Surficial and Internal Geometry of Carbonate Eolianite in Fujian, China: Climatic and Tectonic Implications

Zhao Xitao* and Victor Goldsmithb

*Institute of Geology
Academia Sinica
P.O. Box 634
Beijing 100011,
The Peoples Republic of China

bDepartment of Geology and
Geography
Hunter College (City University
of New York)
695 Park Avenue
New York, NY 10021, U.S.A.

ABSTRACT


Three distinct carbonate-bearing, eolianite sand ridges (two are superimposed), of Mid- to Late-Holocene age, are located on an undulating weathered granite surface about 200 m south of Houshijing Village, Hushi Peninsula (Putian County, Fujian Province, China). The largest, and oldest, of the three coastal ridges is approximately 135 m long, 20-37 m in width, and 2-4.5 m thick. They are all elongated in a northeast-southwest direction, with cross-beds dipping perpendicular to the long axes of the ridges. The mean dip angle of the cross-beds is 16.3 deg, but 20% of the beds dip at angles > 20 deg. The sediment consists of medium to coarse quartz grains (-0.1 to 0.4 phi), and 47-67% biological carbonate fragments forming a cement in this warm, monsoonal climate. This eolianite sediment is similar in size and composition to the sediment presently composing the adjacent beaches, its former source. Root structures, typical of vegetated coastal sand dunes, are common in the ridges. The surficial and internal geometry suggest that these rocks were formed as longitudinal vegetated dunes (Ridges 1 and 2), and as a wind shadow (lee) dune (Ridge 3), from sand funnelled uphill from the beach 400 m to the northeast by the strong monsoonal winds. Similar wind shadow dunes are observed to be presently forming 400th m to the south along the cliff top adjacent to the beach. The long axes of all three ridges are clearly aligned with the present dominant northeast monsoonal wind direction, suggesting that the eolian processes have not changed appreciably along southeastern china's coast in the last 2700 years. Further, the interpretation of these features as dunes, rather than beachrock, means that no tectonic implications can be made, which is a different conclusion than had been previously suggested.

ADDITIONAL INDEX WORDS: Eolianite, geometry, sedimentary structure, Holocene, paleo-wind, Fujian, dune, monsoon.

INTRODUCTION

Dune rock or dune limestone is also called eolianite, carbonate eolianite, eolian calcarenite, eolian limestone, etc. If is formed from a coastal dune under warm climate conditions. The cementing agent is calcium carbonate, from shell debris, ooids, or other substances, and the sand may be either quartz grains or calcium carbonate from nearby beaches.

EVANS (1900) noted the widespread distribution of eolian strata made up wholly or partially of calcium carbonate. The term eolianite was suggested by SAYLES (1931) based on his study of the calcareous sandstones which are over 80 m above the present sea level in Bermuda. Carbonate eolianites are also reported for Florida, Bahamas, Yucatan, Baja California, India, the Persian Gulf, Egypt, Libya, Tunisia, Israel, Algeria, Greece, Malta, Italy, Australia, Gilbert Islands, Christmas Islands, South Africa, and Mozambique, concentrating near the equatorial zone and in Mediterranean climates (McKEE and WARD, 1983; GOLDSMITH, 1985).

Along the coasts of southern Fujian and eastern Guangdong in southeastern China, lithified coastal dunes are well-developed. The cement originates from shell material and the sand is dominently quartz. The dunes are usually locted at an elevation of 20-80 m above sea level in Houshijing, Putian (Fujian) and Guangaojiang in Shantou (Guangdong). They are often
mistaken for beach rocks because of the difficulties in distinguishing between the two (e.g., Yuan and Bi, 1985; BI and ZHOU, 1985).

Typical examples of these lithified dunes are located in Putian on the surface of a weathered granite hill at an elevation of 21-38.4 m above MSL about 200 m south of Houshijing in Hushi Peninsula, Putian County, Fujian Province (Figure 1). The Houshijing lithified sand body is located on a small birdsfoot-shaped bedrock peninsula, projecting to the east into the Taiwan Straits. The rock is 500 m from the sea on the north, separated by a topographic high containing a prominent wind gap on the northeast (i.e., near Yingsunding, opposite the word “Bay” in Figure 1). To the east, the sea is only 150 m distance, with a steep cliff, and to the south the sea is a distance of 400 m with a valley and hill in between. On the cliff top adjacent to the beach, small (lee) wind shadow dunes may be seen to be presently forming under the influence of the strong northeast winds.

