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# PETROLOGY OF CALICHE-DERIVED PELOIDAL CALCIRUDITE/ CALCARENITE IN THE LATE TRIASSIC MALERI FORMATION OF THE PRANHITA-GODAVARI VALLEY, SOUTH INDIA

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## ABSTRACT

Sarkar, S., 1988. Petrology of caliche-derived peloidal calcirudite/calcarenite in the Late Triassic Maleri Formation of the Pranhita-Godavari Valley, South India. Sediment. Geol., 55: 263–282.

The Maleri Formation (Late Triassic) of the Pranhita-Godavari Valley, South India, is a continental red-bed sequence represented mainly by red clays with a few sheet-like bodies of channel-fill sandstone. Crudely bedded and cross-bedded peloidal calcirudite/calcarenite occurs at the base of fining-upward sequences in multistorey sand bodies and also as discrete solitary lenses within red clay.

The calcirudite/calcarenite consists mainly of calcite-cemented spherical peloids which are made up of micrite and microspary calcite with microfabrics characteristic of caliche. Pure calcitic peloids are often reddened and those having a quartzose component are generally not red.

The paucity of broken and abraded peloids, close association with intraformational materials and other evidence indicate a local source of the peloids. The microfabric of the peloids suggests their derivation from caliches. Available evidence favours a pedogenic origin for the peloids which mostly developed by displacive precipitation in a set-up of alternate wetting and drying. The lack of in-situ caliche profiles in the Maleri sequence and the rarity of compound grains imply that the peloids were derived from incipient caliche profiles which were localized at or near the surface and were completely stripped off by subsequent erosion.

The ghost caliche profiles suggest the presence of periodically stable levels in the Maleri alluvial plain and low to moderate rates of alluviation. The residence intervals of channels were long enough to allow incipient pedogenesis in the temporarily stable inactive areas. In the present context, the predominance of smectite in fines, the poor floral content, the Maleri faunal assemblage and the paucity of evaporites point to a low seasonal rainfall in a semi-arid climatic environment.

## INTRODUCTION

Secondary carbonates occurring in alluvial setting may form either by pedogenic or by nonpedogenic processes and commonly develop in the upper part of fining-upward (F-U) fluvial sequences (Allen, 1965, 1974, 1986; Friend and Moody-Stuart, 1970; Steel, 1974; McPherson, 1979). These carbonates are comparable to the

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nodules of Plio-Pleistocene and Holocene caliche profiles, mostly formed at the surface or shallow sub-surface of stable geomorphic levels (Ruhe, 1969; Gile, 1970; Williams and Polach, 1971) in many arid and semi-arid areas (Gile and Hawley, 1966; James, 1972; Goudie, 1973; Harrison, 1977).

Carbonate grainstones, derived through reworking of caliche profiles, occur as channel-fill deposits in many fluvial sequences (Allen, 1965, 1974, 1986; Friend and Moody-Stuart, 1970; Allen and Williams, 1979; Wells, 1983; Blakey and Gubitosa, 1984). These sequences, excepting one (Wells, 1983), are characterized by the presence of well-developed caliche profiles. The intimate association of carbonate grainstones with the profiles has led to the ready interpretation of the former as

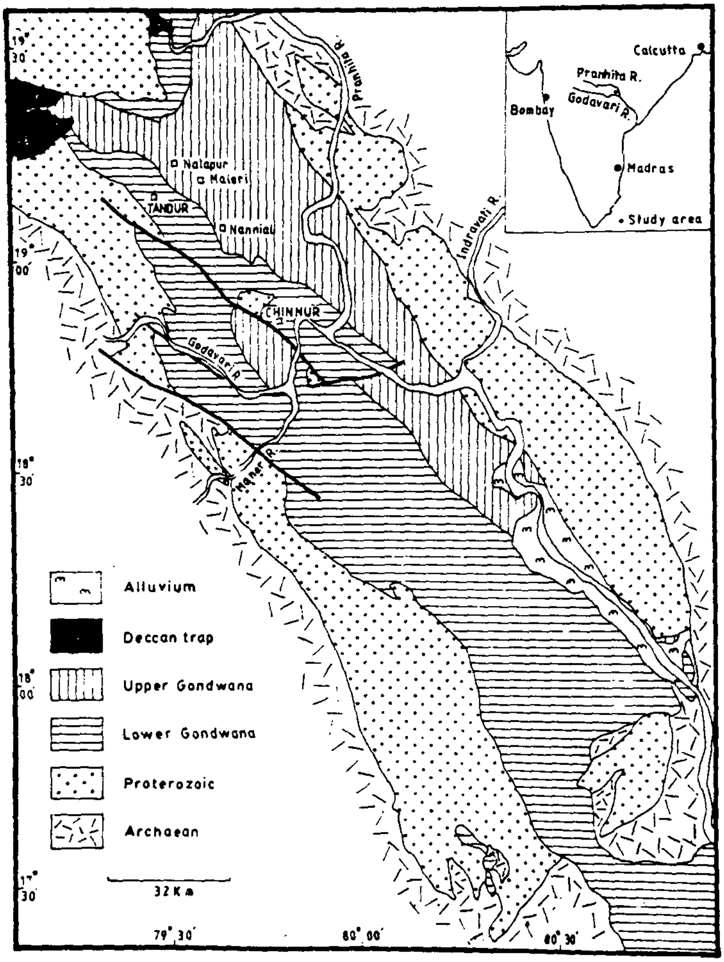


Fig. 1. Geological map of a part of the Pranhita-Godavari Valley (modified after King, 1881). Inset map shows the location of the study area.

intraformational. Similar carbonate grainstones abound in the Late Triassic Maleri Formation (Gondwana sequence, Pranhita-Godavari Valley), but this sequence does not include any caliche profile. With an aim to evaluate the origin of the carbonate grainstones as well as their sedimentologic and palaeoclimatic implications, the Maleri Formation was studied in a number of localities around Tandur and Chinnur, Andhra Pradesh (Fig. 1).

