Phytolith assemblages as indicators of coastal environmental changes and hurricane overwash deposition

Hou-Yuan Lu\textsuperscript{1,2} and Kam-biu Liu\textsuperscript{2*}

\textsuperscript{1}Institute of Geology and Geophysics, Chinese Academy of Sciences, P.O. Box 9825, Beijing 100029, China; \textsuperscript{2}Department of Geography and Anthropology, Louisiana State University, 227 Howe-Russell Geoscience Complex, Baton Rouge LA 70803, USA

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Abstract: We demonstrate that phytolith assemblages are a useful proxy for reconstructing coastal environmental changes and for validating the overwash origin of sand layers in palaeotempestology studies. Phytolith analysis was conducted on 50 topsoil or surface sediment samples collected from a variety of coastal plant communities or depositional environments in the southeastern USA. The data suggest that different coastal subenvironments can be distinguished by their modern phytolith assemblages. For example, coastal marsh samples contain a diverse phytolith assemblage dominated by smooth-elongate and square morpho-types and maritime forest samples are dominated by phytoliths from palms and broadleaf dicotyledonous plants. Remarkably, the phytolith assemblages from sand dunes are characterized by high percentages of two-horned-tower, flat-tower, spool/horned-tower and short-saddle types. Phytolith analysis of three prehistoric sand layers in a sediment core from Western Lake, northwestern Florida, shows that they contain a phytolith assemblage similar to those characteristic of sand dunes and interdune meadows. These observations are confirmed by the results of principal components analysis and discriminant analysis on the modern and fossil phytolith data sets. Our study results support the interpretation that the sand layers in Western Lake were indeed formed by the erosion of sand dunes during overwash processes caused by landfalling catastrophic hurricanes.

Key words: Phytoliths, hurricanes, palaeotempestology, coastal environments, sand dunes, overwash deposition, Atlantic Coast, Gulf of Mexico, late Holocene.

Introduction

In the emerging field of palaeotempestology (Liu and Fearn, 2000a; Liu, 2004), the proxy proven to be most useful in the reconstruction of past hurricane strikes comes from overwash sand layers preserved in sediment cores retrieved from coastal lakes and marshes (Liu and Fearn, 1993, 2000a,b; Zhou, 1998; Donnelly et al., 2001a,b; Scott et al., 2003; Liu, 2004). The principle underlying this research methodology is that when an intense hurricane makes landfall and causes a storm surge that exceeds the height of the sand barrier, sand will be washed over from the beach and dunes into the backbarrier lakes and marshes, forming an overwash fan (Liu, 2004). Although sand layers of recent age (e.g., twentieth century) found in some coastal sediment cores can be reliably attributed to historic storm events and their associated overwash processes by examining historic aerial photos of coastal sand transport and by means of radiometric ($^{137}$Cs and $^{210}$Pb) dating of these cores (Donnelly et al., 2001a,b), independent evidence is needed to verify the overwash origin of the older, especially prehistoric, sand layers because the sand could have come from other coastal or even fluvial environments rather than the sand dunes or beach ridges.

Microfossils such as dinoflagellates, foraminifera, diatoms and pollen have been used as indicators of saltwater intrusion into coastal lakes and marshes resulting from past storm surges and tsunamis (Hemphill-Haley, 1996; Zhou, 1998; Collins et al., 1999; Hippensteel and Martin, 1999; Liu and Fearn, 2000b; Hughes et al., 2002; Liu et al., 2003; Scott et al., 2003). However, some of these conventional proxies for environmental reconstruction, such as pollen, are not very useful for deciphering the provenance of the sand in the sand layers and for identifying the coastal sandy subenvironments from which the sand is derived. In this paper we demonstrate that modern phytolith assemblages in soil or sediment samples can be used to differentiate different coastal subenvironments such as sand...
dunes, marshes, freshwater lakes, estuarine and bay bottoms and maritime forests. In particular, phytolith analysis can be a useful tool to test the hypothesis that the sand in the sand layers used in palaeotempestology studies does indeed come from the coastal sand dunes resulting from overwash processes.

**Material and methods**

**Phytolith surface samples**

Fifty surface samples were collected for phytolith analysis from three coastal locations in the southeastern USA (Figure 1A). Cumberland Island (Figure 1B), a barrier island in southern Georgia, is fringed by a well-developed continuous line of beach and high dunes along the Atlantic coast. Interspersed between and behind the beach and sand dunes is a complex array of freshwater lakes, small *Juncus*/sedge fens, interdune meadows and upland maritime forests dominated by various species of oaks, pines, palms and other hardwoods.

