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Sedimentary Palaeoclimatic Indicators: What they are and what they Tell Us [and Discussion]

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Sedimentary palaeoclimatic indicators: what they are and what they tell us

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The significance of sedimentary indicators of palaeoclimate to future palaeoclimatic research will depend on more rigorous calibration of the climatic controls on the formation of those indicators.

1. Introduction

Climate has an important, if not dominant, effect on sedimentation, especially the formation of chemical and biogenic deposits. The strictly climatic factors that affect sedimentation in the marine and continental realms are temperature, precipitation, and seasonality. Directly or indirectly, these factors control the formation and distribution in time and space of all proxy indicators of palaeoclimate.

The purpose of this short paper is to briefly outline key controls on marine and continental sedimentation, and to illustrate points of uncertainty in interpretation of sedimentary palaeoclimatic indicators. It is at these points that calibration and quantification of the climatic effects on sedimentation will be most helpful for palaeoclimatic interpretation.

In both marine and continental sedimentation, we regard temperature as the primary climatic control. We place it highest in the hierarchy because it is nearly certain that global temperature has changed, and because temperature controls rates of chemical and biological processes. Key factors controlling sedimentation are illustrated in figures 1 and 2. We conceive of these factors as defining fields in multidimensional space, but for ease of illustration, we link the factors in flowcharts that are intended to show how the processes control the formation of continental and marine sediments. The flowcharts include climatic parameters, but also include other factors that cannot be ignored. For example, if 'tectonic activity' in figure 2, were excluded, the picture becomes more obscure with respect to climatic interpretation. We thus explicitly take the position that it is impossible to consider climatic processes alone in interpreting the geologic record of climate change.

2. Marine sediments

Marine sedimentation is controlled by numerous, often interdependent, parameters, most of which are at least indirectly related to climate in some respect. These include temperature, salinity, light, circulation, clastic influx, turbidity, depth, and oxygen and nutrient levels. Three factors – temperature, circulation, and nutrient levels – are particularly important in controlling the type of sediment deposited on open-marine continental shelves. In figure 1, nearshore and deep marine settings are ignored, and clastic input is assumed to be low; biogenic sediments are thus emphasized.

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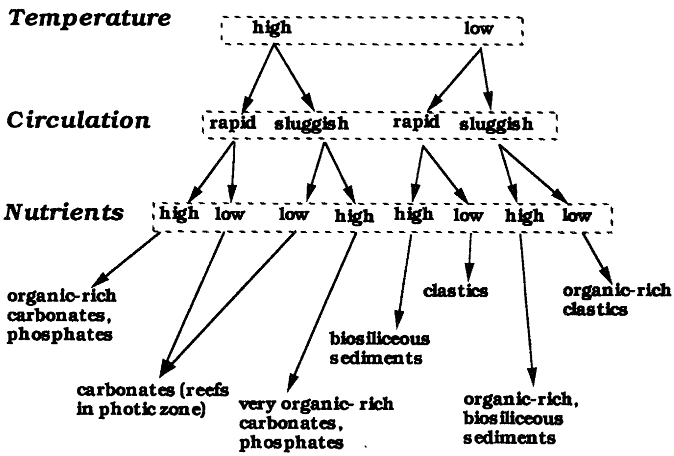

Fig. 1. Flowchart of key factors that determine marine sedimentation on continental shelves. Clastic influx is assumed to be low.