## GEOLOGIC SETTING AND SEDIMENTOLOGICAL BACKGROUND

In the Pranhita-Godavari Valley, Gondwana sediments crop out in a linear belt striking NW–SE (Fig. 1). The sequence (Lower Permian to Lower Cretaceous), represented mainly by alluvial sediments (Pascoe, 1959, p. 911; Sengupta, 1970), is divided into a lower and an upper subdivision. King's (1881) Maleri "Group", one of the components of the upper Gondwana sequence, has recently been subdivided into a succession of formations namely, Yerrapalli, Bhimaram, Maleri and Dharmaram, from older to younger (Jain et al., 1964; Kutty, 1969; Sengupta, 1970; Table 1). The subdivision was based largely on the vertebrate fossil content. The Maleri Formation has an exceptionally rich vertebrate fossil assemblage consisting of aquatic, semi-aquatic as well as terrestrial forms. Invertebrates, in contrast, are represented only by unionids (Kutty, 1971; Chatterjee and Roy Chowdhury, 1974)

TABLE 1

Permo-Triassic (Upper Gondwana) stratigraphic sequence in the Pranhita-Godavari Valley, South India (after Jain et al., 1964; Kutty, 1969; Sengupta, 1970)

| | Formation | Main lithologies | Facies | Age |
|---|---|---|---|---|
| Upper Gondwana | Maleri | red clay; medium to fine grained, calcareous quartzarenite; fine grained quartzwacke; peloidal calcirudite/calcarenite. | floodplain, ephemeral channel-fill | Upper Triassic (Carnian) |
| | Bhimaram | coarse, pebbly, ferruginous, feldspathic quartzwacke with thin intercalations of red clay. | channel/point-bar floodplain | unplaced (?) |
| | Yerrapalli | purple and red clay; medium to fine grained, calcareous quartzarenite; fine grained quartzwacke; calcirudite/calcarenite. | floodplain, ephemeral channel-fill | Middle Triassic |
| Lower Gondwana | Kamthi | coarse to medium quartzwacke (often pebbly); abundant clasts and lenses of purple siltstone at certain levels; thin sheets of claystone. | channel/point-bar floodplain | Permo-Triassic |

and the floral content is limited only to a few pieces of coniferous wood (Pascoe, 1959, p. 971).

The Maleri Formation (Carnian, T.K. Roy Chowdhury, pers. commun., 1986) is composed mainly of dark reddish brown silty clay and clayey silt with a subordinate amount of coarse to fine quartzose sandstone (mean: 2.21–3.53 $\phi$), siltstone, carbonate grainstone and other transitional lithologies, e.g., quartzose sandstone with admixture of carbonate grains. The mud : sand ratio, though variable, appears to be generally high (3.5 : 1 to 2 : 1). Relatively larger sand bodies, dominated by quartzose sandstone, are a few metres in thickness and more than 1 km in strikewise (NW–SE) length. They crop out as low-lying ridges and dip gently (10°–15°) towards the northeast. The sandbodies are sheet-like in geometry and are separated by relatively thicker intervals of red clay. There are also relatively smaller lenticular bodies of carbonate grainstones which are a few metres long, a few decimetres thick and have a ribbon-like geometry. Maleri red clay is soft, friable and forms a slightly undulating ground. Exposures of sandbodies are discontinuous and of very poor quality, mainly due to intense weathering. The nature of the exposures hardly permits any detailed lithological logging. Good sections are available only where the creeks cut across the sandbodies. Palaeocurrent data collected from the sandbodies show a northerly mean palaeoflow direction with a high dispersion both within and between sandbodies.

The sandbodies occur as isolated channel-fill deposits (Sengupta, 1970; Sarkar and Chaudhuri, in prep.), with very low interconnectedness. These sandbodies are generally multi-storey, each storey being separated from the other by strong erosional surfaces. A F-U trend is discernible within each storey (Fig. 2). The coarser components of the F-U sequences are dominated by bundles of parallel-laminated medium to fine quartzose sandstone. The red clay is generally structureless but may display faint lamination where it is interlaminated with fine, white sandstone or siltstone. Desiccation cracks are locally preserved in fine sandstone and siltstone.

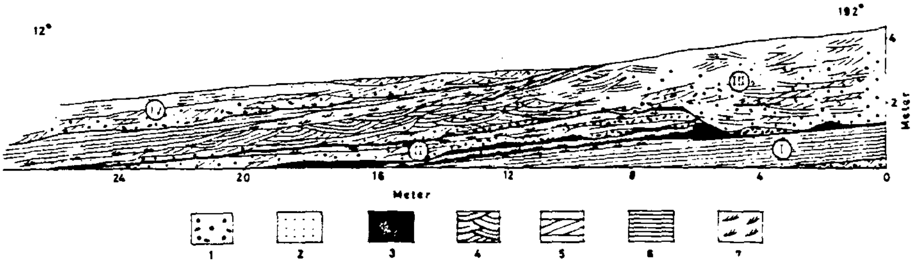


Fig. 2. Superposed fining-upward sequences (*I–IV*) in a sandbody. Note the occurrence of calcirudite/calcarenite at the base of each sequence. *1* = Calcirudite/calcarenite with clay galls; *2* = medium to fine quartzose sandstone; *3* = clay; *4* = trough cross-stratification; *5* = planar cross-stratification; *6* = parallel lamination; *7* = ripple cross-lamination.

The sandbodies were rapidly deposited during short-lived floods in small, shallow, ephemeral channels and adjoining floodplains during overbank flooding (Sarkar and Chaudhuri, in prep.). Multistorey sandbodies are composed of slightly laterally shifted, vertically stacked storeys. These sandbodies were apparently built up through superposition of channels coupled with lateral switching in discrete steps.