The lithified sand ridges were recently discovered by Zhang Dequan, who interpreted them to be beachrocks. According to carbon 14 datings, the ages of ridges 1-3 are 2747 ± 100 to 2700 ± 115 YBP, 2500 ± 80 to 1600(?) ± 130 YBP, and 2314 ± 100 YBP, respectively (XIE, et al., 1983; YUAN and BI, 1985). Based on the beachrock interpretation, and carbon-14 dating, BI and ZHOU (1985) and YUAN and BI (1985) concluded that this coast underwent differential vertical faultblock movement on a large scale with high frequency since Late Holocene.

In this paper we will present topographical...
information including the shape and local setting of this lithified sand body, as well as the internal geometry and sedimentary structures. All of these data will be shown to have strong similarities to eolianites found in other areas (GOLDSMITH, 1985) as well as a clear relationship to the prevailing wind direction. The climatic and tectonic implications of an eolianite interpretation will also be discussed.

**DESCRIPTION OF THE LITHIFIED SAND RIDGES**

**Shape and Geometry**

The shape and the height of the rocks are shown in Figures 2 and 3, which were drawn by Sun Henglung and Zhang Deqian from 1:500 and 1:1000 topographic surveys. Dip information, rock type and other data in these figures are from our field measurements. There is an excellent correspondence between the dominant northeast winds (also shown in Figure 2), the ridge orientation, and the direction of the wind gap to the northeast.

Geometrically, there are three distinct sand ridges. Ridge 1 is elongated in the direction N 40 E, located directly on the granite platform, and is 135 m long, 20-37 m wide and 2-4.5 m thick, with its' base 26-32.5 m above MSL, dipping mainly to the southeast. Ridge 2 is elongated in the direction N 48 E, is located entirely on Ridge 1 but separated by a paleosol, and is 78 m long, 20-30 m wide and 2-5 m thick, with its apex 38.4 m above MSL. Ridge 3 is located on a small step on the downward slope of the granite platform on the extension line of the long axis of Ridge 1, and 65 m apart from Ridges 1 and 2. It is 20 m long, 2-5 m wide, 1.5-2.5 m thick, with the base 21-23 m above MSL.

![Figure 2](image-url)
Figure 3. Geological cross-sections and bed dip directions. LEGEND: (1) Eolianite, (2) Granite and its weathered crust, (3) Apparent dip angle of bed.

Geometrically, the eolianites are "anticline-shaped" ridges, all elongated to the northeast, but with Ridges 1 and 2 having their southeast flanks (the downslope side) mainly preserved, and Ridge 3 (which has a flat contact with the underlying granite) having its northwest and southwest slopes mainly preserved. Further details concerning the interrelationships may be discerned in Figures 2, 3, and 4.

Sediment Composition

Representative samples from the three ridges, as well as samples from adjacent modern beach and dune sands, were selected for grain size and microscopic analyses. The rock contains between 47.1 and 67.1% carbonate. Prominent carbonate components include bioclasts (gastropods and pelecypods) whereas corals, foraminifera, and ostracoda are quite scarce. Heavy minerals include ilmenite and magnetite assemblages, and to a lesser extent hornblende, epidote and biotite assemblages. Mean grain size of the three eolianite ridges varies between -0.1 to 0.4 phi, which is similar to that of the sand on a nearby beach. With respect to grain size and composition, the three ridges are relatively similar.

Petrological studies of the eolianites show that the original aragonite composition of the pelecypod and gastropod fragments are mostly preserved, but partly transformed into the granular calcite. The cements are mainly granular calcite, but mixed with clay, and are developed on the surfaces of grains. The cement forms characteristic pendulus (meniscus) cement texture, suggesting that the diagenesis is not well-developed and that the cementation took place under meteoric fresh water conditions.

