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Catchment Processes and the Quantity and Composition of Sediment Delivered to Terminal Basins [and Discussion]

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Catchment processes and the quantity and composition of sediment delivered to terminal basins

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Although the quantities of sediment exported to the sea by large rivers are relatively well known, information on mineralogical and geochemical characteristics is less readily available. Quantity and composition are strongly influenced by tectonic environment and also by both present and past climate. An analysis of diagenetic processes in fine-grained clastic sediments suggests that bed-parallel changes in the intensity of diagenetic modification (reflected in phenomena such as cemenstone horizons) and marked changes in authigenic mineral assemblages (sulphides, carbonates, silicates) could be explained by changes in sediment supply rate driven by climatic fluctuations. It is less easy to explain fluctuations in detrital sediment composition: diagenetic reorganization would appear to be the most common cause of marked local compositional contrast in mudstones.

1. Introduction

The majority of contributions to this volume are concerned with the diagenetic processes which modify the composition and mineralogy of sediments after they have been buried. To the casual observer, concretions within sedimentary rocks are probably the most obvious manifestation of former diagenetic processes. Diagenetic cements can account for as much as 80% by volume of a concretion whereas the surrounding sediments may be quite without cement (Oertel & Curtis 1972).

An important question is always, 'why should the processes be localized in this way'? Sometimes there are clues. Many concretions contain the most exquisite fossils preserved without apparent crushing. The suggestion is that some sedimentological event (unfortunate for the animal or plant concerned) created a primary compositional heterogeneity which served to initiate the diagenetic fossilization process. In this kind of situation, a focus for microbial activity is formed; as pointed out by many workers. There is little doubt that microbial processes are directly responsible for both cements and their spatial distribution (Coleman & Raiswell, this symposium).

It is interesting to question if all such 'concretionary' diagenetic segregations are triggered by some primary, depositional event? In other words, do diagenetic cements merely amplify the record of primary, depositional signals? Limestone–marl cycles have been studied extensively in this context and it appears that both primary and diagenetic components are readily identifiable. Variations in the proportions of allochthonous and autochthonous sediment create initial compositional oscillations which are then enhanced by diagenetic redistribution of carbonate (Einsele 1982).

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It is important to be able to separate the consequences of primary sedimentation from those of subsequent diagenetic alteration. This is certainly a precondition for unravelling the record of climate change, the evidence for which resides almost exclusively within ancient sedimentary successions. Here, we shall attempt to evaluate the potential for processes wholly external to the sedimentary basin to dictate the course of diagenetic alteration.

2. Diagenetic processes and products

(a) *Evidence from the geological record*

It is helpful to consider an example from coal measures within the Carboniferous of Europe (Ashby & Pearson 1975; Pearson 1979; Love *et al.* 1983; Curtis *et al.* 1986; Curtis & Coleman 1986). Within a short succession (3 m) examples of several different concretion types occur abundantly (50–90% of the rock consisting of diagenetic cement):

siderite concretions and continuous beds (within non-marine mudstones); pyrite-dolomite concretions (marine mudstone; *Gastrioceras listeri* horizon); pyrite-calcite concretions ('coal balls' in the Halifax Hard Bed Coal); siderite concretions in underlying seat earth and underclays.

The sideritic mudstone sequence above the marine horizon continues for some 20 m and substantial intervals have more 20% siderite overall, mostly as numerous, thin (10 cm) beds. This succession was formerly worked as an iron ore.

Petrographic evidence (pre-compaction cementation, undistorted fossil preservation) unambiguously points to the precipitation of this wide range of cement minerals within pore space soon after sediment deposition. More direct evidence of the processes involved has come from combined petrographic, geochemical and isotopic studies (Galimov & Girin 1968). The diagenetic mineral assemblages in these and many other ancient sedimentary sequences (of almost all geological ages) have been interpreted consistently to be by-products of microbial activity within unconsolidated sediments. Such interpretation has rested largely on the findings of investigations in recent sediments (Oana & Deevey 1960; Berner 1970; Claypool & Kaplan 1974; Goldhaber 1974; Goldhaber *et al.* 1977; Froelich *et al.* 1979; and many others).

(b) *Modern sediment process studies*

Microbial reactions take place in buried sediments which modify pore water and sediment composition. It is convenient to refer to some of them by their most obvious effects (the nature of the organisms themselves and their metabolic pathways will be addressed elsewhere in the volume).