## MODE OF OCCURRENCE OF THE CALCIRUDITE/CALCARENITE

Calcirudite/calcarenite occurs in two distinctively different modes, as described below:

### *Type I*

The type I carbonate grainstones are invariably associated with relatively thick quartzose sandstone complexes and are similar to type A of Allen and Williams (1979). They occur in lenticular beds at the base of channel-fill F-U sequences in relatively larger, sheet-like, multi-storey sandbodies (Fig. 2). The lowest unit of a F-U sequence, immediately above the scoured base, is mostly a massive to crudely bedded, generally grain-supported calcirudite followed upward by trough cross-stratified calcarenite. The boundary between the calcarenite and the overlying quartzose sandstone is generally sharp but may be gradational too. The thickness of the calcirudite and calcarenite units varies from 0.1 to 1.2 m. The set-thickness and width of trough cross-strata vary from 0.05 to 0.75 m and 0.3 to 2.5 m respectively.

### *Type II*

Lenticular bodies of calcirudite/calcarenite occur as solitary units within the red clay. They have sharp boundaries with their host sediments and are in many ways comparable with the type B conglomerate of Allen and Williams (1979). Several lenticular bodies appear to be strung out along certain levels and can be traced for hundreds of metres along the general strike direction. Thickness and strikewise length of individual bodies are a few decimetres and few metres, respectively. Internally these bodies are either crudely bedded or cross-stratified. Type II bodies, in contrast to Type I, are free of quartzose sandstone but mudstone occurs as interleaved streaks or lenses at places. These bodies possibly represent deposits of short-lived, local, minor drainage systems.

## TERMINOLOGY: SOME CLARIFICATIONS

The carbonate grainstones in the Maleri Formation have been described as "lime-pellet rock" (Robinson, 1964) and calcirudite/calcarenite (Sengupta, 1970).

Similar rocks have been described as "conglomeratic cornstone" (Allen, 1960), "concretion-clast conglomerate" (Friend and Moody-Stuart, 1970) and "granulestone" (Wells, 1983). The terms calcirudite/calcarenite, though texturally valid, do not convey any information about the nature of the framework grains and the term "lime-pellet" rock is a misnomer since the framework grains match Folk's (1959) pellet neither in texture nor in origin.

It appears that there is no uniformity of nomenclature for such grains. Several terms with genetic connotations, e.g. glaebule, concretion, nodule, pelletoid (Brewer, 1964; Friend and Moody-Stuart, 1970; James, 1972; Allen, 1974; Wieder and Yaalon, 1974, 1982) have been used to describe grains similar to those in Maleri grainstones. In view of the polygenetic origin of similar grains, the non-genetic term peloid is used here following McKee and Gutschick (1969) to describe most of the framework constituents of the Maleri grainstone, and the rock type is described as peloidal calcirudite/calcarenite.

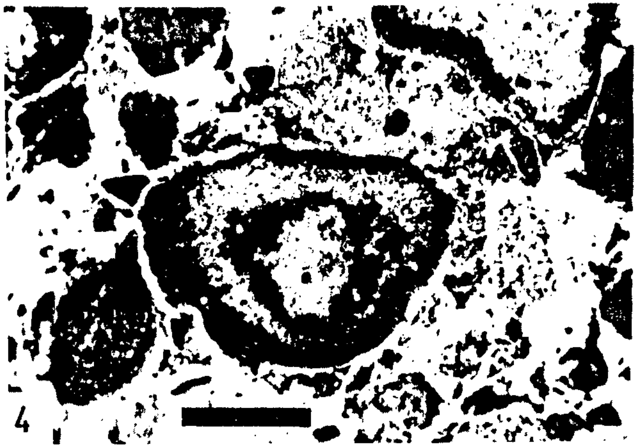
## PETROGRAPHY OF THE CALCIRUDITE/CALCARENITE

Peloidal calcirudite/calcarenite mainly consists of moderately sorted, pebble to medium sand-sized (mean 0.51–0.64 $\phi$) peloids which occupy 68–82% of a sample. Other intraformational framework grains include spherulite, microcodium aggregates, limeclasts, rhizolith fragments, intraclasts of fine sandstone and mudstone, clay fragments, and vertebrate and invertebrate fossil fragments. Quartz, feldspar, garnet are present, though not always, as minor constituents.

### *Framework grains*

#### *Peloids*

They mostly occur as spherical to subspherical, well rounded, solitary grains; compound, broken or abraded grains are rare. Peloids lack a recognizable nucleus and in contrast to an intraclast made of sandstone and siltstone, are devoid of lamination. In rare instances, peloids display a concentric fabric, marked by differential transparency in adjacent laminae (Fig. 3). Such concentric laminations, in contrast to those of vadose pisoliths, are irregular, fuzzy and less than five in number, a feature characteristic of caliche pisoliths (Esteban, 1976; Tandon and Narayan, 1981). Concentric habit is also manifested by alternation of calcite and iron oxide/hydroxide laminae (Fig. 4). Peloids consist essentially of structureless microcrystalline and/or microsparry calcite (Fig. 5), similar to the undifferentiated crystic plasmic fabric of calcareous "glaebules" of Recent and ancient caliche profiles (Allen, 1965, 1974; Nagtegaal, 1969; Folk, 1969; Braithwaite, 1975; Harrison, 1977). Silicate grains, clay pellets, and dispersed clays are uncommon in the peloids (Figs. 6 and 7). Many peloids show clotted micrite fabric and a ramifying net work of microsparry channels (Fig. 8). Peloids are commonly affected by



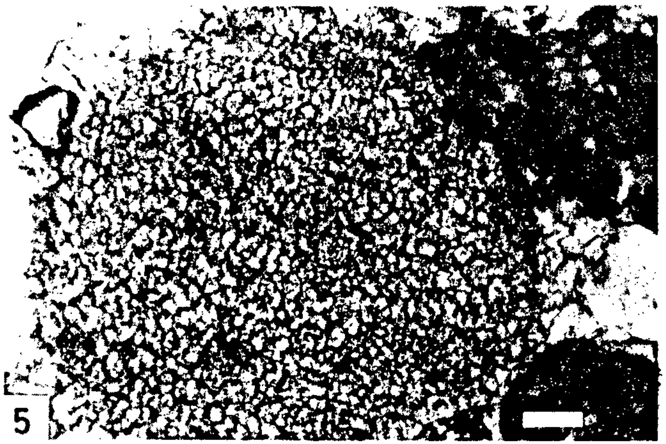


Fig. 3. Peloid with fuzzy concentric laminations. Note the microcrack filled with calcite and opaque cement. Plane-polarized light. Scale bar = 0.5 mm.

