ABSTRACT

The calcareous sandstones and sandy limestones of the Bauru Group have been frequently mentioned in geologic literature of Brazil since the beginning of this century, but this Group has only recently been studied in detail and reliably divided into formations about two years ago. Only in 1973 was a detailed investigation carried out especially focusing on the petrologic, chemical and isotopic properties of these sediments, which for the first time were interpreted as calcretes. This paper reinterprets these petrologic studies and their geological significance in the light of recent literature on the calcretes in the world, and the recent revision of Bauru Group stratigraphy.

INTRODUCTION

Calcretes are continental materials composed predominantly of powdery to nodular calcium carbonate, cementing to a greater or lesser degree quantities of soil or rock, primarily within the vadose zone (GOUDIE, 1975:3). They are known by several names: caliche (United States), croûte calcaire (France), nari (Israel), etc. However, as a term of general utility, calcrete is preferred because it has few local connotations.

The recognition of fossil calcretes in ancient sedimentary sequences, as in the Marília Formation (Upper Cretaceous of southern Brazil) of the Bauru Group holds considerable interest for paleoenvironmental reconstructions for two main reasons. First, calcretes are presently extensively distributed in hot semi-arid regions (GOUDIE, 1973), which supports their use as climatic indicators. Second, they seem to indicate subaerial exposure (MULTER and HOFFMEISTER, 1968, DUNHAM, 1969 and JAMES, 1972), though some authors (ELIAS, 1948 and KENDALL, 1969) have interpreted them as of algal or stromatolitic origin and related to lacustrine, lagoonal or marine environments.

Through the examination of the available literature and the description of thin sections, polished sections and hand specimens of modern calcretes, GOUDIE (1975:4) put forward some general characteristics of calcretes, useful in the recognition of ancient deposits, such as:
a) Laminar features — These are found
in the surficial portions (topmost 1 to 3 cm) and
are characterized in section by laminations
about 0.06 mm thick. When arranged in wavy,
convolute bands, they have often been confused
with algal structures. The laminar structure
can result from alternate layers of more or less
Fe-oxide stained bands or from differences
in calcite crystal size (NAGTEGAAL, 1969).
Laminar features may not be volumetrically
important within common calcrete deposits.
However, they have generally drawn much dis-
cussion, partly because they are readily visible
during field surveys and because of their
similarity to stromatolites (ADAMS, 1980:
656).

b) Concentric structures — These are
features similar to oolitic structures (JAMES,
1972) and have also been termed pisoids,
spherulites and diagenetic ooids. The structures
may or may not have detrital mineral grains
or fossil fragments as nuclei. When asymmetri-
cal, there is a tendency for downward direc-
tional growth of the outer layers (SWINEFORD
et al., 1958 and DUNHAM, 1969), whereas
with algal limestones the growth would tend
to be upward. Larger than the spherulitic
concentric structures are various types of
calcrete nodules. In some cases, such nodules
formed by the deposition of fine grained
carbonate around decaying rootlets, in which
case they may be called rhizocretions (KLAP-
PA, 1980), not really nodules.

c) Brecciated structures — Brecciation
in calcrete occurs at all scales. At macroscale
(tens of cm or larger) it gives rise to pseudo-
anticlines and wedges (BLANK and TYNES,
1965, REEVES, 1970 and GOUDIE, 1973),
while on the mesoscale (a few cm) it leads
to fragmentation of pebbles (YOUNG, 1964),
and, on microscale (fractions of mm), it causes
clastic debris and individual clastic grains to
break up (ROTHROCK, 1925). Brecciated
structures in calcretes may form due to crystal-
lization, hydration and/or thermal expansion
of various salts.

d) “Floating” and corroded grains — A
result of the expansion promoted by calcrete
recrystallization is the widespread occurrence
of “floating” grains which do not exhibit the
point-to-point contacts as they show in the pa-
rent sediment or soil. During later stage in
the development of calcrete crusts, or hardpan,
“floating” grains of quartz or other silicate
minerals are strongly corroded by calcite.
In very advanced diagenetic stages the calcretes
become completely transformed so that virtually
nothing remains of the original detrital constituents of the host sediment or soil
(NAGTEGAAL, 1969). According to SWI-
NEFORD et al. (1958), it seems probable
that small sand-sized areas of coarse calcite
observed in many thin sections could represent
the former position of detrital grains.