Atchafalaya Marsh (Figure 1C), southern Louisiana, is a large coastal/estuarine marsh that extends along the mouth of the Atchafalaya River and the west shore of Atchafalaya Bay to the Gulf of Mexico. This large coastal marsh exhibits a salinity gradient from cypress swamp, fresh marsh, brackish marsh, to salt marsh, whereas the Atchafalaya Bay itself offers a distinct set of open-water, estuarine bay depositional environments.

Western Lake (Figure 1D), a backbarrier oligohaline lake within Grayton Beach State Park, northwestern Florida, is situated behind a barrier beach about 150–200 m wide and a continuous line of sand dunes rising to 6.2–9.3 m above sea level (Liu and Fearn, 2000a). Vegetation around Western Lake is a typical Gulf coastal community (Moreno-Casasola, 1988) consisting of sea oats (*Uniola paniculata*) growing on the sand dunes, cordgrass (*Spartina alterniflora*) growing on the seaward edge of the dunes and marshes around the lake and pine flatwoods, scrub oak thickets and mixed hardwood-palmetto woodlands occurring on the uplands and hammocks.

The 50 surface samples (Figure 1) were collected from nine different coastal vegetation communities or depositional environments representing different ecological conditions: fresh marsh, brackish marsh, salt marsh, maritime forest, freshwater lake, *Juncus*/sedge fen, interdune meadow, primary dune and estuarine bay. Terrestrial samples were collected from the uppermost 2–3 cm of the topsoil (forest, marsh and dune) by means of a small spade. Those derived from the surface mud (lakes and estuarine bay) were collected by means of an Ekman’s dredge.

The samples were prepared by a procedure slightly modified from Piperno (1988) and Runge (1999). It consists of sodium pyrophosphate (Na₄P₂O₇) deflocculation, treatment with 30% hydrogen peroxide (H₂O₂) and cold 15% hydrochloric acid (HCl), zinc bromide (ZnBr₂, density 2.35 g/cm³) heavy liquid separation and mounting on a slide with Canada Balsam. Phytolith counting and identification was performed using a Nikon Optiphot microscope at 400× magnification. More than 350 phytolith grains were counted in each sample. Identification was aided by the use of reference materials (Lu and Liu, 2003a,b) and published keys (Piperno, 1988; Mulholland and Rapp, 1992; Kondo et al., 1994; Piperno and Pearsall, 1998; Runge, 1999; Pearsall, 2000).

**Sediment cores from Western Lake**

To test if the modern phytolith data can be used to aid the reconstruction of coastal palaeoenvironmental changes and the identification of the provenance of lake sediments, we analysed the phytolith contents of a short core (core 9) from Western Lake.
Lake, northwestern Florida (Figure 1). A 6.5-m core (core 1) from Western Lake has yielded a 5000-yr proxy record of hurricane activity that includes 12 direct strikes by catastrophic hurricanes over the past 3400 years (Liu and Fearn, 2000a).

The same processing method was used on the core samples as on the surface samples for the extraction of phytoliths.

**Statistical analysis**

By using the statistical program CANOCO 4.0 (ter Braak, 1996), principal components analysis (PCA) was performed on the 50 surface samples to reveal the internal structure of the modern phytolith data set. The PCA results provided a basis to classify the surface samples into statistically meaningful groups, which could be interpreted in terms of the coastal vegetation communities or depositional environments from which the surface samples were collected. In addition, discriminant analysis (sensu Liu and Lam, 1985), an inferential statistical technique, was performed using SPSS version 10.0 to classify the 50 phytolith samples with reference to the a priori groups suggested by the PCA results. The discriminant functions derived from these surface samples were then applied to the fossil phytolith data obtained from the Western Lake core to predict the group membership of each fossil phytolith sample. These predicted group memberships represent the palaeo-vegetation communities from which the fossil phytolith assemblages are derived and therefore shed light on the provenance of the sediment that contain them (Liu and Lam, 1985).