Fig. 4. Peloid with alternate concentric laminations of iron-oxide/hydroxide and calcite. Plane-polarized light. Scale bar = 0.5 mm.

Fig. 5. Peloid showing a structureless equigranular mosaic of microsparry calcite. Plane-polarized light. Scale bar = 0.1 mm.

Fig. 6. Floating silicate grains in a peloid. Note extensive peripheral etching of silicate grains by replacive calcite. Plane polarized light. Scale bar = 0.1 mm.

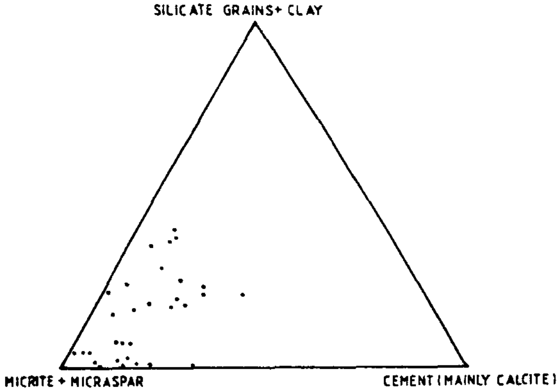


Fig. 7. Triangular diagram based on the relative contents of silicate grains + clays/micrite + microsparry calcite/cement in peloids. Each point represents the composition of an individual peloid.

varying degrees of aggrading neomorphism, both within and between grains. In most cases, the microspar calcite crystals in a peloid are uniform in size and somewhat rhombic in shape (Fig. 5) resembling caliche nodule microtexture (Folk, 1969).

Peloids are commonly reddened by limonite and hematite. The cores of some peloids are reddened. In some broken peloids a reddened cortex is truncated. Reddened peloids are virtually devoid of silicate grains. Non-red peloids, however, may contain quartz, feldspar, garnet and mica grains that float in the groundmass (Fig. 6). These grains are replaced along their surfaces or cleavages by calcite (Fig. 6). In a few instances, quartz grains in peloids are enveloped by an isopachous crust of fibroradial calcite (Fig. 9), similar to "calcitans" (Molenaar, 1984). Displacive calcitization within a peloid is recorded by mica grains "exploded" by emplacement of calcite cement along their cleavages (Fig. 10). The peloids contain a relatively finer fraction (mean 3.45–4.32 $\phi$) of the total size distribution of the Maleri sequence (mean 2.21–3.53 $\phi$).

Incipient arcuate fissures and different types of well-developed, irregular microcracks commonly occur in peloids. They are usually centrally located stellate-like microcracks which die out near the periphery (Fig. 11). A few peloids display a series of concentric microcracks approximately conformable with the periphery of the grain. These microcracks are comparable to those of septarian nodules (Brewer, 1964; Raisewell, 1971) and possibly are syneresis cracks. Circumgranular cracks occur around the constituent peloids of a compound grain (Fig. 12). The cracks are mostly filled with calcite, but barite also occurs locally. That many of these crack-fills are pretransportational is evident from abraded crackfills along grain boundaries as well as fabric discontinuities between crack filling and interpeloidal cement (Fig. 13).

