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Late Quaternary sediment fluxes from tropical watersheds

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Abstract

Inherited saprolite stores and continued weathering in Quaternary time juxtapose abundant clay and fresh rock in tropical landscapes. This influences sediment fluxes and affects the interpretation of sediment sequences derived from tropical watersheds. Detrital kaolinites derive from inherited saprolite sources as well as from soil clays and appear in delta and ocean sediments. These sediments appear to correspond with sub-Milankovitch, millennial-scale cycles of climate change, but may also record century-scale episodes of rapid warming (Dansgaard–Oeschger events). Destabilisation of sediment sources and increased sediment fluxes in the Late Quaternary followed millennia of climatic deterioration (cooling/aridity) and vegetation change and led to altered patterns of sedimentation during the Last Glacial Maximum (LGM). Sediment yield from slopes increased 10 × around the LGM, when rainfall was reduced by 30–60% and led to fan building and braided channels. Rainfall increased 40–80% from the LGM to the Early Holocene maximum and this led to channel cutting and major sediment fluxes to delta and ocean sinks. Vegetation recovery lagged the rapid warming by several millennia and was interrupted by (Younger Dryas) YD aridity, influencing slope and stream behaviour. Holocene sedimentation has been by both vertical and lateral accretion, increasing floodplain sediment stores.

Keywords: Alluvial fans; Late Quaternary; Regolith stores; Saprolite; Tropical sediments

1. Introduction

The availability and supply of sediment to fluvial systems are of key importance to the understanding of sedimentary facies downstream. The downstream fining of channel sediments derived from stores of coarse material such as moraines or rock bars is generally understood. Fine sand and silt are consequently often considered as the products of mechanical comminution of coarser particles due to the time spent in the fluvial system, or to glacial grinding in glacier-fed rivers. In many tropical and some non-tropical river systems, sediment is sourced in the weathered mantle, which may contain core boulders more than 1 m in diameter, as part of a saprolite comprising variable amounts of sand, silt and clay.

Classic interpretations of sedimentary clays come from the work of Millot (1970), who related the sediment sequences in NW Africa and in the basins marginal to the Hercynian massifs of Europe to the dismantling of ancient weathering profiles as a consequence of Early Cenozoic uplift. Millot used the term *siderolithic facies* to describe basal Palaeogene and Eocene sediments and described the formation of the widespread *Continental Terminal* sediments in W Africa as an “invasion par la kaolinite détritique”. Blanc-Valeron and Thiry (1997) have more recently extended this analysis to Palaeogene deposits throughout northern France and made reference to similarities with the Chad Basin in NW Africa. Goldberry (1979) described such sediments as *laterite derived facies* and Pye (1983) considered them a specific type of *red*

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bed sediment. Others have traced the origins of silts not to glacial scour but to chemical weathering (Nahon and Trompette, 1982). More recently, Paquet and Clauer (1997) have cited a wide range of relationships between soils and sediments in different environments. Thus, many interpretations trace these materials back to deep, ferrallitic weathering profiles (Duchaufour, 1982; Geological Society, 1990). In temperate and present-day arid areas, these clay-rich sediments are common in Palaeogene formations and the clays are assumed to have formed beneath Mesozoic or Early Cenozoic landsurfaces of low relief. In humid tropical areas, however, clay-rich saprolites are found in landscapes of younger age.

These interpretations have proved to have wide applicability to the internal and marginal basins of tropical cratons on all continents. Widespread, poorly structured, clayey sediments predominate and can seldom be described in conventional terms. Doubts about their age and processes of formation have been frequently expressed. The sediments result from the erosion of deeply weathered crystalline rocks and have accumulated since the break-up of Gondwanaland. Sediments such as the *Barreiras Formation* in the Amazon Basin and the *Continental Terminal* in West Africa illustrate this problem (see Thomas, 1994a). In the humid tropics, other sediments representing either in situ or transported residues of advanced weathering have led to much debate. Two of these are the *Belterra Clay* formed over ferrallitic (or *lateritic*) weathering profiles (Truckenbrodt et al., 1991) and *white sands* that appear to be the products of tropical podzolisation, whether or not they have been subsequently transported and redeposited (Heyligers, 1963; Fairbridge and Finkl, 1984; Thomas et al., 1999).

All these are instances of the pervasive influence of chemical weathering and pedogenesis on the character of sediments in the humid tropics, but perhaps the most important aspect of this phenomenon is the vast store of saprolite beneath the older landscapes of the tropics and sub-tropics. Continued weathering at rates relevant to the Quaternary timescale is also a significant factor.

2. Regolith as a sediment source

Regolith studies have been advanced by recent reviews, mainly from Australia (Ollier and Pain, 1996; Taylor and Eggleton, 2001), but the immediate connections between regolith and sediment properties are seldom defined. In any case, floodplains of large river systems, deltas and offshore sediment fans integrate many different sediment sources upstream, including mountainous headwaters draining fissile and often soluble rocks with thin regoliths. These headwater areas influence downstream sedimentation for very long distances, even where the river traverses lowland terrain, as in the Amazon basin (Gibbs, 1967; Franzinelli and Potter, 1983; McDaniel et al., 1997). In other catchments the mountain influence may be dominant, as in the Ganges–Brahmaputra system (Goodbred and Kuehl, 2000).

Over much of the humid tropics, however, rivers drain from non-orogenic terranes, underlain by a weathered mantle most of which can be described as saprolite (Becker, 1895; Taylor and Eggleton, 2001). This, often clay-rich, material is not only found beneath extensive and ancient plateau landforms, but also within dissected country. It is also extensive beyond the tropics, well into the warm-temperate zone along eastern continental margins. Mantles of less advanced weathering, with low clay contents, characterise most of the crystalline massifs of cooler climates and are found in tropical areas of steeper slopes, or where ferrallitic saprolites have been partially stripped. When developed from granites these feldspathic sands are commonly known as *grus* (Migoń and Lidmar-Bergström, 2001; Migoń and Thomas, 2002).

Deep saprolite mantles tend to develop on all feldspathic rocks from granites to ultramafic igneous suites, within metasediments and metavolcanics of greenstone belts, and in many other sedimentary and metamorphic rocks. Thickness varies widely from a few metres to more than 100 m, and the mantles are characterised by abrupt variations in depth that often juxtapose hard rock and sandy clay (Branner, 1896; Falconer, 1911; Willis, 1936; Ollier, 1960; Thomas, 1966, 1978, 1994a). Bakker (1957) pointed out that the juxtaposition of fresh rock, often in the form of granite domes or *inselberge*, and deep saprolite containing large quantities of clay, in the landscapes of Surinam, meant that the sediments derived from such landscapes would not conform to facies models developed for temperate regions. Nor would they conform to the models developed by Millot and his followers to describe the progressive stripping of ancient weathering profiles. This is because an abrupt transition from fresh rock to a clay-rich saprolite characterises many of the crystalline terranes in the humid tropics. The juxtaposition or mixing of fine and very coarse sediment is a likely result of denudation in these landscapes. Fresh rock and saprolite may also alternate along river channels (Tricart, 1955), which can form meandering reaches over saprolite, but develop anastomosing patterns, where rock outcrops break the thalweg in an almost imperceptible manner (called *sulas* in Brazil, Zonneveld, 1972); elsewhere, they become the sites of rapids and waterfalls.

Great depths of saprolite occur beneath duricrusted plateaus and summits, but are also present in areas of moderate dissection, especially beneath convex hills developed in granitoids (e.g. the *meias laranjas* relief of eastern Brazil). Less well recognised are the saprolite occurrences along escarpments and within piedmont and foothill zones. Typically, a transect of an escarpment will traverse an upper and deeply weathered plateau via zones of partial stripping, to a steep and rock strewn escarpment with frequent outcropping rock. But, wherever the escarpment slopes lessen (significant regolith can be retained on slopes exceeding 25°) and particularly towards the lower slopes, the saprolite may thicken to 5–10 m. In granite terrain, a stepped relief may develop (Wahrhaftig, 1965), beneath the treads of which there will be deeply weathered rock. On a regional scale, larger catchments may drain through a series of weathered basins alternating with rocky reaches, a phenomenon found in all climates (Godard, 1977; Hall, 1991; Thomas, 1994a, Fig. 11.3).

3. Formation and renewal of regolith stores

Much of the thick saprolite mantle that extends across the plateaux of Brazil, Africa, India and Australia reflects the geological history of Gondwanaland and may have origins in the Mesozoic, even the Late Palaeozoic in the case of Australia (Bird and Chivas, 1988). But the weathering systems were probably reactivated by the dissection of the continents during the Cenozoic and many profiles have returned Miocene ages, using $^{40}Ar/^{39}Ar$ data from manganese oxides (Vasconcelos et al., 1992, 1994). However, doubts surround the interpretation of these age determinations and other authors have provided evidence for the neo formation of specific minerals during the Quaternary (Benedetti et al., 1994; Mathieu et al., 1995). This indicates the continued geochemical evolution of saprolite through time, and makes it difficult to use a single mineral species to provide the 'age' of a regolith.

3.1. Saprolites and sediments in humid tropical environments

It has been argued that in the Southern Hemisphere tropics climatic aridity, corresponding with the early formation of Antarctic ice, may have 'switched off' the weathering systems in the Mid Miocene (Alpers and Brimhall, 1988; Vasconcelos et al., 1994). But it is difficult to apply this reasoning to the equatorial and Northern Hemisphere tropics, where there is good evidence for continued formation of saprolites during the Neogene. Miocene intrusive rocks (granodiorites) in NW Borneo (Kalimantan) have been deeply weathered following exposure and 30+ m saprolite profiles are exposed in low convex hills (ca. 200 m asl) in an area of 900 m relief. The landscape lowering since the Miocene, and the widespread gibbsitic saprolite found below the multi-convex relief, suggest that weathering has continued during the Neogene at rates of 40–50 m/Ma (Thomas et al., 1999).

