Sedimentary Facies as Indicators of Mesozoic Palaeoclimate [and Discussion]

B. W. Sellwood, G. D. Price, N. J. Shackleton and J. Francis

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Sedimentary facies as indicators of Mesozoic palaeoclimate

B. W. SELLWOOD AND G. D. PRICE

Postgraduate Research Institute for Sedimentology, The University, Whiteknights, Reading RG6 2AB, U.K.

SUMMARY

Sedimentary facies alone provide equivocal, and qualitative, evidence about Mesozoic climates and climate changes. The most climatically informative sediments are laterites, evaporites and aeolianites. Tills would also be unequivocal where present. A range of other criteria (e.g. distributions of calcretes, gypcretes, vertisols, clay mineral species, storm deposits, glendonites and specific types of marine carbonates) provide supplementary evidence of climate, as does the distribution of wildfire-generated fusain. Sedimentary evidence must be integrated with other data. Coals, formerly considered to form in moist tropical climates, are now known to accumulate equally well in temperate mires. Oxygen isotopic data must also be critically evaluated in palaeotemperature studies, particularly because of possible diagenetic re-setting. Sedimentary rocks are the products of depositional and diagenetic averaging and seldom faithfully record the more subtle climate signals.

1. INTRODUCTION

Sedimentary facies provide important criteria by which palaeoclimate models may be both tested and refined. The sediments that accumulate on continental surfaces and within sedimentary basins are, at best, imperfect receivers of the climate signal, certain settings, such as arid deserts and ice-caps, being better than others (e.g. those today situated in broadly temperate latitudes).

To appreciate fully the climatic information within a sedimentary succession it is often necessary to integrate large amounts of disparate information, both on the macro- and micro-scales. Data should ideally include: field-based observations (bedding styles and palaeocurrent information); X-ray diffraction; geochemistry; and detailed information on organic components (palaeostratigraphical, palaeobotanical and palaeozoological). It is unfortunate that much regionally based literature, not originally collected for palaeoclimatic purposes, fails to provide an adequate data base.

2. MARINE CARBONATE FACIES

(*a*) *Warm-water and cool-water facies*

It is commonly assumed that ancient carbonate distributions reflect the former existence of warm ancient seaways, the equability of the Mesozoic earth finding expression in the broad palaeolatitudinal spread of carbonate facies. Modern shelf seas are dominated by carbonate facies in areas of high organic productivity and where relatively low rates of terrigenous clastic influx prevail (Sellwood, in Reading 1986). Most marine carbonate is ultimately of organic origin (either as skeletal grains or as a precipitated by-product of organic activity). The rate of marine organic productivity generally increases from the higher to lower latitudes in concert with the increase in solar illumination, and appears to have done so in the Cenozoic and Mesozoic (Ziegler *et al.* 1984). Carbonates may also predominate upon many modern temperate shelves and criteria for their recognition in ancient rock successions, particularly the Cenozoic, are being established (e.g. Lees 1975; Nelson 1988; James & Bone 1991).

Climate-regulated productivity and sediment accumulation is reflected in an equatorial pelagic sediment bulge and depressed (4.5 km) calcite compensation depth (CCD), the CCD being at less than 0.5 km in polar waters. Possible Mesozoic excursions of the CCD are still matters of speculation. Oceanic silica-rich sediments today accumulate in equatorial and circumpolar latitudes associated with nutrient-rich upwelling, but the distribution of these high productivity belts has also changed through time (Jenkyns, in Reading 1986).

Recent warm water shelf carbonates form between about 30°N and 30°S (figure 1), are diverse, and include hermatypic (reef-building) corals, codiacian algae and may include ooids, aggregates and pellets (chlorozoan skeletal grain association of Lees (1975)). Modern temperate water carbonates are dominated by benthic foraminiferans, molluscs, bryozoans, barnacles and calcareous red algae (foramol skeletal grain association of Lees (1975)). Only ahermatypic corals occur in this association. Mesozoic equivalents are poorly known.