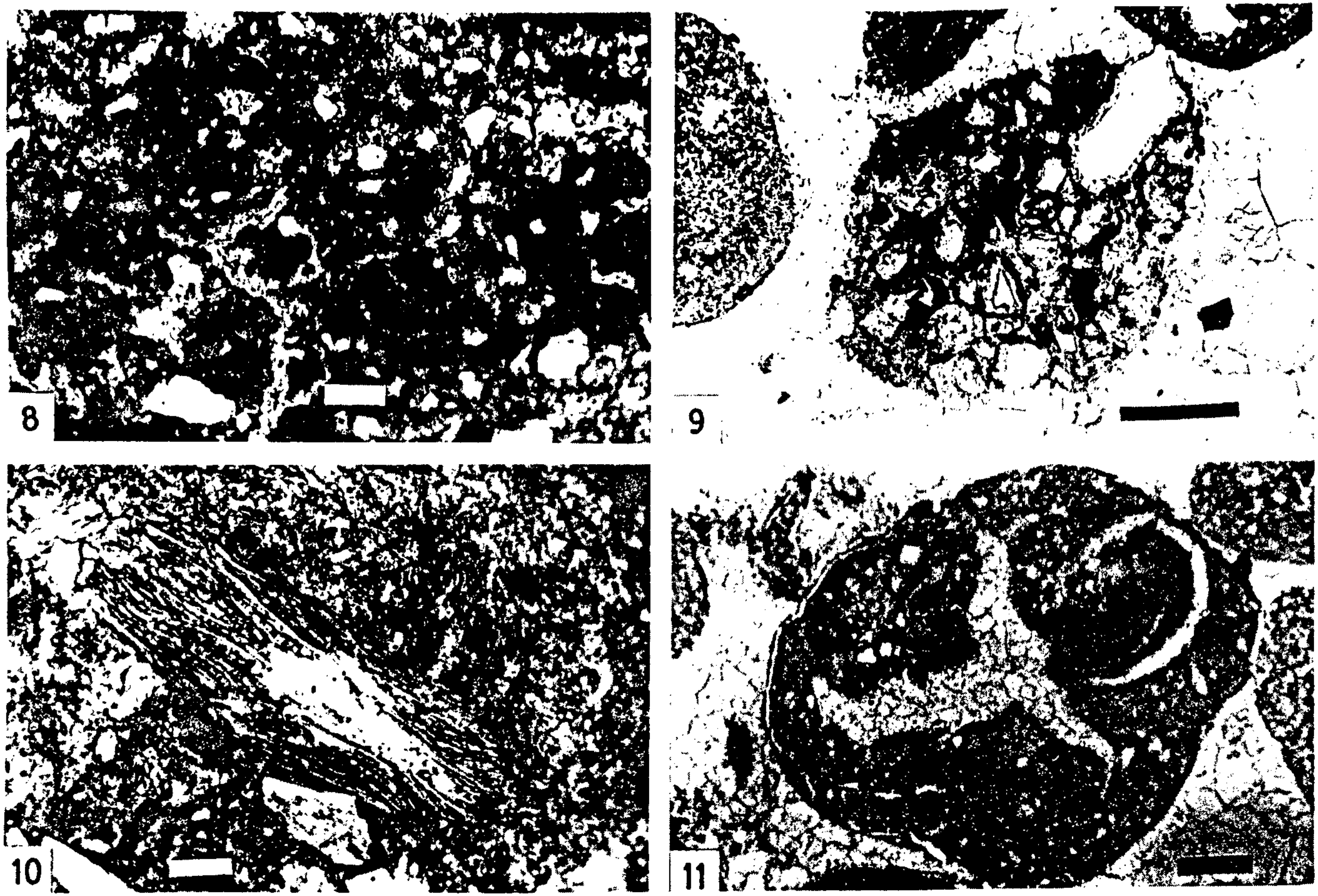


Fig. 8. Clotted micrite fabric and incipient channels in a peloid. Note the presence of silicate grains. Plane-polarized light. Scale bar = 0.2 mm. Fig. 9. Fibro-radial calcite developed around quartz grains in a peloid. Plane-polarized light. Scale bar = 0.5 mm. Fig. 10. A mica grain in a peloid "exploded" by displacive calcitization. Plane-polarized light. Scale bar = 0.1 mm. Fig. 11. A peloid with typical radiating microcrack filled with sparry calcite cement. Note that the cracks are tapering out towards the periphery of the peloid. Plane-polarized light. Scale bar = 0.5 mm.

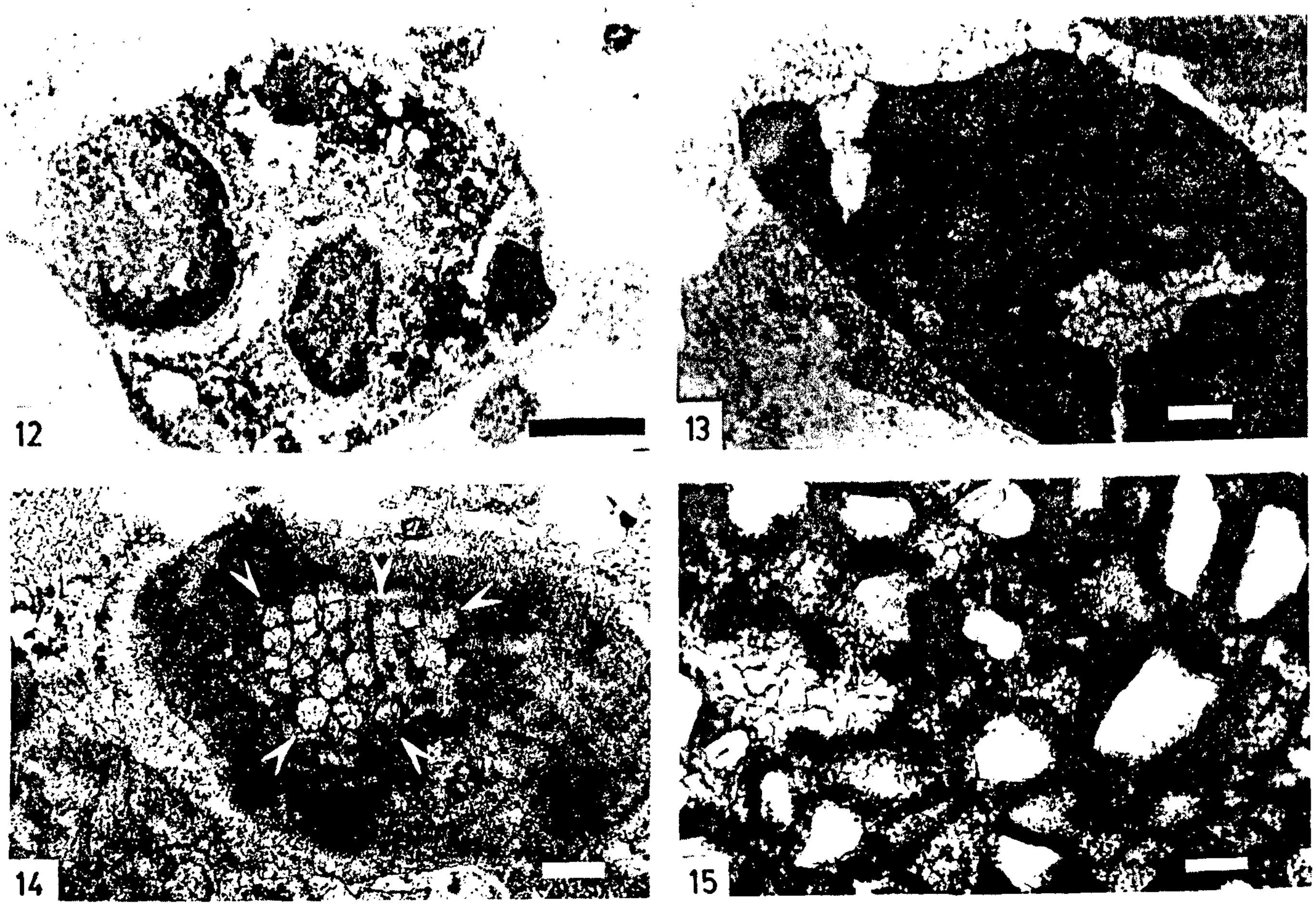


Fig. 12. Circumgranular crack around constituent peloids in a compound grain. Plane-polarized light. Scale bar = 0.5 mm. Fig. 13. Crack-filling calcite cement abraded along the periphery of the peloid (upper left corner). Note the fabric discontinuity between the crack-filling cement and the interpeloidal cement. Plane-polarized light. Scale bar = 0.1 mm. Fig. 14. A detrital carbonate grain characterized by a core of *Microcodium* aggregate (marked by arrows). Plane-polarized light. Scale bar = 0.1 mm. Fig. 15. Micrite envelopes around silicate grains within an intraformational clast. Note the development of micritic meniscus cement between closely spaced grains. Plane-polarized light. Scale bar = 0.1 mm.