The most striking observation is that most unconsolidated sediments exhibit vertical zonation. Within each zone one microbial process appears to dominate overall reaction:

Ox organic matter oxidation (dissolved molecular oxygen),

$$CH_2O + O_2 = H^+ + HCO_3^-$$

SR sulphate reduction,

$$2CH_2O + SO_4^{2-} = HS^- + H^+ + 2HCO_3^-$$

Me microbial methanogenesis,

$$2CH_2O + H_2O = CH_4 + H^+ + HCO_3^-$$

MnR manganese reduction,

$$2MnO_2 + CH_2O + H_2O = 2Mn^{2+} + HCO_3^- + 3OH^-$$

FeR iron reduction,

$$2Fe_2O_3 + CH_2O + 3H_2O = 4Fe^{2+} + HCO_3^- + 7OH^-.$$

In near-shore marine sediments which accumulate relatively rapidly and which contain abundant organic matter, the normal sequence is oxidation, sulphate reduction, methanogenesis (Claypool & Kaplan 1974). In much more slowly accumulating sediments remote from the detrital source, the bulk of organic matter is destroyed by molecular oxygen after which the residue is unable to sustain sulphate reducers. Higher valence manganese and iron minerals are then reduced in successive: 'post-oxic' or 'sub-oxic' zones once molecular oxygen has been reduced to very low concentrations (Froelich *et al*. 1979; Berner 1981). The solute products of early diagenetic processes thus differ very markedly depending upon rate of sediment accumulation beneath oxygenated marine waters. These zonal sequences are described in table 1.

When organic-rich sediment accumulates relatively rapidly (tens of cm per thousand years), oxygen is quickly removed in the uppermost Ox Zone and microbial activity in the anoxic sediments below is dominated by sulphate reduction. Manganese present in relatively reactive minerals (such as soil sesquioxides) is reduced to Mn^{2+} and this tends to be fixed in authigenic carbonates. Iron is reduced to Fe^{2+} and stripped by HS^- (mackinawite, greigite and/or pyrite precipitate). Reactive iron surviving burial through the SR zone precipitates as carbonate (siderite, ankerite, ferroan calcite, dolomite). Other authigenic Fe^{2+} minerals (berthierine) are possible products of the Me Zone.

When the sedimentation rate is very slow (mm per thousand years), absence of SR means that a range of iron carbonates and aluminosilicates can form. In pelagic sediments, upward migration of Mn^{2+} and Fe^{2+} to finite oxygen partial pressures can result in mixed, higher valence oxide precipitation (manganese nodules). Evidence from the past suggests silicate–carbonate assemblages form in equivalent shallow marine situations (sedimentary ironstones).

Rate of sedimentation imposes other, more subtle controls. In the faster deposition zonal sequence in table 1, diagenetic alteration will depend on for how long a sediment package resides within each zone. Relatively slow sedimentation will destroy and degrade organic matter, lessening the amount and reactivity of the only reducing agent available for any of the subsequent zonal reactions. Somewhat faster burial and SR will be enhanced (although too rapid burial will isolate the sediment from sea water sulphate above). Relatively rapid sedimentation in this zonal sequence will favour siderite. Clearly, there is an optimum rate of sedimentation for pyrite precipitation: too rapid and there is not enough time for conversion, too slow and near-surface oxidation of organic matter limits sulphate reduction by lessening the amount and quality of organic substrate (Curtis 1977). It is a relatively simple matter to model these reactions and demonstrate this behaviour by using experimentally determined diffusion and reaction rates (Curtis 1987). The significance of the relative rates of competing early diagenetic processes in determining mineral assemblages was elegantly explored by Coleman (1985).