Cross-Beds and Internal Geometry

Sedimentary structures are clearly discerned because of the differential sorting in the coarse and medium-sized sand (Figures 5a and b). Tabular and wedge-shaped crossbeds are the most common types. Tabular beds are of large scale,
and continuous for up to several tens of meters, with their bedding planes slightly curved in the longitudinal profiles. In the cross-profile they are equally long with bedding planes curved noticeably convex upward (Figure 5a). Wedge bedding is also common (Figure 5b).

Trough cross-beds are located in the southeast flank of the middle part of Ridge 2. They are several meters long, 1-2 m wide, and about 1 m thick. Horizontal beds are also found in Ridge 2, and are up to 10 m long, and 1-3 m wide. Although a few blocks showed evidence of slumping, all cross-beds were measured on rocks in place.

The mean orientation of 122 measured cross-beds has been calculated using Hoque's formula:

$$\tan(\bar{\theta}) = \frac{\sum_i^n \sin \theta}{\sum_i^n \cos \theta} (i = 1, 2, 3 \ldots n)$$

$$\sigma^2 = \frac{\sum_i^n (\theta_i - \bar{\theta})^2}{\sum_i^N N - 1}$$

where \(N\) is frequency, and \(\bar{\theta}\) = mean azimuth

$$L = \frac{(w^2 + v^2)^{1/2}}{N}$$

where

\(L\) = vector percentiles

\(w = \sum_i^n \sin \theta, v = \sum_i^n \cos \theta\)

The results are shown in Table 1 and Figure 6. It can be clearly seen that the beds are dipping primarily to the southeast (AZ = 129 deg, St. Dev. = 31.7 deg), which is perpendicular to the long axes of all three sand bodies. A small secondary dip direction mode occurs to the WNW, but these beds are nearly all from Ridge 3. Thus, for Ridges 1 and 2, only the southeast flank (the downslope side) is preserved. However, for Ridge 3 which is located on a flat surface, the southwest slope is preserved.

The mean dip angles of Ridges 1 and 2 are 16 and 15 deg, respectively, but Ridge 3 has steeper dips (mean = 24 deg). There is a tendency for steeper dips on the lower flanks of Ridges 2 and 3. Approximately 20% of the dips are > 20 deg, suggesting a bimodal dip distribution found in many vegetated coastal dunes.
Table 1. Cross-stratification data of the eolianites in Houshijing, Putian

<table>
<thead>
<tr>
<th>Ridges</th>
<th>No. of readings</th>
<th>Mean foreset</th>
<th>Vector mean dip (deg)</th>
<th>S.D. (deg)</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>34</td>
<td>16</td>
<td>129</td>
<td>32</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>75</td>
<td>15</td>
<td>143</td>
<td>28</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>13</td>
<td>24</td>
<td>270</td>
<td>35</td>
<td>9</td>
</tr>
<tr>
<td>sum</td>
<td>122</td>
<td>16.3</td>
<td>150</td>
<td>48</td>
<td>8</td>
</tr>
</tbody>
</table>

S.D. = standard deviation. L = Magnitude of mean vector in %.

Concentrated along bedding planes. They are seen in both longitudinal sections and as holes 0.5-15 cm in diameter (Figure 7). They are from plant rhizomes (Goldsmith, 1985), and typify vegetated coastal dunes. Here, the vegetation acts as a “roughness” element trapping the sand and causing the dune to grow upward resulting in relatively low angle beds.

Deformational structures, in the form of slide structures with clearly shown concave surfaces, are found on the southeast flank of the middle part of Ridge 2. They are up to several meters in length and width. Associated with these slides are small folds 5-6 cm high and 15-20 cm long (Figure 8).

Paleosol

A prominent paleosol bed, approximately 0.6-1.0 m thick, is located at the contact between Ridges 1 and 2. The bed is light brown yellow in color, and appears sponge-like on the weathered surface.

Present Wind Conditions

Wind data from the nearby Qianqing station in Putian indicates that the northeast is presently the dominant wind direction. Specifically, wind blows today from the NE and NNE, 34% and 14% of the time, respectively. The northeast is the most frequent wind direction in all months except June, July and August. During the winter monsoon season the mean monthly northeast wind velocities are between 5.9 and 8.6 m/s.