### *Spherulite*

Pebble- to sand-sized, spherical to elliptical, rounded, intraformational carbonate grains displaying spherulitic growth are not very uncommon. Spherulites are composed of a micritic and/or microsparitic core surrounded by a cortex of short prismatic or sheaf-like bundles of acicular calcite arranged radially around the core. A single bundle of calcite in the cortex commonly shows undulose extinction and consists of several close-packed, radiating, ghost acicular crystals. The radial fibrous calcite transgresses the relict concentric laminations in spherulites. A few spherulites have more than one concentric layers in their cortex. Each layer consists of radially arranged stubby calcite crystals which may transgress the layer boundaries as well as the grain boundary. The abraded fabric of spherulite clearly indicates that growth of spherulite predates transportation.

### *Microcodium aggregates (?)*

In rare situations carbonate grains, otherwise very similar to peloids, are characterized by an internal fabric of several equal-sized grains of clear sparry calcite. Individual grains may be quadrangular to hexagonal and their diameter may vary from 0.05 mm to 0.07 mm (Fig. 14). Apparently the fabric is similar to the *Microcodium* aggregates of Klappa (1978, fig. 8a).

### *Intraformational limeclasts*

Besides peloids there are other varieties of limeclasts enriched in secondary calcite. Major types are described below:

(1) Pebble-sized, subangular to subrounded, apparently massive elongate clasts with sparsely distributed, medium to very fine sand-sized silicate grains. These grains, mostly quartz, are corroded along their surfaces by relatively clear calcite followed outward by a thin envelope of micrite. These envelopes, when close enough, touch each other and give rise to micritic meniscus cement (Fig. 15).

(2) Pebble- to cobble-sized, subangular to angular, elongate fragments in which certain laminae with clotted micritic fabric and microspar channels alternate with others consisting of very fine sand- to silt-sized quartz grains floating in a micritic and microspar groundmass.

(3) Subangular to angular, pebble- to cobble-sized fragments with poorly defined alternate laminations of microspar calcite intermixed with a subordinate amount of medium to very fine sand-sized quartz grains and fan-like, radiating bundles of brown calcite at high angle to the laminations.

### *Rhizolith fragments*

There are a few subspherical to elongate, sub-angular to sub-rounded, pebble- to cobble-sized rhizolith fragments in the calcirudite/calcarenite. In perpendicular to long axis sections, these fragments show vague concentric laminations of translucent micrite around a few widely spaced centres, similar to the rhizoconcretions of calcreted root systems (see Arakel, 1982, fig. 6B), and the remaining part is occupied by vaguely laminated micrite and complexly arranged arcuate voids filled up with sparry calcite. In a few instances, the central part is occupied by medium to fine sand-sized siliciclastic grains set in a sparry calcite groundmass. These are possibly root casts formed by filling of tubular root moulds in the root system (see Klappa, 1980, fig. 5C). In another variety centrally located spherical to elliptical voids, filled with sparry calcite are surrounded by a dark micritic layer followed outward by a layer of micrite/microsparry calcite with floating silicate grains. Similar rhizomorph concretions were also noted by Wieder and Yaalon (1982) and the layer differentiation, as suggested by them, appears to be related to the decreasing influence of roots.

### *Other varieties of intraclasts*

Subangular to angular, intraformational fragments of thinly bedded/laminated calcareous sandstone occur commonly in association with calcirudite. They are mostly tabular to platy, their sizes vary from a few millimetres to more than 10 cm. Sand-sized quartz grain is the dominant constituent of such clasts; feldspar, clay pellets, garnet, zircon and opaque grains occur subordinately. Framework grains often float in a sparry calcite groundmass that replaces the grains to a varying extent.

Red and green, subspherical to spherical, well rounded, relatively larger (a few centimetres in diameter) clay galls occur preferentially in association with calcirudite and calcarenite. Clay pellets are, however, more common and more widespread in their occurrence.

### *Epiclastics*

In impure calcirudite/calcarenite siliciclastic grains (mean 1.43–2.74 $\phi$) are finer than the associated peloids (mean 0.51–0.64 $\phi$) and grainsize distributions are invariably bimodal. Angular to subangular, monocrystalline quartz is most common whereas polycrystalline varieties are rare. Feldspar, mica, garnet and opaque grains occur in subordinate amounts.

### *Matrix and cement*

Intergranular porespace in a few samples is occupied by varying amounts (max. 7.1%) of clay matrix which at places appears to have recrystallized. Thin strings of clay matrix often occur in between two adjacent peloids with mutually fitting boundaries.

Calcite cement is ubiquitous and occurs in varying amounts as intragranular and intergranular void-fills (max. 30%). Barite occurs as a minor constituent in a few samples. Intrapeloidal microcracks are commonly healed by calcite cement. These calcite crystals bordering the walls of the microcracks are normally stubby and are oriented perpendicularly to the walls of the cracks. In a few larger microcracks, the thin crust of stubby calcite is succeeded by a hematite film followed inward by blocky calcite spars or barite. These crack-filling cements mostly pre-date transportation.