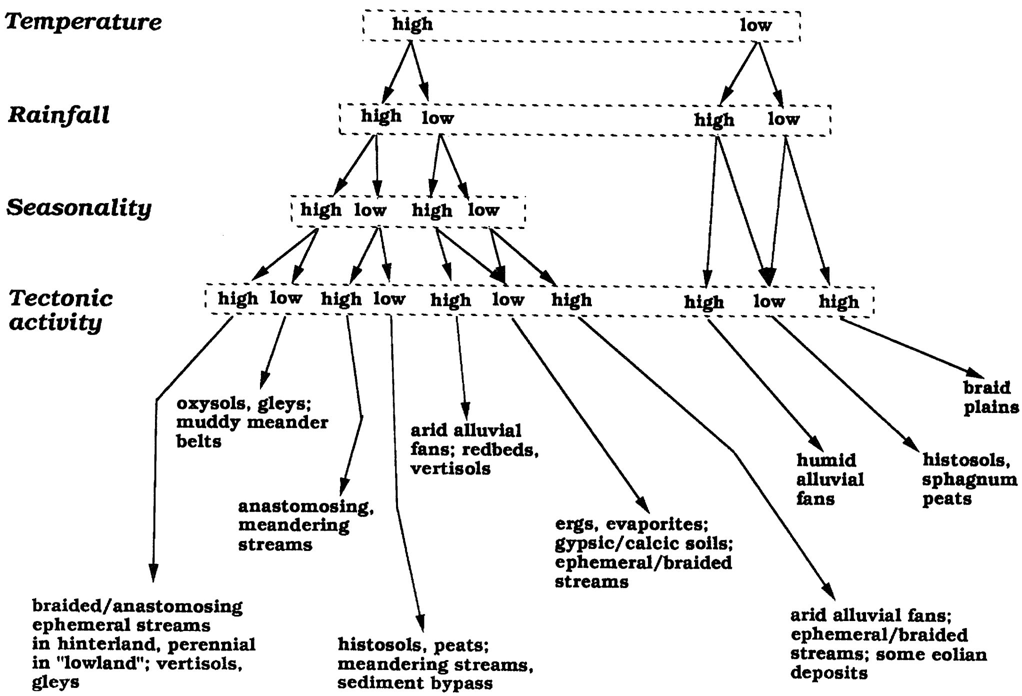

Fig. 2. Flowchart of key factors that determine continental sedimentation.

Temperature exerts the primary control on sediment type by determining whether or not carbonate will dominate the sediment. This reflects the dependence of carbonate deposition on warmer temperatures and lower latitudes. Colder waters, in contrast, are dominated by biosiliceous and/or clastic sediments.

Circulation controls sedimentation in several ways, especially with regard to the establishment and maintenance of density stratification. Stratification, and the resultant reduction in the supply of oxygen to bottom waters, limits or eliminates benthic faunal abundance and reduces oxidation potential in the sediments. This

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promotes the preservation of organic matter, which is sourced in the photic zone. Sediments in this setting will generally be organic-rich, unless nutrient availability is low and thus productivity so constrained as to allow even the limited clastic influx assumed above to dilute the organic matter.

Although sluggish circulation may promote the deposition of organic-rich sediments through preservation of organic matter, high nutrient levels also can produce sediments rich in organic carbon even with quite vigorous circulation. This occurs in many upwelling zones, where the constant input of nutrients to the photic zone produces sustained high productivity. A high sedimentation rate, coupled with an oxygen demand sufficient to deplete the bottom water of oxygen, leads to the preservation of sediment rich in organic carbon. In contrast, high-latitude, cold-water, nutrient-rich environments are less likely to produce organic-rich sediments where circulation is relatively vigorous, because of the greater oxygen-carrying capacity of cold water.

Figure 1 and the above discussion are meant to illustrate briefly some of the key controls on marine sedimentation. This simple approach to categorizing marine sediments by climatic and other factors that are responsible for their formation can be used to demonstrate some of the problems faced in attempting to reconstruct past climate from sedimentary indicators. Most of the concepts illustrated in figure 1 are well entrenched in the literature. The real need, then, is to define the thresholds at each of the 'decision points' in the flowchart. For example, perhaps the most important threshold is the temperature that determines a left-or right-hand path in the flowchart in figure 1. The absolute value of this temperature might have been different for different times in geologic history, depending on the ecology of the carbonate- and silica-secreting organisms. Another example is the role of nutrient levels in the production and preservation of organic matter, which is currently a matter of intense debate (e.g. Calvert *et al*. 1992).

3. Continental sediments

The three most important climatic variables affecting continental sedimentation are temperature, rainfall, and seasonality of precipitation, especially in warmer climates. However, the effects of these variables must be separated from those inherent to the tectonic setting of the sediment source area and depositional basin. For this reason, figure 2 includes tectonic activity as a variable in the flowchart. Tectonic activity in the sediment source area will control relief and, therefore, affect the sediment production rate. Tectonic activity in the depositional basin, which may be connected to source-area tectonics, as in foreland basins, will control depositional slope and subsidence, that is, the rate of generation of accommodation space. Depositional slope will, in turn, affect fluvial style and sediment transport rates, whereas subsidence will affect rates of deposition, the stability and longevity of surface, and the preservation potential of any particular sedimentary facies.

Temperature and precipitation affect the rate of weathering processes in the sediment source area and in areas of temporary storage of sediment along the transport pathway. The rate and extent of chemical weathering of bedrock and/or recycled or reworked sediments will determine the texture, and, to some extent, the composition of the sedimentary products in the depositional basin. The relative proportion of clay minerals and clay-sized material in the clastic sediments will be

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highest in hot, humid areas and lowest in cold, dry areas. Sediment texture, in turn, affects fluvial style. Streams carrying coarse clastic sediments as bedload will exhibit braided and anastomosing (vegetated bars) channel patterns in arid and humid areas, respectively, whereas streams with a high silt- to clay-sized sediment load in suspension will exhibit meandering channel patterns (Miall 1992).