Modern warm-water shelf carbonates are dominated by Mg calcite and aragonite whereas modern

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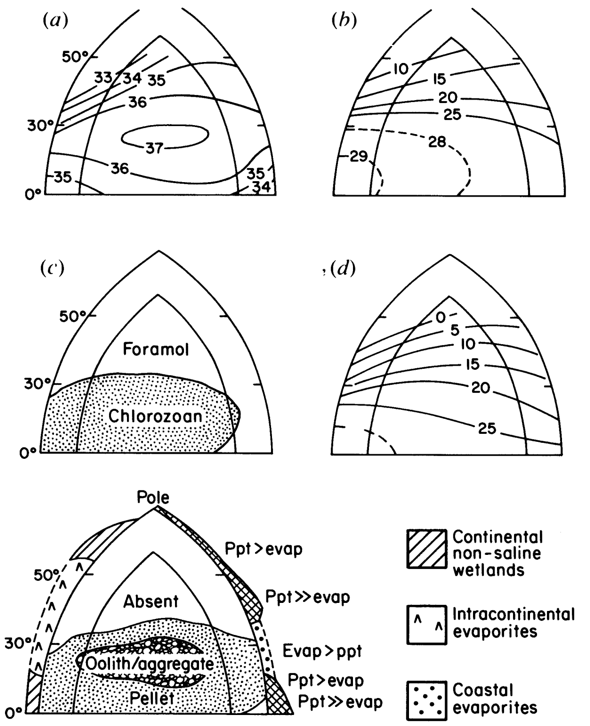

Figure 1. Predicted distributions of shallow-water (less than 100 m depth) carbonate grain associations according to their salinity–temperature annual ranges (after Lees 1975). (*a*) Salinity (‰); (*b*) maximum temperature (°C); (*c*) skeletal associations; and (*d*) minimum temperature (°C). Predicted evaporite and continental wetlands distributions after Parrish & Barron (1986) and McCabe & Parrish (1992).

temperate water carbonates are predominantly low Mg calcite. Calcite predominated in most Jurassic and Cretaceous shelf carbonates (Sandberg 1985). The skeletal compositions of major carbonate producers appears to have changed through time (Wilkinson 1979). Modern aragonitic ooids form in less than 5 m of water but the direct equivalence of calcitic Jurassic and early Cretaceous ooids may be questionable (Wilkinson *et al.* 1985). There is an apparent absence, globally, of Late Cretaceous oolites, raising questions about the constancy of composition of seawater throughout the Cretaceous, as well as the probability that significant changes occurred from the Mesozoic to the present.

The ecological requirements for many Mesozoic biota are poorly known, and it is often difficult to evaluate the influence of salinity, turbidity, terrigenous sedimentation rates and nutrient supply on ancient communities. Late Cretaceous (Campanian) shore-zone carbonates in southern Sweden (Sellwood, in Reading 1986) and bryozoan- and sponge-rich quartzose carbonates of Aptian and Albian age (southern Britain and France) formed at about 40°N palaeolatitude and are possible temperate water facies, as are the more northerly of the late Cretaceous chalks which extended to 50°N palaeolatitude in north Europe.

(*b*) *Reefs and buildups*

The distributions of fossil reefs and carbonate buildups are often interpreted as reflecting the presence of ancient warm water seaways analogous in terms of their distributions with those of the present day (e.g. Crowley & North 1991; Hallam 1985; Frakes 1979; Flügel & Flügel-Kahler 1992; James 1983). However, the communities of organisms that constructed many ancient buildups were often dissimilar to the coral-rich (chlorozoan association) ecosystems represented by modern reefs, as may have been their trophic requirements.

Middle Triassic buildups were dominated by calcisponges and algae but late Triassic carbonate buildups (formed by corals, calcisponges, hydrozoans and algae) became both large and widespread throughout the Tethyan margins. Buildups comprising calcareous sponges and shell banks, extended well beyond palaeolatitude 30°N but are distinctly different from the Tethyan associations (reviewed in Flügel & Flügel-Kahler 1992).

At the end of the Triassic a significant reduction in the size, abundance and distribution of buildups occurs which may have been the result either of lower palaeotemperatures or sea-level changes (discussed in Hallam & Goodfellow 1990). Jurassic buildups have a predominantly Tethyan distribution (see Hallam, this volume).

Coral-dominated buildups arose once more at the end of the Jurassic and continue into the early Cretaceous. During the Cretaceous rudistid bivalves became important constructors of mounds and mudbanks well beyond palaeolatitude 30°N, especially in N America (Flügel & Flügel-Kahler 1992). Corals are also distributed well beyond these palaeolatitudes, although those in the highest palaeolatitudes were often ahermatypic (Beauvais 1992).

3. OXYGEN ISOTOPES

The principles of palaeotemperature determination from carbonates using oxygen isotope ratios are well established and measurement techniques highly refined (e.g. Savin 1981; Anderson & Arthur 1983; Hudson & Anderson 1989; Spicer & Corfield 1992; Marshall 1992). Measurements are generally made on carbonate grains and cements but palaeotemperature interpretation of these measurements is often complicated because of uncertainties over the composition of the water from which the carbonates precipitated (e.g. due to evaporation or meteoric in-put), 'vital effects' at the time of skeletal formation, and diagenetic alteration of the carbonates themselves. In addition, the oxygen isotopic composition of seawater is known to have varied in response to the formation and disappearance of ^{16}O-rich icecaps (e.g. Hudson & Anderson 1989). Sea-surface temperatures interpreted from isotopic results are the only quantitative geological data available as inputs to global circulation model (GCM) experiments.

