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An unique record of a coastal aeolian paleo-system

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The eolianites, distributed along the northwestern part of Ceará State coast, are formed by arenaceous rock deposits of quartz-bioclastic composition, cemented by calcium carbonate. This unit establishes an unique record of aeolian activity with peculiar features, rare on the brazilian littoral, whose particular characteristics, preserved in its structures and composition, highlight a large potentiality to provide relevant informations about coastal environment conditions at the time of its formation. The lithified character of these deposits has provided its preservation along the time; however, more friable parts have facilitated erosive wind action, contributing for the discontinuity of distribution and morphology of eolianites. The eolianite deposits invariably display outcrops with large scale sedimentary inner structures, mainly plane-parallel and planar cross-strata, although cross-braided and festooned forms are also relatively well represented, besides other less common. The deposits display aeolian abrasion "ruin" morphology and have a high rigidity comparatively to other aeolian deposits. The correlation between them and current active dunes has lead to the interpretation that most of eolianites records are representative of an evolution phase represented by the formation of compound dunes, with parabolic dunes accumulation at the final stage. An important aspect of these deposits is also the presence of ancient human occupation records, represented by man fragments of manufactured lithics tools and fires.

Keywords: *eolianite, sedimentary structures, aeolian morphology, coastal area of Ceará state*

INTRODUCTION

The coastal zone of Ceará extends for 570 km, between the states of Rio Grande do Norte and Piauí. The main geomorphologic units present in this stretch of coastline are low sedimentary plateaus supported by the Tertiary "Barreiras" Formation. Quaternary deposits from various sources (rivers, lakes, lagoons and specially, of aeolian origin) recover this plateaus. The aeolian deposits form extensive dune fields, which are present from the post-beach to about 10 km towards into the continent.

The term eolianite was defined by Sayles (1931) as any sedimentary rock whose deposit was controlled by the wind. Generic definitions, such as "rock dune" and "aeolian calcarenite" were also used. In coastal areas, the rock is composed of a large amount of biogenic carbonate reworked from shallow marine sediments (Fairbridge and Johnson, 1978; Tinley, 1985; Brooke, 2001 and Price *at al.*, 2001). Tinley (1985) explained the cementation as the result of percolation of ground water containing calcium carbonate derived from biogenic fragments.

In the northwestern state of Ceará coast, eolianites were identified (Maia *et al.*, 1997) as aeolian deposits cemented by calcium carbonate, in a manner that involved the dissolution of carbonates present in marine biogenic fragments and shells which have been transferred, during periods of low sea level and/or falling sea level, to the coast, coming from the adjacent inner shelf, where they occur in abundance (Coutinho, 1993). Such a context would have allowed the migration and further stabilization of the aeolian sands. In the sequence, two other processes took place: (1) meteoric water saturation and (2) cementation, allowed by the precipitation of dissolved carbonates. Carvalho (2003) found that the process of cementation have been similar to what occurs in the formation of calcretes.

An important element of eolianite fields is the excellent state of preservation of their internal depositional structures (Fig. 1), facilitating the interpretation of morphodynamics at the time of its formation. Added to this fact, it is worth mentioning the beauty of the coastal landscape the outcrops produce.

The process of characterization and mapping of eolianite in Ceará State is relatively advanced compared to the coast of the states of Rio Grande do Norte, Piauí and Maranhão, where such forms are also present. Still, they need more specific studies, and require greater disclosure on national and regional levels so they can arouse interest in the science and policy. The lack of adequate protection for these rocks can lead them to a process of general deterioration, especially given the urban pressures which currently characterize the coast of Ceará State. If this situation materializes, it will frustrate the implementation of new studies on this important record of the geological past, not yet completely understood in its fullness.

Figure 1 – Outcrop of sedimentary crossed, braided and festooned structures over a tabular set, in Flecheiras beach eolianites. The outcrop is longer of 3 m and 2 m high. Photo by A.M. Carvalho

LOCATION

The eolianites are distributed discontinuously along almost the entire stretch of the northwest coast of Ceará (Fig.2), and is more common among the localities of Pecém, Flecheiras, Mundaú and Acaraú.

