kuldana paleosols in the Kala Chitta Hills region are developed primarily in the laterally-persistent purple and red mudstones that overlie the lenticular sandstones and conglomerates. Recognition of paleosols in the study area is based on the presence and distribution of matrix and mottle colors, slickensides, carbonate nodules, and the cyclic vertical arrangement of Kuldana lithofacies. A representative paleosol from the lower half of the Kuldana Formation near the town of Jhalar is described below (Fig. 1).

MORPHOLOGY

The paleosol is overlain by a 60-cm-thick, well-cemented and bedded, grey (N7) limestone with common ostracod remains (ostracod wackestone). The limestone also contains sub-vertical gypsum- and clay-filled cracks that cross-cut bedding planes and the lower boundary of this unit is typically sharp.

The uppermost unit of the paleosol consists of a 40-cm-thick, partially-cemented and massive purple (5RP) to black (N3) mudstone. The gypsum- and clay-filled cracks within the overlying limestone extend down into this unit. The lower boundary of the purple mudstone is gradational in color.

A 40-cm-thick red (10R 4/6) clayey mudstone is present beneath the purple mudstone. The red mudstone contains common grey mottles and slickensides that impart a subangular blocky structure to this unit. In addition, rare carbonate nodules that are typically 1 to 5 mm in diameter are present in this unit. Cross-sectional geometries of the grey mottles are oblate or cylindrical and the mottles probably represent root traces. The lower boundary of the red mudstone is gradational in texture.

The purple and red mudstones overlie a 60-cm-thick and partially-cemented red (5RP 6/2) muddy sandstone with abundant carbonate nodules that are 1 to 5 cm in diameter. The abundance of nodular carbonate in this unit causes it to appear mottled. In
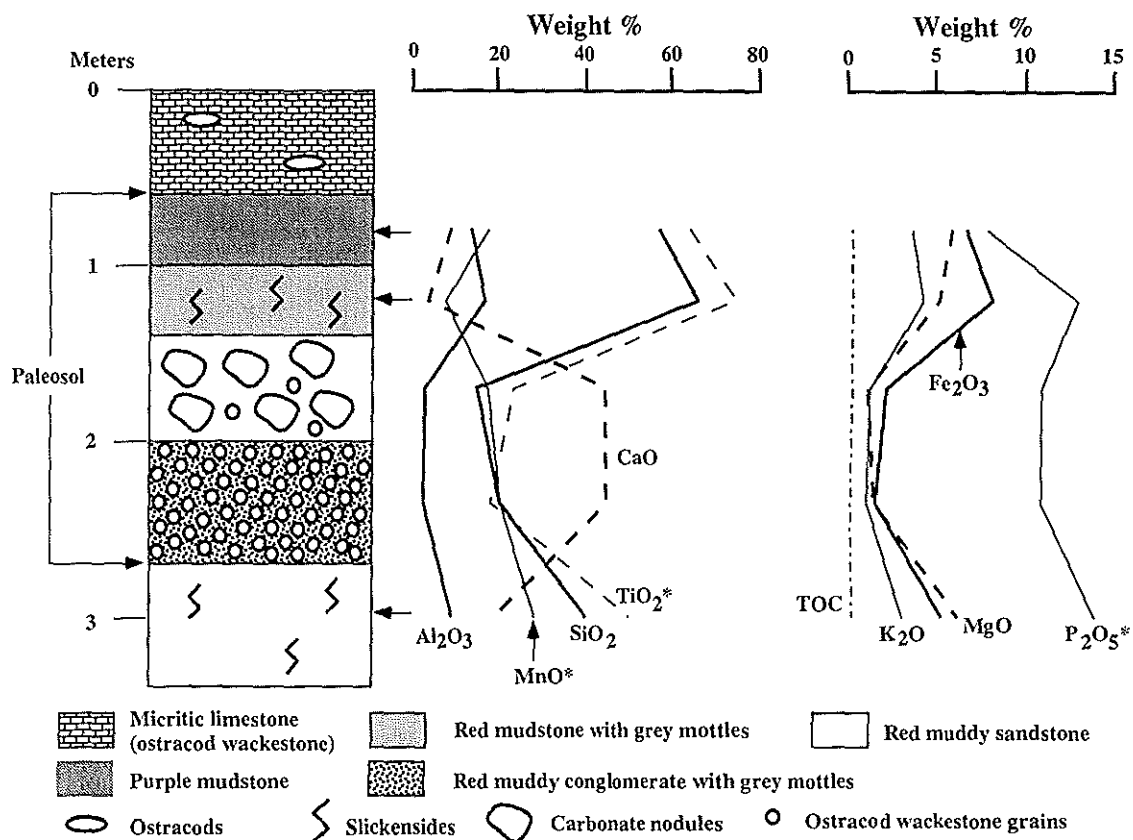
Figure 1.— Stratigraphic section showing the typical vertical distribution of lithofacies, paleosol features, and major oxide contents of Kuldana deposits in the Kala Chitta Hills region. Weight percent values for oxides marked with an (*) have been multiplied by 100. Arrows mark location of samples used for mineralogic analyses shown in Figure 2. TOC = total oxidizable carbon.

thin-section, the nodules consist of smaller, micritic nodules that contain detrital metamorphic rock fragments, which are occasionally stained by iron oxides (Plate 1A). The smaller micritic nodules are cemented with sparry prismatic carbonate cement and intercrystalline pores are commonly filled with iron-stained clay minerals (Plate 1B).