**Results**

**Phytolith assemblages in modern coastal subenvironments**

Thirty phytolith morpho-types (including two ‘unknown’ morpho-types) were recognized in the 50 surface samples (Figure 2). Figure 3 shows some of the more common or characteristic types. All surface samples from coastal marshes are characterized by high percentages of smooth-elongate (16 ± 6%) and square (11 ± 6%) phytoliths. Remarkably, marshes of different salinity environments seem to be distinguishable by the occurrence of certain associated phytolith types. Fresh marsh samples tend to have higher percentages of dumbbell (Figure 3a) and sinuate-elongate (Figure 3i) phytoliths than the brackish and salt marshes and the presence of Pteridophyte phytoliths reflects the presence of ferns in fresh marshes. Between the brackish marsh and salt marsh samples, brackish marsh samples seem to have higher percentages of spool/horned towers (Figure 3d), whereas salt marsh samples generally have higher percentages of fan-shaped (7 ± 5%) and *Spartina*-type (6 ± 2%) phytoliths. The *Spartina*-type (Figure 3f) is a rondel/saddle ellipsoid morpho-type typically produced by *Spartina alterniflora*, the dominant grass of salt marshes (Lu and Liu, 2003b).

Phytolith assemblages from the topsoil samples of maritime forests on Cumberland Island are characterized by very high percentages of broadleaf-types (30 ± 23%) (Figure 3l, m) and Palmae-type 1 (43 ± 28%) (Figure 3g). The broadleaf-types include many phytolith morpho-types (Piperno, 1988; Kondo et al., 1994; Runge, 1999) such as the elongate phytolith type A4 (equivalent to broadleaf-type 1 in this study, Figure 3l) and type A5 (equivalent to broadleaf-type 2 in this study, Figure 3m) of Runge (1999). They are characterized by the presence of facets and are mainly produced by broadleaf trees or shrubs. Palmae-type 1 (Figure 3g) is a spherical phytolith with a spinulose surface, typically produced by palms (e.g., Piperno, 1988; Runge, 1999).

Phytolith assemblages from freshwater coastal lakes on Cumberland Island are different from those of the adjacent maritime forests in having very high percentages of both Palmae-type 1 (74 ± 6%) and Palmae-type 2 (9 ± 6%), whereas the broadleaf types are absent. Palmae-type 2 is a spherical...
phytolith with a regularly spinulose surface like Palmae-type 1, but the spinule apices are round instead of sharp; they are probably derived from a specific member of the Palmae family or from another monocotyledonous plant (Runge, 1999).

Three surface samples from Juncus/sedge fens in Cumberland Island are characterized by abundant sinuate-elongate, smooth-elongate and Cyperaceae type phytoliths (8.0–12.1%). The abundance of the Cyperaceae type is attributed to the predominance of sedges (especially Carex spp.) in these small wetlands, some of which are probably developed on dried or ephemeral lake beds. The spikes of broadleaf-type 2 and Palmae-type 1 in two samples collected near the edges of these small fens are probably due to local influence from the adjacent forest vegetation.

The phytolith composition of the surface samples from interdune meadows shows very high frequencies of dumbbell phytoliths (47±13%). Cross-shaped phytoliths (Figure 3b) reach values of around 2–8%. Dumbbell and cross phytoliths

**Figure 3** Photomicrographs of the main phytolith morpho-types counted in this study: (a) dumbbell, (b) cross, (c) long-saddle, (d) spool/horned tower, (e) flat tower and two-horned tower, (f) Spartina-type, (g) palmace-type 1, (h) short-saddle, (i) sinuate-elongate, (j) smooth-elongate, (k) long-point, (l) broadleaf-type 1, (m) broadleaf-type 2, (n) square.
are produced at high percentages by grasses of the Panicoideae subfamily, such as Cenchrus incertus and Panicum hemitomon (Lu and Liu, 2003b).

The modern phytolith composition of the primary dunes in both Cumberland Island and Western Lake is characterized by high amounts of two-horned-tower (30% ± 25%) (Figure 3e), flat-tower (13% ± 7%) (Figure 3e), spool/horned-tower (14% ± 6%) and short-saddle (9% ± 6%) (Figure 3h) phytoliths. This assemblage is produced by the dominant grasses of coastal sand dunes, such as Uniola paniculata and Aristida desmantha (Lu and Liu, 2003b). Although, to some extent, these characteristics are also found in samples from the coastal marshes, the dune samples can be distinguished from the marsh samples by having very low percentages of square, smooth-elongate, sinuate-elongate and long-point types (Figure 3k).

