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KEYSTONE VUGS IN COASTAL DUNES; AN EXAMPLE FROM THE PLEISTOCENE OF ELEUTHERA, BAHAMAS

Pascal Kindler
Department of Geology
University of Geneva
13 Rue des Maraichers
Geneva, 1211, Switzerland

ABSTRACT

Keystone vugs (Dunham 1970) are small millimeter-sized voids which can be found in carbonate rocks and sediments. These features have long been used to characterize the intertidal zone and as sea-level indicators in ancient sequences. This paper reports on the occurrence of such voids in a Pleistocene eolianite on Eleuthera (Bahamas), more than 35 m above the coeval sea-level. Three possible mechanisms accounting for the formation of these subaerial features are presented: storm-swash action, the decay of organic matter and rainfall effect. This new evidence suggests that keystone vugs should be used as a sea-level indicator only when they are associated with other charateristic trace or body fossils.

INTRODUCTION

Dunham (1970) coined the term "keystone vugs" for "voids that are considerably larger than interstices, ...in ancient grainstone, in modern beachrock and in loose carbonate beach sand". In cross section, keystone vugs have a subcircular or a linear shape; their size ranges between 1 and 5 mm and they are often associated with sand domes and sand holes (Emery 1945). Similar voids have also been described in siliciclastic sands as "air spaces" (Kindle 1936), "cavities" (Emery 1945) and "bubbles" (Hoyt and Henry 1964). Geologists developed an early interest in such small features for two reasons: (1) keystone vugs are related to the distribution of firm and soft sands on beaches, and (2) they may enhance the reservoir capacity of sediments.

Except for Stieglitz & Inden (1969), Shinn (1983) and Bain (1985), all workers correlate keystone vugs with a beach environment. More specifically, Emery (1945) noticed that these features are present on the entire intertidal zone of protected beaches, and that they are restricted to the upper part of the beach on exposed shorelines. In a few instances, these cavities have been observed on the backshore, following exceptional flooding events during spring tides or storms (Emery 1945, Hoyt & Henry 1964, Deville 1989, Wanless et al. 1989). In many cases (Gerhardt 1983, Davaud and Strasser 1984, Garrett and Gould 1984), keystone vugs have been used as a sea-level indicator in ancient sequences.

According to a majority of authors, keystone vugs form in beach sands by the trapping of air between water percolating downwards from a breaking wave and interstitial ground water. Hoyt and Henry (1964) observed that the dryer the sand, the more susceptible it was to develop "bubble structure". The cavities are supposed to be preserved either by the surficial tension of interstitial water holding the surrounding grains, followed by sea-salt cementation (Emery 1945), or by the arch shape of the voids themselves (hence the name keystone, Dunham 1970).

In summary, keystone vugs are primary millimeter-sized gaps larger than grain-supported interstices which appear in sand-sized carbonate and terrigeneous rocks and sediments. They result from the entrapment of air in loose sands and characterize intertidal environments, although similar features have been described on a few occasions in other settings.

NEW EVIDENCE FROM ELEUTHERA

Geological setting

Eleuthera is a long (100 km) and narrow (2-5 km) carbonate island, located on the northeastern and windward margin of the Great Bahama Bank (Fig. 1). Except for an unpublished work by Mattes and Ginsburg (1982) and a study about soil mineralogy by Foos (1989), it has received little attention from earth scientists.