Temperature and precipitation also affect the deposition of terrestrial chemical sediments. Coals, or histosols (see below), will form in vegetated areas with perennially high water tables. These may be maintained by either high precipitation, at low latitudes, or low evaporation, at higher latitudes. Evaporites form in areas of little precipitation and high evaporation, but with some input of marine or ground water, giving rise to coastal and continental sahbkas, respectively.

Sediment may be altered *in situ* in surficial environments that are proximal and distal to major clastic sediment pathways. These processes, which are mostly chemical, form soils. Temperature, precipitation, and seasonality affect the genesis and character of soils, although other factors, including depositional rates (which also are, in part, climatically controlled), are involved. Soil features characteristic of areas with high temperatures and high, seasonal rainfall may include: (1) rubefaction and leaching and reprecipitation of mobile constituents (oxisols, including redbeds, laterites, and bauxites); (2) cracking and pedoturbation due to shrinking and swelling clays (vertisols); (3) oxidized and reduced zones (gleyed soils). In areas with high temperature, high rainfall, and little or no seasonality of precipitation, histosols or oxisols may form, depending on the position of the water table. Soils in high temperature, low rainfall areas are characterized by accumulations of salts including carbonate and gypsum. Soils formed in areas with lower temperatures are generally less well developed. They may exhibit some features indicative of leaching and reprecipitation of mobile constituents and translocation of clay in areas of high rainfall (argillic and spodic soils), pedoturbation due to freezing (cryic soils) at high latitudes, and accumulation of surficial organic matter in areas with high water tables (histosols).

As in figure 1, most of the concepts in figure 2 are well established, and the real contribution in palaeoclimatic interpretation will come with calibration of the climatic controls on the formation of continental sediments, particularly soils. A step in the right direction is recent work on isotopes of oxygen and carbon in soil carbonates (Cerling *et al.* 1989). The realization that peat deposits tend to form in climates that lack seasonality of rainfall (Gyllenhaal 1991) will lead to further investigations of the importance of temperature and length of growing season on formation of these deposits.

4. Conclusions

To a first-order approximation, all global climate models explain geographic aspects of the geologic record of climate, as that record is traditionally interpreted. However, the traditional interpretations of the climatic significance of various proxy indicators are very simplistic. Advances in climate modelling and in both temporal and spatial resolution of the geologic record require a critical examination of proxy indicators of palaeoclimate in order to improve calibration of those indicators with climate. There are two ways this calibration will be accomplished. First, detailed studies of modern occurrences of sedimentary indicators of climate, and calibration of those occurrences to modern climate, will permit some quantification of the climatic significance of those indicators. Second, different sedimentary indicators of

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climate must be cross-calibrated. One way to partly accomplish both is to classify sedimentary palaeoclimatic indicators in a climate framework, paying particular attention to overlap and exclusion.

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Discussion

B. W. Sellwood. The Earth's sedimentary record has been an imperfect receiver of the climate signal. Subtle variations may only be extracted from the record through a very full integration of apparently disparate data, as the authors suggest. It is possible that a more systematic evaluation of ancient wildfire distributions (marked by the absence of fusinite within sediments) may help to distinguish between 'hot' and 'wet' seasonality. Fusinite abundances and distributions may be used in concert with other data (such as palaeosols and palaeobiology) thus providing additional evidence from which models might be more finely tuned.

Z. Reut. Milankovitch theory explains the changes in climate on long (order 10^4 years) timescale by taking into account variations in the Earth's orbital parameters; the ice ages are correctly predicted (good evidence from ocean sediment cores).

J. T. Parrish. Milankovitch theory undoubtedly is important but there are problems with the sediment core evidence: radiometric dating shows that the cycles do not correlate with isotopic shifts.

C. D. Curtis. What help can palaeobotanical evidence give in calibration of former climates (or is the stratigraphy insufficiently precise to obtain regional pictures)?

J. T. Parrish. Ecological studies related to soil types, etc., should continue: some problems can be resolved. There are difficulties and time determination is very important (e.g. N. American Cretaceous Seaway where cross-basin correlation is needed to distinguish between alternatives such as climate or sea level/base level).

M. L. Coleman. One challenge is duration of events. Do we have the tools available to determine how long, for example, it takes to deposit a bed?

J. T. Parrish. Some stratigraphic models attempt to get at that kind of information, and some palaeosol research is concerned with time of exposure.