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CORRESPONDENCE AND NOTES

Estimating rates of calcrete formation and sediment accretion in ancient alluvial deposits

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Abstract – The use of calcrete horizons as a means of assessing rates of sediment accretion in ancient alluvial sequences is reviewed. Any attempt to use such horizons in quantifying ancient alluvial deposition must appreciate that accurate data on rates of formation of Quaternary calcretes are limited. Such data show considerable variations in the rates and no reliable data exist at all for some calcrete types. The abundance of calcretes in the geological record warrants a new initiative to improve our understanding of their origins and rates of formation.

1. Introduction

Accurate time resolution has been an objective of many stratigraphers and sedimentologists working in ancient sedimentary sequences. With the developments in quantitative stratigraphic models the need for means of estimating time periods has increased. Much emphasis has been placed on the use of calcrete-bearing palaeosols (fossil soils) as a means of assessing time periods and depositional rates. However, the basis on which these estimates are made must be seriously questioned for a variety of reasons which are discussed below.

Calcretes are secondary accumulations of calcium carbonate in near surface settings, which result from the cementation and/or replacement of host material by the precipitation of calcium carbonate from soil water or ground water (Goudie, 1983; Netterberg, 1980). They are widespread in many semi-arid and arid areas on the Earth at the present time and are widespread in a variety of continental deposits in the geological record (Retallack, 1986).

They are particularly common in many ancient 'red bed' deposits and have been used as palaeoenvironmental tools for reconstructing palaeoclimates and for estimating floodplain accretion rates (e.g. Allen, 1974; Hubert, 1977; McPherson, 1979; and many other studies). Their use in estimating accretion rates is based on the fact that they develop in a regular series of easily identifiable stages (Gile, Peterson & Grossman, 1966; Allen, 1974; Steel, 1974; Machette, 1985) (Fig. 1). The stage of maturity of the calcrete is a function of its residence time within that part of the soil where carbonate precipitation occurred (Leeder, 1975). The residence time is determined by the rate of accretion of the sediment surface. If the accretion rate is high the level will become isolated from the zone of carbonate precipitation and calcrete development will cease at that level and move to a higher one. If the rate of accretion has been negligible for long periods mature profiles can develop, but if the rate of accretion in very high either immature carbonate accumulations or none at all develop. These are end-member situations and a variety of combinations of stages and thicknesses can arise (Fig. 1*b*).

These simple relationships have been widely applied in studies of ancient floodplain deposits and alluvial architecture, and Leeder (1975) presented an elegant quantitative model for estimating ancient floodplain accretion rates based on these relationships and on the then known rates of calcrete formation. This study has been much used by later workers and the age estimates quoted have been applied in various time resolution calculations (e.g. Behrensmeyer & Tauxe, 1982; Nickel, 1982; Collinson, 1986; Marzo, Nijman & Puigdefabregas, 1988).

The use of calcretes for time resolution depends on two main assumptions. Firstly, the time estimates used for each stage of calcrete growth must be based on the rates of formation of Quaternary calcretes which, to be usable, should be consistent or exhibit a small standard deviation. Secondly, for direct comparisons to be made, the dated Quaternary forms must be similar in origin to the ancient form. The following discussion aims to show that it is practically impossible to make such assumptions.

2. Rates of calcrete formation

Leeder (1975) compiled a series of known ages for Quaternary calcretes of different growth stages. Many of the key datings in the compilation were based on the studies of Gile and co-workers who have provided a detailed picture of the soil-landscape evolution of part of the Rio Grande rift zone in New Mexico. Leeder noted that stage 3 calcretes of the Gile, Peterson & Grossman (1966) classification (equivalent to stage 3 of Machette, 1985) required 10 ka to develop. Such horizons occur on the Picacho surface in New Mexico which had been dated at 10,000 B.P. However, the Picacho surface is now known to be late Pleistocene in age (25–75000 B.P.; (Gile, Hawley & Grossman, 1981). Indeed nowhere in the southwestern United States has a stage 3 calcrete horizon been found on a non-gravelly surface younger than late Pleistocene (Machette, 1985) and in New Mexico calcrete development has only reached the stage 3 level on late to middle Pleistocene surfaces (250000–400000 B.P.). Regrettably the idea that stage 3 calcretes represent periods of soil formation of 10 ka has seemingly become entrenched in the literature (Collinson, 1986; Marzo, Nijman & Puigdefabregas, 1988).