Much of the alluvium in this area consists of *white sands* and intercalated pale, kaolinitic, clays (Thorp et al., 1990). These materials can be interpreted as products of advanced tropical podzolisation (Dubroeucq and Volkoff, 1998; Thomas et al., 1999), involving the lateral eluviation of clay from kaolinitic saprolite. Some of the white sands form amorphous fan-like bodies of sediment, directly linked to adjacent hillslopes and minor catchments; others form clear fans and terraces and contain evidence for strong water flows, that have modified the sedimentary structures during sedimentation.

One issue here is the time required to reduce a feldspathic crystalline rock (of Miocene age) first to a gibbsite-rich saprolite and then to a quartz sand residue. Others have discussed such issues but have not been able to place them into a time frame (Stallard and Edmond, 1981, 1983, 1987; Chauvel, 1977; Lucas et al., 1987; Boulet et al., 1997; Dubroeucq and Volkoff, 1998). Estimates of the rates of weathering penetration into bedrock range over at least an order of magnitude. Pillans (1997) calculated the rate of soil formation on Quaternary basalts in NE Queensland as 2–4 m Ma, but rates of 20–40 m Ma are offered in other studies (Cleaves, 1989; Benedetti et al., 1994; Mathieu et al., 1995; Thomas et al., 1999).

Continued weathering penetration beneath pre-existing regoliths is conditional on the water regime and dissection during the Neogene will have accelerated water movement beneath many landscapes, enabling the weathering reactions to continue. The formation of new weathering profiles may, however, take much longer. A fresh basalt flow will have no water-retentive soil cover and initial rates of weathering will be slow, and studies from Japan have demonstrated an increasing rate of weathering with time (Oguchi et al., 1999). Volcanic materials also exhibit major variations in susceptibility to weathering.

This issue is important, because renewal of the regolith during Quaternary time (~ 2 Ma) will influence sedimentary outcomes. Clearly, 40 m of weathering penetration in 2 Ma would imply significant renewal of regolith stores during this period. In glaciated areas, repeated stripping of saprolite during each glacial cycle and lack of significant renewal during the interglacials has led in some areas to sediment exhaustion. In extra-glacial areas and especially in the tropics and sub-tropics, the store of pre-glacial regolith was almost certainly deeper and more intact at the onset of the Quaternary. However, the loss of weathered material due to surface stripping during the (glacial) cycles of climate change was probably more incremental, and the weathering systems will have remained active across most of the zone, even if temperatures were depressed by 5 °C and rainfalls by 30–60% at the glacial maxima. The wider point here is that weathering systems are continuous in their operation and the Quaternary is a more or less arbitrary slice of geological time (Stallard, 1995; Thomas, 1994b).

4. Saprolite as a source of colluvium and alluvium

4.1. The escarpment zone in NE Queensland, Australia

Many areas of coastal-plain sedimentation are derived from rivers either crossing inland escarpments or generated on their steeper slopes, and their sediments will reflect this setting. Studies of the escarpment and coastal plain around Cairns in NE Queensland (Nott et al., 2001; Thomas et al., 2001) provide a clear illustration of the influence of these sediment source zones on the coastal plain sediments. The area is underlain by metamorphosed sedimentary rocks (mostly siltstones and greywackes) and by granites. Cenozoic, often Quaternary, lavas are widespread on the inland plateaux. Where the escarpment (relief ca. 500–600 m) slopes decline to below ca. 20°, a red saprolite, at least 5 m in depth has developed. But if slopes increase to 30–40°, the rocks show only incipient decay and break off into large angular boulders. Major rivers draining the plateau have also eroded gorge sections through the escarpment zone, exposing the fresh rock.

Fronting the escarpment is a series of alluvial fans, debris flows and a more amorphous apron of fine colluvium. Small catchments draining the steeper slopes have supplied very coarse sediments to form fanglomerates. These are crudely but clearly stratified (Fig. 1), containing frequent clasts of 40–100 cm diameter. Streams generated on the mid-lower slopes, by contrast, have supplied mainly fine sediment (Fig. 2), and in addition a direct connection between the saprolite and colluvial deposition from adjacent, unchannelled hillslopes can be demonstrated. This indicates widespread slope erosion during the cool–dry climates of the Last Glacial Maximum (LGM), to which these sediments have been dated (Nott et al., 2001; Thomas et al., 2001; Moss and Kershaw, 2000). Several rivers drain the hinterland (Atherton Tableland) and have formed gorge sections several kilometres in length. In these systems, boulder beds give way to finer sediments and large fan-terrace units in front of the escarpment.

4.2. The Bananal basin, Rio de Janeiro, Brazil

The formation of a widespread sandy-clay colluvium in tropical landscapes is very common, and estimates in São Paulo State, Brazil suggest that it may cover 50% of the land area (Ferreira and Monteiro, 1985). In the Bananal basin (Rio de Janeiro), a programme of radiocarbon dating has established that most of the alluvium and colluvium is Early Holocene in age (Coelho-Netto, 1997), and is derived by local

Fig. 1. Coarse fanglomerate, N of Cairns, NE Queensland, Australia. Coarse angular blocks dominate scarpfoot fans derived from short, steep catchments (slopes >27°) with no saprolite cover.

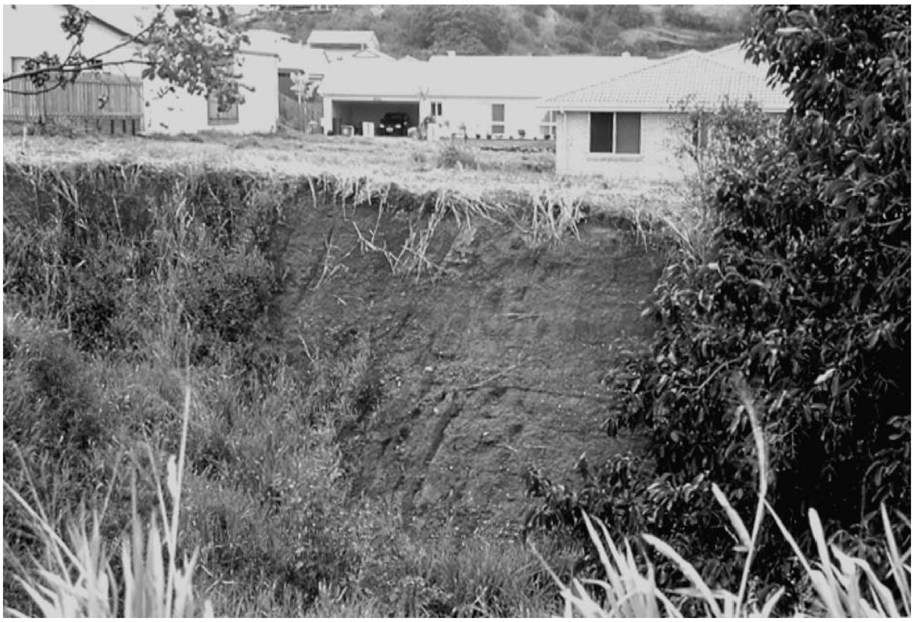

Fig. 2. Fine laminated sediments, S of Cairns, NE Queensland, Australia. These sediments resemble colluvium and are dominated by sandy clays derived from scarpfront saprolite stores (slopes generally <20°).

colluviation from multi-convex relief compartments that are underlain by deep saprolite (ca. 20 m). A ‘synchronous aggradation cycle’ is described as having started ca. 10 ^{14}C ky BP, terminating abruptly around 8 ^{14}C ky BP (ca. 11.2–9 cal. ky BP). Only a few hillslope deposits in this area date to the late glacial period, 38–17 ^{14}C ky BP (20 cal. ky BP).

4.3. East central African plateau

The age of the main colluvium in NE Queensland corresponds to a period bridging the LGM (ca. 27–14 ky TL), but studies of colluvium from east–central Africa (Tanzania, Sørensen et al., 2001; Zambia, Thomas and Murray, 2001) have demonstrated that the sediments span most of the Last Glacial Cycle (LGC). How much sediment has also been eroded from these slopes during this period is unknown, but an incremental growth in sediment storage has been the principal result of landscape change. In Eastern Zambia, the colluvium (Thomas, 1999) is derived directly from the slopes of residual hills, which retain a thick saprolite (ca. 30 m), formed in Archaean granulites, probably in the Late Mesozoic or Early Cenozoic.

These examples demonstrate the importance of local saprolite sources and sediment stores in tropical landscapes and show clearly some of the complexities in the Late Quaternary chronology of sediment transfers.

5. The chronology of Late Quaternary alluvial sedimentation

Changes in regime and sediment markers for tropical rivers during the Late Quaternary have been documented from many different tropical rivers and some general patterns have emerged (Thomas and Thorp, 1995; Thomas, 2000). However, we have few records beyond the limits of the ^{14}C timescale. TL dates for sediments in central Australia have indicated increased discharges and sedimentation during Isotope Zones 7, 5 and 3 (Nanson and Price, 1998; Nanson et al., 1991), but we only have corroboratory information for the last of these. The Middle Pleniglacial or Isotope Zone 3 (58–27 ky BP) appears to have been cool but moist across much of the tropics, in contrast to the cold–dry conditions of the preceding Stage 4 and following LGM. Dupont et al. (1998) detected high oceanic productivity alongside weak atmospheric circulation during this period, which also began with significant climate warming (Jouzel et al., 1987). Scattered long-range radiocarbon dates have recorded a prolonged period of sedimentation corresponding with these conditions, in S America (Van der Hammen et al., 1992; Servant et al., 1993) and in Borneo (Kalimantan) (Thorp et al., 1990).