e) Indicators of subaerial exposure —
As a consequence of the exposure of sediments
to subaerial conditions, and their expansion
and contraction due to wetting and desiccation,
polygonal structures can develop at both the
macro and microscale. Also suggestive of a
probable subaerial origin is the development
of rhizocretions. Incomplete replacement of
the pre-existing sediments or soil leads to
the preservation of unaltered pockets of sedi-
ment or soil.

The limestone deposits characterizing
the Marília Formation (ALMEIDA and BAR-
BOSA, 1953), mostly the Ponte Alta Facies
(BARBOSA et al., 1970 and BARCELOS et
al., 1981) here named Ponte Alta Member,
of the Bauru Group have long been known
but were recognized for the first time in 1973
as calcrete and described in detail by SUGUIO.
Since then many papers on this subject have
been published (SUGUIO et al., 1975, SUGUIO
and BARCELOS, 1978 and 1980) and the
stratigraphy of the Bauru Group, to which
these calcrete deposits belong, has been the
subject of extensive investigation. This paper
reinterprets SUGUIO’s 1973 work in the light of
these recent developments.

FIELD CHARACTERISTICS AND
DISTRIBUTION

The Bauru Group calcrete is best de-
veloped in the Triângulo Mineiro (south-central
Brazil), near Uberaba, Minas Gerais, but is also
found in the States of São Paulo, and southern
parts of the States of Goiás and Mato Grosso
do Sul (Fig. 1).

According to NETTERBERG’s calcrete
classification (1967), the following types of
Fig. 1 — Geologic map showing the areal extent of the Bauru Group (Based on Geologic Map of Brazil, Departamento Nacional da Produção Mineral, Rio de Janeiro, 1971).
calcrete are present in the Bauru Group: calcified soil, nodular calcrete, honeycomb calcrete and hardpan calcrete. The calcified soil and nodular calcretes are not restricted to the Ponte Alta Member and Echaporã Member (name for the first time used here to designate the lithofacies of the Marília Formation outcropping in the Marília and Echaporã plateaus) of the Marília Formation, frequently being found in other formations of the Bauru Group, such as in the Adamantina Formation as defined by SOARES et al. (1980). Some nodular calcrete of the Marília Formation (Echaporã Member) found between Duartina and Gália, in the State of São Paulo, shows evidence of probable reworking after its formation, as it is associated with cut-and-fill structures exhibiting possible unclear cross-bedding.

In the Triângulo Mineiro area, the calcrete seems to be associated laterally and vertically with playa lake limestones, extending from Sacramento to Frutal, over a distance of about 100 km. The average thickness of the hardpan type of calcrete deposits at the village of Ponte Alta (near Uberaba), including the lacustrine limestone, is about 8 m. This value is very small when compared with the maximum recorded thicknesses of 50-60 m and 47 m for calcrete profiles from South Africa (GOUDIE, 1973) and at Millstream, Western Australia (DAVIDSON, 1968), respectively. Drilling near Ponte Alta village has revealed the subsurface character of the calcrete deposit (Fig. 2) in the area. Its thickness is very uniform, ranging from a minimum of 7.0 m (hole 32B) to a maximum of 8.9 m (hole 38B), with an average value of 8.0 m. Moreover, the calcrete bed, including the lacustrine limestone, is situated everywhere virtually at the same stratigraphic level and at nearly the same altitude. The conglomeratic portion of the calcrete is known in the Uberaba area under the local name “casco de burro” (“donkey hoof”), which can be described as light coloured (moderate orange pink = 5YR 8/4 to yellowish gray = 5Y 7/2) limestones, with sandy impurities and well rounded quartz, quartzite and chert pebbles. Frequently, they are nodular with a mottled appearance due to the presence of the more or less sandy portions. These portions can be enhanced through the action of pluvial leaching, thus acquiring a “brecciated” aspect due to the strong angularity of the sandy spots (Fig. 3). The hardpan calcrete deposits are commonly lenticular, but when better developed, as in the Ponte Alta area, they are associated with purer lacustrine deposits and exploited to make cement. In this area the calcrete deposits run along the cliffs bordering the “chapadão”, a geomorphological feature characterized by an extensive very flat plateau interrupted only by shallow valleys carved by local drainage.