The base of the profile consists of a 70-cm-thick and well-cemented red (10R 4/6) muddy conglomerate with common grey mottles. The conglomerate consists primarily of large detrital fragments of an ostracod wackestone that have been partially replaced by authigenic quartz and, which are similar to the limestone that overlies the paleosol (Plate 1C). The limestone rock fragments are surrounded and cemented by common iron-stained clay coatings. The base of the profile is characterized by a sharp and irregular contact.

Beneath the profile occurs a poorly-cemented red (10R 4/6) muddy sandstone with common grey mottles and slickensides. Sand grains in this unit include micritic carbonate nodules and mudstone rock fragments. Clay coatings are absent.
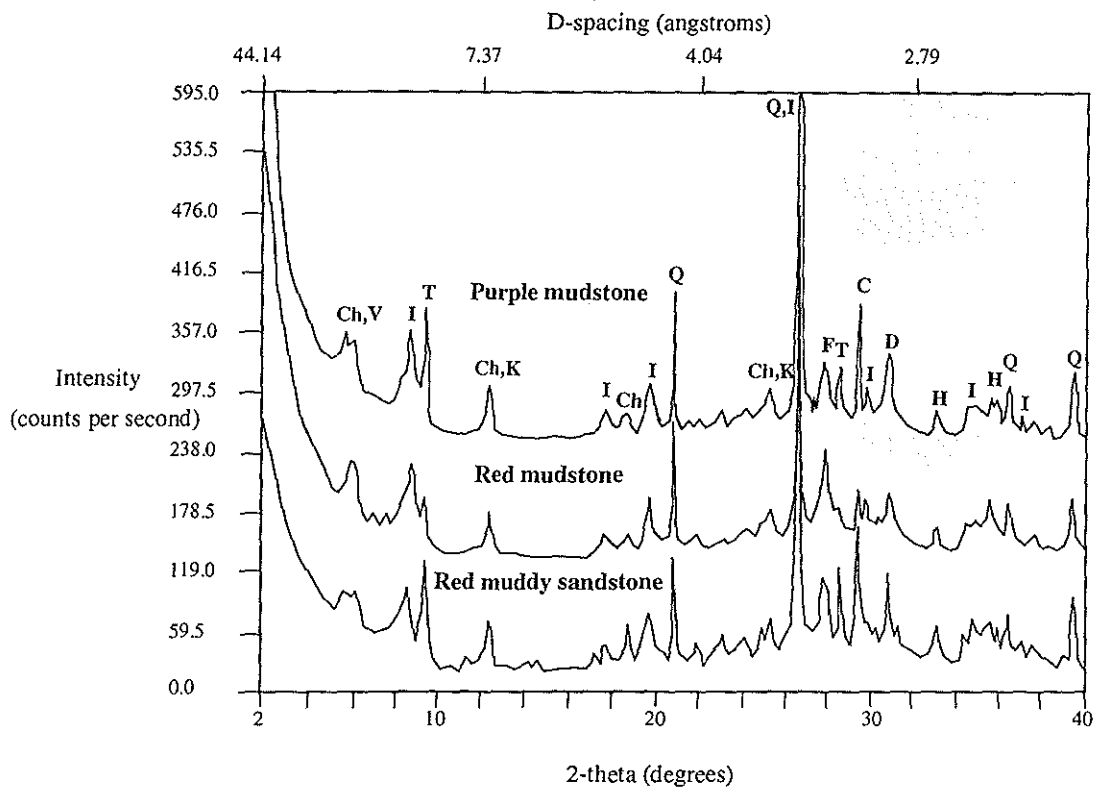
Figure 2.— X-ray diffraction patterns of air-dried (untreated) Kuldana paleosol samples (clay-sized fraction, < 2 μm in diameter). The paleosol mineralogy is generally uniform and is characterized by abundant clay minerals and quartz. Ch = chlorite, V = vermiculite, I = illite, T = talc, K = kaolinite, Q = quartz, F = feldspar, C = calcite, D = dolomite, H = hematite.

CHEMISTRY AND CLAY MINERALOGY

The chemistry of the Kuldana paleosol shows erratic down-profile changes (Fig. 1). For instance, the purple and red mudstone in the upper half of the profile are enriched in SiO_2, Al_2O_3, Fe_2O_3, TiO_2, K_2O, MgO, and P_2O_5 relative to the underlying red sandstone and conglomerate. Down-profile depletions in these compounds are accompanied by a decrease in clay and increases in sand and gravel contents. In contrast to the down-profile chemical depletions, CaO and MnO contents are highest in the basal sandstone and conglomerate, which contain abundant carbonate cement and grains. Organic carbon contents are uniformly low (< 1 wt. %) throughout the profile.