(c) *The key role of sediment accumulation rate*

Based on these observations, therefore, it seems that a detrital sediment entering

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Table 1. *Dependence of zonal sequence on rate of sediment accumulation*

rapid sedimentation (marine) Claypool & Kaplan 1974 overlap of zonal reactions pyrite > siderite			slow sedimentation (marine) Froelich *et al.* 1987 separation of zonal reactions siderite/berthierine/glauconite		
zone	reaction	products	zone	reaction	products
Ox	Ox	HCO_3^- H^+	Ox	Ox	HCO_3^- H^+
SR	SR + MnR + FeR	HCO_3^- H^+ HS^- OH^- Fe^{2+} Mn^{2+}	MnR	MnR	HCO_3^- OH^- Mn^{2+}
Me	Me + FeR	CH_4 HCO_3^- OH^- Fe^{2+}	FeR	FeR	HCO_3^- OH^- Fe^{2+}
			SR	SR + FeR	HS^- OH^- HCO_3^- Fe^{2+}

Table 2. *Sediment load data for selected river systems*

(Sources: Degens 1989; Martin & Meybeck 1979; Deer *et al.* 1966; The Times Concise Atlas of the World, 5th edn, 1986.)

river soil[a]	Niger savannah	Amazon tropical forest	Ganges mixed	Mackenzie boreal forest	Congo tropical forest	Nile steppe
catchment/(10^3 km^2)	1200	7050	1000	1765	3700	1900
detritus/(10^6 t a^{-1})	40	900	1670	100	43	1
salts/(10^6 t a^{-1})	10	292	152	70	47	17
runoff/(km^3 a^{-1})	192	6300	971	306	1250	30
load[c]/(10^6 t km^{-3} a^{-1})	0.21	0.14	1.72	0.33	0.03	0.03[b]
load[d]/(10^3 t km^{-2} a^{-1})	0.03	0.13	1.67	0.06	0.01	0.001[b]
SiO_2 wt%	49.2	57.1	61.0	63.1	51.1	52.2
Al_2O_3 wt%	29.5	21.7	14.5	14.7	22.1	18.5
Fe_2O_3 wt%	13.1	7.8	5.3	5.3	10.1	15.4
MgO wt%	1.5	1.8	2.0	0.6	0.9	3.0
CaO wt%	0.5	2.2	3.8	5.0	1.3	6.1
Na_2O wt%	0.1	1.1	1.5	0.3	0.2	0.8
K_2O wt%	2.3	2.2	2.5	4.2	2.6	2.1

[a] Principal type; obviously a gross approximation for massive drainage basins.
[b] Aswan Dam sediment capture.
[c] Load = detrital load per unit water runoff.
[d] $Load^2$ = detrital load per unit area drainage basin.

a depositional basin can be modified in very different ways. For a silty clay derived by soil erosion (much the most common source mechanism):

(i) very slow deposition (small input to large basin, long transport path) will favour organic-poor sediments with diagenetic iron carbonates and silicates (plus phosphates);

(ii) slow deposition will favour pyrite/Fe-poor carbonate assemblages;

(iii) faster sedimentation will favour siderite and ferroan carbonates as principal early diagenetic cements.

Obviously freshwater sedimentation (sulphate-free) will greatly reduce the incidence of pyrite and non-ferroan authigenic carbonates.

It follows simply from this analysis that fluctuations in the supply of sediment to a basin will have a profound influence not only on the extent of diagenetic alteration, but also on its very nature; substituting one diagenetic mineral assemblage for a completely different one. Uniform sedimentation will give assemblages as listed above. Alternations of somewhat faster with somewhat slower rates will be recorded as oscillations between sideritic or ankeritic beds with more pyritic units. A hiatus with relatively rapidly accumulating sediments would allow much more time for sediments already buried (with substantial organic matter) to be markedly modified by SR or Me reactions: horizons marked respectively by extensive pyrite/non-ferroan carbonate cements or siderite/ferroan carbonate cements. Sediments above, close to the sediment–water interface at such a time might become sufficiently depleted in organic matter for suboxic conditions to be established, in which case authigenic silicates as well as carbonates with distinctive isotopic signatures might precipitate (no Me zone ^{13}C enrichment; Curtis *et al.* 1986).

The controls above assume no variations in the composition of incoming sediment (local diagenetic redistribution). It is not uncommon, however, to find significant intervals within mudstone sequences where diagenetic cements account for as much as 20% of the rock as a whole (Carboniferous Coal Measures example above). Could these larger excursions from 'norm' bulk sediment composition also be determined outside the depositional basin?