In the southern parts of the States of Goiás and Mato Grosso do Sul, and in the State of São Paulo, the calcrete is more impure (sandy and pebbly), very frequently silicified, and inferior in both volume and quality to that of the Ponte Alta area. However, it shows some development as in the Agudos (State of São Paulo).

Elsewhere the calcium carbonate occurs as a cement in sandstone and other clastic sedimentary rocks or as irregular nodules scattered within sandy marls or clayey sandstones (Fig. 4). In other places, the calcrete deposits comprise much more impure, calcium-carbonate-cemented conglomerates, occurring as caprocks of residual hills in the Marília Formation (southern State of Goiás).

LABORATORY STUDIES

The surface and subsurface calcrete samples from the Bauru Group were examined macroscopically in polished sections, microscopically in thin sections, and chemically by analysing major, minor and trace elements, HCl-insoluble residues and carbon and oxygen isotopes. Geochemical data, including chemical and isotopic compositions, have been discussed elsewhere by SUGUIO et al. (1975), so that only the results of other laboratory analysis are presented here.

MACROSCOPIC DESCRIPTION

Larger features visible to the naked eye or in hand lens were examined in polished sections of 58 calcrete samples. The commonest feature observed is a mottled pattern produced by both nodular and brecciated structures, although some homogeneous micritic limestones are also found. Macroscopically, the following limestone types can be recognized:
Fig. 2 – Drilling logs in the Buracão area, Ponte Alta village, vicinity of Uberaba (State of Minas Gerais).
a) **Homogeneous limestone** – Unmottled, very pure, micritic limestone, characterized by light colours generally between grayish pink (10R 8/2) and very pale orange (10YR 8/2).

b) **Brecciated limestone** – It is possible to distinguish two subtypes, both characterized by a mottled pattern. The first one, made up by angular pockets of sandy (quartzose) sediment (“sand pocket”) separated by homogeneous limestone. This feature is also visible on a microscopic scale. The second type comprises angular homogeneous limestone fragments separated by sandy limestone.

c) **Conglomeratic limestone** – This occurs as lenses of CaCO₃ – cemented conglomerates within purer limestones. The clasts, which range from granules to pebbles (to more than 5 cm), consist of quartz, quartzite and chert.

d) **Sandy limestone** – This is commonest and most varied limestone type, ranging from purer sandy limestones to CaCO₃ – cemented sandstones.

e) **Silicified limestone** – In general the
limey portions are characterized by light colours (pinkish gray = 5YR 8/1) and the silici­fied portions by dark colours (medium gray = N5 to dark gray = N4). The contact between these portions is very irregular.

**MICROSCOPIC DESCRIPTION**

Ninety-five thin sections of 72 calcrete samples were examined microscopically. Some of the textural and structural details, visible only under the microscope, were very important in both petrologic description and in the identification of the calcretes.

![Calcrete from a quarry in Ponte Alta, Uberaba area, State of Minas Gerais](image)

Textural aspects

Description of textural aspects is here limited to calcite crystallinity, calcite crystalline habit and grain size of insoluble residues.

a) **Calcite crystal size** — Crystal sizes vary from cryptocrystalline, where individual calcite crystals are not resolvable even at magnifications of 320X, to 0.60 – 0.80 mm and, in veins and druses, more than 1 mm. Even in a restricted area of a thin section, variation in crystallinity is a rule, and uniformity an exception (Fig. 5). However, apparent crystal size classes occur between 0.002 and 0.005, 0.005 and 0.010 mm, 0.040 and 0.100 mm, and 0.200 and 0.400 mm (Fig. 6).