The mineralogy of the clay-sized fraction of the paleosol samples is generally uniform (Fig. 2). Clay minerals present include illite, talc, chlorite, and lesser amounts of vermiculite. Non-clay minerals present include quartz, feldspar (albite), calcite, dolomite, and hematite. Variations in mineralogy between paleosol samples are

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minimal. The red mudstone is slightly depleted in talc, calcite, and dolomite relative to the overlying purple mudstone whereas heating of the samples to 550° C demonstrated that the purple mudstone is slightly enriched in vermiculite relative to the underlying red mudstone. The mineralogies of the purple mudstone and the red muddy sandstone that immediately underlies the paleosol are virtually identical.

KULDANA PALEOSOL INTERPRETATION

Comparisons between the morphology and geochemistry of the Kuldana paleosol and modern soils provide insight on the weathering environment and the length of time represented by paleosols in the study area. In addition, information on soil Eh-pH conditions and chemical weathering recorded by the paleosol is useful for understanding the distribution and taphonomy of vertebrate fossils in the Kuldana Formation.

PALEOSOL Eh - pH CONDITIONS

Red matrix colors and common carbonate nodules suggest that the Kuldana paleosol formed in a generally dry, oxidizing, and alkaline soil environment. Under these conditions, iron oxides such as hematite precipitate and produce red soil colors (Schwertmann & Taylor 1977) and hematite is the pigmenting agent in Kuldana deposits (Fig. 2). Alternatively, red colors can also develop in originally brown or yellow-brown soils over time due to the progressive dehydration of iron compounds during diagenesis (Walker 1967, 1974, Retallack 1991). Even if the Kuldana paleosol matrix was originally yellow-brown, soils with this color also form under well to moderately drained and oxidizing conditions (Schwertmann & Taylor 1977). Furthermore, the presence of grey mottles in the Kuldana paleosol suggests that the deposits were not originally grey and subsequently oxidized red during diagenesis, otherwise the paleosols would be uniformly red.

The grey mottles and slickensides in the Kuldana paleosol also provide evidence for periodic soil wetting and drying, perhaps related to seasonal rainfall. In modern soils, grey mottles within an oxidized matrix represent areas of localized iron reduction along roots and soil channels (Retallack 1991) that form in soils, which are saturated by surface or ground waters for 10-25% of the year (Daniels et al. 1971, Coventry & Williams 1984). Because grey mottles are not abundant in the Kuldana paleosol, soil conditions were probably dry for most of the year. In addition to the grey mottles, slickensides in the upper half of the Kuldana paleosol are similar to pedogenic slickensides that are present in contemporary clayey soils (Vertisols), which experience seasonal rainfall and soil wetting and drying (Dudal & Eswaran 1988, Wilding & Tessier 1988). By analogy with contemporary clayey soils, slickensides in the Kuldana paleosol provide evidence of seasonal rainfall in the study area during the Eocene.

The presence of carbonate nodules and detrital limestone fragments in the lower half of the Kuldana paleosol indicates that at least this portion of the paleosol was

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alkaline. Because the solubility of calcium carbonate increases with decreasing pH (Arkeley 1963), pedogenic carbonate is present in modern soils that are generally alkaline (Birkeland 1984). Conversely, the scarcity of carbonate nodules in the upper half of the Kuldana paleosol suggests that this portion of the profile was acidic. Evidence of a pedogenic origin for the Kuldana nodules includes 1) light carbon isotopic compositions (Wells 1984), 2) similarities between the micromorphologic fabrics of the Kuldana nodules and modern soil nodules (Sehgal & Stoops 1972, Wells 1984, Drees & Wilding 1987), 3) the presence of iron-stained clay within nodule pores (Plate 1B and C), which indicates that clay infiltration, a typical pedogenic process (Birkeland 1984), post-dated carbonate precipitation, and 4) the nodules are associated with other pedogenic features such as mottles and slickensides.

PALEOSOL WEATHERING

Mineralogic and chemical data for the Kuldana paleosols suggest that the paleosols in the study area experienced minimal chemical weathering. For instance, the presence of chlorite and the scarcity of vermiculite in the paleosol shows that the mineralogy of the paleosol is immature (Fig. 2). Studies of Quaternary soils have shown that chlorite is commonly transformed to vermiculite in soils that have experienced significant chemical weathering (Weaver 1989, Mohindra $et\ al.$ 1992).

The strong similarity between the erratic down-profile changes in paleosol chemistry and texture further suggests that the vertical changes in the paleosol chemistry are related to differences in depositional texture, rather than chemical weathering (Driese $et\ al.$ 1992). For instance, the purple and red mudstones are enriched in Al_2O_3, SiO_2, TiO_2, K_2O, MgO, Fe_2O_3, and P_2O_5 compared to the underlying sandy paleosol units (Fig. 1). In modern alluvial soils that have experienced little chemical weathering, textural differences in the soil parent materials commonly reflect episodic sedimentation, rather than pedogenic processes (Holmes & Western 1969, Schumacher $et\ al.$ 1988, Aslan & Autin 1992). Furthermore, depositionally-related textural variations in young alluvial soils commonly coincide with down-profile changes in soil chemistry (Sidhu $et\ al.$ 1977, Hayward 1985). Thus young alluvial soils typically have multiple parent materials and show erratic down-profile variations in chemistry. In contrast to young soils, old and deeply-weathered soil profiles are characterized by unidirectional or gradual down-profile variations in soil composition that reflect pedogenic, rather than depositional processes. The similarity between the textural and chemical changes in the Kuldana paleosol suggest that chemical variations in Kuldana paleosols were caused by depositional processes and do not reflect significant chemical weathering of the paleosol parent materials.