The phytolith composition in the surface samples of estuarine bay bottoms is characterized by high percentages of fan-shaped, square, smooth-elongate and long-point phytoliths of silt sizes (10% ± 7%, 13% ± 9%, 28% ± 7%, 8 ± 4%, respectively) that are derived from epidermal long-cells, trichome-cells and bulliform-cells of grasses. Not surprisingly, these samples from the Atchafalaya Bay are generally similar to the marsh samples collected from the adjacent Atchafalaya Marsh in terms of their predominant morpho-types. However, the estuarine bay bottom samples can be distinguished from the marsh samples by having no or few dumbbell, spool/horned-tower and Spartina-type phytoliths. The lower diversity of phytoliths in the estuarine and bay bottom samples may be due to differential dispersal and deposition abilities of different phytolith morpho-types in a fluvial-estuarine environment.

**Numerical analysis of modern phytolith data**

Percentage data from 23 phytolith types (see Figure 4a) were used in the principal components analysis (PCA) and discriminant analysis. The PCA biplots of the 23 phytolith types and the 50 surface samples are shown in Figure 4. The first two principal components, axis 1 and axis 2, account for 56.1% and 18.8% of the variance in the phytolith data, respectively. On the biplot of principal component loadings for the 23 phytolith types (Figure 4a), Palmae-types and broadleaf-type 1 have the highest loadings on axis 1, whereas two-horned-tower, flat-tower and dumbbell+cross have the highest loadings on axis 2. On the biplot for principal component scores for the 50 surface samples (Figure 4b), samples from freshwater lake and maritime forest sites have the highest positive scores on axis 1, where the Palmae-types and broadleaf-type 1 also have the highest loadings. Samples from estuarine bay and marsh sites score most negatively on the far left of axis 1, corresponding to highly negative loadings for fan-shaped, square, smooth-elongate and long-point phytolith types. The second principal component, axis 2, primarily distinguishes the samples from sand dunes and interdune meadows from the rest of the samples. Thus, the results of the PCA ordination analysis suggest that the 50 surface samples can be divided into five primary groups: (1) estuarine bay; (2) marsh (including fresh marsh, brackish marsh and salt marsh); (3) Juncus/sedge fen; (4) sand dune/interdune meadow; and (5) freshwater lake/maritime forest. With only a few exceptions (e.g., A18, C37, C46, C47), the phytolith 'signatures' of these five groups are quite well-defined with little overlap among them (Figure 4a, see also Figure 2).

After these five groups were delineated by PCA, discriminant analysis was used to validate the classification and to generate probability estimates for statistical inference (Liu and Lam, 1985). All (100%) of the samples were correctly classified into their respective *a priori* groups (Table 1). Figure 5 shows the five groups of surface samples plotted against discriminant functions 1 and 2, which account for 40.1% and 33.5% of the variance, respectively. Again, the five groups and their centroids are clearly distinct from each other with very little overlap between groups. The high degree of correct classification suggests that the classification of the surface samples into the five groups is statistically robust.

These surface sample results indicate that the phytoliths deposited in the different coastal subenvironments in our study areas are reliable indicators of the major vegetation communities at or around the site. These results can then be applied to the fossil phytolith spectra from a sediment core from Western Lake to reconstruct palaeoenvironmental changes and to infer the provenance of the sediment.
Table 1 Classification results of the discriminant analysis performed on the 50 surface samples from the five vegetation groups and on 14 fossil samples (bold) from core 9 of Western Lake

<table>
<thead>
<tr>
<th>Group no.</th>
<th>Actual group</th>
<th>Predicted group membership</th>
<th>Total cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Estuarine Bay</td>
<td>14* (100%)b</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>Marsh</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Juncus/sedge fen</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>Sand dune/interdune meadow</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>Freshwater lake/ Maritime forest</td>
<td>0</td>
<td>11 (100%)</td>
</tr>
<tr>
<td>Ungrouped</td>
<td>(Core 9 samples)</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*Number of samples classified as that group.

Phytolith record from Western Lake

Core 9 from Western Lake, a short core taken near core 1, contains 90 cm of organic lake mud (organic matter content 10–13% as determined by loss-on-ignition) interrupted by seven sand layers. These sand layers have been interpreted to be formed by overwash processes occurring during strikes by catastrophic hurricanes of category 4 or 5 intensity according to the Saffir/Simpson scale (Liu and Fearn, 2000a). For the phytolith analysis we selected eleven samples from the organic lake mud and three samples from three thick sand layers (referred to as sand layers 1, 2 and 3, respectively) occurring at depths of 52.0–53.0 cm, 58.5–60.0 cm and 66.0–68.5 cm as measured on the core (Figure 6). These three sand layers were selected because they were sufficiently thick to provide clean samples of sand uncontaminated by the embedding organic sediments. These prominent sand layers were radiocarbon dated to 1320 ± 50, 1410 ± 50 and 1850 ± 50 yr BP (uncalibrated 14C ages), respectively (Liu and Fearn, 2000a).