b) **Calcite crystal habit** — In cryptocrystalline calcite crystal outlines are not visible even under 320X magnification. In coarser portions the calcite crystals exhibit very distinct outlines and striated surfaces, and comprise a mosaic of more or less equidimensional crystals. The striations are attributed to crystal cleavage. The crystalline mosaic is frequently interrupted by coarser crystalline veins or by finer grained spots (Fig. 5). In general the calcite crystals are sharply penetrated each other.

c) **Grain size of insoluble residues** — Only the sandy and silty microscopic insoluble residues, predominantly falling within 0.030 to 0.060 mm and 0.200 to 0.500 mm intervals (Fig. 7), have been considered. Eight thin sections were completely free of sandy and coarse-silty insoluble residues, indicating that the Marilia Formation limestones are locally very pure.
Fig. 6 – Some calcite crystallinity intervals in the Marília Formation calcretes: 0.002 – 0.005 mm, 0.005 – 0.010 mm, 0.040 – 0.100 mm and 0.200 – 0.400 mm.
Fig. 7 - Insoluble residues grain sizes predominantly consisting of the 0.030 - 0.060 and 0.200 - 0.500 mm intervals, Marília Formation calcretes.
Structural aspects

Microscopic structures recognized in thin sections include silicification structures, vugs and druses, laminar structures, pisolithic and alveolar structures, "sand pockets", sand grains and chalcedony with calcite halos, microporosity, and corroded detrital grains.

a) Silicification structures – Fifty-six thin sections, mostly from the Uberaba area, presented silicification structures evidenced either by very restricted silicification nuclei or by the generalized transformation of calcite into fibrous chalcedony, partially recrystallized into quartz. It seems that silicification preferentially occurs within portions characterized by abundant fragments of quartz and quartzite. According to WALKER (1960), the intimate relationship between silicification and calcretes suggests that the major source of silica is that released during the replacement of silicates by calcite.

b) Vugs and druses – Vugs and druses, as well as geodes, are very characteristic features of these calcretes, having been found in 43 of the thin sections. They show varied shapes and sizes, and occasional geopetal filling by sparry calcite or fibrous chalcedony. Silicification features are commonly associated with spar-filled voids exhibiting coarser crystallinity.

c) Laminar features – Laminar structures are observed in a dense micritic limestone with crystals 0.005 to about 0.010 mm in diameter. The laminae average 0.1 to 0.4 mm in thickness and have slight undulating boundaries. Such features, similar to the "algal coating" mentioned by MÜLLER-JUNGBLUTH (1968), were identified in 42 of the thin sections.

d) Pisolithic and alveolar structures – The pisolithic structures are spherical or elliptical and characterized by insoluble nuclei. The laminae are concentric and the outer surface is smooth or undulatory. Pisolithic structures frequently develop in a vadose environment (DUNHAM, 1969).

In many places, alveolar structures, 0.80 to 2 mm in diameter, are well developed in the laminar unit as flattened rhizocretions with many insoluble residues. SUGUIO (1973) records the presence of frequent alveolar structures within the Mangabeira quarry near the Uberaba – Uberlândia Federal Highway (Fig. 8).

e) "Sand pockets" – These features associated with abnormal concentrations of sand-sized (0.04 to 0.08 mm), insoluble clastic residues (quartz, quartzite, feldspar, etc.) contained within "sand pockets" a few mm to several cm in diameter. This structure,
present in at least 15 thin sections, probably developed through the concentration of these residues associated with segregation phenomena during the diagenetic recrystallization, penecontemporaneous with sedimentation.

f) **Sand grains and chalcedony with calcite halos** — Insoluble san grains and chalcedony are frequently enveloped by a halo of sparry syntaxial calcite crystals. This feature is easier to see when surrounded by cryptocrystalline calcite.