The limited evidence of chemical weathering in Kuldana paleosols could reflect soil development in a relatively dry or semi-arid climate, which would have favored slow mineral weathering (Birkeland 1984). Alternatively, limited weathering could simply reflect that the paleosols in the study area had little time to develop.

The morphology and composition of Kuldana paleosols and comparisons with Quaternary soils suggest that paleosol development in the study area occurred over time intervals of less than 10^5 and probably closer to 10^3 years. Quaternary soils in the southwestern U.S. that contain pedogenic carbonate accumulations similar to those in the Kuldana paleosol, form in less than 10^5 years (minimum age for K horizons, Machette 1985). Pedogenic carbonate in Quaternary soils of the Gangetic Plain in India provides additional insight on the amount of time represented by the Kuldana paleosols. For instance, Gangetic Plain alluvial soils that contain acidic A and shallow B horizons that overlie alkaline B horizons with carbonate nodules similar to those in the Kuldana paleosol, range in age from 10^2 to 10^3 years B.P. (Mohindra *et al.* 1992). Furthermore, the Gangetic Plain soils that are older than 2,500 years B.P. contain virtually no chlorite, common vermiculite, and a moderate amount of illuvial clay in Bt horizons. The presence of chlorite and the scarcity of illuvial clay in the Kuldana paleosol suggests that the paleosol formed over a shorter time period (< 2,500 years) than the Gangetic Plain soils. Because the Gangetic alluvial soils and the Kuldana paleosols could have formed under different climatic conditions, and thus, at different rates, the comparison between the Quaternary soils and Kuldana paleosols can only be used to broadly estimate the amount of time represented by the paleosols. Thus, the Kuldana paleosols are interpreted to have probably formed over thousands (10^3) of years.

Comparisons between the geometries of Kuldana sandstones and conglomerates and models of alluvial stratigraphy indicate that Kuldana deposits accumulated rapidly, which supports the suggestion that Kuldana paleosols formed over short time periods. For instance, models of alluvial stratigraphy predict that rapid sediment accumulation produces alluvial deposits that are characterized by abundant mudstones, which locally encase lenticular or ribbon-shaped sand bodies (Allen 1978, Bridge & Leeder 1979). In contrast, the models predict that slow sedimentation favors continual lateral channel migration and produces alluvial fills with thick sheet sandstones and small quantities of mudstone. Based on these stratigraphic models, the lenticular geometry of Kuldana sandstones and conglomerates and the abundance of mudstones present in the study area suggest that Kuldana sediments accumulated rapidly. Rapid sedimentation would have minimized the amount of time available for Kuldana paleosol development, which is consistent with the morphology and immature composition of the Kuldana paleosols.

TAPHONOMY OF KULDANA FOSSIL ASSEMBLAGES

Vertebrate fossils from the lower Kuldana Formation are found primarily in well-cemented, lenticular sandstones and conglomerates (West & Lukacs 1979, Wells 1983, 1984). The fossils are commonly associated with sand- and gravel-sized micritic and iron-stained carbonate nodules as well as with detrital quartz grains (West & Lukacs 1979, Wells 1983, 1984) (Plate 1D). Vertebrate fossils, however, are rarely found in Kuldana paleosols.

Barbora Banda I and II

PLANTAE

Charophyta
    Chara (BB I only)

Ulmacea
    Celtis (BB I only)

Labiatae
    Ajunginucilla (BB I only)

VERTEBRATA

Reptilia
  Crocodilia indet. (BB II only)

Mammalia

  Artiodactyla
    Dichobunidae
      Diacodexis pakistanensis (BB I and II)

  Perissodactyla
    Isectolophidae
      unnamed species (BB I and II)

  Rodentia
    Paramyidae
      unidentified species (BB I only)
    Cocomyidae
      two unidentified species (BB I only)
    Rodentia indet.
      incisor fragments from BB II

  Mammalia indet.
      unidentified large mammal incisor (BB II only)

Locality H-GSP 62, Kala Chitta Hills

MOLLUSCA

Gastropoda
    Planorbis

VERTEBRATA

Osteichthyes
  Channidae
    Eochama

  indet. (including "catfish")

Reptilia

  Chelonia indet.

  Crocodilia indet.

  Squamata indet.

Mammalia

  Lipotyphla
    Seia?

  Rodentia
    Chapattimyidae
      Chapattimys debruijni
      Saykanomys ijlsti
      Saykanomys sondaari

  Perissodactyla
    Tapiroidea
      unidentified species

  Primates
    Adapidae
      Panobius afridi

  Artiodactyla
    Dichobunidae
      unidentified species
    Raoellidae
      Khirtharia dayi

  Cetacea
    Protocetidae
      Pakicetus sp.
      Ichthyolestes

Table 1.— List of recovered biota from Kuldana fossil localities Barbora Banda I and II, Northwest Frontier Province and H-GSP 62, Kala Chitta Hills region.