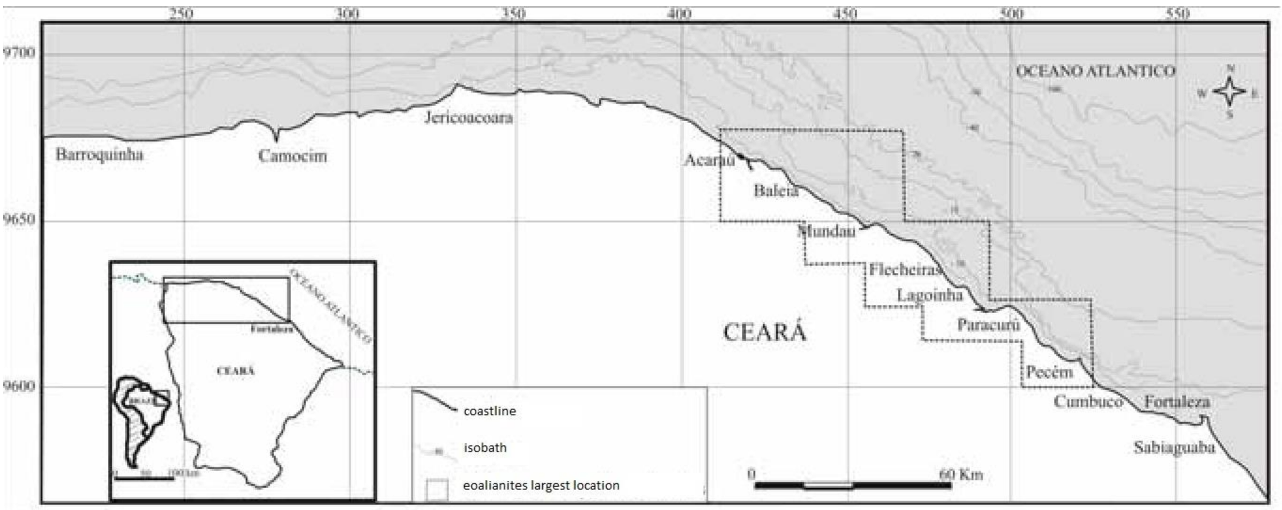

Figure 2 – Location of the studied area, highlighting the segment of highest presence of eolianites in the Ceará State coast.

This occurrence is explained by the presence of carbonates on the adjacent inner shelf, near to the beach-shore. For the purpose of take out a particular study area, we considered the representativeness of internal structures of rocks and outcrops, as well as the facility to access them. These criteria indicated the site located between Flecheiras and Mundaú towns (Fig.2), which is positioned at coordinates 03º12'07"S - 039º19'21"W.

SITE DESCRIPTION

Three to four generations of aeolian deposits were identified on the coast of Ceará State (Carvalho & Maia, 1990; Maia, 1998; Castro, 2001; Claudino-Sales, 2002; Carvalho, 2003). In short, it can be described as follows:

1) Palaeodunes of Pleistocene age, without defined forms, located at the top of the sedimentary Barreiras Formation, consisting of unconsolidated quartz sand, ranging from fine grained to medium grain of a dark red color;

(2) Stabilized parabolic dunes formed by unconsolidated quartz sand, with medium to fine particles size, with colors ranging from orange to gray;

(3) Friable and strongly lithified eolianite, formed by medium to fine quartz sands cemented by calcium carbonate, located above the Holocene marine plain, but below the Present dunes system. These dunes originated after the Holocene transgression. They represent a package of mobile dunes that have been stabilized, subsequently partially lithified by carbonate cementation;

(4) Current active dunes, including barchans, barchanoids and sand-sheets, formed by quartz sands of medium to fine grain. These active dunes are separated from the shoreline by a deflation plain of 600 m to 2000 m wide, and migrate on the top of older dunes.

Eolianites are distributed in oblique bands along the coast, with a distance ranging from 3 to 6 km from the coastline to the coastal zone internal limit. Eventually the seaward side of these deposits is located at a distance of no more than a few tens of meters, often turning up on the beach, when they come to the attack of sea waves. Outcrops commonly expose vertical sections that were highlighted according to the abrasive action of wind. This abrasion clearly set out defined strata, as well as surfaces with tabular ruiniform aspect, characterized by the presence of erosion marks oriented downwind of steep slopes and irregular ridges (figure 3 and 4). These characteristics create features as "yardang" and "zeugen", as it was observed by Carvalho *et al.* (1994) and Claudino-Sales (2002).