Prior to ca. 28 ky BP rivers across Africa, and also in tropical S America and NE Queensland, had experienced humid forested conditions for 10^4 years. The sediments from this period are only occasionally well documented but many rivers had stable channels contained within thick overbank deposits. Organic-rich swamp sediments have been dated from the river terraces of West Africa (Thomas et al., 1985). Progressive cooling of tropical climates and widespread reductions in rainfall characterised the period leading to the LGM (22/21 cal. ky BP), and these conditions persisted for a variable time period according to the response of regional climates to early climate warming. In the inner Congo, Preuss (1990) recorded a switch from braided to meandering river behaviour by 18.5 cal. ky BP, but this remains an isolated case and most rivers appear to have adapted to low rainfall and increased sediment yields over a period of 5–7(10) ky. Often, there is a problem of missing data for this period. In West Africa, no sedimentary units were dated to the period between 22 and 15.3 cal. ky BP (Thomas and Thorp, 1980; Hall et al., 1985), and this hiatus has been recorded in several Amazon tributary catchments (Van der Hammen et al., 1992; Latrubesse and Rancy, 1998). This evidence also corresponds with many lacustrine pollen records (Ledru et al., 1998). In other accounts, braided conditions persisted during all or part of this period (Preuss, 1990; Turcq et al., 1997). The fan deposition in NE Queensland (discussed above) is dated to this cool, dry period between ca. 26/27 and 15 ky TL. It can be attributed to loss of stream power and increased sediment yield in a region of high rainfall (3000+ mm years^{-1}) that experienced a reduction at the LGM estimated at 64% (Moss and Kershaw, 2000). The fans were trenched after ca. 15 ka, with the recovery of the climate (Nott et al., 2001; Thomas et al., 2001).

The changes brought about by the climate warming and increased rainfall following the last Termination were fundamental. A period of erratic climates brought flooding and erosion to many river systems, and rapidly melting glaciers also caused a major influx of sediment to rivers such as the Amazon, and the Ganges–Brahmaputra system, where Goodbred and Kuehl (2000) have recorded the rapid build-up of the Early Holocene delta. Considerable landscape instability appears to have characterised this period, until the recovery of the rainforest in humid tropical areas was fully accomplished between 11 and 10 cal. ky BP (Maley, 1992, 1996; Moss and Kershaw, 2000).

The long delay in re-establishing the rainforest vegetation was probably due to a number of causes. Major increases in rainfall appear to postdate 15.5 cal. ky in many records, though warming began earlier and wetter conditions may have returned to the inner Congo basin before this time. However, the warming trend with increasing rainfalls, indicated by many lake-level records, was interrupted by the Younger Dryas (YD) (13.2–11.5 cal. ky), which appears to have been cool and dry across most of the tropics. Recovery of the lowland forest then took another millennium to accomplish. The erratic transitional climates of the Late Pleistocene were probably not conducive the rapid spread of forest taxa to areas that had been open woodland or savanna for several millennia. The soil cover would have been modified with the loss of organic matter and clays, and the remaining soils would have been less moisture retentive. It is possible that the climates were also either too seasonal or too erratic to sustain a rainforest ecosystem with its continuous, high evapotranspiration demands, until the Early Holocene Pluvial period that followed the YD. Under these conditions, fire, either as wildfire or induced by human populations, would have been an effective factor delaying forest recovery.

The Early Holocene Pluvial lasted from before 11 until around 7.8 cal. ky BP. During this period, precipitation may have been elevated 20–35% above recent means (Hastenrath and Kutzbach, 1983; Dong et al., 1996) and a major expansion of African lakes occurred (Thomas and Thorp, 2003). Many records indicate a marked drying of climates after ca. 8 cal. ky BP, corresponding with Greenland ice-core evidence and the appearance of cool–wet conditions in the N Atlantic, but the most severe Mid Holocene aridity occurred after 5 cal. ky BP, reaching its peak around 4.5–4 cal. ky BP. At this time, hyper-aridity became established in the Sahara and cool–dry conditions penetrated the humid tropics (Guo et al., 2000; Gasse, 2000; Lamb et al., 1995). De Menocal et al. (2000) refer to the ‘African Humid period’, which lasted from 14.8–5.5 cal. ky BP according to their analysis of the ocean core site 658C off the Mauritanian coast. The 8- and 4-ka events have been attributed to a weakened monsoon system (Gasse and Van Campo, 1994). After 3 cal. ky BP, it becomes difficult to distinguish climatic signals from the impacts of land use at many sites.

6. The record of off-shore sediments

The analysis of off-shore sediments of major rivers such as the Amazon, Congo and Niger has provided some additional evidence. It is known that sediment influxes to the ocean from tropical rivers increased rapidly after ca. 11.7 ^{14}C ky BP (15.3 cal. ky BP) and that changes in the clay mineral content of the sediments were concomitant. A change from smectites to kaolinites has been detected in the Niger delta, as climates became wetter (Pastouret et al., 1978; Zabel et al., 2001). Broadly similar records exist for the Congo (Giresse and Lanfranchi, 1984; Giresse et al., 1982; Jansen and Van Iperen, 1991; Marret et al., 1999), Nile (Rossignol-Strick et al., 1982) and Amazon (Damuth and Fairbridge, 1970; Damuth, 1977; Showers and Beavis, 1988).

A widespread grey clay layer has been identified from ODP cores in the western equatorial Atlantic (Biscaye, 1965; Showers and Beavis, 1988; Broecker et al., 1993; Hemming et al., 1998). This has been interpreted as either a product of continental erosion, or a result of shelf erosion during post-glacial sea level rise. It has been dated to ca. 16–14 ky ^{14}C BP (ca. 19–17 cal. ky BP) (Hemming et al., 1998). Close to the Amazon delta, the sediments were clearly of Andean provenance, but off NE Brazil the proportion of kaolinite to chlorite in the fine sediments was greater, suggesting to the authors erosion from the deeply weathered Brazilian shield. A more detailed data set from the ocean sediments off NE Brazil has recently been interpreted in terms of millennial-scale climate changes and their impacts on the supply of terrigenous sediment to the ocean (Arz et al., 1998).

The authors note a correspondence between increased sediment influx, elevated Ti/Ca and Fe/Ca ratios, and patterns of Heinrich events and Dansgaard–Oeschger cycles or interstades as revealed in GISP2 ice-core records for the last 85,000 years. These data were interpreted as showing that millennial-scale warming led to pulses of sediment containing higher amounts of kaolin clays due to renewed soil formation. Estimated rates of soil renewal by termites in the tropics range from < 10 to >20 cm 10^3 years (see Thomas, 1994a). This means that over centuries a few centimetres of kaolinitic saprolite could be added to the surface, while some smectites could also be weathered to kaolinite with loss of Ca in the same period. However, it is more likely that most of the kaolin has come from erosion into the saprolite mantle on the Brazilian plateau during periods of enhanced discharge, as suggested by Hemming et al. (1998). During the cool, dry stadials, the deposition of smectite clays may reflect more widespread loss of surface soil. Since NE Brazil has a dry climate, this interpretation is easier to justify than the neoformation of kaolins during periods of rapid warming lasting 10^2 years.

7. Coupling of sediment sources and stores

If kaolins had formed during humid phases and found their way into ocean sediments of similar age, this would imply a rapid coupling of soil clay formation, erosion and ocean sedimentation. The term 'rapid' here is taken to infer a transfer and linkage between sediment source and sediment store within the millennial scale of sub-Milankovitch cycles. In the North Atlantic, the rapid warming associated with Dansgaard–Oeschger events is found to occur every ca. 1500 years (Bond et al., 1993, 1997; Campbell et al., 1998). According to Arz et al. (1998), these cycles are accurately reflected in tropical ocean sedimentation and it is possible that the rhythm itself is a response to insolation forcing in equatorial regions (Broecker, 1995; Curry and Oppo, 1997). Warming episodes within this periodicity appear to have taken only decades or centuries (Stuiver et al., 1995; Taylor et al., 1993, 1997), while subsequent cooling was more gradual. This asymmetry in the pattern of global climate change must also have importance in the context of rates of Quaternary erosion and sedimentation.

When applied to the rapid warming of climate during the Pleistocene–Holocene transition, the argument for rapid transfer of sediment to the ocean encounters a number of problems. These include:

- Climate warming and increased humidity at the end of the Pleistocene took place, in many areas of Africa, at least one millennium prior to the change in sediment fluxes and clay mineral dominance recorded offshore (see Thomas and Thorp, 1995).
- Large rivers such as the Amazon, Congo, Niger and Nile have major sediment stores within extensive floodplains, and all have tectonically determined basins in their middle courses that function as sediment sinks.
- In the cases of the Niger and the Nile, the delta areas had no connection to important headwater areas for much of the Pleistocene, and were not reconnected until 2–4 ky after the establishment of post glacial warming.
- Hillslope-channel coupling occurs where there is a high drainage density and moderate to steep slopes, conditions that obtain mainly in mountain headwaters and along escarpment zones or dissected passive margins of continents.
- In continental interiors long-term (10^4–10^5 years) storage of fragile colluvium and alluvial fills implies a lack of coupling between these areas and coastal sedimentation on the millennial time scale.
- The major exceptions to this will be tectonically active systems with direct linkage to the ocean such as the Ganges–Brahmaputra system (Goodbred and Kuehl, 2000) and short, steep catchments in orogenic areas.
- The rapidly rising sea level during the Early Holocene is likely to have disturbed sediments on the ocean shelf areas confusing the signals for sediment movement from continental areas.

However, the evidence presented by Arz et al. (1998) requires explanation and two factors may reduce the objections listed above. First, kaolinite clays derived from saprolite mantles in eroding areas may bypass the major sediment sinks and accurately reflect fluvial discharges. Second, the increased fluvial discharges will have entrained stored sediment in channels and floodplains. This material probably contained small amounts of clay, accumulated in backswamps or developed in the soil cover. However, these sources are unlikely to have contributed more than a small proportion of measured fluxes to the ocean.

As a general observation catchments can be divided into those within plateau settings and those with mountain headwaters. Of course many systems are complex and the distinction is mainly illustrative.

These attributes (Table 1) are deceptively simple, and clearly rivers that drain from elevated but gently sloping watersheds will acquire some attributes of mountain systems when crossing (and dissecting) escarpment zones. Upper catchments of plateau rivers will derive mainly fine-grained sediment from saprolite stores and from floodplains, but as the trunk rivers cross the escarpment zone coarse sediment from channel scour and from slope failures in rocky gorge sections will alter the nature of the sediment load. Downstream sorting will, however, modify this effect within a few kilometres (Pickup, 1984).