g) **Microsporosity** — Tiny voids of varied shapes and sizes have been seen in 7 thin sections. In some cases they are solution voids and, in other cases, they represent the spaces left within voids partially filled by spar.

h) **Corroded detrital grains** — Detrital silicate minerals are corroded by calcite so that grain edges are strongly indented. Quartzite fragments have apparently been more affected than detrital quartz grains, due to the preferential replacement along crystal boundaries within the quartzite. As silica shows an inverse solubility relationship with calcite (CORRENS, 1950), this corrosion phenomenon, evident in at least 6 thin sections, may well have occurred when the pH was above 9 (ALEXANDER, et al., 1954), where calcite begins to precipitate and silica begins to dissolve.

### Insoluble residues

Insoluble residues of the calcretes, consisting both of detrital and non-detrital (authigenic) silicate minerals, were isolated into two size fractions, i.e., finer than 0.062 mm (silt and clay) and coarser than 0.062 mm (sand).

**Percentage of CaCO₃ and insoluble residues** — Ten of the 112 samples are not called limestones, but rather calcareous sandstones, with CaCO₃ contents lower than 50% (Table I, Fig. 9 and 10).

From the Table I it is evident that the average compositions in insoluble residues of the calcrete samples in Uberaba area are quite similar, both in outcrop samples and in drill cores. Locally, however, these limestones can consist of more than 99% CaCO₃ samples, showing probable lacustrine origin. On the other hand, the average composition of calcrete samples from Frutal and Prata (State of Minas Gerais) and Rio Verde (State of Goiás) show lower CaCO₃ content and consequently more insoluble residues than in the Uberaba area.

The calcrete samples from the Agudos (State of São Paulo) show an average CaCO₃ composition lower than that of the Uberaba area, with a corresponding increase in the sandy insoluble residue content and decrease in the clayey-silty insoluble residue. The calcrete nodules, also from the State of São Paulo, show the lowest CaCO₃ values of the analysed samples. Nevertheless, they may still be considered as limestones, as they have more than 50% CaCO₃. They are, however, as sandy as Agudos area calcretes and have a higher silt and clay content.

In summary, the Marília Formation calcretes are, in general, purer and more extensively developed in the Uberaba area, where no significant difference could be detected between surface and subsurface samples. On the other hand, where the calcrete’s CaCO₃ content is high, its silt and clay content is also relatively high with respect to its sand content, a common relationship in calcretes (GOUDIE, 1973:25).

**Mineralogical composition of insoluble residues** — Sand-sized insoluble residues (coarser than 0.062 mm), consist predominantly of quartz grains. Heavy minerals, quartzite fragments, feldspar, and other forms of authigenic silica (e.g. chalcedony) are less important.

Clay minerals in the silt and clay fractions have been identified by X-ray diffraction analysis of 35 samples from the Uberaba, 10 from drill cores of the Ponte Alta, 10 from west of Uberaba (Frutal, etc.), 11 from the Agudos, and 23 from calcrete nodules mentioned previously (Fig. 11). Following are some of the conclusions from these analyses:

a) There are seven types of clay minerals: attapulgite (also known as palygorskite), illite, kaolinite, chlorite, montmorillonite (also known as smectite); sepiolite and vermiculite have been questionably identified in some of the samples. This suite of clay minerals is practically the same as that found by WATTS (1980:668) in Kalahari calcretes.