Figure 3 – Deflation surface exposing tabular eolianites. Surface of ca 2000 m^2. Baleia Beach, Ceará. Photo by A.M.Carvalho.

Figure 4 – Large scale estratified eolianites in Fleicheiras beach, Ceará. They expose a yardang and zeugen ruin morphology. Photo by A.M.Carvalho

The eolianites are largely stratified, with varying degrees of lithification - from crispy to strongly lithified. Commonly, there are also lithified roots (Fig. 5), what shows partial substitution of carbonate by organic matter and indicate the dunes have been fixed by coastal vegetation before the cementation process.

Figure 5 – Pseudomorphosed roots by $CaCO_3$, longer than 10cm, in eolianite of Flecheiras beach, Ceará state, Photo by A.M.Carvalho.

They have a dominantly quartz composition, plus a variety of fragments of organic carbonate of marine origin, with subordinate proportions of terrigenous, opaque heavy minerals as tourmaline and feldspar. Among the skeletal components, which represent about 15% of the sediments, clams predominate, followed by algae, foraminifera, commonly of the genera Quinqueloculina and Globigerina, bryozoans, and small proportion of Halimeda. This biodetritical content represents the main differential of these aeolian deposits in relation to their equivalents, older or younger.

In thin sections, the cement represents almost 50% of the rock, and is primarily composed by sparry calcite, distributed between (1) primary, coming from precipitation, which ranges in size from 50 to 100μ, and (2) neomorphic (300μ), the latter rare. Maia *et al.* (1997) observed the predominance of calcite with low magnesium content on the cement, highlighting the occurrence, for a first generation of cement, of the types isopach and meniscus, which represent 16 to 31% of the contents of the samples. Among terrigenous constituents, quartz predominates, accounting for about 70 to 80% of the total grain size, generally exhibiting a grain size from 0.07 to 1.00 mm, being rounded to subdued. Feldspars and other opaque minerals occur as accessories, in proportions of 2 to 5%. The porosity of the eolianites is predominantly inter-granular, distributed by dissolution of calcium carbonate between primary and secondary.

Internal sedimentary structures are visible in all outcrops, being the most common parallel-stratifications (fig. 6), cross-tangential wedge-shaped and strata truncated by deflation, besides zigzag forms (fig. 7). Eventually, there are fluted or scalloped stratifications (Fig.7), and climbing translatent strata (Fig. 8).

Figure 6 – Plan-parallel estratification, dipping with low angle to SW. Outcrop thick of 1,5m. Flecheiras Beach, Ceará state. Photo by A.M.Carvalho

Figure 7 – Cross-bedding stratification, originated by fluctuations in the wind direction. Photo by A.M.Carvalho

The packages of eolianites show a predominance of sub-strata horizontal inclined to Az 110 °. The dips of the sets are stressed on the southeastern edge of the outcrops, especially in its portions inclined to the northwest, defining, respectively, the deposits of faces windward and leeward of the dunes, as can be seen in the GPR profile P1 (Fig. 9), carried along and transverse to the axis of the dunefield. Structures that show parallel stratifications and cross-fluted strata with dips directed primarily to the northwest and southwest were observed.

Figure 8 – Trough cross-beds over planar laminated beds, indicating the presenc of climbinb translatent strata. Outcrop longer of 5m and 2 m high. Migration direction rougly from right to left. Photo by A.M.Carvalho