As Bull (1991) has pointed out, most rivers actively erode their channels in the long term and, therefore, episodes of major sedimentation require explanation. Observations indicate that, even in many deeply weathered terrains, perennial streams have excavated bedrock channels (Thomas, 1966). In the northern Sierra Leone diamond fields, rocky channels predominate in the headwater drainage within a low relief zone (50–150 m), but some features indicate active bedrock weathering below thin residual quartz sands (Teeuw, 1991; Thomas and Thorp, 1980, 1985). Where rivers flow over a weathered mantle, this is usually due to alignment along shatter-zones, very low gradients or ephemeral flow. As noted above, many rivers traversing crystalline rocks, pass through a succession of weathered basins and rock thresholds.

There is some evidence to support the view that many tropical rivers excavated deep rocky channels as a result of high discharges during the climate warming episodes at the during the Pleistocene–Holocene transition. This also led to some coarse depositional units in the rivers of West Africa, for example (Thomas and Thorp, 1980; Thomas et al., 1985; Hall et al., 1985). In many instances, these channels have subsequently become infilled with sediment and experienced frequent, but lesser, cut-and-fill episodes during the Holocene. In Sierra Leone (8°N lat.), excavations have revealed coarse sediments of post 15.3 cal. ky BP (12.7 ^{14}C ky) age, embedded within the corestone zone of granite weathering profiles (Thomas, 1994a). In southern Ghana (6°N lat.), a buried channel occurs on the Birim River and contains sediments of comparable age (Thomas and Thorp, 1993). These events tracked the postglacial rise of nearby Lake Bosumtwi (Talbot and Johannessen, 1992), but preceded by one to two millennia the great increase in terrigenous muds recorded in offshore sediments derived from the Nile, Congo and Niger basins (Rossignol-Strick et al., 1982; Pastouret et al., 1978; Giresse and Lanfranchi, 1984; Marret et al., 1999; Talbot et al., 2000; Williams et al., 2000). Increases in freshwater discharge to the Amazon cone also began after ca. 16 cal. ky BP and reached a maximum between 13.5 and 10.2 cal. ky BP according to Showers and Beavis (1988). Although the grey clay layer discussed by Hemming et al. (1998) has returned older radiocarbon dates (19–17 cal. ky BP), its origin remains uncertain. These authors also recorded a minimum of carbonate abundance prior to 11 ^{14}C ky BP (13 cal. ky BP), which would be in agreement with other records for freshwater influx.

Table 1
A comparison between mountain and plateau catchments[a]

Mountain catchments	Plateau catchments
Short, steep catchments; coastal plain sedimentation	Long channels, low gradients—even in headwater zones
Slope-channel coupling through mass movement	Slope-channel coupling mainly in escarpment zones of dissection
Rapids but few waterfalls	Many rock barriers and waterfalls
Sediment storage in intra- and sub-montane basins	Extensive basins of weathering and/or sedimentation
Limited floodplain storage	Extensive floodplains with major sediment storage (10^4 years)
Otherwise rapid delivery of sediment to ocean sink	Long delays in sediment delivery

[a] The category of 'lowland river' common within the sedimentary basins of Mesozoic–Cenozoic origin, as found in NW Europe, is not considered here.

8. Rapid climate change and the destabilisation of sediment stores

Sub-Milankovitch cycles of climate change during the Late Quaternary have been determined from analyses of ice-cores and evidence of iceberg surges in N Atlantic sediments. These have revealed a millennial-scale oscillation (Heinrich events) and the periodicity of rapid warming (Dansgaard–Oeschger events) (Vidal et al., 1997; Bond et al., 1993; Campbell et al., 1998). It has also been suggested that these events may have been a response to insolation forcing in tropical regions (Broecker, 1995; Arz et al., 1998; Curry and Oppo, 1997). Within the millennial scale of climate oscillation, warming episodes may have had a duration of centuries or only decades (Stuiver et al., 1995; Taylor et al., 1993, 1997). Periods of cooling, however, were more protracted, taking place over 10^3 years. The nature of these climate rhythms and the asymmetry in the pace of change must have had important impacts on sediment fluxes.

A number of recent studies have drawn attention to issues surrounding the interpretation of clastic sediments in NW Europe, arising from high amplitude climate changes during the Quaternary (Fard, 2001; Lewis et al., 2001; Vandenberghe and Maddy, 2001; Veldkamp and Tebbens, 2001). All of these have focused on a millennial scale of enquiry as being appropriate to the nature of fluvial response to climate change. Vandenberghe and Maddy (2001), for example, ask whether the Younger Dryas cold period (ca. 1100 years) in northern Europe lasted long enough to evoke a fluvial response. The nature of this discussion is quite different from the construction of a high-resolution 'event stratigraphy' based on sediment couplets or other evidence for individual storm events lasting hours or days and analysed within a spectrum of decadal fluctuations in discharge. Research in fluvial geomorphology that concentrates on these shorter timescales, is inevitably concerned mainly with the impacts of individual storm events. But the pattern of system behaviour is seldom fundamentally changed by single extreme events, providing other parameters remain constant. On the other hand, if vegetation or land-use changes take place, shifts in system response to events over a range of magnitude and frequency may occur (Knox, 1993, 1995). On the scale of Quaternary climate change, shifts in rainfall patterns have been accompanied by vegetation changes. However, regional vegetation change may lag climate change by 10^2, even 10^3 years, and both the spectrum and the impact of extreme events may change along this time sequence (Figs. 3 and 4).

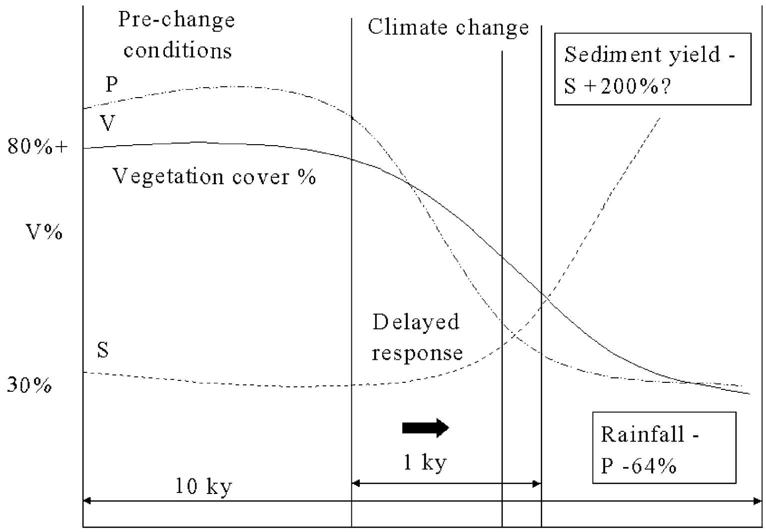

Fig. 3. Schematic diagram to illustrate the delayed (or lagged) response of fluvial systems to climate and vegetation changes, as shown by sediment yield, and based on the major decline in rainfall over a 10-ky period. Vegetation decline and major changes to sediment yield lag climate change by up to 1 ky.

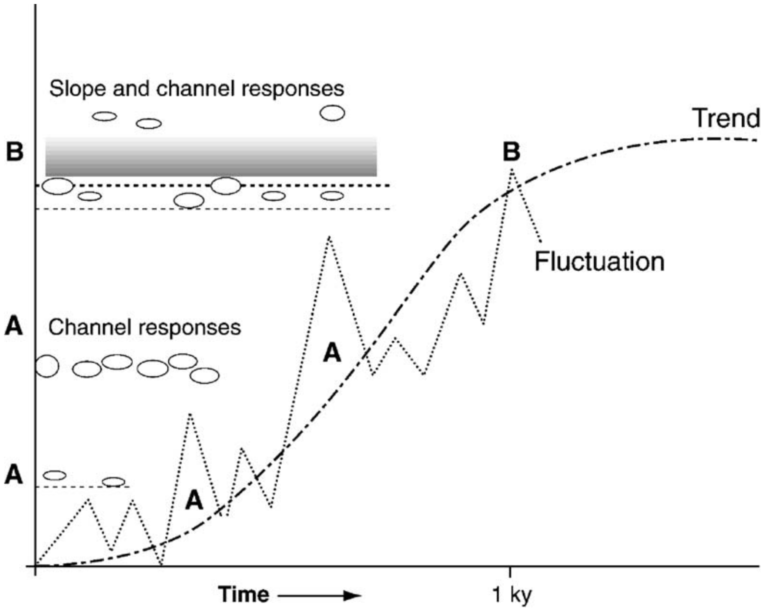

Fig. 4. Schematic diagram to show that extreme events (‘fluctuation’ curve) are likely to have more severe and widespread effects on sediment production when they follow some period (possibly 10^2-10^3 years) of climate change (‘trend’ curve). Extreme rainfalls indicated by **A** on the fluctuation curve cause flooding and channel responses, but at **B** comparable or lesser events may lead to catchment-wide slope and channel changes.

Cooling of climate during glacial advance is characterised in most records as taking place over 10^3-10^4 years and, in the tropics, this cooling is associated with a reduction in the strength of the Intertropical Convergence (ITC), weakened monsoons and lessened cyclone activity. This scenario would bring with it reduced annual rainfall totals and fewer large storms, but may have increased seasonal contrasts. Records from NE Queensland show that vegetation cover changed towards sclerophyll woodlands and, in many parts of Africa and S America, open woodlands or forest-savanna mosaics replaced the rainforests. But these changes must have taken place very gradually and differentially between sites in the landscape. Natural and anthropogenic fires probably became effective in former rainforest areas, exposing fragile soils to erosion. Increased slope erosion combined with reduced peak discharges and the loss of dry season flows would account for fan building, braided channel systems, and an absence of sedimentary units according to regional and local environmental controls.

There is some consensus concerning a major stepwise warming and recovery of the monsoon in tropical Africa and the Indian Ocean: post 18/17; around 16/15.5 and 11.5/11 cal. ky BP (Gasse, 2000). Changes to river regimes can be tentatively related to these events. The Congo may have adopted a meandering course as early as 18.5 cal. ky BP, possibly because of an early extension of the rainforest from core areas (refugia) within the basin (Preuss, 1990; Runge, 2001) . But most rivers in the tropics appear to have responded to rapid climate change around 15.5 cal. ky BP. Between 6° and 8°N latitude in West Africa major changes took place after ca. 15.3 cal. ky BP and were reinforced after 13.5 cal. ky BP, when East African lakes also overflowed into the Nile and Congo headwaters (Thomas and Thorp, 1995; Talbot et al., 2000; Williams et al., 2000). The YD intervened before further warming and increases in rainfall took place after 11.5 cal. ky BP, initiating the Early Holocene Pluvial.