DISCUSSION

These three ridges are interpreted as eolianite in origin for the following reasons: (1) The

Internal Structures

Root structures are commonly found scattered throughout all three ridges, but generally

Figure 5 (Facing page). Photographs of eolianite illustrating: (a) Wedge and tabular bedding (Ridge 1) (top), (b) Convex cross-beds dipping northwest (Ridge 3).
long axes and stratigraphic strikes of the three ridges are oblique to the shoreline and parallel
to the present day dominant wind direction (and
directly downwind from a topographic wind
gap); (2) The ridges are shaped like coastal and/
or (lee) wind shadow dunes observed by the
authors actively forming in other areas; (3) The
sand is similar in composition and size to the
sand on the nearby beach, but the ridges do not
contain any gravel or cobbles as is found on the
beaches; (4) Petrographic studies suggest fresh
water karstification rather than sea water
cementation; (5) The dip angle distribution is
typical of coastal vegetated dunes (e.g., eolian-
ite in Israel, YAALON and LARONNE, 1971),
rather than beaches which are noted for their
absence of high angle dipping beds; (6) Wind-
shadow dunes, of similar geometry and of simi-
lar sedimentary composition may be seen to be
presently forming on the cliff top adjacent to
the beach, only a few hundred meters from the
ridges, and also under the dominant influence
of the strong northeast winds; and (7) Root
structures, typical of vegetated coastal dunes,
are abundant in these ridges; (further discus-
sions are found in Zhao and Goldsmith, in
prep.).

Recently, biological calcarenite has been
reported in Shidao Island of Xisha Islands,
China (ZHU and ZHONG, 1984; YE et al., 1984)
and quartz sandstones with biological frag-
ments have been found at the tops of sand
ridges along the southwest and northeast coasts
of Hainan Island. They are also believed to be
carbonate eolianites.

These eolianites have characteristics typical
of the coastal wind-shadow dune of McBRIDE
and HAYES (1962), which is the incipient veg-
etated coastal dune of the classification of
GOLDSMITH (1985). This eolianite does not fit
the classifications of BAGNOLD (1954) nor of
McKee (1979), both of which are based on
desert dunes. The azimuth and dip angle distributions, and their relationship to the dominant winds, the presence of root structures, and the local topographic relationships, all indicate that they are vegetated coastal sand dunes similar to coastal dunes from many other areas (GOLDSMITH, 1973; 1985). Incipient vegetated coastal dunes typically form as sand accumulations downwind from a clump of vegetation. The sand accumulation is in the form of a wind shadow with the crest elongated downwind, and sand avalanching down from the crest and thereby forming beds oriented oblique to both the wind direction and the dune crest. As vegetation increases in density, the dune grows upward, forming low angle dipping beds (typically about 12 deg).

Here in Fujian, however, local topography appears to have strongly influenced the dominance of cross-bed azimuths dominantly on the downslope (southeast) side of the dune; i.e., the dipping beds may have formed preferentially in the downslope direction. Alternatively, the southeast flank may have been preferentially preserved since the mid-Holocene.

Ridge 3, located in a topographic low downwind from Ridges 1 and 2, and with high angle beds dipping to the southwest and northwest, appears to better resemble the shadow dune of BAGNOLD (1954) or the pyramidal wind shadow dune of GOLDSMITH (1985). Whereas Ridges 1 and 2 appear to have grown dominantly upward, Ridge 3 appears to have had a greater horizontal movement. (This difference appears to reinforce the field observations that Ridge 3 is distinct, and was always separate from the other two ridges.) In each case, however, the beds are clearly dipping in a direction perpendicular to both the long axes of the sand bodies and the dominant wind approach direction, which is typical of vegetated coastal dunes.
COMPARISON OF PALEOWIND AND PRESENT WIND DIRECTIONS

As previously stated, the long axes of the three eolianite ridges are N 40 E, N 48 E and N 40 E, with the crossbeds dipping perpendicular to this direction. This suggests that the wind forming this eolianite originated from the northeast. The presence of a small gap in this direction (located east of Yingsunding in Figure 1) probably enhanced the movement of sands up the hill from the beach. Upon reaching the elevated weathered granite terrain the wind velocity would have been expected to decrease, depositing the sand in the form of sand drifts, further enhanced by the presence of the vegetation acting as a "roughness element." Thus the formation of this Mid- to Late-Holocene eolianite appears to be due to a strong northeast wind, probably all within a period of a few hundred years.