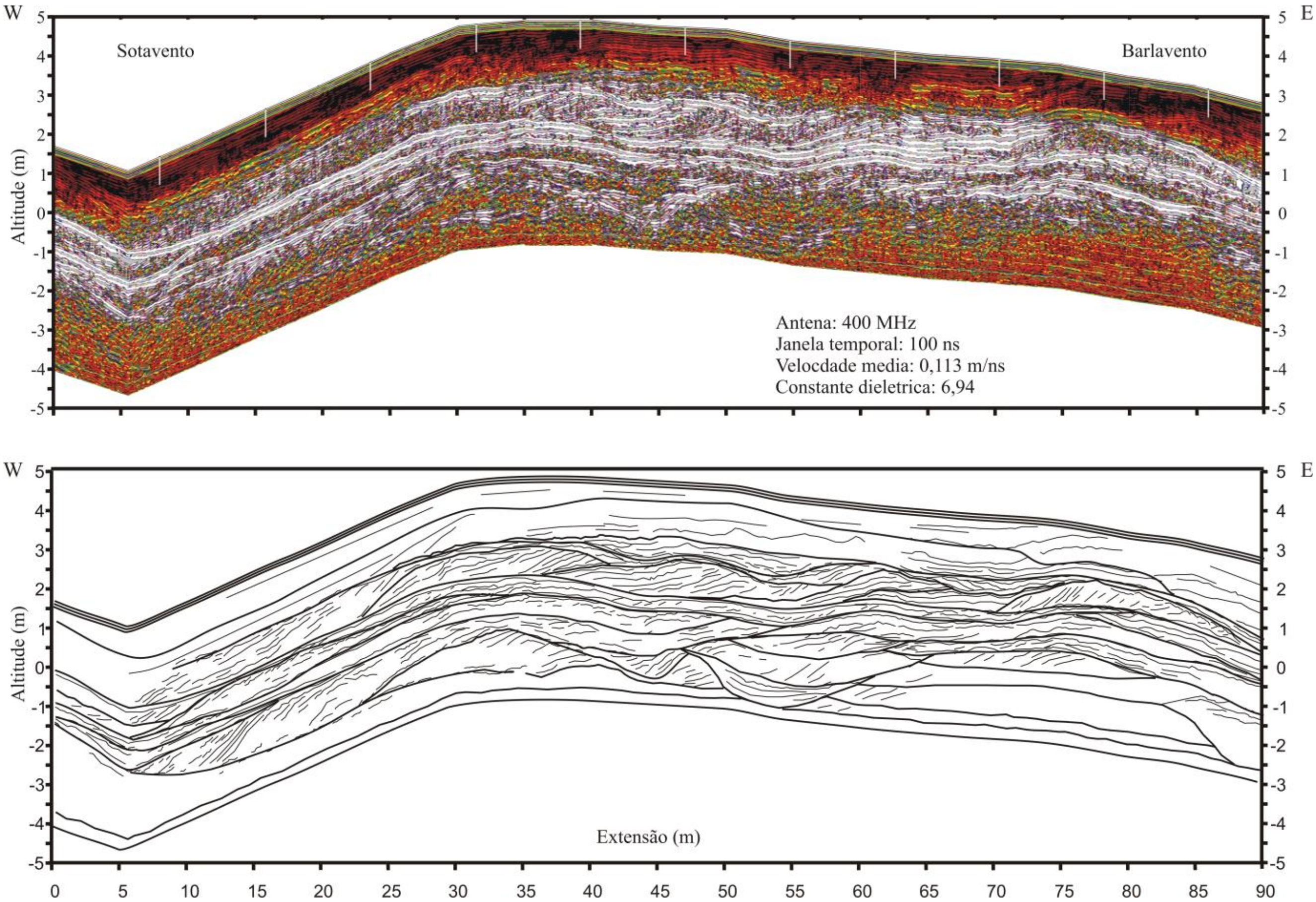

Figure 9 – GRP section exposing trough cross-beds differ from the underllieing plan-parellel strata. It also highlights the superposition of truncated strata (re-interpretated after Castro *et al.*, 2006).

Measures of attitudes held in outcrops along the stretches of those GPR profiles show dives from 16 ° to 20 ° SW and 5 to 7 in NW face of leeward. In the central part of the package, the dives were 4 to 10 °, both to SW and NW. The presence of sets of cross-shaped wreath is also supported by major in-depth reflections GPR (Fig.9). Figure 9 – GRP section exposing trough cross-beds differ from the underlying plan-parallel strata. It also highlights the superposition of truncated strata (reviewed after Castro *et al.*, 2006).