Marshall (1992) has evaluated those fossils in which a high preservation potential of the original isotopic

Table 1. *Preservation potential of original isotopic signals from marine carbonates (after Marshall 1992)*
(W:R ratio, water:rock ratio; LMC, low Mg calcite.)

ISOTOPE SIGNAL PRESERVATION POTENTIAL	**COMPONENT MINERALS**	**COMPONENT TYPES**		**BULK SEDIMENTS**
		Skeletal	**Non skeletal**	
HIGH Good chance of preservation of Carbon and Oxygen values	**Pristine aragonite** **Pristine Low Magnesium calcite**	Molluscs Brachiopods Belemnites Foraminifera Bivalves	Marine cements Marine cements LMC Ooids	Pelagic sediments particularly coccolith oozes
MODERATE Carbon values may be preserved oxygen values commonly altered	**Secondary calcites (stabilised in relatively closed system with low W/R ratio)**	Molluscs Foraminifera Corals Echinoderms Calcareous algae	Marine cements Ooids, peloids intraclasts	Some Micrites Some shallow water limestones Some dolomites
LOW Carbon and Oxygen values likely to have been altered	**Secondary calcites (stabilised or cemented in relatively open systems with high W/R ratio)**	Limestones and components altered by near surface meteoric diagenesis or intensive cementation or recrystallisation during burial. Many Dolomites		

signal is to be expected (table 1), but the life habits of some of the prime groups are not fully known (e.g. belemnites) and shell material may not have been precipitated under constant conditions throughout the life of the animal. Diagenetic alteration of shells presents a major problem, particularly for older Mesozoic materials. Even the original porosity of belemnite rostra is unknown (Veizer 1974), the precipitation of low Mg calcite marine cements might have masked original palaeotemperature signals (Sælen 1989). The 'vital effects' exhibited by many organisms causes the secretion of their organic carbonate not to be in isotopic equilibrium with the water. This is well known in corals, but planktonic foraminifera (e.g. studies by Shackleton *et al.* 1973; Williams *et al.* 1977) and coccoliths also show some departure from isotopic equilibrium (e.g. Dudley *et al.* 1986).

Results of oxygen isotope palaeotemperature determinations from cherts and phosphates (e.g. Karhu & Epstein 1986) are often difficult to assess whereas those from chert-phosphate pairs provide temperatures comparable with values calculated from oxygen isotopes in well preserved calcareous marine skeletal remains. Temperature determinations from diagenetic concretions are problematic, but 5°C mean annual temperatures have been suggested for the high latitude early Cretaceous of Victoria, Australia from such evidence (Gregory *et al.* 1989).

Isotopic data suggest a phase of early Cretaceous global warming which reached an optimum in the Cenomanian–Turonian before temperatures declined towards the end Cretaceous (summaries in Crowley & North 1991). Within sequences palaeotemperature trends, both short-, and long-term, may be as significant as the absolute temperature values obtained (Marshall 1992). Oxygen isotopic analyses of phosphatic fish (Kolodny & Raab 1988) provide data agreeing with the Cretaceous trends already discussed but in which the absolute temperature values differ slightly from values obtained by other means.

4. EVAPORITES

Evaporites may form anywhere on the Earth where evaporation exceeds rainfall and rate of water inflow (figures 1 and 2). Their preservation is controlled by the nature of the post-depositional climate, ingress of burial waters and the subsequent burial history. The palaeoclimatic significance of evaporites has been reviewed by many authors (e.g. Parrish *et al.* 1982).

Because of their solubility most evaporites, apart from gypsum and anhydrite, are only known in the sub-surface and so detailed facies associations are sometimes difficult to define. Modern coastal evaporites accumulate in two broad zones between 15° and 35° latitudes, but are known intracontinentally in Central and Eastern Asia, and in South America, extending to 50° (figure 1; Parrish *et al.* 1982). Some modern salt lakes are frozen for several months in the year, so salt precipitates do not necessarily imply permanantly warm systems.