The sedimentary records of large drainage systems can be ambiguous, where cores are taken from delta deposits. This is due less to the impact of post-glacial sea-level rise than to the way in which rivers such as the Niger or Congo integrate the responses of many hundreds of tributary catchments across several climatic and ecological zones. A diachronous recovery of climate following the LGM has been indicated across latitudinal zones in NW Africa with the appearance of humid conditions in the Sahel being delayed by 3 ky, when compared with equatorial Africa. There may also be a hemispheric asymmetry due to the early warming of Antarctica (18.5 cal. ky).

8.1. Sediment fluxes and rates of denudation

Major sediment fluxes are related to these events, but for each period it is necessary to specify the sediment sinks, if not also the sediment sources (on which we lack data). An illustration of this is the response of rivers draining the Atherton Tableland towards the Coral Sea in NE Queensland, Australia. Climate here deteriorated sharply after 79 ka and again post 38 ka, Varieties of vine forest survived until 27/26 ky BP (Kershaw, 1976, 1978, 1992; Moss and Kershaw, 2000), when sclerophyll woodland began to dominate the vegetation. Estimates of the reduction of rainfall reach 64% at the time of the LGM. A series of alluvial fans dominates the coastal plain, characterising the main rivers as well as the short streams draining the escarpment. TL and AMS dating of these sediments has shown (Nott et al., 2001; Thomas et al., 2001) that fan deposition began some time before ca. 26 ka TL and continued until ca. 15–14 ka TL, when incision of the fans by the present linear drainage system took place. Thus, the sediment flux that characterised the 10–12 ky of dry climates led to a marked accumulation along the scarpfoot zone. An important aspect of this sedimentation is the contribution from weathered hillslopes. Fine-grained colluvium extends from the hillfoot zone all along the escarpment with thicker and coarse deposits marking the exits of small streams.

This makes it possible to estimate the rate of erosion. If the sediments in fans derived from local drainage form a wedge, thinning from 10 m to 0 over a distance of 1 km, and they derive sediment from a 500-m scarp face, then 10 m of sediment has been lost from the escarpment in 10 ky, at a rate of 1 m ky^{-1}. This estimate is obviously very crude and makes no allowance for the seaward projection of fan sediments, or loss of fines to former lower areas. By comparison steep catchments in Switzerland (Ahnert, 1998, Table 3.1) with mean slopes of ca. 24°, return contemporary rates of denudation of 0.42/43 mm $years^{-1}$. Using Ahnert's (1998) equation relating slope angle to denudation rate ($d = 0.967\sin\alpha - 0.007$ m/1000 years) indicates that these catchments should erode at a rate of 0.42 m ky^{-1}. However, these figures are based on temperate comparisons in high relief areas and could be misleading. Short-term (1963–1965) catchment studies were undertaken in the Cairns area by Douglas (1973), who obtained a range of figures for total sediment yield from small E flowing catchments of 10–44 (270) m^3 km^{-2} $years^{-1}$. Mountainous regions in the humid tropics can produce < 500 to >2000 m^3 km^{-2} $years^{-1}$ of sediment (see Douglas and Spencer, 1985). This is equivalent to a rate of groundsurface lowering of 0.5–2.0 m ky^{-1}. However, this ignores the *sediment delivery ratio*, which expresses the percentage of sediment reaching the catchment outlet. This was calculated for NE Queensland by Neil and Yu (1996) as 0.19, but is probably higher for many scarpface streams. These authors also indicate the total sediment yield in this area as 51 t km^{-2} $years^{-1}$. The specific gravity of the sediments may approach the rock average figure of 2.7 in the steep catchments, but will be much lower where sediment is derived from regolith stores (< 2.0). Using all these figures gives a denudation rate of 0.1 m ky^{-1} ($\pm$15%), which is one order of magnitude less than calculations of the late glacial rate for fan accumulation. For comparison, a figure of 1.5 m ky^{-1} was derived from the 11.2–9 cal. ky BP aggradation cycle in the Piracema valley in the Bananal basin (Brazil) (Coelho-Netto, 1997).

Methodological problems make direct comparisons between these figures dangerous, but it is possible to conclude that the rates of erosion represented by the alluvial fans were far higher than known rates of denudation under present-day conditions of extensive forest cover. Furthermore, estimated rates of scarp retreat over geological rime periods tend to produce figures from ca. 10–25 m my^{-1} (Nott et al., 1996), which is two orders of magnitude less than short-term rates or estimates of Late Quaternary sediment flux. The widespread apron of colluvium found along the scarpfoot zone also makes it difficult to argue that the stream sediments are derived mainly from channel erosion and, therefore, record valley deepening rather than slope erosion.

Initial warming and recovery of the ‘postglacial’ climates would have preceded the recovery of the forest vegetation by several millennia, possibly increasing the sediment yields further for a significant period. In many areas, there is evidence for channel cutting early in this phase. In West Africa, coarse gravels were deposited in newly excavated bedrock channels after 13.5 cal. ky BP (Thomas, 1994a; Thomas and Thorp, 1995; Thorp and Thomas, 1992), while in NE Queensland the alluvial fans were trenched post 14.5 ky TL. In records worldwide, too numerous to detail, Holocene floodplains are incised below ‘late glacial’ terraces, and a switch from braided to meandering streams also took place in the Early Holocene. Major sediment fluxes associated with the Early Holocene have been recognised at many different scales: in small headwater streams in Sierra Leone (Thomas and Thorp, 1980), in tropical rivers with significant floodplains (Adamson et al., 1980; Hall et al., 1985; Van der Hammen et al., 1992), and in the deltas and off-shore fans of the Amazon, Ganges–Brahmaputra, Congo, Niger and Nile as discussed above.

Several aspects of temporal change appear to determine these outcomes. These include:

- long-term (10^4 years), step-wise changes in climate such as that culminating with the cool-arid conditions of the LGM.
- the periodicity of climate change on a millennial (10^3 years) scale, recorded as Heinrich and DO events, interpreted as Bond cycles of ca. 1500 years duration.
- the amplitude of these changes and whether they led to major changes to vegetation cover.
- the impact of century (10^2 years) scale, rapid warming phases.
- the rate of change over decades (10^1 years).
- the magnitude and frequency of individual events (10^0–10^{-1} years) occurring within longer-term changes.

The role of extreme events in remodelling the landscape depends on four further factors: (a) their magnitude or intensity, (b) their recurrence intervals, (c) where they occur on the curve of climate and vegetation change and (d) the time required to restore system equilibria (relaxation time) (Fig. 4). The last of these is the most problematic, because previous equilibria may never be restored and new equilibria may be sensitive to lesser, and more frequent, events in the future, or may resist change over long time periods.

The impact of rising sea level on sediment sinks has been clearly demonstrated for the Ganges–Brahmaputra systems (Goodbred and Kuehl, 2000), and there is evidence that Holocene sediment supplied to the Coral Sea in NE Queensland has accumulated behind the Great Barrier Reef (Heap et al., 2001a,b). The effect of rising sea level on shelf deposits was probably highly variable, according to the wave energies experienced. Hemming et al. (1998) have discussed this as a possible explanation for the redistribution of ocean clays off the Atlantic coast of NE Brazil. However, in semi-enclosed seas such as the Sunda Sea between Borneo and Sumatra, a suite of undated sediments that contain important cassiterite placer deposits appear to record the complex history of sea level change without evidence for major episodes of marine erosion (Aleva et al., 1973; Aleva, 1985).

9. Conclusions

Late Quaternary climates in the tropics were subject to prolonged cooling leading towards the LGM, but also experienced the rapid changes in temperature and rainfall seen in high latitudes as Heinrich and Dansgaard–Oeschger events, which may in turn have had their origins in the tropical ‘moisture pump’ (Broecker, 1995; Arz et al., 1998). The vegetation changes brought in train with these climatic oscillations were probably critical to any explanation of the climatic impacts on erosion and sedimentation patterns during this period.

Humid tropical areas are characterised by an extensive mantle of saprolite that extends well beyond the confines of both the tropics and of the humid zone, as a consequence of both climatic changes over geological eras and of prolonged weathering in temperate zones. This mantle represents a vast store of material available to erosion and sedimentation processes and strongly influences sediment properties and distribution. In humid areas, rates of chemical weathering are sufficient to renew weathered material on slopes within Quaternary time, thus further influencing the sediment fluxes from these areas (Benedetti et al., 1994; Thomas, 1994b; Thomas et al., 1999).

Although ocean sediment signals document many of the climate changes during this period, and rivers delivered greatly increased sediment loads to the ocean, rising seal levels contributed decisively to deltaic accumulation. Moreover, the most spectacular examples of these sediment fluxes come from systems with major mountain catchment areas or, as in East Africa, where major lakes overflowed into headwater areas. Over tectonically quiescent terrain, represented by the Gondwanaland fragments, much of the sediment flux comes from plateau areas (Table 1) and such areas are characterised by long-term (10^4–10^5, even 10^7 years) sediment storage. Subsiding foreland and intra-cratonic basins account for much of this storage on major river systems such as the Amazon and Nile, but the local patterns of sediment accumulation are also significant.

Sediment transferred from erosional catchments and from hillslopes, to piedmont fans and as colluvium characterises escarpments and residual hills. In the wet tropics, increased seasonality of discharges combined with reduced plant cover led to the widespread development of braided channel systems and alluvial fans around the LGM. In the drier tropics (savannas), by contrast, lower rainfalls probably led to reduced rates of sediment transfer, and increases in sediment flux may have occurred during periods of rapid warming and precipitation increase. The elevation of Early Holocene rainfalls, perhaps by 25% above present day averages, represented an increase in precipitation of 50% to >80% from the LGM minima in many areas. Large floods resulted from lake overflows into some major African rivers. Elsewhere, both erosional scour and deposition of coarse sediment are recorded, for example, from rivers in W Africa after 15 cal. ky BP (Hall et al., 1985; Thomas et al., 1985). This presumably reflected intensified storm activity associated along the ITCZ. These changes were sufficient to destabilise many landscapes across the tropics and led to reorganisation of fluvial systems, from fan building to incision and, after several millennia, from braidplains to single-thread meandering channel systems in the Early–Mid Holocene. This transition was almost certainly mediated by recovery of the rainforest after ∼ 10.5 cal. ky BP and by the stabilisation of post-glacial rainfall patterns.