3. Fluctuations in sedimentation rate and sediment composition

(a) *Sedimentation rates in muds and mudstones*

The more obvious examples of diagenetic alteration (concretions) tend to be of the order 10 cm in vertical dimension. The average rates of accumulation of classic mudstone sequences tend to be of the order mm to tens of cm per thousand years (Kimmeridge Clay Formation 50–110 mm per thousand years (Macquaker 1993); Oxford Clay, 1–15 mm per thousand years (Hudson & Martill 1988)). It should be emphasized that these are very approximate, gross averages over large time intervals.

Much more recent sediments in the Black Sea (Degens 1989) yield not very different rates bearing in mind compaction:

(i) deglaciation, 15000–8000 years BP; 700–1020 mm per thousand years;
(ii) climatic optimum, 8000–2000 years BP; *ca.* 100 mm per thousand years;
(iii) during more recent human activities; *ca.* 300 mm per thousand years.

These figures suggest that 10 cm of muddy marine sediment (sufficient to host a concretion) can take anything from 10^2 to 10^5 years. It would take an order of magnitude longer (at a steady rate) to carry this unit down and out of easy diffusive contact with sulphate-rich seawater (when SR-induced diagenesis would no longer be possible). Compositional fluctuations sufficient for the iron enrichment in bedded siderites would have to last for similar intervals with a sediment supply enriched in iron.

We shall now examine plausible processes and controls whereby major (and repeated) fluctuations in either (or both) supply rate and detrital sediment composition could be generated within river catchments.

(b) *Regional denudation rates and sediment composition*

Major controls on regional denudation rates (or sediment yields) include climate and geology, with human activity becoming increasingly important in the 20th century. Climate is expressed primarily through the annual amount, the seasonality and the intensity of precipitation. Geology is expressed through the rocks of the catchment area and the tectonic style of the terrain over which the catchment is developed. The highest sediment yields occur in tectonically active areas, where earth tremors trigger frequent mass movements which supply large volumes of sediment to rivers. The lowest sediment yields are on old land surfaces of low relief and deep weathering profiles. The contrast quantitatively is the difference between yields of the order of 10000 t km^2 a^{-1} in catchments in mountains of New Guinea, Taiwan and the South Island of New Zealand (Pickup *et al.* 1981; Shimen Reservoir Authority 1975; Whitehouse 1983) and yields of around 100 t km^2 a^{-1} in Africa (Milliman & Meade 1983). Data for some major catchments illustrate these points well (table 2). High rates of sediment delivery from tectonically active areas (Ganges) contrast sharply with those from stable, tropical rainforest catchments (Congo). It is also instructive to examine sediment composition data and to compare them with global averages and examples of soil composition (table 3). The Niger and Congo sediments are poorer in silica and much richer in alumina and iron than high altitude (Ganges) or high latitude (Mackenzie) sources. This surely reflects input from chemically mature tropical soils in the former whereas immature soils and regoliths dominate the latter (see also Curtis 1990). The chemical composition data for the Amazon are also instructive. As 80% of sediment discharged by the river comes from the Andean foothills, sediment composition does not reflect the composition of soils within the drainage basin as a whole.

Even within tropical rain forest, equatorial climates, tectonic influences create differences of four orders of magnitude in sediment yield are found (table 4). Small mountainous rivers, especially those discharging directly on to active margins (e.g. western South and North America, New Guinea, New Zealand) have high sediment yields. They have been mostly ignored in global sediment budget calculations: overall yield may have been underestimated, perhaps by as much as a factor of three (Milliman & Syvitski 1992). Sediment yields are clearly dependent upon both tectonic setting and climate. In large catchments, however, sediments may well be derived from specific, restricted regions and not reflect the prevailing climate of the catchment as a whole.

(c) *Sediment storage within catchments*

Accepting the qualification above, the bulk of sediment delivered to marine basins today does come from very large river catchments. Much eroded material is stored within such catchments and only a small proportion is exported annually. Three spatial scales of sediment transfer may be envisaged. Many soil particles are detached and carried downslope only to be held and trapped by a plant, tree or other obstacle a little further downslope. Such retention on hill slopes builds up colluvial deposits. The sediment reaching the valley floor may not be completely removed by the river, but may be redistributed as alluvial floodplain deposits. The sediment carried downstream may be redeposited again on another part of the plain or, in regulated rivers, behind weirs and dams. Much of the sediment now being carried by rivers is derived from the erosion of channel banks in alluvial material (Douglas 1967, 1990). For example, in the Mississippi between 1880 and 1911 (before most of the modifications were made to the river), bank caving was the major source of suspended and bed load material entering into transport between Cairo and the Gulf of Mexico. During this period, about 62% of the sediment input to the lower