Previous studies have suggested that the carbonate nodules, which occur with vertebrate fossils in Kuldana sandstones and conglomerates, represent reworked soil nodules (Wells 1983, 1984). Similarities between the micromorphologic fabrics of *in situ* carbonate nodules from Kuldana paleosols and detrital nodules in Kuldana conglomerates support this interpretation (Plate 1A and D). Thus, it seems likely that a significant proportion of the vertebrate fossils in Kuldana sandstones and conglomerates were reworked into channels from floodplain soils during episodes of channel erosion (Wells 1983, 1984). In the following sections, faunal lists and the taphonomic contexts of two important Kuldana fossil localities are discussed (Barbora Banda and H-GSP 62, Wells 1983, West & Lukacs 1979). Information on the taphonomy of Kuldana fossils and paleosols is used to discuss factors that influenced fossil preservation and the amount of time represented by individual fossil assemblages in the study area.

LOWER KULDANA FOSSIL ASSEMBLAGES

The Barbora Banda and H-GSP 62 localities of the lower Kuldana Formation illustrate important differences in the taphonomy of Kuldana fossil assemblages. The two Barbora Banda localities occur in the North-West Frontier Province of Pakistan. The localities are referred to as Barbora Banda I and II and consist of well-cemented and lenticular sandstones and conglomerates (Wells 1983) that have yielded an abundant vertebrate fauna, though one of low diversity (Table 1, based on Thewissen *et al.* 1983, de Bruijn *et al.* 1982). The majority of specimens represent the artiodactyl *Diacodexis pakistanensis* (approximate bodyweight 300 g). Many of the specimens of *D. pakistanensis* and an undescribed tapiroid from the same localities are partially articulated skeletons that show little evidence of abrasion. These two forms constitute most of the vertebrate fossils from the localities (Barbora Banda I yielded 138 specimens of *Diacodexis pakistanensis*, Barbora Banda yielded 24). Bones at Barbora Banda are sorted by size and shape, and paleoflow measurements indicate that heavier elements, such as skulls, were deposited upstream of lighter bones, such as vertebrae (Wells 1983).

The H-GSP 62 locality is present east of the Barbora Banda localities in the Kala Chitta Hills region. Similar to the Barbora Banda sites, the fossils are found primarily in well-cemented sandstones and conglomerates. In contrast to the other localities, however, the vertebrate fauna of the H-GSP 62 locality is diverse and consists of both small (approximately 90 g, rodent-sized) and large (approximately 25 kg, dog-sized) animals (Table 1). In addition, articulated elements are absent at the locality and the fossils are unsorted and show evidence of abrasion.

KULDANA PALEOSOLS AND CONTROLS ON FOSSIL PRESERVATION

The scarcity of vertebrate remains in Kuldana paleosols in the study area is probably related to 1) paleosol Eh-pH conditions and 2) sediment accumulation rates.

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As discussed previously, Kuldana paleosols developed under generally dry, oxidizing, and alkaline conditions. The rarity of carbonate nodules in the upper half of the paleosol, however, suggests that this part of the profile was acidic. Acidic soil conditions near the floodplain surface would have inhibited the preservation of bones and teeth in Kuldana paleosols (Retallack 1984). Additionally, dry and oxidizing soil conditions could have caused bones on the floodplain surface to crack, flake, and disintegrate. In contrast, well-preserved vertebrate fossils from Eocene paleosols in North America are commonly encrusted with iron and carbonate compounds that precipitated in association with shallow fluctuating water tables (Bown & Kraus 1981). The mineral coatings probably helped preserve the fossils in these seasonally wet paleosols. The relatively dry soil conditions evidenced by Kuldana paleosols in the study area could have prevented the precipitation of the mineral coatings necessary to preserve vertebrate remains in these paleosols.

A second and possibly more important factor related to the scarcity of vertebrate fossils in Kuldana paleosols is sediment accumulation rate. As discussed previously, the morphology and composition of Kuldana paleosols and the lenticular geometry of Kuldana sandstones and conglomerates in the study area suggests that Kuldana paleosols formed over short time periods and that sedimentation was rapid. Rapid sedimentation would disperse, rather than concentrate, vertebrate remains in Kuldana floodplain deposits, including those in paleosols. Studies in Amboseli Park in Kenya for comparison, have suggested that 10^3–10^4 years are necessary for bones to accumulate in "fossiliferous" concentrations on floodplain surfaces (Behrensmeyer 1982). Thus, rapid rates of sediment accumulation could have prevented bones and teeth from accumulating in "fossiliferous" concentrations in Kuldana paleosols. In contrast to the Kuldana Formation, Eocene paleosols from the Willwood Formation in Wyoming contain abundant vertebrate remains (Bown 1979, Bown & Kraus 1981). The abundance of vertebrate fossils in Willwood paleosols with well-developed A horizons probably reflects the greater length of time (10^3–10^5 years, Kraus & Bown 1986) represented by these paleosols (Stage 1-6 paleosols, Bown & Kraus 1981, 1987).