The formation and preservation of the more soluble salts of potassium and magnesium also requires low atmospheric relative humidities (less than 50%). Carnallite ($\mathrm{KMgCl3 \cdot 6H_2O}$), for example, is being formed today in salt pans of the Tunisian Sahara, the Qaidam Basin (China) and the Danakil Depression, carnallite precipitation occurring diagenetically in the shallow sub-surface (Bryant *et al.* 1993; Casas *et al.* 1991). Evaporites frequently lack stratigraphically

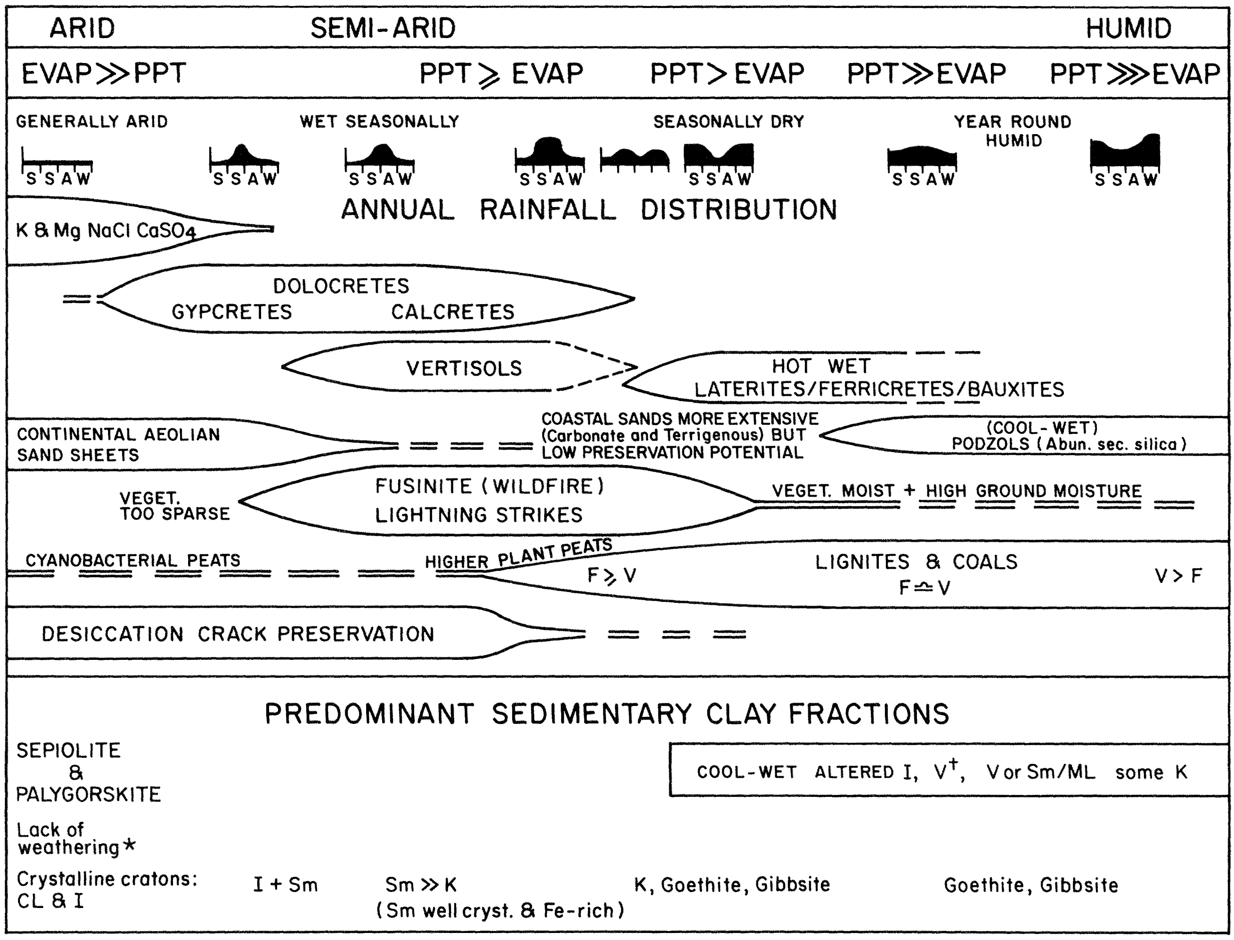

Figure 2. Possible climatic interrelationships between particularly significant sedimentary parameters. Annual rainfall distribution is schematically shown (generally low, a single wet season, more than one wet season, generally wet, generally very wet). Coals/lignites: F = fusinite; V = vitrinite. Clay fractions: I = illite; V = vermiculite/vermiculitic; Sm = smectite; K = kaolinite; CL = chlorite. †Vermiculite can form under a wide variety of conditions. *Unaltered parent rock within fines under both arid and frigid terrains.

significant biota and may accumulate very rapidly (100 m in 1000 years according to Schreiber, in Reading 1986) so short-lived evaporative episodes may generate major thicknesses of salts.