In these GPR studies, Castro *et al.* (2006) found that carbonate cementation decreases the hydraulic flow in the eolianites, allowing to the accumulation of interstitial water, mostly between plane-parallel strata. This situation, according to these authors, would favor the generation of contrasts in dielectric permittivity between the higher and less saturated. The GPR response is marked by strong layered reflections, with peak of amplitude on the electromagnetic spectrum. The study, conducted in Flecheiras town (Castro *et a*l., 2006), showed that the more superficial portion of the GPR profile is dominated by a continuous band of plane-parallel reflectors of low amplitude with thickness around 1.0 to 2.0 m (Figure 9). This geophysical unit is represented by eolianite and by dry or little saturated more recent aeolian sediments. The underlying sequence is highlighted by striking reflectors of meteoric water saturated eolianites, locating at the depth of 1.5 to 2.0 m. This character marked by GPR draw or highlights eolianite lower units and also shows that they took profit, in many cases, of the oldest dunes of different composition as a substrate for overriding. Such GPR profiles also confirm the good homogeneity and continuity in subsoil of these rocks, with hundreds of meters along its greatest elongation (Figure 9).

The GPR, according to Castro *et al.* (2006), demonstrates the thinness of eolianites, ranging from 1.0 to 5.0 m in the region of Flecheiras, adding overlap of geoelectric layers. These features are also found in other localities where eolianites are present. The rapid decay of the amplitudes of reflections on the basis of the GPR profile is due to the decreased level of lithification of the packages of sand. Castro *et al.* (2006) also confirm the thesis pointed out by Carvalho (2003), that eolianite are remnants of a process of transgression of sand over compound dunes rich on bioclastic carbonate, recovering other dunes with less or any bioclastics.

To Maia *et al.* (1977), the values of $^{13}C_{PDB}$, ranging from -8.19 and -8.66% with an average of -8.46% for certain eolianites, signify the existence of an environment of continental cement precipitation of meniscus type (gravitational); the precipitation would have take place in the vadose zone. Unpublished data from isotopic analysis of the cement of these rocks, carried out by "Stable Isotope Laboratory" of the Federal University of Pernambuco (LABISE/ UFPE) in 1992, pointed to a similar result.

The age of these deposits has been dated using ^{14}C method of carbonate cement. Results showed ages between 1780 ± 80 to 1320 ± 50 years BP, calibrated by the program CALIB 5.0.1 in 736 to 1481 years BP (Castro *et al.*, 2006). Nevertheless, it is uncertain the time of formation of sand dunes that gave rise to eolianites, considering that the dating so far have revealed only the time of lithification of these deposits. One of the first studies to use this method to the area was this by Castro, in 2001.

The genesis of eolianite and the dunes in general, has often been associated with sea level fluctuations (e.g. Cooper, 1958; Rodriguez-Ramirez *et al.* 1996; Kindler & Mazzolini, 2001; Arbogast *et al.*, 2002; Catto *et al.*, 2002; Pereira & Angelucci, 2004, among others). On the coast of Ceará, this type of correlation began with Carvalho & Maia (1990), followed by Maia (1993), Carvalho *et al.* (1994), Claudino-Sales (2002) and Carvalho (2003). The vast majority of these works considers the ideal condition for the formation of these morphologies wind associated with a sea level lower than the current. This understanding would explain, to many of those authors, the composition and spatial distribution of eolianites along the coastal area, far away from the shoreline, in more internal segments. Nevertheless, Carvalho (2003) and Branco *et al.* (2007) consider, taking as example the dynamics pattern of today dunes, that such an understanding is incompatible with the position of the present-day shoreline. In terms of wind, the dominant direction at the time of their formation, as identified by the analysis of the internal sedimentary structures, was SE-NW. This direction situation is similar to what happens today.

SYNOPSIS OF THE ORIGIN, EVOLUTION AND IMPORTANCE OF EOLIANITES

The eolianite represent sediments of ancient aeolian deposit that went through the process of carbonate cementation, relatively common in coastal areas. The deposits are composed of quartz sand and of a large amount of carbonate of organic origin (biogenic carbonate). In Ceará State coastal area, the eolianites occur as natural features with little altitude, obliquely distributed for miles along the coastline, and sometimes in direct contact with the sea. The amount of biogenic carbonate, as fragments of shells, present in those rocks, was originated in shallow marine environments. Within a life cycle of evolution, their origin can be synthesized by the following steps of removal, accumulation and cementation of the material:

(1). Accumulation of biogenic carbonate (mostly shell fragments) in shallow marine and coastal areas;

(2). Falling sea level, allowing the sediments of the continental shelf, rich in biogenic carbonates, to be exposed to the wind;