TIME AVERAGING OF KULDANA CHANNEL FOSSIL ASSEMBLAGES

Because channels can rework bones from older floodplain deposits, fossil assemblages in channel deposits are generally thought to represent longer time intervals than attritional floodplain fossil assemblages (Behrensmeyer 1982). Factors that control the input of bones from older floodplain deposits and thus the maximum length of time represented by fossil assemblages in channel deposits include:

1) the availability of fossils in floodplain deposits,

2) the ability of a channel to rework older floodplain deposits.

For instance, if fossils are not preserved in floodplain deposits, the amount of time represented by channel fossil assemblages will not be affected by the reworking of older

floodplain deposits. Similarly, if floodplain sedimentation is rapid or if clayey floodplain deposits inhibit lateral channel migration, bone inputs from older floodplain deposits will be minimized.

Studies of experimental and natural bone accumulation in the East Fork River in Wyoming have shown that channel bone assemblages can represent short time intervals (Behrensmeyer 1982, Aslan & Behrensmeyer in press). For instance, experimental bones, representing a point source within the channel, became sorted by size and shape in 1 to 10 years. In contrast to the sorted distribution of experimental bones, natural bone assemblages in the same channel were unsorted and randomly distributed. This random and unsorted distribution of the natural bones was attributed to the varying locations and times at which bones were introduced into the channel. Furthermore, reworking of older floodplain deposits by the river produced natural bone assemblages that represent time intervals of up to 10^4 years.

Comparisons between the taphonomic characteristics of the Kuldana channel fossil assemblages and the patterns of bone accumulation in the East Fork River provide a basis for estimating the amount of time represented by Kuldana fossil assemblages. First, the presence of partially-articulated skeletons and bones sorted by size and shape at the Barbora Banda localities suggests that the assemblages represent short time intervals (1-10 years), based on the time required to sort the experimental bones representing point sources in the East Fork River. This time estimate is also consistent with the suggestion that the Barbora Banda fossils represent a mass mortality event caused by a flood (Wells 1983).

In contrast to the Barbora Banda localities, fossils from locality H-GSP 62 represent a wide variety of species and bone sizes and shapes. The unsorted distribution of these fossils is similar to the distribution of natural bones in the East Fork River, which suggests that the fossils from H-GSP 62 accumulated over longer time intervals than the Barbora Banda fossils. Because Kuldana fossils were reworked from floodplain soils, the estimated amount of time represented by Kuldana paleosol development also provides a maximum age for the length of time represented by Kuldana channel fossil assemblages. Based on the previous suggestion that Kuldana paleosols formed over time intervals of less than 10^5 years and probably closer to 10^3 years, unsorted fossil assemblages in Kuldana channel deposits should represent similar time spans.

CONCLUSION

Integrating information on paleosols and the taphonomy of vertebrate fossil assemblages in the Kuldana Formation of northern Pakistan is important for two reasons. First, information on Kuldana paleosols provides a better understanding of the factors that controlled the preservation and distribution of the vertebrate remains in Kuldana deposits. Specifically, acidic, dry, and oxidizing soil conditions in the upper half of Kuldana paleosols as well as stratigraphic evidence for rapid sediment accumulation could explain the scarcity of vertebrate remains in Kuldana mudstones. Second, comparisons between the taphonomic characteristics of Kuldana fossil

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assemblages and bone accumulations in modern channels are useful for estimating the amount of time represented by fossil assemblages from different localities. These temporal inferences are important for interpreting evolutionary relationships between Kuldana vertebrate fossils and those from Eocene deposits of other continents.

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REFERENCES

ALLEN, J.R.L., 1978. — Studies in fluviatile sedimentation: An exploratory quantitative model for the architecture of avulsion-controlled alluvial suites. *Sedimentary Geology*, 21: 129-147.

ARKELEY, R.J., 1963. — Calculation of carbonate and water movement in soil from climatic data. *Soil Science*, 96: 239-248.

ASLAN, A. & AUTIN, W.J., 1992. — Holocene floodplain development: implications for the interpretation of alluvial paleosols. *Geological Society of America Abstracts with Programs*, 24: 228.

ASLAN, A. & BEHRENSMEYER, A.K.B., in press. — Taphonomy and time resolution of bone assemblages in a contemporary fluvial system: The East Fork River, Wyoming. *Palaios*.

BEHRENSMEYER, A.K., 1982. — Time resolution in fluvial vertebrate assemblages. *Paleobiology*, 8: 211-227.

BIRKELAND, P.W., 1984. — Soils and geomorphology. Oxford University Press, 372 p.

BOWN, T.M., 1979. — Geology and mammalian paleontology of the Sand Creek facies, lower Willwood Formation (lower Eocene), Washakie County, Wyoming. *Wyoming Geological Survey Memoir*, 2: 1-151.