For all the age ranges quoted by Leeder it is now

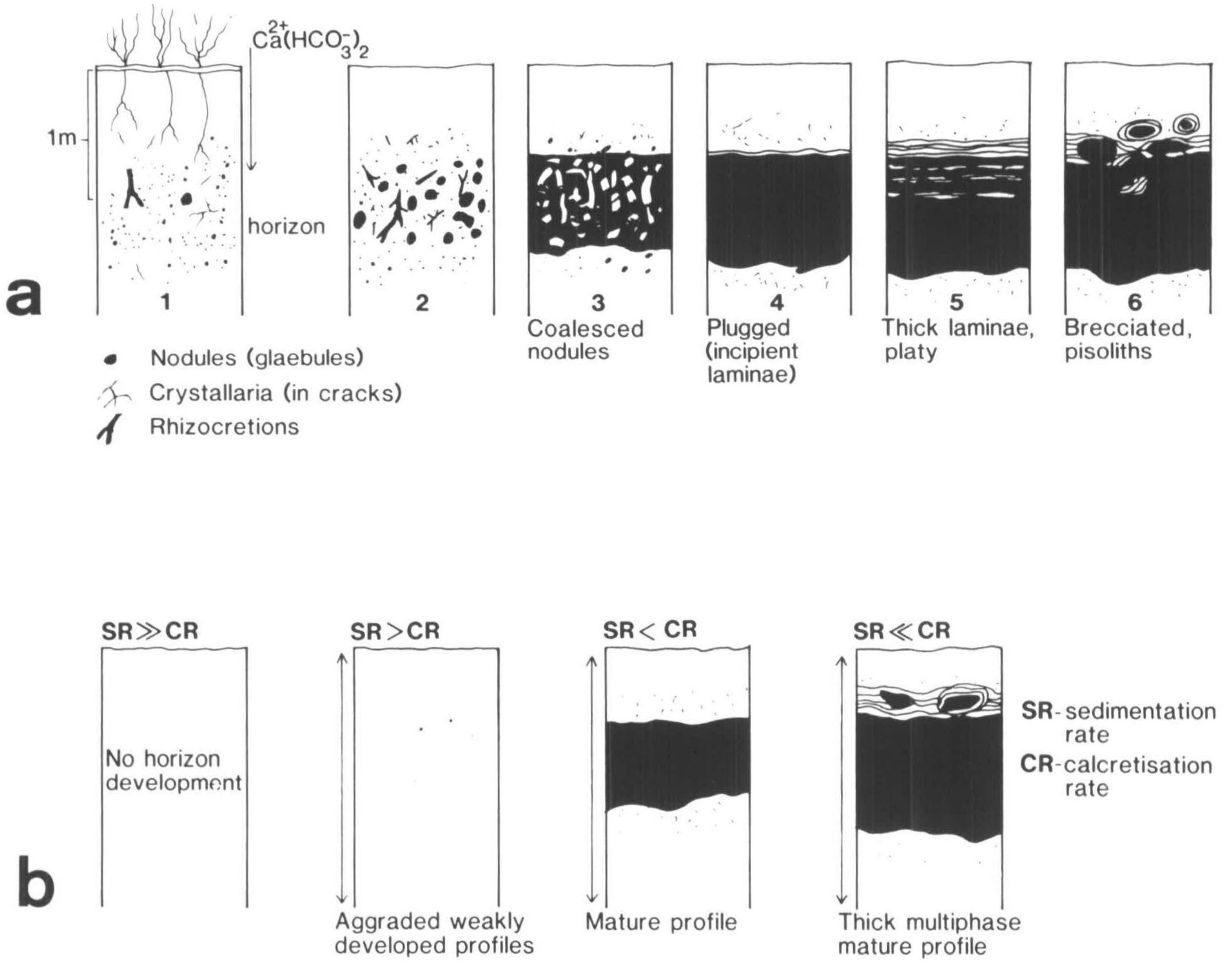

Figure 1. (a) Stages of calcrete development; based on Machette (1985). (b) Relationship between rate of calcrete formation and the rate of accretion (see text).

reasonable, using the well constrained calcrete dates from the southwest United States, to increase them by at least one order of magnitude (Gile, Hawley & Grossman, 1981; Machette, 1985; Shlemon, 1978). However, the picture is not straightforward for there are marked regional differences in the rates of calcrete formation (Machette, 1985), reflecting both climatic differences (particularly rainfall) and the availability of airborne Ca^{2+}. Thus it is not possible to derive a set of reliable time estimates for each stage of calcrete development. It might be argued that calcretes within a region should have similar time ranges such that, in a study of an ancient sedimentary basin, the calcretes could be used as a relative guide to assess time periods and accretion rates. Regrettably, even this rather simple application could be unreliable, for even within one basin considerable differences in the rates of carbonate accumulation occur (Gile, 1977; McFadden, 1988). Such differences are usually the result of altitudinal effects on rainfall but can also be caused by very local variations in the supply of Ca^{2+}, such as proximity to playas (Lattman, 1973).

While it is likely that the rates of calcrete formation which have been used by workers interpreting ancient fluvial sequences are gross underestimates, examples are known of very rapid carbonate accumulation. Hay & Reeder (1978) have described calcretes from Olduvai Gorge in east Africa which developed to stage 4 in only a few thousand years, and not the 100 ka or more required in the southwest United States. This rapid rate of growth is probably a consequence of very high Ca^{2+} input from nearby carbonate-producing volcanoes. What can be said is that, based on reliably dated Quaternary calcretes, the time estimates for a mature (stage 4) profile range from 3 ka to over 1 Ma, more than two orders of magnitude variation.