b) Attapulgite and illite are the dominant clays of the analysed samples, the former represented in 45 samples, the latter in 43 samples; in 30 of these samples the two minerals occurred together. Attapulgite is considered
<table>
<thead>
<tr>
<th>PROVENANCE</th>
<th>Number of samples</th>
<th>SOLUBLE</th>
<th>INSOLUBLE RESIDUES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>% CaCO₃</td>
<td>&lt; 0.062mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>Maximum/ minimum</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minimum</td>
</tr>
<tr>
<td>1) Uberaba area</td>
<td>48</td>
<td>78.84</td>
<td>99.08/ 51.28</td>
</tr>
<tr>
<td>surface samples</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) Uberaba area</td>
<td>11</td>
<td>79.63</td>
<td>99.44/ 64.00</td>
</tr>
<tr>
<td>drill core samples</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3) Frutal and Prata (MG);</td>
<td>12</td>
<td>71.82</td>
<td>88.38/ 54.72</td>
</tr>
<tr>
<td>Rio Verde and Jataí (GO)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4) Agudos and Piratininga (SP)</td>
<td>15</td>
<td>69.36</td>
<td>89.16/ 51.48</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5) SP-294 highway (Bauru-</td>
<td>25</td>
<td>63.78</td>
<td>80.92/ 50.08</td>
</tr>
<tr>
<td>Herculândia) and SP-333</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Guarantã-Echaporã)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: 1), 2), 3), 4) = Hardpan and calcified soil type calcretes.
5) = Nodular type calcretes.
1) = Partially, lacustrine limestones.
MG = State of Minas Gerais, GO = State of Goiás and
SP = State of São Paulo.
Calcretes of the Bauru Group (cretaceous), Brazil: petrology and geological significance

Calcrete samples from Triângulo Mineiro and southern State of Goiás

Fig. 9 – Size frequency of insoluble residues in samples of calcretes from the Triângulo Mineiro and southern State of Goiás.
Fig. 10 – Size frequency of insoluble residues in samples of calcretes from the Agudos and other regions of the State of São Paulo.
Calcretes of the Bauru Group (Cretaceous), Brazil: petrology and geological significance

a typical authigenic silicate frequently identified within modern and ancient calcretes (GARDNER, 1972, NAHON and RUELLAN, 1975 and REEVES, 1976), and in other semi-arid soils (BLOM, 1970 and GUPTA and RAYCHAUDHURI, 1973).

c) In the Uberaba area, the surface samples clay mineralogy was more constant than in the subsurface samples. In the State of São Paulo, clay mineralogy was more variable in the calcite nodules than in the sandy calcretes (calcified soils).

CONCLUSIONS

General features observed in the field, together with laboratory data, indicate that majority of the Bauru Group carbonates are undoubtedly calcretes. Practically all features listed by GOUDIE (1975:4) as calcrete recognition criteria have been identified within these limestones.

The purer limestone found near Ponte Alta could have been formed under a semi-arid climate within ephemeral playa lakes. This
limestone is associated with hardpan calcretes with a total thickness of about 8 m. Except for this occurrence, there is no lacustrine limestone within the Marília Formation. Rather, practically the entire thickness of this formation can be classified as calcified soils or nodular calcretes. In this case, the maximum thickness of the calcrete deposits of the Marília plateau is more than 200 m, thus representing the thickest such deposit in the world.

Some periods during the sedimentation of the Adamantina Formation (also within the Bauru Group) were also characterized by a semi-arid paleoclimate, as evidenced by the extensive distribution within this formation of nodular calcretes and calcified soils, similar to those of the Marília Formation.

REFERENCES


BARCELOS, J.H., LANDIM, P.M.B. and SUGUIO, K. - 1981 - Análise estratigráfica das seqüências cretáceas do Triângulo Mineiro (MG) e suas correlações com as do Estado de São Paulo. 3a Simpósio de Geologia Regional, Sociedade Brasileira de Geologia, Núcleo de São Paulo, Atas v. 2:90-102.


Without excluding Ca-bearing minerals in underlying basaltic rocks as a possible source of the calcium carbonate for the Bauru Group calcretes (especially for the Marília Formation), the extensive development of the CaCO₃-rich deposits in the Uberaba area may be more readily explainable if one assumes a substantial contribution of carbonate from the nearby Precambrian Bambuí Group limestones. This argument may also explain the absence of pure limestones in other areas, as in the State of São Paulo, where Precambrian limestones apparently do not occur nearby, either in stratigraphic or in geographic terms.

The authors wish to express their sincere gratitude to Dr. Thomas R. Fairchild of the University of São Paulo for careful revision of the English text.
Calcretes of the Bauru Group (cretaceous), Brazil: petrology and geological significance