(3). The winds removed the sediments with high contents of biogenic carbonates from the discovered continental shelf and transported it to the coastal zone, where they mixed with quartz sediment of other dunes;

(4.) Given the end of the marine regression, dune migration ceased, and the dunes were stabilized by coastal vegetation cover. Along time, it was subject to the action of rain: meteoric water dissolved the fragments of biogenic shells in the buffer. Thus, water rich in dissolved calcium carbonate infiltrated into the dune;

(5). Near the surface, the higher temperature of the air promoted water evaporation, which rose dissolved carbonates by capillarity. Not being volatile, the carbonate crystallized in the pores of the sand deposit, hardening the material that formed the dunes. In the process, they ended up acting as cement that solidified the dunes;

(6.) Later in its evolution, the cemented packages were worked by wind. The cemented dunes imposed some resistance to deflation, what is the origin of the it curious "ruin" forms, which resemble the ruins of old buildings, characterizing the "ruiniform" geomorphological appearance displayed by eolianite.

In the coast of Ceará State, the eolianite, as natural, are identified by the local population exactly because of their degree of hardening of the sand, a fact that makes them stand out among the other dunes in the surrounding neighbor area. This condition of hardened material seems to have worked as an area of significant support for the groups of nomadic Indians, who traveled along the coast of Ceará before the period of Portuguese colonization. Indeed, there is evidence of the formation of fires on the ancient lithified material. In the vicinity of the fires, ancient human artifacts were found, demonstrating that the area was largely used by this ancestral population as a place to stop for meals during transfers in the coastal zone, since eolianites provide shelter against strong winds (figures 8 and 9).

The eolianites, when closely analyzed, expose petrified roots, giving an indication that the dunes were fixed by coastal vegetation before the process of cementation. Also occur truncated strata and cross-strata, showing layers with different inclinations in relation to each other. These facts point to the existence, during the period of their migration, of overlapping of other dunes, e.g. migration of transgressive sand dunes covering pre-existing dunes. Cross-bedding strata is evidence of this overlap. The stratification also identified the direction and performance of the winds at the time of its formation. For these reasons, they have great potential to indicate the climatic and geographical conditions existing in the geological past in their areas of occurrence. For example, the sand that formed the eolianite seems to have been transported by winds that traveled from southeast toward the northwest. In the Present, this is also the situation of prevailing winds that shape the dunes at the coastal zone of Ceará. In this context, in terms of wind direction, the fact shows a relative stability of conditions in Late Holocene. By this way, the accumulated knowledge about its dynamics contributes to the understanding of current processes, and also helps to predict future *scenarii*. Considering the degree of environmental degradation the dunes are exposed to today, it may help in finding way to conserve this special coastal geosites.

PROTECTIVE MEASURES

The fragile nature of eolianite is demonstrated by the susceptibility to wind erosion and anthropogenic inputs that they present (Figure 10). The need for preservation is also shown by the fact that there are numerous instances of archaeological interest, such as old fires and fragments of ceramic and stone tools usually associated with them (Fig.11). Because of the importance of this geosite, the "State Plan of Coastal Management" in Ceará state defined, in its Art.15, the eolianites as a feature of total and permanent preservation. Despite legal advances, it is necessary to implement concrete measures for their preservation, dependent on specific studies that can define methods of protection against erosion and the spread of urbanization, as well as those involving the interests of the communities located around these wonderful natural features.

Figure 10 – Disorganized occupation with house building in the eolianites outcrops in the Baleia beach, Ceará state. Photo by A.M.Carvalho

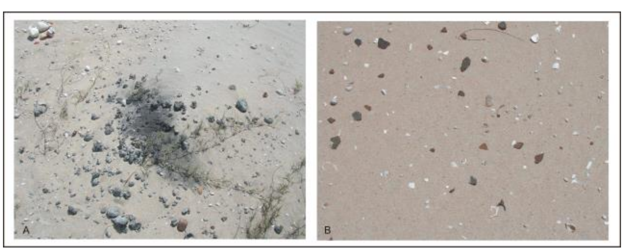

Figure 11 – Archeological evidences of ancient uses on the eoalinites sites, as fire and lithical fragment s, in the coastal area of Itapipoca, Ceará state. Photo by l.p.Maia

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