5. STORM DEPOSITS

Climate models provide insights into global storminess. In the sedimentary record storm deposits are becoming increasingly recognized, and are to be expected in many shallow marine and lacustrine settings because they have a high preservation potential (Johnson, in Reading 1986). Being the deposits of high energy events, which punctuate otherwise 'fair-weather' phases, they can occur almost anywhere. The recognition of storm-dominated areas, and storm tracks themselves are of paramount significance in palaeoclimatic modelling. But the very features most important for modellers namely: storm strength, storm frequency and storm track direction, are most difficult to interpret because of Coriolis and palaeogeographic effects.

6. GLACIAL SEDIMENTS

About 10% of the Earth is covered by ice today and at times of glacial maxima this extended to 30%. The direct products of glaciation are tills (generally unsorted boulder clays) that are dumped in glaciated areas. Sedimentary facies associated with glacial terrains are fluvioglacial outwash, wind-blown loess and glaciomarine muds with dropstones (Edwards, in Reading 1986).

Glacial debris originates either by erosion of the subglacial bed, or by incorporation of material dropped onto it from valley walls. Subglacial abrasion provides very poorly sorted, rounded or sub-rounded clasts which often exhibit very characteristic striations and facets. In contrast, supraglacial frost-shattering generates coarse-grained angular debris. The dumping of material directly from glacial ice leads to the formation of till (a diamicton). The proglacial setting includes glacio-marine environments over which glacier ice floats and is able to drop glacially-transported materials. Such environments are reported in the Mesozoic record (e.g. Aptian Bulldog Shale of Australia, Francis & Frakes 1993). Detailed sedimentological descriptions of this unit, and equally importantly the associated facies (see Edwards, in Reading 1986) await publication. The assertion that occasional exotic clasts (including granite) in the English Chalk are glacial dropstones (Jeans *et al.* 1991) awaits fuller justification, the roots of floating trees being equally

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capable of transporting such materials. Periglacial features and the general range of cryoturbational structures produced by freeze-and-thaw processes are not yet recognized in Mesozoic successions.

7. GLENDONITES

Glendonite carbonate nodules are taken to reflect cold subaqueous depositional conditions (Frakes & Francis 1988; Francis & Frakes 1993). Glendonites are pseudomorphs after the mineral ikaite, the low-temperature polymorph of calcium carbonate ($CaCO_3 \cdot 6H_2O$), and Shearman & Smith (1985) have elegantly examined the significance of ikaite (and glendonite) in palaeothermometry. Ikaite crystallizes at temperatures close to 0°C but readily decomposes to calcite and water at higher temperatures, but its morphology is distinctive. The pseudomorphs comprise obliquely striated and stepped crystals with a characteristic curved and tapered form. Ikaite characteristically grows in cold-water sediments that are rich in organic matter, are highly alkaline, reducing, and have a high hydrostatic pressure. Antarctic shelf ikaite occurs in 1950 m of water at -1.6°C and more than 6 kbar (Suess *et al.* 1982). Occurrences at temperate and tropical latitudes are known from deep (4 km) waters with higher temperatures (4.6 to 7.7°C; e.g. Stein & Smith 1986). An association with clathrates (methane-rich ice) has been noted by several authors. The palaeothermometric relationships are not yet perfectly known, even where glendonites are correctly identified in ancient successions. Descriptions of Mesozoic glendonites, and their facies associations, are relatively brief by comparison with their significance, and some key occurrences await fuller description (e.g. those in the Cretaceous of Australia and Canada, and the Jurassic of Siberia).

8. COALS AND LIGNITES

Coals and lignites (figures 1 and 2) have long been taken as indicators of terrestrial humidity (precipitation exceeding evaporation; reviewed in Parrish *et al.* 1982; Hallam 1985). Climatic and tectonic factors are the more significant factors influencing: mire type; type and rate of vegetation growth; rate and degree of humification; rate of base-level change and rate of terrigenous sediment input (McCabe & Parrish 1992). Where precipitation occurs on most days the opportunity exists for mires to be constructed by organic growth and to accumulate above the general level of the regional water table. Such raised mires are generally restricted to humid maritime climates.