Table 3. *Some comparative compositional data: tropical soils with average sediments*

	average river load[b]	average deep sea clay[b]	tropical soil examples, Guyana[a]			
			primary laterite (dolerite)	ferruginous bauxite (dolerite)	soil (top 25 cm) (dolerite)	soil (top 25 cm) (schist)
wt %						
SiO_2	61.0	60.6	3.36	0.84	52.81	43.07
Al_2O_3	17.8	17.9	46.80	37.70	24.97	18.74
Fe_2O_3	6.8	8.5	26.14	34.28	11.07	20.05
MgO	2.0	3.0	0	0	0.07	0.23
CaO	3.1	1.4	0	0	0.02	0.03
Na_2O	1.0	2.7	0	0	0.16	0.08
K_2O	2.4	3.4	0	0	0.02	0.19

[a] Mohr & Van Baren 1959.
[b] Martin & Meybeck 1979.

Mississippi was stored. Three-fifths (61%) of that stored went into short-term channel storage, while 39% went into longer-term overbank storage (Kesel *et al.* 1992).

River sediment records rarely extend over more than a few decades. All such records exhibit considerable variation from year to year and reveal the role of extreme events such as hurricanes. The material carried past a downstream point on a river may have been supplied to the channel upstream some years before and may have been stored in the system. In many environments, the climatic oscillations of the Quaternary have left slope and valley floor deposits, from glacial moraines in high latitudes to wind-blown sands in equatorial regions, which are now being evacuated by fluvial erosion under more humid conditions. This means that the weathering process which detached and transformed original rock minerals may not be characteristic of the climate under which a river discharged its present-day sediment load to a terminal deposition basin. In discussing the climatic and tectonic controls of sedimentation, it must be remembered that what is measured today may reflect reworking by the present climate of clays, minerals and rock fragments weathered and transported by previous climates (Douglas 1980).

In the Howgill Fells in the Pennines of England, the major sediment sources for local streams are gullies and scars cut in late glacial soliflucted Devensian tills. Major sediment production events occur about 30–35 times each year, building up sediment at bases of gullies. These accumulated sediments are flushed into the bedload of streams by floods with a return period of 2–5 years. Floods which recur less than once in 100 years scour out channels and move sediment that has been stable for long periods (Harvey 1991).

(*d*) *Variability of sediment yield on different timescales*

As the Howgill Fells case illustrates, the rate at which sediment is exported from a small catchment or large drainage basin is subject to processes which operate at very different time scales (table 5). Disruptions of established patterns of surface processes occur at all scales from daily oscillations of the weather (especially during short lived phenomena such as tropical cyclones and earthquakes) to the scales of drifting continents and the opening and closure of oceans.

Extreme rainfalls creating large volumes of runoff excavate a high proportion of

Table 4. *Types and characteristics of humid tropical rivers*
(From Douglas 1992.)

tectonic setting	major channel characteristics	dominant sediment source	estimated erosion rate (range of annual sediment yield)/($t\ km^{-2}\ a^{-1}$)	general depth of soil on slope	example
active plate margin rift or half graben edge	braided channels abundant gravel	mass movement often triggered by earthquakes	up to 10000	thin	Markham River, Papua New Guinea
active volcanic areas of recent lava flows	braided channel	volcanic debris unstable ash deposits	up to 10000	skeletal	Toto Amarillo Costa Rica
tectonically active mountain areas	deep gorge sections where river usually occupies whole valley floor in flood; some braiding, but lateral movement of river restricted	valley wall failure, land sliding associated with seismic activity	7000–10000	thin	Upper Fly River Papua New Guinea
late Tertiary tectonic activity and weak mud rocks	wide channel with gravel bare, frequent undercut banks and grassed flood deposits	bank erosion in main channel and tributaries, erosion by saturated overland flow in streamhead hallows	*ca.* 1000	*ca.* 1 m	Segama River Sabah, Borneo
passive margin with relief of 2000 m in equatorial climate	in upland, boulder strewn channels, with mature trees right up to water's edge; abundant quartz sand between boulders	continuation of boulders, surface wash on slopes, bank erosion	50–100	up to 30 m	Gombak, Malaysia
passive margin with relief of 2000 m in tropical cyclone zone	upland boulders strewn or rock-cut channels, with areas of exposed rock or boulders at low flows; channels capacities much greater than previous case	disintegration of boulders, surface wash on slopes, bank erosion	50–200	up to 30 m	Babinda and Behana Creeks, North Queensland