The sensitivity of the landscape to change is influenced by these rates of change as well as by their periodicity and amplitude. Individual, extreme events are superimposed on these changes, and their impacts may well depend on when they occur on longer timescales of change that bring about altered plant cover (Thomas, 2003). Vegetation recovery from aridity may be delayed by many factors, and in the postglacial period by instability in the climate itself. This included the Younger Dryas, which was cool and dry for 1 ky, and appears to have delayed the regeneration of the rainforest. Delay may have been caused by many other factors including the absence of soil organic matter, depletion of ground water stores, frequent fires (quite possibly anthropogenic) and a slow rate of seed dispersal and migration from Pleistocene ‘refugia’.

The Late Quaternary sedimentary record in the tropics and near-tropics, therefore, reflects the influence of saprolite sources, continued weathering, multiscaled climate oscillations, and sea level changes. In addition, the complexity of response by major river systems, such as the Amazon, Congo, Niger and Nile, to these factors inevitably complicates ocean sediment signals based on interpretation of terrigenous sediment fluxes.

References

Adamson, D.A., Gasse, F., Street, F.A., Williams, M.A.J., 1980. Late Quaternary history of the Nile. Nature 287, 50–55.

Ahnert, F., 1998. Introduction to Geomorphology. Arnold, London, p. 352.

Aleva, G.J.J., 1985. Indonesian fluvial cassiterite placers and their genetic environments. Journal of the Geological Society, London 142, 815–836.

Aleva, G.J.J., Bon, E.H., Nossin, J.J., Sluiter, W.J., 1973. A contribution to the geology of part of the Indonesian Tinbelt: the sea areas between Singkep and Bangka Islands and around the Karimata Islands. Geological Society of Malaysia, Bulletin 6, 257–271.

Alpers, C.N., Brimhall, G.H., 1988. Middle Miocene climatic change in the Atacama Desert, northern Chile: evidence from supergene mineralisation at La Escondida. Geological Society of America Bulletin 100, 1640–1656.

Arz, H.W., Pätzold, J., Wefer, G., 1998. Correlated millennial-scale changes in surface hydrography and terrignenous sediment yield inferred from Last-Glacial marine deposits off Northeastern Brazil. Quaternary Research 50, 157–166.

Bakker, J.P., 1957. Quelques aspects du problème des sédiments correlatives en climat tropical humide. Zeitschrift für Geomorphologie, N.F. 1, 3–43.

Becker, G.F., 1895. Goldfields of the southern Appalachians. Annual Report USGS: Part III. Mineral Resources of the United States. Metallic Products 16, 251–331.

Benedetti, M.F., Menard, O., Noack, Y., Carvalho, A., Nahon, D., 1994. Water–rock interactions in tropical catchments—field rates of weathering and biomass impact. Chemical Geology 118, 203–220.

Bird, M.I., Chivas, A.R., 1988. Oxygen isotope dating of the Australian regolith. Nature 331, 513–516.

Biscaye, P.E., 1965. Mineralogy and sedimentation of recent deep-sea clay in the Atlantic ocean and adjacent seas and oceans. Geological Society of America Bulletin 76, 803–832.

Blanc-Valeron, M.-D., Thiry, M., 1997. Clay minerals, palaeoweathering, palaeolandscapes and climatic sequences: the Palaeogene continental deposits of France. In: Paquet, H., Clauer, N. (Eds.), Soils and Sediments—Mineralogy and Geochemistry. Springer, Berlin, pp. 223–247.

Bond, G., Broecker, W., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J., Bonani, G., 1993. Correlations between climate records from North Atlantic sediments and Greenland ice. Nature 365, 143–147.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., de Menocal, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G., 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and Glacial climates. Science 278, 1257–1266.

Boulet, R., Lucas, Y., Fritsch, E., Paquet, H., 1997. Geochemical processes in tropical landscapes: role of soil covers. In: Paquet, H., Clauer, N. (Eds.), Soils and Sediments—Mineralogy and Geochemistry. Springer, Berlin, pp. 67–96.

Branner, J.C., 1896. Decomposition of rocks in Brazil. Bulletin of the Geological Society of America 7, 255–314.

Broecker, W.S., 1995. Cooling the tropics. Nature 376, 212–213.

Broecker, W.S., Lao, Y., Klas, M., Clark, E., Bonani, G., Ivy, S., Chen, C., 1993. A search for an Early Holocene $CaCO_3$ preservation event. Palaeoceanography 8, 333–339.

Bull, W.B., 1991. Conceptual models for changing landscapes. In: Bull, W.B. (Ed.), Geomorphic Responses to Climatic Change, Oxford, New York, pp. 3–31.

Campbell, I.D., Campbell, C., Apps, M.J., Rutter, N.W., Bush, A.B.G., 1998. Late Holocene ~ 1500 yr periodicities and their implications. Geology 26, 471–473.

Chauvel, A., 1977. Recherches sur la transformation des sols ferrallitiques dans la zone tropicale à saisons contrastées. Travaux et Documents de L'ORSTOM 62, 532 (Paris).

Cleaves, E.T., 1989. Appalachian piedmont landscapes from the Permian to the Holocene. Geomorphology 2, 159–179.

Coelho-Netto, A.L., 1997. Catastrophic landscape evolution in a humid region (SE Brazil): inheritances from tectonic, climatic and land use induced changes. Geografia Fisica e Dinamica Quaternaria, Supplement 111 (T.3), 21–48.

Curry, W.B., Oppo, D.O., 1997. Synchronous high frequency oscillations in tropical sea-surface temperatures and North Atlantic Deep Water production during the Last Glacial Cycle. Palaeoceanography 12, 1–14.

Damuth, J.E., 1977. Late Quaternary sedimentation in the western equatorial Atlantic. Geological Society of America Bulletin 88, 695–710.

Damuth, J.E., Fairbridge, R.W., 1970. Equatorial Atlantic deep-sea arkosic sands and Ice-age aridity in tropical South America. Bulletin of the Geological Society of America 81, 189–206.

De Menocal, P., Ortiz, J., Guilderson, T., Adkins, J., Sarnthein, M., Baker, L., Yarusinski, M., 2000. Abrupt onset and termination of the African Humid Period: rapid climate responses to gradual insolation forcing. Quaternary Science Reviews 19, 347–361.

Dong, B., Valdes, P.J., Hall, N.M.J., 1996. The changes of monsoonal climates due to Earth's orbital perturbations and Ice Age boundary conditions. Palaeoclimates 1, 203–240.

Douglas, I., 1973. Rates of denudation in selected small catchments in Eastern Australia. University of Hull Occasional Papers in Geography 21, 128 (Hull).

Douglas, I., Spencer, T., 1985. Present-day processes as a key to the effects of environmental change. In: Douglas, I., Spencer, T. (Eds.), Environmental Change and Tropical Geomorphology. Allen and Unwin, London, pp. 39–73.

Dubroeucq, D., Volkoff, B., 1998. From oxisols to spodosols and histosols: evolution of the soil mantles in the Rio Negro basin (Amazonia). Catena 32, 245–280.

Duchaufour, P., 1982. Pedology, Pedogenesis and Classification George Allen and Unwin, London. English edn., Trans. T.R. Paton.

Dupont, L.M., Marret, F., Winn, K., 1998. Land-sea correlation by means of terrestrial and marine palynomorphs from the equatorial East Atlantic: phasing of SE trade winds and the oceanic productivity. Palaeogeography, Palaeoclimatology, Palaeoecology 142, 51–84.

Fairbridge, R.W., Finkl Jr., C.W., 1984. Tropical stone lines and podzolised sand plains as palaeoclimatic indicators for weathered cratons. Quaternary Science Reviews 3, 41–72.

Falconer, J.D., 1911. The Geology and Geography of Northern Nigeria. Macmillan, London, p. 295.

Fard, A.M., 2001. Recognition of abrupt climatic changes in clastic sedimentary environments: an introduction. Global and Planetary Change 28, ix–xii.

Ferreira, R.C., Monteiro, L.B., 1985. Identification and evaluation of collapsibility of colluvial soils that occur in the Sao Paulo State. First International Conference on Geomechanics in Tropical Lateritic and Saprolitic Soils, Brasilia, vol. 1, pp. 269–280.

Franzinelli, E., Potter, P.E., 1983. Petrology, chemistry and texture of modern river sands, Amazon River system. Journal of Geology 91, 23–39.

Gasse, F., 2000. Hydrological changes in the African tropics since the Last Glacial Maximum. Quaternary Science Reviews 19, 189–211.

Gasse, F., Van Campo, E., 1994. Abrupt post glacial climatic events in West Asia and North Africa monsoon domains. Earth and Planetary Science Letters 126, 435–456.

Geological Society, 1990. Engineering group working party report: tropical residual soils. Quarterly Journal of Engineering Geology 23, 1–101.

Gibbs, R.J., 1967. The geochemistry of the Amazon River System: Part I. The factors that control the salinity and composition of the suspended solids. Geological Society of America Bulletin 78, 1203–1232.

Giresse, P., Lanfranchi, R., 1984. Les climats et les océans de la région congolaise pendant l'Holocène-Bilans selon les échelles et les méthodes de l'observation. Palaeoecology of Africa 16, 77–88.

Giresse, P., Bongo-Passi, G., Delibrias, G., Du Plessy, J.C., 1982. La lithostratigraphie des sediments hemiplagiques du delta profond du fleuve Congo et ses indications sur les paléoclimats de la fin du Quaternaire. Bulletin Société Géologie française, Série 24, 803–815.

Godard, A., 1977. Pays et Paysages du Granite. Presses Universitaire, Paris.