The fabric of intergranular calcite cement is similar to that of crack-filling cement and commonly develops into a drusy mosaic. Occasionally peloids are rimmed with an isopachous crust of stubby calcite crystals oriented perpendicularly on the grain surface, and the central part of the interpeloidal pore is filled by a large crystal of calcite. In exceptional cases, bundles of acicular calcite crystals may develop at certain points on the surface of a peloid and splay out like a worn tooth brush. Calcite and barite often show a tendency of poikilotopic growth where framework grains float in a large calcite or barite crystal. Most of the siliciclastic grains are nibbled by calcite along their surfaces or cleavages, and a few of them have been completely replaced. Clay matrix, though rarely, is also replaced by calcite. Similar replacement features are also noted within peloids (Fig. 6) and other intraformational grains. The displacive growth of calcite is quite common in inter-peloidal pores. Though rare, displacive calcitization within peloids is recorded by mica grains "exploded" by the emplacement of calcite along cleavages (Fig. 10). Barite cement occurs in different modes both within and outside the peloids. Intrapeloidal microcracks are often occupied by a single large crystal of barite. Intergranular barite cement commonly displays an interlocking mosaic of large, equant and prismatic crystals. Barite also occurs as randomly oriented small prismatic laths and as radiating rosettes both within peloids and in interpeloidal voids. There is, however, no unequivocal evidence to suggest a pre-transportational development of barite in peloids. In intergranular pores barite is often associated with the clay matrix and its euhedra appear to have shoved off clays during their growth. Opaque minerals (varieties of manganese oxides), when present, occur in close association with carbonate cement. In intrapeloidal microcracks this may occur as a central filling following a calcite crust along the crack wall. Manganese oxides also occur as randomly oriented needle-like crystals or as thin stringers and pods set in sparry calcite. In rare cases, iron-oxide and hydroxide occur along the intercrystalline boundaries of calcite cement.

## PROVENANCE OF THE PELOIDS

The occurrence of type II calcirudite/calcarenite implies that peloids were derived from local sources and siliciclastic influx was virtually absent. Derivation from a nearby source is also implied by the preservation and retention of odd-shaped grains and compound grains and the paucity of broken and abraded peloids. Even though tell-tale evidence is lacking, the invariable association of peloids with other intraformational material and the absence of any exotic pebbles weighs in favour of the intraformational origin of the former.

The presence of preferentially reddened peloids in a non-red groundmass and the close association of red and non-red peloids precludes post-transportation pigmentation or bleaching. Concentrically arranged, alternate red and non-red laminae in peloids (Fig. 4) suggest that the pigments or their precursors must have been incorporated in the peloids during their growth (Molenaar, 1984). Red peloids possibly developed in a fine grained host, i.e., silty clay or clayey silt which were either originally red or contained iron-bearing precursors to become red through ageing. Irregular pods and stringers of clays and finely disseminated clays in peloids also indicate their development in a clayey host. Non-red peloids which generally contain sand- to silt-sized silicate grains possibly developed in drab sandstone. In rare instances, non-red peloids are virtually devoid of silicate grains. They might have developed either in non-red sandstone by shoving off the silicate grains during their displacive growth or in reddish host and became drab later but presumably before their reworking and transportation to the present site of accumulation. Though rare, late-stage reduction and remobilization of iron from red peloids during the post-transportation period is indicated by the presence of bleached spheres in reddish calcirudite and calcarenite.

## ORIGIN OF THE PELOIDS

Maleri peloids are strikingly similar to the glaebules of caliche profiles in their internal fabric and texture. The analogy between Maleri peloids and caliche features is enumerated below:

(1) The microcrystalline and microspar nature of Maleri peloids (Fig. 5) resembles the "undifferentiated crystic plasmic" fabric of "glaebules" described from soil carbonates (Gile et al., 1965; Folk, 1969; Allen, 1974).

(2) The clotted texture and microspar channels characteristic of these peloids (Fig. 8) are known from many caliche facies (James, 1972; Esteban, 1974, 1976; Arakel, 1982; Esteban and Klappa, 1983).

(3) Intraformational clasts and peloids in the Maleri Formation are often characterized by corroded silicate grains floating in micritic/microsparitic matrix (Fig. 6). Such floating textures, though not diagnostic, are typical of caliche facies (Allen, 1974; Tandon and Narayan, 1981; Esteban and Klappa, 1983).

(4) Displacive calcitization, as recorded by "exploded" mica grains in Maleri peloids (Fig. 10), is believed to be an important phenomenon in caliche (Watts, 1978; Tandon and Narayan, 1981).

(5) Isopachous crust of bladed spar ("calcitans") as developed around quartz grains within the peloids (Fig. 9) are comparable with such features described from caliche profiles (Nagtegaal, 1969; Molenaar, 1984).

(6) Micritic envelopes around silicate grains in intraclasts (Fig. 15) and micritic cement within the peloids are not uncommon. Similar features are also well known from vadose diagenetic environments affected by evapotranspiration (Esteban, 1976) and are often associated with pedogenic caliche profiles (Read, 1974; Warren, 1983).

(7) Septarian cracks in the peloids and circumgranular cracks in compound grains of the Maleri calcirudite/calcarenite (Figs. 11 and 12) are known to be common features of caliche profiles (Brewer, 1964; Riding and Wright, 1981; Esteban and Klappa, 1983).

(8) Rhizoliths, a feature of caliche facies (Esteban and Klappa, 1983), occur as intraformational fragments in Maleri calcirudite/calcarenite.

(9) *Microcodium* aggregates, known to be a characteristic component of caliches (Klappa, 1978), are found in the Maleri grainstone.

From the above discussion it may be argued that the peloids were derived by reworking of caliche profiles. The paucity of compound grains in calcirudite/calcarenite suggests that the peloids were sparsely distributed and uncemented in the incipient caliche profiles. Lack of any preserved caliche profile further implies that they developed within the zone of scouring and erosion, i.e. at or near the surface.