ancient craton with relief of 2000 m	upland channels guided by ancient structural lineaments, resistant angular blocks and some derived gravel; monsoonal climates produce large broad lowland valleys	little sediment supply except through river action on rock of channel wall	up to 50	up to 30 m	Mahaweli Ganya System, Sri Lanka
ancient craton with erosion surface	wide sandy channels, little incision; occasional rock bars which suffer little erosion	wash from etchplain surface	up to 30	up to 30 m	Zaire, Africa
sedimentary basin on ancient craton	wide anastomising channels, often with legacies of past phases of fluvial erosion	little locally derived sediment, except from bank erosion	up to 30	up to 30 m	Amazon basin

Table 5. *Scales of variation of sediment yield*

time interval	important processes	examples
minutes/hours	earthquakes landslides debris flows	—
5–25 h	tropical cyclones volcanic eruptions	tropical storm Agnes Mt St Helens
days	major floods	recent Bangladesh flood
weeks/months	seasonal floods seasonal drought	monsoon effects on major Asian Rivers; blocking of river mouths by coastal sand drift causing hiatus in sedimentation
years	aridity, possibly associated with ENSO events	cessation of sedimentation in drought affected ephemeral streams, temporary dominance of wind blown sediments; role of fire in vegetated areas
decades	minor climatic trends, retreat of glaciers	changes in sediment sources and thus in types of deposit
centuries	diversions of drainage; impacts of people on ground cover	change in rates and nature of sediments; effects of natural and artificial changes in river flows
10^3–10^4 years	major climatic oscillations, changes in climatic controls of sedimentation, e.g. glaciation; significant shifts in sea level and thus in zones of deposition	breaks in sedimentation caused by major vegetation changes, e.g. alternating sequences on fringes of Amazonia, invasion of Kalahari sands into Congo basin
10^5–10^6 years	tectonic controls altered, changes in directions of minor streams, especially in high yielding small coastal basins in tectonically active areas	disruption of sedimentary sequences in Indo-Gangetic Plain as result of Himalayan uplift; changes in major drainage patterns, e.g. inland basins becoming linked to sea
10^7–10^8 years	effects of plate tectonics	changes in depositional basins

the long term sediment loads from small river catchments. Tropical storm Agnes, for example, produced a sediment yield equivalent to 1008 t km^{-2} in an hour from the small Steve Run catchment at Reston, Virginia (Guy & Clayton 1973; the long-term rate is of the order 100 t km^{-2} a^{-1}). The processes listed in table 5, however, operate on different spatial as well as timescales. Extreme storm events are usually local in extent and their influence on sediment delivery is greatly damped by the sediment holding capacity of major catchments. Further 'smoothing' of delivery patterns is evidenced by the more uniform accumulation (especially of fine-grained clastics) in terminal basins (sediment comes from several river systems draining even larger areas). This is well illustrated by the record of sedimentation over the last 2×10^4 years preserved in cores from the Black Sea (summarized in Degens 1989, figs 8.20 and 8.21). Significant shifts in mean sedimentation rate occur at intervals of the order 10^3 years and variability about the mean is small compared with the shifts.

These intervals are of the same order as documented climate change. The most rapid of such changes probably occur when catchments lie in regions of significant climate gradient. One such would be that between tropical rain forest and monsoonal excursion zones (Zeigler *et al.* 1987). In the former, a continuous vegetation protects the soil against erosion while the latter supports incomplete cover and a greater erosion potential. Climatic oscillations of this type correlate with the deep sea core evidence of repeated cooling and warming during the Quaternary. The critical distinction is between incomplete vegetation cover characteristic of seasonal climates and the full cover of ever-wet climates. Changing sedimentation rates driven by such climatic fluctuations must be good candidates for altering patterns of sediment diagenesis.