BOWN, T.M. & BEARD, K.C., 1990. — Systematic lateral variation in the distribution of fossil mammals in alluvial paleosols, lower Eocene Willwood Formation, Wyoming. *In*: BOWN, T.M. & ROSE, K.D. (Eds.), Dawn of the Age of Mammals in the Northern Part of the Rocky Mountain Interior, North America. *Geological Soc. of America Special Paper*, 243: 135-151.

BOWN, T.M. & KRAUS, M.J., 1981. — Vertebrate fossil-bearing paleosol units (Willwood Formation, lower Eocene. northwest Wyoming, U.S.A.): Implications for taphonomy biostratigraphy, and assemblage analysis. *Palaeogeography, Palaeoclimatology, Palaecology*, 34: 31-56.

BOWN, T.M. & KRAUS, M.J., 1987. — Integration of channel and floodplain suites. I. Developmental sequence and lateral relations of alluvial paleosols. *J. of Sedimentary Petrology*, 57: 587-601.

BOWN, T.M. & ROSE, K.D., 1987. — Patterns of dental evolution in early Eocene anaptomorphine primates (Omomyidae). *J. of Paleontology*, Memoir 23: 1-162.

BRIDGE, J.S. & LEEDER, M.R., 1979. — A simulation model of alluvial stratigraphy. *Sedimentology*, 26: 617-644.

BRUIJN, H. de, HUSSAIN, S.T. & LEINDERS, J.J.M., 1982. — On some early Eocene rodent remains from Barbara Banda, Kohat, Pakistan, and the early history of the order Rodentia. *Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen,* B, 85: 249-258.

CERLING, T.E., 1991. — Carbon dioxide in the atmosphere: evidence from Cenozoic and Mesozoic paleosols. *American J. of Science,* 291: 377-400.

CERLING, T.E., QUADE, J., WANG, Y. & BOWMAN, J.R., 1989. — Carbon isotopes in soils and paleosols as paleoecological indicators. *Nature,* 341: 138-139.

COVENTRY, R.J. & WILLIAMS, J., 1984. — Quantitative relationships between morphology and current soil hydrology in some Alfisols in semiarid tropical Australia. *Geoderma,* 33: 191-218.

DANIELS, R.B., GAMBLE, E.E. & NELSON, L.A., 1971. — Relations between soil morphology and water-table levels on a dissected North Carolina coastal plain surface. *Soil Sci. Soc. of America Proc.,* 35: 781-784

DREES, L.R. & WILDING, L.P., 1987. — Micromorphologic record and interpretations of carbonate forms in the Rolling Plains of Texas. *Geoderma,* 40: 151-175.

DRIESE, S.G. & FOREMAN, J.L., 1992. — Paleopedology and paleoclimatic implications of late Ordovician vertic paleosols, Juniata Formation, southern Appalachians. *J. of Sedimentary Petrology,* 62: 71-83.

DRIESE, S.G., MORA, C.I., COTTER, E. & FOREMAN, J.L., 1992. — Paleopedology and stable isotope chemistry of late Silurian vertic paleosols, Bloomsburg Formation, central Pennsylvania. *J. of Sedimentary Petrology,* 62: 825-841.

DUDAL, R. & ESWARAN, H., 1988. — Distribution, properties and classification of Vertisols. *In:* WILDING, L.P. & PUENTES, R. (Eds.), Vertisols: Their distribution, classification and management. Texas A&M Univ. Printing Center: 1-22.

GINGERICH, P.D., 1980. — Evolutionary patterns in early Cenozoic mammals. *Annual Review of Earth and Planetary Sciences,* 8: 407-424.

GINGERICH, P.D., 1989. — New earliest Wasatchian fauna from the Eocene of Northwestern Wyoming: Composition and diversity in a rarely sampled high- floodplain assemblage. *Univeristy of Michigan, Papers on Paleontology,* 28: 1- 97.

HAYWARD, M., 1985. — Soil development in Flandrian floodplains: River Severn case- study. *In:* BOARDMAN, J. (Ed.), Soils and Quaternary Landscape Evolution: 281-299.

HOLMES, D.A. & WESTERN, S., 1969. — Soil texture patterns in the alluvium of the Lower Indus Plains. *J. of Soil Science,* 20: 23-37.

JANITZKY, P., 1986. — Particle size analysis. *In:* SINGER, M.J. & JANITZKY, P. (Eds.), Field and laboratory procedures used in a soil chronosequence study. *U.S. Geol. Survey Bull.,* 1648: 1-84.

JOECKEL, R.M., 1991. — Paleosol stratigraphy of the Eskridge Formation; Early Permian pedogenesis and climate in southeastern Nebraska. *J. of Sedimentary Petrology,* (61): 234-255.

KRAUS, M.J. & BOWN, T.M., 1986. — Paleosols and time resolution in alluvial stratigraphy. *In:* WRIGHT, V.P. (Ed.), Palaeosols: Their recognition and interpretation. Blackwell, London: 180-207.

KRAUS, M.J. & BOWN, T.M., 1993. — Short-term sediment accumulation rates determined from Eocene alluvial paleosols. *Geology,* 21: 743-746.

MACHETTE, M.N., 1985. — Calcic soils of the southwestern United States. *In:* WEIDE, D.L. (Ed.), Soils and Quaternary geology of the southwestern United States. *Geological Society of America Special Paper,* 203: 1-21.