The overwhelming red colouration of the floodplain sediments in contrast to drab channel deposits, the desiccation cracks and the paucity of evaporites are related with aerating, pervasive oxygenating conditions and periodic wetting in the vadose zone and possibly reflect generally a low palaeogroundwater level (Friend, 1966; Moody-Stuart, 1966; Van Houten, 1973; Turner, 1974; Leeder, 1975). In such low water conditions, "groundwater calcrete" (Semeniuk and Meagher, 1981) if any should have been preserved in the Maleri sequence. Absence of any in-situ caliche profiles precludes formation of "groundwater calcrete".

Robinson (1964) suggested that these peloids formed due to weathering of Maleri sediments under fluctuating groundwater levels in alternate wet and dry season. The possibility of solution-reprecipitation of carbonate by fluctuating groundwater levels cannot be altogether excluded. But the groundwater fluctuation does not appear to have played any significant role in caliche formation due to the presence of thick impermeable red clay in this sequence. On the other hand, some micromorphological features of the peloids, e.g. micritic and equigranular microsparry constituent, the rarity of concentric laminae, and the nature of concentric laminae suggest that some sort of pedogenic processes played a major role in the growth of Maleri peloids (Folk, 1969; Steel, 1974; Allen, 1974; Tandon and Narayan, 1981).

The equigranular, rhombic morphology of calcite crystals in the peloids together with the presence of spherulite imply precipitation in narrow porespaces at or near the surface from a rapidly evaporating supersaturated solution (Folk, 1969; James, 1972; Klappa, 1983). The near absence of host material within most of the peloids indicates growth by displacive precipitation. Though the peloids have been transported to a certain extent, their sphericity appears to be inherent to them. That these peloids initially developed as spherical bodies is evident from (1) concentric laminae of iron oxides alternating with calcite laminae, (2) poorly developed, fuzzy concentric laminae of calcite, (3) concentric syneresis cracks conforming with the periphery of the grains and (4) circumgranular cracks in compound grains. The septarian peloids presumably formed in water-laden sediment during early diagenetic stages, possibly near the sediment–water or sediment–air interface. Such peloids, during their initial phase of growth, passed through a gel-like stage followed by case hardening and colloid contraction due to irreversible chemical desiccation (Brewer, 1964; Neal, 1978).

## SEDIMENTOLOGICAL AND PALAEOCLIMATIC IMPLICATIONS

The Maleri Formation abounds with reworked intraformational caliche material indicating the presence of ghost caliche profiles. Such a situation requires a periodically effective agent of erosion, a geomorphic set-up characterized by insufficient relief, and possibly a gentle slope. Scouring by wandering channels, rain wash, sheetflow and sheetflood were probably responsible for the erosion of incipient caliche in a poorly vegetated terrain with low soil permeability.

The former occurrence of incipient caliche profiles suggests the presence of periodically stable geomorphic levels and a low to moderate rate of alluviation balancing subsidence (Allen, 1974, 1986; Leeder, 1975). However, it should be remembered that the actual rate of aggradation must have varied both in space and time. It seems that at any instant of time the Maleri alluvial plain consisted of depositionally active and virtually inactive areas and recurrence intervals of avulsions were just long enough to allow the incipient development of caliches in the inactive areas.

Though caliches have been reported from widely varying climatic zones, Quaternary caliches are largely restricted to the semi-arid areas (Goudie, 1973). The poor floral content of the Maleri Formation does not indicate intense humidity. Poor accumulation of plant material as rhizoliths rather than as organic material or humus, clearly implies a lower plant biomass production and low water table which caused the partial oxidation of organic matter (Rust, 1981). The presence of a few herbivorous reptiles, e.g. cynodonts, rhynchosaurs, aetosaurs, does not, however, necessarily indicate the presence of a dense canopy of forest, as visualized by Chatterjee (1978). A savanna or a grassland biochore may have enough food potential to support a vast multitude of grazing animals. Locally abundant unionids, the presence of an aquatic and semi-aquatic fauna, the absence of aeolian sediments and the paucity of evaporites on the other hand preclude extreme aridity. The presence of large ectotherms implies that the climate must have been amenable to the large, land-dwelling reptiles which could not aestivate, and the daily or annual fluctuations in temperature were limited.

The Maleri climate appears to be semi-arid because too little water prevents mobility of calcium carbonate and too much water causes extensive leaching of soils. The high smectite content (48–75% determined by D.T.A. and X-ray analysis) in Maleri clays ($< 62$ $\mu$m) is indicative of low rain fall ($< 500$ mm yr$^{-1}$, Singer, 1980). The peloids which developed at or near the surface, possibly reflect semi-arid conditions because the depth of caliche profiles decreases with increasing aridity (Sehgal and Stoops, 1972). Nevertheless, the sporadic presence of barite, a common mineral in deserts (Collinson and Thompson, 1982) coupled with the ubiquitous presence of displacive and replacive calcite cements and above all the former presence of caliches point to a warm to hot climate with low seasonal rainfall and annual deficit in water budget (Goudie, 1973). The presence of circumgranular cracking in compound grains, curved fissures of retraction and bursting, clotted micrite with microspar channels clearly reflect shrinkage of peloids caused by alternate wetting and drying. Concentric laminae of iron oxide/hydroxide alternating with calcitic laminae also point to alternating wet and dry periods.

## SUMMARY AND CONCLUSIONS

(1) Maleri peloids are intraformational and were derived by reworking of incipient pedogenic caliche profiles which developed in Maleri floodplains as well as in abandoned channels and levees.

(2) The peloids developed by displacive calcite precipitation nucleated within pores of host soil and/or sediment.

(3) The incipient caliche profiles possibly developed at or near the surface and were efficiently eroded by channel wandering as well as overland flow over a sparsely vegetated terrain with low relief and low infiltration capacity of the ground.

(4) Peloids were intraformationally reworked and were deposited as carbonate grainstones in channels as well as in transient local drainage.

(5) The ghost caliche profiles imply the presence of temporarily stabilized geomorphic levels, and a low to moderate rate of alluviation.

(6) The Maleri climate was semi-arid characterized by a low seasonal rainfall.

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