(*e*) *Obvious and less obvious tectonic influences*

The obvious effects of tectonic activity operate on both very short (volcanicity, earthquakes) and very long scales (orogeny and uplift). Major adjustments of drainage basins can be one consequence of importance here, although such events are likely to be infrequent if of sufficient spatial scale to influence basinal sedimentation. Satellite radar imagery has revealed the existence of a trans-African drainage system (TADS; McAuley *et al.* 1982) dating back to the Middle Tertiary. This giant ancestral river rose in the high plateaus to the west of the Red Sea in Egypt and the Sudan and flowed towards the Cenozoic Chad Basin. A precursor of the modern Zaire (Congo) River also flowed into the Chad Basin (Faure & Lang 1991). Sediments that would have gone into the Nile delta or Zaire offshore fan were feeding the Upper Cretaceous and Cenozoic continental formations of Chad. Uplift of the region between the present Zaire and Chad basins diverted the Zaire waters to the Atlantic. Such diversions produce breaks in sedimentation and abruptly alter sedimentation rates and compositions. They would not occur sufficiently frequently to explain repeated changes in diagenetic style.

(*f*) *Documented variations in sediment load mineralogy*

Climate, through its influence on soil moisture which determines the soil chemical environment, is the dominant control of the clay minerals in the A-horizons of soils. The intensity of seasonal leaching may be the primary climatic control of clay mineral assemblages (Folkoff & Meentemeyer 1985), but palaeoclimate and soil age are also important. Thus in the United States, soils in many arid areas and in places overlain by glacial deposits do not have the type of clay mineral assemblages that would be expected from the present-day climate.

Abrupt vegetation changes in low latitude upland areas are similar to those which occurred during deglaciation in higher latitudes. The phases of rapid sedimentation during the periods 14500–10500 BP illustrate that accumulation of sediments is also regulated by the way in which vegetation responds to climatic fluctuation (Vincens & Bonnefille 1986).

In the 520 km^2 Girou catchment, a tributary of the Garonne, S.W. France, illites dominate the suspended sediment most of the time, but during high flows and particularly in storm periods, there is a decrease in the percentage of illite and an associated increase in the percentage of smectite, an important component of the soils of the region (Probst 1986). Illite has also been found to be the major clay in suspended sediment in four S.W. England catchments (Walling & Kane 1982). In the northeastern U.S.A. (Kennedy 1965), in the Pyrenean zone of the Garonne catchment and the mountainous part of the Amazon catchment (Gibbs 1967). Illite, however, is not an authigenic soil mineral (hence no reflection of climate). It is probable that erosion of partly weathered or poorly consolidated bedrock is releasing old clay minerals for recycling through the modern sediment transport and deposition system.

The mineralogy of sediments carried through the Amazon River system is dominated by erosion in the mountanous headwaters. The clay mineral assemblage exported to the Atlantic strongly resembles the suite of minerals from the mountainous tributaries and is radically different from those in the tropical lowland tributaries. The significance of this observation is borne out by the measurements of the sediment load of the Amazon at Obidos. The one-day suspended sediment transport rate was 4.7×10^6 t, of which about half was contributed by the Rio Solimoes and at least another fourth by the Rio Madeira. The Rio Negro contributed less than 1% of the total sediment load (Meade *et al.* 1979).

In the Amazon, reworking of sediments occurs as the lowland channels erode their banks, thereby incorporating older material stored on the floodplain in their sediment loads. The older sediments will have undergone weathering while on the floodplain and will thus have a much higher proportion of kaolinite and vermiculite among the total clays than younger sediments (Johnson & Meade 1990). The downstream increase in the compositional maturity of bed-material sands in the Amazon cannot be explained by variations in the composition of material carried by incoming tributaries alone.

The historical influence of former climate episodes and the ability of large drainage basins to store material for times greater than those of climate fluctuation are both clearly seen in the examples cited above. Short-term variations in sediment composition due to hydrometeorological events occur but it is doubtful whether these would generate anything other than extremely fine scale compositional variations in sediments accumulating in large terminal basins. Such variation would almost certainly be destroyed by bioturbation except in basins like that of the euxinic Black Sea.

4. Conclusions

The major influences on the nature and rate of delivery of sediment from drainage basins are tectonic environment and climate. An analysis of diagenetic processes in fine-grained clastic sediments suggests that fluctuations in the rate of sediment supply would force (*a*) bed-parallel changes in the intensity of diagenetic modification, and (*b*) radical variations in the mineralogy of the early authigenic phases (sulphides, carbonates, silicates).