MOHINDRA, R., PARKASH, B. & PRASAD, J., 1992. — Historical geomorphology and pedology of the Gandak Megafan, Middle Gangetic Plains, India. *Earth Surface Processes and Landforms,* 17: 643-662.

275

MORA, C.I., DRIESE, S.G. & SEAGER, P.G., 1991. — Carbon dioxide in the Paleozoic atmosphere: evidence from C-isotopic compositions of pedogenic carbonate. *Geology*, 9: 1017-1020.

QUADE, J., CERLING, T.E. & BOWMAN, J.R., 1989. — Development of the Asian monsoon revealed by marked ecological shift during the latest Miocene in northern Pakistan. *Nature*, 342: 163-166.

RETALLACK, G.J., 1984. — Completeness of the rock and fossil record: some estimates using fossil soils. *Paleobiology*, 10: 59-78.

RETALLACK, G.J., 1991. — Untangling the effects of burial alteration and ancient soil formation. *Annual Review of Earth and Planetary Science*, 19: 183-206.

SCHUMACHER, B.A., DAY, W.J., AMACHER, M.C. & MILLER, B.J., 1988. — Soils of the Mississippi River alluvial plain in Louisiana. *Louisiana Agricultural Experiment Station, Bull.*, 796: 1-275.

SCHWERTMANN, U. & TAYLOR, R.M., 1977. — Iron oxides. *In*: DIXON, J.B. & WEED, S.B. (Eds.), Minerals in soil environments. *American Society of Agronomy and Soil Sci. Soc. of America*: 145-180.

SEHGAL, J.L. & STOOPS, G., 1972. — Pedogenic calcite accumulation in arid and semi- arid regions of the Indo-Gangetic alluvial plain of Erstwhile Punjab (India) - Their morphology and origin. *Geoderma*, 8: 59-72.

SIDHU, P.S., SEHGAL, J.L. & RANDHAWA, N.S., 1977. — Elemental distribution and associations in some alluvium-derived soils of the Indo-Gangetic Plain of Punjab (India). *Société Belge de Pédologie*, 27: 225-235.

THEWISSEN, J.G.M., 1992. — Temporal data in phylogenetic systematics: an example from the mammalian fossil record. *Journal of Paleontology*, 66: 1-8.

THEWISSEN, J.G.M., RUSSELL, D.E., GINGERICH, P.D. & HUSSAIN, S.T., 1983. — A new dichobunid artiodactyl (Mammalia) from the Eocene of North-West Pakistan. Dentition and classification. *Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen*, B, 86: 153-180.

WALKER, T.R., 1967. — Formation of red beds in modern and ancient deserts. *Geological Society of America Bull.*, 78: 353-368.

WALKER, T.R., 1974. — Diagenetic origin of continental red beds. *In*: FALKE, H. (Ed.), The continental Permian in central, west, and south Europe. *Proc. of the NATO Advanced Study Institute*: 240-282.

WEAVER, C.E., 1989. — Clays, muds, and shales. Developments in Sedimentology 44, Oxford, 819 p.

WELLS, N.A., 1983. — Transient streams in sand-poor redbeds: early-Middle Eocene Kuldana Formation of northern Pakistan. *Spec. Publs. int. Ass. Sediment.*, 6: 393-403.

WELLS, N.A., 1984. — Marine and continental sedimentation in the Early Cenozoic Kohat Basin and adjacent northwestern Indo-Pakistan. Ph.D. dissertation, U. of Michigan, 438 p.

WEST, R.M. & LUKACS, J.R., 1979. — Geology and vertebrate-fossil localities, Tertiary continental rocks, Kala Chitta Hills, Attock District, Pakistan. *Milwaukee Public Museum Contributions in Biology and Geology*: 1-20.

WILDING, L.P. & TESSIER, D., 1988. — Genesis of Vertisols: shrink-swell phenomena. *In*: WILDING, L.P. & PUENTES, R. (Eds.), Vertisols: Their distribution, classification and management. Texas A&M Univ. Printing Center: 55-81.

LEGEND OF THE PLATE

PLATE 1

Photomicrographs of Kuldana paleosol and conglomerate samples.

A. Sample from a pedogenically-modified sandstone showing detrital micritic carbonate nodules (m) that are present within larger, pedogenic carbonate nodules. The smaller nodules contain common metamorphic rock fragments (rf) and in some instances, are partially stained red by iron oxides (i).

B. Same sample as in A showing close-up of a detrital micritic carbonate nodule (m) and sparry carbonate cement (s). Iron-oxides (i) have filled intercrystalline voids.

C. Sample from a pedogenically-modified conglomerate showing abundant ostracod wackestone rock fragments (w) surrounded by iron-stained, illuvial clay coatings (c). Wackestone rock fragments have been partially replaced by authigenic quartz crystals.

D. Conglomerate sample showing abundant micritic carbonate nodules (m) and irregularly-shaped bone fragments (b). Some nodules are partially-stained red by iron oxides (i). All photomicrograph views are in plane-polarized light.

Scale bars = 500 μm.

PLATE 1