Goldberry, R., 1979. Sedimentology of the Lower Jurassic flint clay bearing Mishor Formation, Makhtesh Ramon, Israel. Sedimentology 19, 229–251.

Goodbred, S.L., Kuehl, S.A., 2000. Enormous Ganges–Brahmaputra sediment discharge during strengthened Early Holocene monsoon. Geology 28, 1083–1086.

Guo, Z., Petit-Maire, N., Kröpelein, S., 2000. Holocene non-orbital climatic events in present-day arid areas of northern Africa and China. Global and Planetary Change 26, 97–103.

Hall, A.M., 1991. Pre-Quaternary landscape evolution in the Scottish Highlands. Transactions Royal Society of Edinburgh: Earth Sciences 82, 1–26.

Hall, A.M., Thomas, M.F., Thorp, M.B., 1985. Late Quaternary alluvial placer development in the humid tropics: the case of the Birim Diamond Placer, Ghana. Journal of the Geological Society 142, 777–787.

Hastenrath, S., Kutzbach, J.E., 1983. Palaeoclimatic estimates from water and energy budgets of East African lakes. Quaternary Research 19, 141–153.

Heap, A.D., Dickens, G.R., Stewart, L.K., 2001a. Late Holocene sediment in the Nara Inlet, central Great Barrier Reef platform, Australia: sediment accumulation on the middle shelf of a tropical mixed clastic/carbonate system. Marine Geology 176, 39–54.

Heap, A.D., Dickens, G.R., Stewart, L.K., 2001b. A source to sink explanation for clastic sediment around islands on the middle shelf of the Great Barrier Reef platform. Eos. Trans. AGU 82 (47) (Fall Meeting Supplement, Abstracts F656).

Hemming, S.R., Biscaye, P.E., Broecker, W.S., Hemming, N.G., Klas, M., Hajdas, I., 1998. Provenance change coupled with increased clay influx during deglacial times in the western equatorial Atlantic. Palaeogeography, Palaeoclimatology, Palaeoecology 142, 217–230.

Heyligers, P.C., 1963. Vegetation and soil of a white-sand savanna in Suriname. Verhandelingen der koninkluke Nederlandse, Akademie van Wetenschappen, AFD Natuurkunde. N.V. Noord-Hollandshce Uitgevers Maatschappij, Amsterdam. p. 148.

Jansen, J.H.F., Van Iperen, J.M., 1991. A 222,000 year climatic record for the east equatorial Atlantic Ocean and equatorial Africa: evidence from diatoms and opal phytoliths in the Zaire (Congo) deep sea fan. Paleoceanography 6, 573–591.

Jouzel, J., Lorius, C., Petit, J.R., Genthon, C., Barkov, N.I., Kotlyakov, V.M., Petrov, V.M., 1987. Vostok ice core: a continuous isotope temperature record over the last climatic cycle (160,000 years). Nature 329, 403–408.

Kershaw, A.P., 1976. A Late Pleistocene and Holocene pollen diagram from Lynch's Crater, northeastern Queensland, Australia. New Phytologist 77, 469–498.

Kershaw, A.P., 1978. Record of last interglacial–glacial cycle from northeastern Queensland. Nature 272, 159–161.

Kershaw, A.P., 1992. The development of rainforest–savanna boundaries in tropical Australia. In: Furley, P.A., Proctor, J., Ratter, J.A. (Eds.), Nature and Dynamics of Forest–Savanna Boundaries. Chapman and Hall, London, pp. 255–271.

Knox, J.C., 1993. Large increases in flood magnitude in response to modest changes in climate. Nature 361, 430–432.

Knox, J.C., 1995. Fluvial systems since 20,000 years BP. In: Gregory, K.J., Starkel, L., Baker, V.R. (Eds.), Global Continental Palaeohydrology. Wiley, Chichester, pp. 87–108.

Lamb, H.F., Gasse, F., Benkaddour, A., El Hamouti, N., van der Kaars, S., Perkins, W.T., Pearce, N.J., Roberts, C.N., 1995. Relation between century-scale Holocene arid intervals in tropical and temperate zones. Nature 373, 134–137.

Latrubesse, E.M., Rancy, A., 1998. The Late Quaternary of the Jurua River, southwestern Amazonia: geology and vertebrate palaeontology. Quaternary of South America and the Antarctic Peninsula 11, 27–46.

Ledru, M.-P., Bertaux, J., Sifeddine, A., Suguio, K., 1998. Absence of Last Glacial Maximum records in lowland tropical forests. Quaternary Research 49, 233–237.

Lewis, S.G., Maddy, D., Scaife, R.G., 2001. The fluvial system response to abrupt climate change during the last cold stage: the Upper Pleistocene River Thames fluvial succession at Ashton Keynes, UK. Global and Planetary Change 28, 341–359.

Lucas, Y., Boulet, R., Chauvel, A., Veillon, L., 1987. Systèmes sols ferrallitiques-podzols en région amazonienne. In: Righi, D., Chauvel, A. (Eds.), Podzols et Podzolisation. Comptes Rendus de la Table Ronde International, 1986. Association Française pour l'Étude du Sol, INRA/ORSTOM, Poitiers, pp. 53–65.

Maley, J., 1992. The African rainforest vegetation and palaeoenvironments during The Quaternary. In: Myers, J. (Ed.), Tropical Forests and Climate. Kluwer, Rotterdam.

Maley, J., 1996. The African rain forest-main characteristics and changes in vegetation and climate from the Upper Cretaceous to the Quaternary. In: Alexander, I.J., Swaine, M.D., Watling, R. (Eds.), Essays on the Ecology of the Guinea-Congo Rain Forest. Proceedings of the Royal Society of Edinburgh (Section B), vol. 104, pp. 31–73.

Marret, F., Scourse, J., Jansen, J.H.F., Schneider, R., 1999. Changements climatiques et paleooceanographiques en Afrique centrale Atlantique au cours de la derniere deglaciation: contribution palynologique. Comptes Rendus de l'Academie des Sciences, Serie IIa 329, 721–726.

Mathieu, D., Bernat, M., Nahon, D., 1995. Short-lived U and Th isotope distribution in a tropical laterite developed from granite (Pitinga river basin, Amazonia). Earth and Planetary Science Letters 136, 703–714.

McDaniel, D.K., McLennan, S.M., Hanson, G.N., 1997. Provenance of Amazon fan muds: constraints from Nd and Pb isotopes. Proceedings of the Ocean Drilling Program, Science Results 155, 169–176.

Migoń, P., Lidmar-Bergström, K., 2001. Weathering mantles and their significance for geomorphological evolution of central and northern Europe since the Mesozoic. Earth Science Reviews 56, 285–324.

Migoń, P., Thomas, M.F., 2002. Grus weathering mantles—problems of interpretation. Catena 49, 5–24.

Millot, G., 1970. Geology of Clays. Chapman and Hall, London, p. 429. Engl. transl. W.R. Farrand and H. Paquet.

Moss, P.T., Kershaw, P.A., 2000. The Last Glacial Cycle from the humid tropics of northeastern Australia: comparison of a terrestrial and a marine record. Palaeogeography, Palaeoclimatology, Palaeoecology 155, 155–176.

Nahon, D., Trompette, R., 1982. Origin of siltstones: glacial grinding versus weathering. Sedimentology 29, 25–36.

Nanson, G.C., Price, D.M., 1998. Australian flow regime and climate over the past 300 ka. Third International Meeting on Global Continental Palaeohydrology, Rissho University Japan. Abstracts 28, Kumagaya, Japan.

Nanson, G.C., Price, D.M., Short, S.A., Young, R.W., Jones, B.G., 1991. Comparative uranium–thorium and thermoluminescence dating of weathered Quaternary alluvium in the tropics of northern Australia. Quaternary Research 35, 347–366.

Neil, D.T., Yu, B., 1996. Fluvial sediment yield to the Great Barrier Reef lagoon: spatial patterns and the effect of land use. In: Hunter, I.M., Eyles, A.G., Rayment, G.E. (Eds.), Proceedings Conference on Downstream Effects of Land Use, Rockhampton, April 1995. Dept. Natural Resources, Queensland.

Nott, J., Young, R., McDougall, I., 1996. Wearing down, wearing back, and gorge extension in the long-term denudation of a highland mass: quantitative evidence from the Shoalhaven catchment, southeast Australia. Journal of Geology 104, 224–232.

Nott, J., Thomas, M.F., Price, D.M., 2001. Alluvial fans, landslides and Late Quaternary climatic change in the wet tropics of northeast Queensland. Australian Journal of Earth Sciences 48, 875–882.

Oguchi, C., Hatta, T., Matsukura, Y., 1999. Weathering rates over 40,000 years based on changes in rock properties of porous rhyolite. Physics and Chemistry of the Earth 24, 861–870.

Ollier, C.D., 1960. The inselbergs of Uganda. Zeitschrift für Geomorphologie N.F. 4, 43–52.

Ollier, C.D., Pain, C., 1996. Regolith, Soils and Landforms. Wiley, Chichester, p. 306.

Paquet, H., Clauer, N. (Eds.), 1997. Soils and Sediments: Mineralogy and Geochemistry. Springer, Berlin, p. 369.

Pastouret, L., Chamley, H., Delibrias, G., Duplessy, J.C., Thiede, J., 1978. Late Quaternary climatic changes in western tropical Africa deduced from deep-sea Sedimentation off the Niger Delta. Oceanologica Acta 1, 217–232.

Pickup, G., 1984. Geomorphology of tropical rivers I. Landforms, hydrology and sedimentation in the Fly and Lower Purari, Papua New Guinea. Catena Supplement 5, 1–18.

Pillans, B., 1997. Soil development at a snail's pace: evidence from a 6 Ma soil chronosequence on basalt in north Queensland, Australia. Geoderma 80, 117–128.

Preuss, J., 1990. L'évolution des paysages du bassin intérieur du Zäire pendentes les quarantes derniers millénaires. In: Lanfranchi, R., Schwartz, D. (Eds.), Paysages Quaternaires de lAfrique centrale Atlantique. ORSTOM, Paris, pp. 260–270.

Pye, K., 1983. Red beds. In: Goudie, A.S., Pye, K. (Eds.), Chemical Sediments and Geomorphology. Academic Press, London, pp. 227–263.