Although difficult to evaluate, changes in delivery rate over 10^3 years or longer are suggested to be necessary for significant variations in diagenetic style in mudrocks (this contrasts with catastrophic processes within basins, such as turbidity flows, which can deposit large sediment packages at infrequent intervals).

The most likely cause of change on this timescale is climate: minor trends or major oscillations. Orbital cycling could be recorded by patterns of diagenetic alteration driven by sediment input variations but the signal must be complicated by longer-term and non-systematic influences of bedrock geology and tectonic style.

Interpretation of diagenetic alteration preserved in ancient sedimentary rocks must be seen in this temporal context. Simple extrapolation from studies of processes operating today (solute distributions in sediment pore waters), which provide only snapshots, is difficult. Such studies are excellent for process description but less reliable for product prediction.

Over periods of 10^3–10^4 years, the composition of sediment exported from a sedimentary basin will also fluctuate. The proportion of material recently detached from bedrock to that previously stored within the drainage basin (and more extensively weathered) will vary as the catchment moves from phases of accumulation to degradation. We have no direct records of such variation but sediment presently being exported from different major river systems rather suggests that extreme variations are unlikely (sufficient to account, for example, for sideritic ironstones). Redistribution by diagenetic processes in response to variations in sediment accumulation rate seems a more probable explanation for many marked compositional contrasts in ancient mudstone successions.

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Discussion

Z. Reut. The climatic fluctuations affect the accumulation rate due to the flow of water and the amount of carried sediment; the effects of catastrophic events such as meteor impacts, volcano eruptions and earthquakes should be included.

C. D. Curtis. Catastrophic events could certainly have an effect. Massive turbidity flows, for example, cause a package of sediment to be 'instantaneously' deposited (see below).

P. Meadows. The paper has drawn attention to the importance of longer-term climatic fluctuations. This must be right but what about the short-term episodic events which happen every day (for example, heavy winter storms in the Clyde estuary and episodic floods of major rivers such as the Indus)? Perhaps episodic events should be regarded as scatter in a statistical sense on long-term climatic trends. What are your views on the relative importance of these two aspects of sedimentation on a geological timescale?

C. D. Curtis. Episodic events certainly can determine the style of diagenesis. Probably the best-documented examples are infrequent turbidites within deep-sea pelagic sediments which show oxidative processes 'burning down' into the instantaneously deposited turbidites. In these cases, extremely slowly deposited sediments are infrequently interrupted by very rapid sedimentation. Single flood events are unlikely to involve such massive volumes of sediment and are thus less likely to be dramatically documented in fine-grained sediment accumulations such as those discussed here. The Black Sea sediment cores document a record of both types of sedimentation and allow comparison; for that special case.

J. P. N. Badham. Professor Curtis demonstrated the influence of man on sedimentation rates in the Black Sea. You later made the point that we could/should use modern environments as snapshots which could be keys to past environments. I suspect that all modern sedimentary environments have an anthropogenic signature. We should then be very careful in using data from the present to extrapolate to fossil environments.

C. D. Curtis. I think that you are almost certainly correct. That means that we should always exercise caution. We can have confidence about some processes operating in the past but it is very difficult to be at all confident about the scale (rate, overall importance).

C. S. Bristow. Climate control in temperate régimes was mentioned but tectonic uplift is more important than climate in the tropics.

C. D. Curtis. Climate and tectonics are certainly both important (see table 4 of text).

J. T. Parrish. How good a guide is the present to the past? We perhaps need to go back to fundamentals which do not depend on what is seen in modern sediment. Has very slow sedimentation been studied other than in the deep Oceans? How close are we to understanding modern processes sufficiently well to judge if the present is the key to the past?

C. D. Curtis. Perhaps the only principles that we can always rely on are those of basic physics and chemistry. Many authors have demonstrated that diffusion, advection and reaction can be handled successfully (thermodynamics for reaction trends, kinetics for some quantification). Very slowly accumulating shallow water present-day sediments have not been studied in detail to my knowledge. They may not exist now (patterns of sea-level change) but the geological record would seem to provide plenty of examples (sedimentary ironstones).