Holocene low-latitude mires exhibit the highest organic productivity, and faster rates of peat accumulation. Both incident solar radiation and precipitation exert important controls on peat accumulation (McCabe 1991). The preservation of organic matter requires either rapid burial or anoxic conditions, and this is favoured in zones permanently below the water table, especially in areas of high organic influx. Decay acts more rapidly at higher temperatures, frigid conditions also favouring peat preservation. Plant material becomes more readily preserved as charcoal (fusain), fires burning peats down to the water table will generate fusain in seasonally drier régimes (figure 2), and may selectively preserve twigs and stems (Harris 1981).

The high water tables necessary for peat accumulation tend to occur in climates where precipitation exceeds evaporation and where rainfall is evenly distributed throughout the year (figure 2; McCabe & Parrish 1992). Such conditions occur today in equatorial and high mid-latitudes (Parrish & Barron 1986), but may well have been different in the past (Crowley & North 1991).

9. WILDFIRES

Fusain, comprising almost pure carbon, in sedimentary rocks is fossil charcoal and was the product of ancient wildfires (Harris 1981; Scott 1989; Scott & Jones 1991). Even before the advent of man many terrestrial environments were either influenced, or even controlled, by wildfires in terms of their ecology and the adaptive traits of fire-resistant plants (Kozlowski & Ahlgren 1974; Mueller-Dombois & Goldhammer, in Goldhammer 1990). Natural fires are usually triggered by lightning, but may also result from volcanic eruptions, boulder slides, earthquake rock-fracture and more rarely through bacterial combustion (Edwards 1984; Schule, in Goldhammer 1990).

Ideal conditions favouring regular and natural frequent firing are those which provide a sufficient supply of dry fuel to allow fires to propagate laterally, steady uni-directional winds and 'sparks' applied when the tinder is dry. Fire régimes in tropical and sub-tropical conditions have been typed in terms of their ecological gradients and predicted trends have been established for fire frequency, climate seasonality, erosion rates and fire-tolerance adaptation (Goldhammer 1990).

Fire frequency depends upon the distribution of fuel, its humidity and its ignition frequency whereas fire intensity depends upon the wind, and on both the quantity and quality of the fire potential (Schule, in Goldhammer 1990). The susceptibility of an environment to fire is thus influenced by the climate (figure 2). Fire-prone environments are predominantly those experiencing a burst of seasonal growth (usually triggered by rains) followed by seasonal drought, the droughts ending with thunder storms, which produce lightning but not always rain (e.g. Edwards 1984).

Fire plays a less significant role in year-round wet biomes because of their permanently warm temperatures and continuously high atmospheric and soil moisture levels (figure 2). High rates of decomposition usually preclude the possibility of organic accumulation on forest floors so lightning strikes rarely gain access to primary rain forests (Mueller-Dombois & Goldhammer, in Goldhammer 1990). Forest fires are not confined to seasonally dry areas, even though it is in such areas that their effects are most commonly seen. During extreme droughts areas that are normally swamplands may be ignited (Goldhammer & Siebert, in Goldhammer 1990).

Long-range transport of combustion-derived aerosols has been reported from the remote tropical regions of the Atlantic (Andrae 1983). Soot (and smectite clay) abundances in these areas were comparable with those recorded from the rural continental areas of Africa from which they were derived, thus underlining the significance of fine fusain as a marker of such fire-prone regions, and the palaeo-downwind direction.

Lands laid-bare by fire suffer greatly increased erosion rates. Fires followed by torrential rains, or winds, will result in both sediment and charcoal being transported into adjacent depositional sites (SCUBA observations on modern carbonates in Corsica 1989 confirm this (B.W. Sellwood, unpublished results)).

The presence of abundant fossil charcoal probably reflects seasonally wet and seasonally dry climate. In combination with other evidence (e.g. from palaeosols and clay minerals) a qualitative breakdown of climatic régimes may be possible (figure 2). Fusain is well represented in Cretaceous and Jurassic successions, but appears to be less well recognized in the Triassic but systematic documentation of fire-prone Mesozoic regions is needed.

10. PALAEOSOLS AND CLAY MINERALOGY

(*a*) *Palaeosols*

The composition of terrigenous clastic sediment deposited in sedimentary basins is controlled by climate, the initial weathering profile, and the length of time that the sediment has spent in soil profiles after its release from the parent rock (Wright 1993). Weathering profiles reflect the interaction between parent rock, climate and geomorphic régime, and most clay minerals are created within terrestrial weathering profiles. Detrital clay mineral associations are useful in qualitative palaeoclimatological and sediment provenance studies (Chamley 1989).