Wind data from the nearby Qianqing station in Putian indicites that the northeast is presently the dominant wind direction. In conclusion, the dominant paleo-wind direction appears to be clearly the same as today. Perhaps, there was either a slight hiatus in strong winds, or the sand supply was interrupted, allowing the formation of the paleosol on top of Ridge 1. Also, there may have been a minor change in the wind direction of 8 deg during the formation of Ridge 2. The absence of preserved eolianites between 2,700 YBP and those observed to be forming today may be explained either by the above reasons, or by the absence of climatic conditions necessary for the preservation of the dunes in place.

Thus, we interpret these rocks as being of dune origin formed by the strong northeast monsoon winds. They were then cemented by fresh water subaerially during the end of the Mid-Holocene and the beginning of the Late Holocene. Because these lithified sand ridges are of eolian origin which formed in place at the cliff top, and not beachrocks which can form only at sea level, they can not be used to indicate relative sea level changes due to vertical movements of the earth's crust.

CONCLUSIONS

(1) The calcarenites in Houshijing are shown to be three distinct coastal dunes, and are not beach rocks.

(2) Ridges 1 and 2 are two overlapping vegetated longitudinal dunes or sand drift dunes, whose formation (if erosion of one side can be eliminated as a possibility) was affected by the slopes of the underlying weathered granite terrain (i.e., dune cross-bed dips dominate in the direction of the granite slope). Ridge 3, to the southwest, formed in the lee of the two larger ridges on a flat surface, appears to be a more typical wind shadow dune in that beds dip in two directions perpendicular to the long axis of the sand body.

(3) These eolianites were formed by reworking of adjacent beach sands by strong northeast winds during the Mid- to Late-Holocene. Thus, the conditions of the northeast monsoon do not appear to have changed in the last 2,700 years.

(4) Since they are not beach rocks, these eolianites can not be used to suggest crustal movement and/or relative sea-level changes. Therefore, this interpretation alleviates the local concerns of earthquake hazards, and thereby encourages the economic development of Fujian Province.

(5) The discovery and identification of these Fujian eolianites gives impetus to our understanding of paleo-dune formation and history, and encourages the search for such rock bodies both along the coast of China and worldwide.

DEDICATION

This paper is dedicated to the late Professor Walter Newman, Quaternary Geologist at Queens College, City University of New York, who, by inviting the second author for a sabbatical visit, and many other kindnesses, helped make this work possible.

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LITERATURE CITED


RÉSUMÉ

Près de Houshijing (province de Fujian en Chine), on distingue trois sand ridges composés d’âolitanites carbonatées, situées sur un granite altéré ondulé, deux sont surimposées. La plus large et la plus ancienne des trois a 135 m de long, 20 à 37 m de large et 2 à 5 m d’épaisseur. Elle s’allongera avant le NE-SW avec des interstratifications plongeant perpendiculairement au grand axe. L’angle moyen des interstratifications est de 16,3°, mais 20% dépassent 20°. Les sand ridges sont composés de grains grossiers de quartz (-0,1 à 0,4 phi) et de 47 à 67% de particules carbonatées d’origine biogène qui ont été cimentées sous ce climat chaud de mousson. Ces âolitanites sont semblables en granulométrie et composition aux sédiments qui composent actuellement les plages adjacentes, desquelles elles proviennent. On retrouve sur les sand ridges les structures des racines, typiques des dunes littorales à végétation. Les géométries interne et de surface suggèrent que ces roches ont subi des formes comme une dune à végétation longitudinale (ridges 1 et 2) et comme côté sous le vent de la dune (ridge 3), à partir des sables canalisés vers le sommet depuis la plage située à 400 m au NE, sous l’action des vents de mousson. Sur l’île de Mustang Island, dans sa longueur, il y a aussi des sand ridges. Sur l’île de Shidao Island, à Xisha Archipelago, on retrouve des structures similaires de dunes littorales à végétation. Cela diffère de ce qui avait été suggéré précédemment. — Catherine Bressolier (Géomorphologie EPHE, Montrouge, France).