Although there are at present relatively few areas where calcretes have been rigorously dated, it is clear that the estimates used in the studies of ancient alluvial sequences, as stated above, are unlikely to be representative of the actual rates. Their use, even in a very general sense, to estimate accretion rates also depends on the assumption that calcrete development is progressive with time. This is not always the case. Changes in climate can lead to carbonate being leached from earlier calcic horizons, but perhaps one of the most remarkable examples of the remobilization of calcrete comes from the Merida area of Spain (Elbersen, 1982). In this region the surface is being lowered by erosion and the calcic horizons in the soils are penetrating downwards in the soil profile. This downward movement is apparently not due to leaching but to mechanical processes. The result is relatively mature carbonate horizons but in a geomorphically unstable situation. Such calcretes do not provide an accurate picture of the age of the surface with which it is associated.

Calcrete-bearing palaeosols strikingly like those from the Quaternary deposits of the southwest United States, both as regards macro- and microstructure, are relatively common in mid-Palaeozoic continental sequences of the Northern hemisphere (Allen, 1986). They present particular problems as regards estimating rates of formation because they would have developed at a time when soils were only weakly biologically active. The solubility of $CaCO_3$ is of critical importance in calcrete formation and will be affected by the partial pressure of CO_2 in the soil. The low partial pressures in arid and semi-arid soils are a contributory factor leading to carbonate precipitation (Marion, Schlesinger & Fonteyn, 1985). In the weakly biotic soils which covered the land surface prior to later Palaeozoic time, CO_2 levels must have been much lower than at present, perhaps facilitating carbonate precipitation. However, evapotranspiration is another, perhaps more important, influence on carbonate precipitation in calcretes, which would have been of less significance in weakly biotic soils. Extrapolating rates of calcrete formation from Quaternary to mid to early Palaeozoic time is unlikely to provide reliable time estimates.

3. Types of calcrete

The age estimates discussed above relate to a limited number of pedogenic calcretes. From the descriptions provided by the authors of these studies all these calcretes represent Alpha calcretes in the sense of Wright (1990), in that they show very little, if any, evidence of direct biological influences on carbonate precipitation. Instead the microfabric consists of a dense crystalline mass with floating sediment grains, various fractures and relic nodules. However, many calcretes exhibit striking evidence of biological involvement in carbonate formation (Calvet, 1982; Jones & Kwok-Choi, 1988; Klappa, 1979, 1980; Phillips, Milnes & Foster, 1987; Semeniuk & Meagher, 1981). They contain such features as rhizocretions, microbial coatings and fungal products such as needle-fibre calcite. These constitute Beta calcretes in the sense of Wright (1990). Little is known on the rates of formation of such forms although the occurrence of relatively thick carbonate concretions around living roots is clear evidence that such precipitation can be very rapid (Klappa, 1980; Semeniuk & Meagher, 1981). Further studies on the rates of formation of Beta calcretes are urgently needed, but any estimates of the likely time intervals represented by ancient calcretes must distinguish between these two end-member types, of which one type exhibits two orders of magnitude variation in rates of formation, whereas the other type lacks any accurate rate documentation.

One aspect of this problem has recently come to light following the recognition of the polygenetic origin of laminar calcretes (Wright, Platt & Wimbledon, 1988). The occurrence and thickness of such forms is age-related in the Quaternary calcretes of the southwest United States, and they are used to distinguish stage 4 and 5 profiles (Machette, 1985; Fig. 1). Very long time periods are required for thick forms to develop (see also Robbin & Stipp, 1979). However, similar laminar horizons also originate by the calcification of root-mats (Wright, Platt & Wimbledon, 1988), and by analogy with other types of rhizocretions are likely to have formed very rapidly. Using the thickness of laminar calcretes as even a very rough guide to the maturity of a calcrete will depend on the correct diagnosis of whether it is abiogenic (as, apparently, in the case of those forms associated with calcretes in the southwest U.S.A.) or the result of root activity.

Yet another complication arises as regards the recognition of ground-water (*syn.* phreatic, valley) calcretes. These are calcretes which form around the water table (Arakel & McConchie, 1982; Carlisle, 1983; Semeniuk & Meagher, 1981). They produce features identical to pedogenic calcretes but again very little is known about their rates of formation. Such calcretes are widespread in arid to sub-humid areas, yet there appear to be no records of such types in the stratigraphic record. It leads one to suspect that some records of ancient pedogenic calcretes may represent ground-water forms.

4. Summary

The possibility of putting time constraints on geological phenomena is a seductive one. It allows rates to be estimated and built into even more seductive quantitative models. Calcretes have been used for this purpose but there is great variability in the rates of formation of Quaternary calcretes for which accurate dating exists. In addition there are types of calcrete for which reliable rate estimates are not available at the present time. Assigning specific periods of formation to ancient calcretes is not, at present, justifiable.

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