Weathering profiles comprise two major zones: the soil (the topmost biologically active zone) and the saprolite below. The amount of chemical weathering is directly related to the amount of water entering the profile and is controlled by climate (Nahon 1991). Soils form quickly and are better represented than saprolites in the geological record. Very thick weathering profiles can only develop where erosion rates are very low, particularly in areas with little relief. Such surfaces may remain stable, and thus become deeply weathered over vast periods of geological time, recording an aggregation of changing climatic effects (Wright 1993).

Laterites (or ferricretes) represent a relative accumulation of haematite, goethite, Al hydroxides (e.g. gibbsite), kaolinite and certain other minerals which remain after the removal of other labile components. Pedogenic and groundwater laterites form best in humid tropical climates with a long dry season (figure 2). Pedogenic laterites are frequently associated with a characteristic and extensive weathering profiles which may be tens of metres thick (Wright 1993), and many 'modern' ones appear to be relics of former conditions. Fully developed profiles may require 1 to 10 Ma to form (Nahon 1991). Although most bauxites (Al-rich laterites) occur with laterites, some are associated with karst (and palaeokarst; Wright 1993), developing from the insitu weathering of already weathered materials derived from lateritized areas and trapped in karstic depressions such as those occurring in association with Cretaceous shelf carbonates in Provence (southern France).

Groundwater laterites occur in lowland and coastal settings (e.g. deltas and alluvial plains) deriving their iron from the groundwaters. Iron is fixed when oxidation occurs during seasonal falls in the water-table. Such laterites may form over a wide range of climatic settings (even hypersaline and evaporitic; Wright 1992), and more rapidly than pedogenic ones.

Vertisols are soils containing 30% or more clay, usually as smectite. They lack horizonation because of 'self mixing' of the material within the soil profile caused by intense swelling and shrinking of the clay during successive phases of wetting and drying. These effects produce characteristic features (e.g. deep wide cracks, gilgai (undulating micro-relief), slickensides and wedge-shaped structural aggregates). These special characteristics depend both on the type and amount of clay and an almost exclusively warm-temperate to tropical climate with 4–8 dry months each year (figure 2; Wright 1992). Such soils may also form in playas within otherwise arid or semi-arid regions and may have carbonate or gypsum precipitated on slickenside surfaces (e.g. in Triassic redbeds of the U.K.; Wright 1992).

Calcretes and dolocretes are nodular to massive carbonate soil accumulations generally one to two metres in thickness (Tucker & Wright 1991). The carbonate is usually sourced from aeolian dust but may be provided from lithogenic carbonate in the host sediment. They are generally formed in arid and semi-arid areas and are often found in association with zones of gypsum precipitation (gypcretes), some carbonate zones may reach 10m in thickness and extend over 1000 km^2. Authigenic Mg-rich clays such as sepiolite and palygorskite form if evaporative concentration of cations has occurred (figure 2). The isotopic compositions of ancient calcretes has been related to palaeotemperature and vegetation type, but serious objections to some of these conclusions have been raised by Wright & Vanstone (1991).

Silcretes form where soils and saprolites become cemented by secondary silica (Milnes & Thiry 1992; Wright 1993). Pedogenic silcretes appear not to be forming at the present time and their exact climatic requirements remain unclear. Groundwater silcretes are best developed in areas experiencing strong fluctuations in the groundwater table, silica cementation often occurring in concert with calcrete dissolution.

Cool-wet environments permit the accumulation of humus which promotes acidic ($\mathrm{pH} < 5$) soils. Such podzols are black or brown in colour and sometimes have secondary silica accumulations. Podzol formation causes micas and chlorites to be hydrolysed to open illites and chlorites, and vermiculitic or smectitic mixed-layer clays also become significant (figure 2). Vermiculitic mixed-layers dominate in cool temperate régimes while degraded smectites are abundant in warm temperate areas (Chamley 1989). If the parent rocks are rich in feldspar then localized kaolinite generation can occur. Well-drained siliceous substrates may develop podzols even under warmer climatic régimes.

(*b*) *Clay mineralogy*

The distributions of clay minerals in recent oceanic sediments reflects weathering processes on the adjacent continental areas and the predominantly climatic distribution of soils. Clays, in both marine and non-marine sequences, can provide significant palaeoclimatic information (figure 2). Differential settling caused depositional segregation of clays (e.g. near-shore kaolinite deposition) and the effects of burial diagenesis (smectite degradation at more than 2.5 km) cannot be ignored. Cretaceous marine clays of the Atlantic–Tethyan region are characterized by an abundance of Al–Fe smectites suggesting the widespread distribution of a warm hydrolysing climate (Chamley 1989). The general dominance of smectite over kaolinite reflects strong fluctuations in seasonal humidity. Late Jurassic sediments in this area exhibit kaolinite contents that are higher than those of smectite suggesting year-round humid conditions and warm temperatures. In southern England and northern France, poorly leached alkaline pedocals of the Latest Jurassic were replaced by acidic and well-leached podzols (with a more diverse flora) in the Early Cretaceous (Sladen & Batten 1984). Their data appear to show a negative correlation between kaolinite and fusain, possibly reflecting a diminution in wildfires as humidity increased.