ZUSAMMENFASSUNG

Die verschiedenen kalkhaltigen Äolitanitwälle, von denen zwei über einanderlagern und die aus dem Mittel-bis Jungpleistozän stammen, liegen auf einer flachwelligen Granitlandschaft ca. 200 m S des Dorfes Houshijing, Hushu-Halbinsel (Bezirk Putian, Provinz Fujian, China). Der größte und älteste der drei Küstenwälle ist ca. 135 m lang, 20-37 m breit und 2-4,5 m mächtig. Alle sind in NE-SW-Richtung gestreckt, wobei die Kreuzschichtung senkrecht zur Längsachse weist, der mittlere Einfallwinkel der Kreuzschichtung beträgt 16,3°, aber 20% der Schichten fallen mit mehr als 20° ein.

Das Sediment besteht aus mittlerem bis groben Quarzsand (0,1-0,4 mm), und durch 47-67% Karbonatpartikel wird in diesem warmen Monsunklima ein Bindemittel gebildet. Diese Äolitanit-Sedimente ähneln in Korngrößes-Zusammensetzungen sehr denen der benachbarten Strände, von denen sie herstammen. In ihnen sind vermehrt Wurzelreste zu beobachten, was für vegetationsbedeckten Kustendünen typisch ist.

Oberfläche und innerer Bau deuten darauf hin, daß die Ablagerungen als gestreckte, vegetationsbedeckte Dünen (Wall 1 und 2) und Windhaldendüne (Leedune, Wall 3) gebildet wurden, und zwar von Sand, der vom nordöstlich gelegenen Strand durch starke monsunale Winde aufgewegt wurde. Ähnliche Leedünen können heute in Bildung beobachtet werden 400 m südlich auf einem Kliff oberhalb des Strandes. Die Längsachsen aller drei Wälle sind in Richtung der gegenwärtig dominierenden Monsunwinde nach NE gestreckt, was darauf hinweist, daß die äolischen Prozesse an der Küste Südost-Chinas sich in den letzten 2700 Jahren nicht nennenswert geändert haben. Weiterhin schließt die Interpretation dieser Erscheinungen als Dünen und nicht als Beachrock aus, daß tektonische Bewegungen stattgefunden haben, wie in früheren Publikationen behauptet wurde. — Dieter Kelletat, Essen (FRG)
Se han estudiado tres diferentes formaciones del Holoceno medio-final localizadas sobre una cobertura de granito, a unos 200 m al Sur de Houshijing, en la península de Hushi (condado de Putian, provincia de Fujian, China). La mayor y más antigua de estas formaciones tiene aproximadamente 135 m de largo, 20-37 m de ancho y 2-4.5 m de espesor. Todas ellas se encuentran en dirección Noeste-Suroeste con un ángulo de buzamiento medio de la sección transversal de 16.3 °C, aunque un 20% buzan con ángulo 20 °C.

Los sedimentos están formados por granos de cuarzo (−0.1 a 0.4 phi) y un 47-67% de fragmentos carbonatados de origen biológico que forman un cemento en este clima cálido de los monzones. Este sedimento es similar en tamaño y composición al sedimento que compone actualmente las playas próximas, su fuente originaria. Estructuras de raíces, típicas de dunas con vegetación se encuentran también en estas formaciones antes citadas.

La geometría superficial e interna sugiere que estas rocas fueron formadas en dunas con vegetación (formaciones 1 y 2) y dunas de viento (formaciones 3), con arenas transportadas de la playa por los fuertes vientos del monzón de la playa situada 400 m al Noreste. Dunas de viento similares se establecen actualmente 400 m al Sur a lo largo del acantilado adyacente a la playa. Los ejes de estas tres formaciones están claramente alineados con la dirección actual de los monzones sugiriendo que los procesos eólicos no se han modificado apreciablemente en la costa Sur de China en los últimos 2700 años. La interpretación de estas formaciones como dunas, más que como playas fósiles, significa la no existencia de procesos tectónicos, lo cual difiere de conclusiones que habían sido sugeridas con anterioridad.—Department of Water Sciences, University of Cantabria, Santander, Spain.