Rossignol-Strick, M., Nesteroff, W., Olive, P., Vergnaud-Grazzini, C., 1982. After The deluge: Mediterranean stagnation and sapropel formation. Nature 295, 105–110.

Runge, J., 2001. Central African palaeoclimates and palaeoenvironments since 40 ka—an overview. Palaeoecology of Africa 27, 1–10.

Servant, M., Maley, J., Turcq, B., Absy, M.-L., Brenac, P., Fournier, J., Ledru, M.-P., 1993. Tropical forest changes during the Late Quaternary in African and South American lowlands. Global and Planetary Change 7, 25–40.

Showers, M., Beavis, W.J., 1988. Amazon cone isotopic stratigraphy: evidence for the source of the tropical freshwater spike. Palaeogeography, Palaeoclimatology, Palaeoecology 64, 189–199.

Sørensen, R., Murray, A.S., Kaaya, A.K., Kilasara, M., 2001. Stratigraphy and formation of Late Pleistocene colluvial apron in Morogoro district, central Tanzania. Palaeoecology of Africa 27, 95–116.

Stallard, R.F., 1995. Tectonic, environmental, and human aspects of weathering and erosion: a global view using a steady state perspective. Annual Review of Earth and Planetary Sciences 23, 11–39.

Stallard, R.F., Edmond, J.M., 1981. Geochemistry of the Amazon: 1. Precipitation chemistry and the marine contribution to the dissolved load at the time of peak discharge. Journal of Geophysical Research 86 (C10), 9844–9858.

Stallard, R.F., Edmond, J.M., 1983. Geochemistry of the Amazon: 2. The influence of geology and weathering environment on the dissolved load. Journal of Geophysical Research 88 (C14), 9671–9688.

Stallard, R.F., Edmond, J.M., 1987. Geochemistry of the Amazon: 3. Weathering chemistry and limits to dissolved inputs. Journal of Geophysical Research 92 (C8), 8293–8302.

Stuiver, M., Grootes, P.M., Brazunas, T.F., 1995. The GISP2 δ^{18} climate record of the past 16,500 years and the role of the sun, ocean and volcanoes. Quaternary Research 44, 341–354.

Talbot, M.R., Johannessen, T., 1992. A high resolution palaeoclimatic record of the last 27,500 years in tropical West Africa from the carbon and nitrogen isotopic composition of lacustrine organic matter. Earth and Planetary Science Letters 110, 23–37.

Talbot, M.R., Williams, M.A.J., Adamson, D.A., 2000. Strontium isotope evidence for Late Pleistocene re-establishment of an integrated Nile drainage network. Geology 28, 343–346.

Taylor, G.A., Eggleton, R.A., 2001. Regolith Geology and Geomorphology. Wiley, Chichester, p. 375.

Taylor, K.C., Alley, R.B., Doyle, G.A., Grootes, P.M., Mayewski, P.A., Lamorey, G.W., White, J.W.C., Barlow, L.K., 1993. The "flickering switch" of Late Pleistocene climate change. Nature 361, 432–436.

Taylor, K.C., Mayewski, P.A., Alley, R.B., Brook, E.J., Gow, A.J., Grootes, P.M., Meese, D.A., Saltzmann, E.S., Severinghaus, J.P., Twickler, M.S., White, J.W.C., Whitlow, S., Zelinsky, G.A., 1997. The Holocene–Younger Dryas transition recorded at Summit, Greenland. Science 278, 825–827.

Teeuw, R.M., 1991. A catenary approach to the study of gravel layers and tropical landscape morphodynamics. Catena 18, 71–89.

Thomas, M.F., 1966. Some geomorphological implications of deep weathering patterns in crystalline rocks in Nigeria. Transactions of the Institute of British Geographers 40, 173–193.

Thomas, M.F., 1978. The study of inselbergs. Zeitschrift für Geomorphologie, Supplementband 31, 1–41.

Thomas, M.F., 1994a. Geomorphology in the Tropics. Wiley, Chichester, p. 460.

Thomas, M.F., 1994b. Ages and relationships of saprolite mantles. In: Robinson, D., Williams, R. (Eds.), Rocks, Rock Weathering and Landform Evolution. Wiley, Chichester, pp. 287–301.

Thomas, M.F., 1999. Evidence for high-energy landforming events on the central African plateau: eastern Province Zambia. Zeitschrift für Geomorphologie, N.F. 43, 273–297.

Thomas, M.F., 2000. Late Quaternary environmental changes and the alluvial record in humid tropical environments. Quaternary International 72, 23–36.

Thomas, M.F., 2003. Landscape sensitivity to rapid environmental change—a Quaternary perspective with examples from tropical areas. Catena.

Thomas, M.F., Murray, A.S., 2001. On the age and significance of Quaternary colluvium in eastern Zambia. Palaeoecology of Africa 27, 117–133.

Thomas, M.F., Thorp, M.B., 1980. Some aspects of the Geomorphological interpretation of Quaternary alluvial sediments in Sierra Leone. Zeitschrift für Geomorphologie, N.F., Supplementband 36, 140–161.

Thomas, M.F., Thorp, M.B., 1985. Environmental change and episodic etchplanation in the humid tropics of Sierra Leone: the Koidu etchplain. In: Douglas, I., Spencer, T. (Eds.), Environmental Change and Tropical Geomorphology. Allen and Unwin, London, pp. 239–267.

Thomas, M.F., Thorp, M.B., 1993. The geomorphology of some Quaternary placer deposits. Zeitschrift für Gemorphologie, Supplementband 87, 183–194.

Thomas, M.F., Thorp, M.B., 1995. Geomorphic response to rapid climatic and hydrologic change during the Late Pleistocene and Early Holocene in the humid and sub-humid tropics. Quaternary Science Reviews 14, 193–207.

Thomas, M.F., Thorp, M.B., 2003. Palaeohydrological reconstructions for tropical Africa since the Last Glacial Maximum—evidence and problems. In: Gregory, K.J., Benito, G. (Eds.), Palaeohydrology—A Contribution to Global Change. Wiley, Chichester, pp. 167–192.

Thomas, M.F., Thorp, M.B., Teeuw, R.M., 1985. Palaeogeomorphology and the occurrence of diamondiferous placer deposits in Koidu, Sierra Leone. Journal of Geological Society l42, 789–802.

Thomas, M.F., Thorp, M.B., McAlister, J., 1999. Equatorial weathering, landform development and the formation of white sands in north western Kalimantan, Indonesia. Catena 36, 205–232.

Thomas, M.F., Nott, J.M., Price, D.M., 2001. Late Quaternary stream sedimentation in the humid tropics: a review with new data from NE Queensland, Australia. Geomorphology 39, 53–68.

Thorp, M.B., Thomas, M.F., 1992. The timing of alluvial sedimentation and floodplain formation in the lowland humid tropics of Ghana, Sierra Leone, and western Kalimantan (Indonesian Borneo). Geomorphology 4, 409–422.

Thorp, M.B., Thomas, M.F., Martin, T., Whalley, W.B., 1990. Late Pleistocene sedimentation and landform development in western Kalimanatan (Indonesian Borneo). Geologie en Mijnbouw 69, 133–150.

Tricart, J., 1955. Types de fleuves et systèmes morphogénétiques en Afrique occidentale. Bulletin Section Géographique, Comité Travaux Historique et Scientifique 68, 303–345.

Truckenbrodt, W., Kotschoubey, B., Schellmann, W., 1991. Composition and origins of the clay cover on north Brazilian laterites. Geologische Rundschau 80, 591–610.

Turcq, B., Pressinotti, M.M.N., Martin, L., 1997. Palaeohydrology and palaeoclimate of the past 33 000 years at the Tamanduá River, central Brazil. Quaternary Research 47, 284–294.

Vandenberghe, J., Maddy, D., 2001. Editorial—the response of rivers to climate change. Quaternary International 79, 1–3.

Van der Hammen, T., Duivenvoorden, J.F., Lips, J.M., Urrego, L.E., Espejo, N., 1992. Late Quaternary of the middle Caquetá River (Colombian Amazonia). Journal of Quaternary Science 7, 45–55.

Vasconcelos, P.M., Becker, T.A., Renne, P.R., Brimhall, G.H., 1992. Age and duration of weathering by $^{40}K-^{40}Ar$ and $^{40}Ar/^{39}Ar$ analysis of potassium manganese oxides. Science 258, 451–455.

Vasconcelos, P.M., Renne, P.R., Brimhall, G.H., Becker, T.A., 1994. Direct dating of weathering phenomena by $^{40}Ar/^{39}Ar$ and K–Ar analysis of supergene K–Mn oxides. Geochimica et Cosmochimica Acta 58, 1635–1665.

Veldkamp, A., Tebbens, L.A., 2001. Registration of abrupt climatic changes within fluvial systems: insights from numerical modelling experiments. Global and Planetary Change 28, 129–144.

Vidal, L., Labeyrie, L., Cortijo, E., Arnold, M., Duplessy, J.C., Michel, E., Becqué, S., van Wearing, T.C.E., 1997. Evidence for changes in the North Atlantic Deep Water linked to meltwater surges during the Heinrich events. Earth and Planetary Science Letters 146, 13–27.

Wahrhaftig, C., 1965. Stepped topography of the southern Sierra Nevada, California. Bulletin Geological Society of America 76, 1165–1190.

Willis, B., 1936. East African Plateaux and Rift Valleys—Studies in Comparative Seismology, vol. 470. Carnegie Institute, Washington, p. 358. Publication.

Williams, M.A.J., Adamson, D., Cock, B., McEvedy, R., 2000. Late Quaternary environments of the White Nile region, Sudan. Global and Planetary Change 26, 305–316.

Zabel, M., Schneider, R.R., Wagner, T., Adegbie, A.T., de Vries, U., Kolonic, S., 2001. Late Quaternary climate changes in central Africa as inferred from terrigenous input to the Niger fan. Quaternary Research 56, 207–217.

Zonneveld, J.I.S., 1972. Sulas and sula complexes. Göttinger Geographische Abhandlungen (Hans–Poser–Festschrift) 60, 93–101.