11. AEOLIANITES

Aeolian sandstones (figure 2) as discussed by Allen (this symposium) are often assumed to have accumulated under hot arid conditions, but such beliefs have been seriously questioned (Bigarella 1972; Ahlbrandt & Andrews 1978; see references in Kocurek 1988). Abundant precipitation does not prevent aeolian sand deposition but sand stabilization and reductions in sand supply result from: water saturation and freezing of the sand surface; formation of desert pavement, and growth of vegetation cover. These factors are climate related (figure 3; Marzolf, in Kocurek 1988). Coastal dune complexes (either carbonates or terrigenous sands), form across a wide range of latitudes and climates (except the humid tropics) but generally have variable preservation potential, being favoured by rapid rates of sea-level rise (usually glacio-eustatic) in low energy basins (Chan & Kocurek, in Kocurek 1988). Palaeowind directions derived from ancient aeolianites provide both local and regional data critical to the testing and refinement of palaeoclimate models (e.g. Parrish & Peterson, in Kocurek 1988; Moore *et al.* 1992; Valdes & Sellwood 1992).

12. CONCLUSIONS

Mesozoic sedimentary facies alone provide qualitative information about the general climatic setting under which sedimentary rocks accumulated. Detailed information, required in palaeoclimatic modelling, necessitates a fuller integration of facies parameters than is often provided by existing sedimentary literature and subtle features (e.g. palaeosols and fusinite content, figure 2) are often missed in regional geological studies. In addition, sedimentary data must be integrated with the fullest range of palaeobiological and stratigraphic information.

With systematic searching it should be possible, in terrestrial facies, to trace lateral transitions from areas accumulating evaporites (arid), to those with calcretes (semi-arid), vertisols associated with fusain (strong seasonal wetting–drying–firing), through those with fusain but non-mineralized soils, to coal or lignitic systems reflecting moist mire régimes. Within coals the fusain to vitrain ratio may vary regionally. This ratio should change from fusain-rich to fusain-poor as the general humidity increases (figure 2). To trace co-eval lateral transitions requires refined stratigraphic frameworks.

Sea-surface temperature information, critical for GCMS, is still best interpreted by reference to stable isotopic values (δ^{18}O) from pristine shells. Glendonites and glaciogenic deposits are of paramount importance in Mesozoic palaeoclimate modelling but published accounts often lack essential details on the facies context within which such materials occur.

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Discussion

N. J. Shackleton (*Godwin Laboratory for Quaternary Research, University of Cambridge, U.K.*). Might there be a climatic control on the incidence of lightning-induced structures such as fulgarites?

B. W. Sellwood. Unfortunately, lightning does not appear to be confined to particular climate régimes, lightning effects being wider distributed than those of lightning-ignited wildfires. Lightning is also often associated with other hazards unrelated to climate, such as earthquakes, impactites and volcanic eruptions. Lightning is also well known in the atmosphere of Venus, so it is not even earth-bound.

J. Francis (*Department of Earth Sciences, University of Leeds, U.K.*). Dr Sellwood is sceptical about the significance of glendonite nodules as indicators of cold temperatures in marine basin waters, suggesting that they could have formed instead in any organic-rich sediment in over 4 km of water. Glendonite nodules (aggregates of ikaite pseudomorphs) are well known from Permian glacial sediments of Australia, from where they were first described, and from modern high-latitude ocean sediments. They are also extremely abundant in Early Cretaceous (but not Late Cretaceous) marine shales in central Australia, Spitsbergen and the Canadian Arctic, all sites positioned at high-latitudes at that time and representing marine environments less than 1 km in depth. Surely it is more than a coincidence that there are no reports of glendonite nodules in low- or mid-latitude Cretaceous sediments, even though this was a time when organic-rich sediments were common in all latitudes and in many marine settings, including deep basins, and yet glendonites are extremely abundant in many Cretaceous polar environments?

B. W. Sellwood. We have merely reiterated the physico-chemical controls on ikaite formation and its present day occurrence, glendonites being pseudomorphs after this mineral. In addition we re-emphasize the need for more fully documented and detailed accounts of glendonites (and presumed glacial dropstones), particularly in terms of their facies and stratigraphic context and not just of their asserted occurrence.