Phytolith analysis of the eleven organic lake sediment samples shows that they are dominated by the Palmae-type 2 (41 ± 9%), Palmae-type 1 (12 ± 3%) and smooth-elongate (9.6 ± 3.7%) morpho-types. Dumbbell and cross (7.4 ± 3.9%) and flat-tower and two-horned-tower (5.8 ± 2.5%) morpho-types are also present consistently in the organic mud at lower percentages (Figure 6). The presence of broadleaf-type 1 and broadleaf-type 2 phytoliths is also notable. This apparently mixed assemblage suggests that the organic sediments in Western Lake come from multiple sources, but the principal contributors are maritime forests and freshwater wetlands around the lake. On the other hand, the sand sampled from the three thick sand layers contains very high percentages of flat-tower phytoliths (at 20.1%, 18.6% and 51.1% in sand layers 1, 2 and 3, respectively), along with somewhat elevated percentages of short-saddle and two-horned-tower phytoliths. This unusual assemblage, especially the prominent spikes of the flat-tower type, is similar to the modern phytolith assemblages characteristic of the sand dunes near Western Lake and in Cumberland Island.

The contrast in phytolith assemblages between the organic lake sediment and the sand layers is confirmed by the results of discriminant analysis. The same discriminant functions derived from the surface sample data set were used to classify the 14 fossil phytolith samples. All 11 samples from organic lake sediment were classified as freshwater lake/maritime forest (group 4), whereas the three samples from the sand layers were classified as sand dune/interdune meadow (group 5) (Table 1; Figure 6). When the fossil samples from Western Lake are plotted against the same discriminant functions as the surface samples (Figure 5), the three sand layer samples are located closer to the centroid of the sand dune/interdune meadow group than the rest of the core samples. Therefore, the phytolith evidence from the Western Lake core suggests that the sand in the three prominent sand layers was derived from the sand dunes separating the lake and the Gulf. Grasses growing on the dune ridges, such as Uniola paniculata, Aristida desmantha and Panicum amarum, are the principal producers of flat-tower and two-horned-tower phytoliths.
Overwash processes associated with catastrophic hurricane landfalls are the most likely mechanism that washed sand from the sand dunes to the bottom of Western Lake. (Lu and Liu, 2003b). This study demonstrates that, in association with overwash sand layers, phytoliths can be used as a useful proxy for the reconstruction of past hurricane activity from coastal lake sediments.

Discussion and conclusions

Previous palaeoecological applications of phytolith studies have focused mainly on the reconstructions of broad vegetation types at regional or continental scales, such as temperate or tropical grasslands (e.g., Fredlund and Tieszen, 1994; Barboni et al., 1999; Binnikov et al., 2002) as well as Mediterranean woodlands and tropical forests (Piperno and Becker, 1996; Delhon et al., 2003; Piperno and Jones, 2003). Except in a few cases (Fearn, 1998; Horrocks et al., 2000), phytolith analysis has not been applied to the study of coastal environmental changes, especially at the finer spatial scales that identify coastal subenvironments such as salt marshes, maritime forests and sand dunes.

In this paper, we demonstrate that different coastal sub-environments can be distinguished by their modern phytolith assemblages. Notably, surface samples from coastal marshes contain a diverse phytolith assemblage dominated by the smooth-elongate and square types, whereas soil samples from maritime forests are dominated by phytoliths from palms and broadleaf dicotyledonous plants. Moreover, surface samples from coastal sand dunes are characterized by high percentages of two-horned-tower, flat-tower, spool/horned-tower and short-saddle phytoliths. These results confirm and reinforce our previous conclusion that grasses typically growing on sand dunes (e.g., *Uniola paniculata*, *Aristida desmantha*) produce distinctive phytolith assemblages (Lu and Liu, 2003b). Thus, phytoliths found in the sand layers of sediment cores taken from Western Lake could be used to reveal the provenance of the sand that embeds them. Data from core 9 show that the three most prominent sand layers contain a phytolith assemblage similar to those derived from the grass plants and sediment samples from the primary dunes. This finding supports our previous interpretation that the sand layers were formed by the erosion of sand dunes during overwash processes caused by catastrophic hurricane landfalls (Liu and Fearn, 2000a).

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