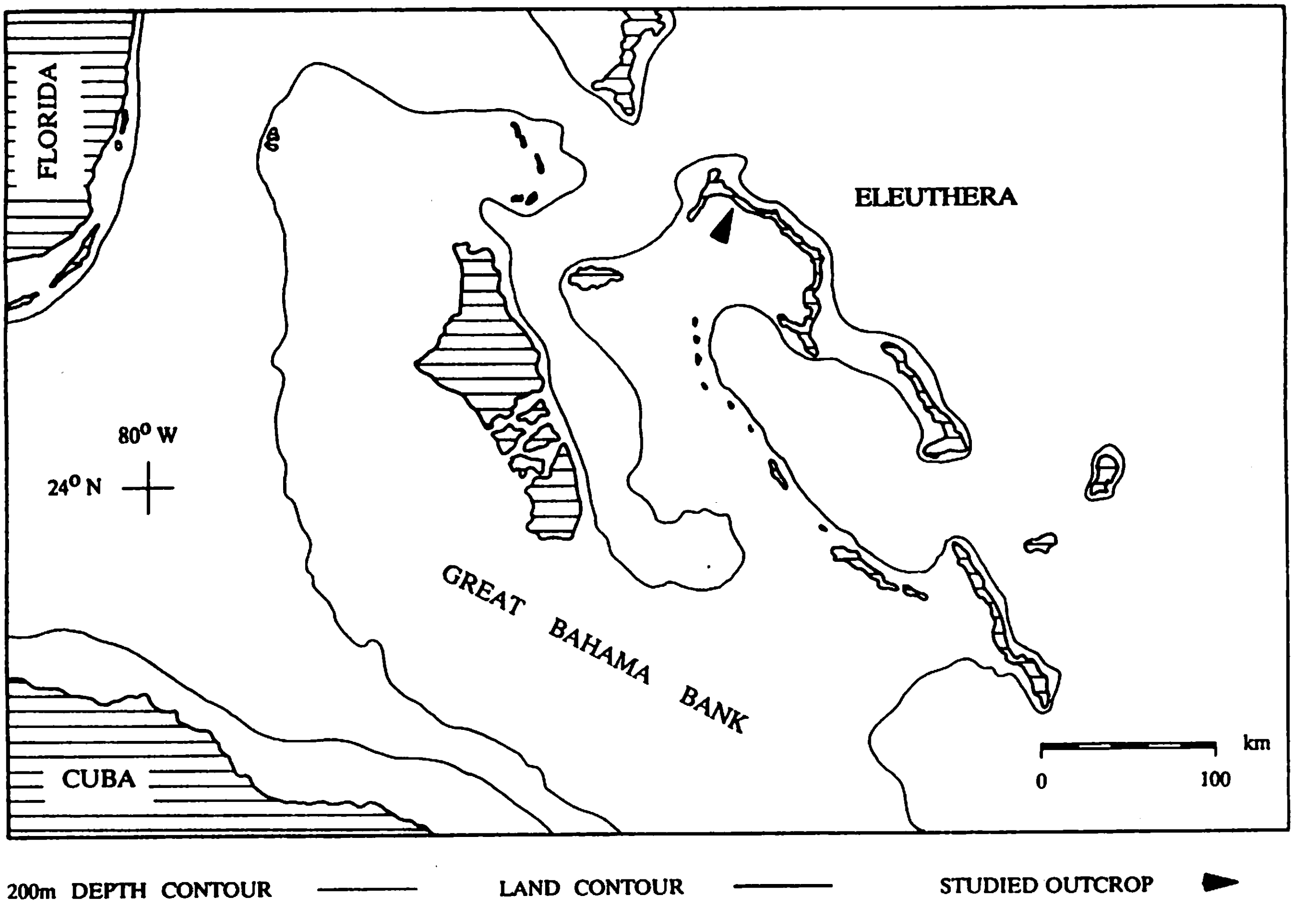


Fig. 1. Location of study area.

During a recent survey of the island, I recognized two distinct limestones units, separated by an important discontinuity.

The lower unit (U1) consists of well lithified, wind- and water-laid, bioclastic or peloidal/ooidal limestones. The upper unit (U2) is made of weakly cemented, wind-deposited, bioclastic calcarenites. Due to a lack of radiometric dates and to the absence of diagnostic fossils, the age of these limestones is not known precisely. However, lithologic comparison with radiometrically dated units on New Providence (Garrett and Gould 1984) and on San Salvador (Carew and Mylroie 1987) suggests a Late Pleistocene age for U1 and a Holocene age for U2.

The U1 eolianites form the bulk of the Eleutheran limestones. They comprise several (up to 5) lesser discontinuities (paleosols, caliche horizons) and frequent rhizoliths. The shallow marine and beach deposits of U1 characterize the northern part of the island. The beach facies occur at an elevation of up to 4 m above the present sea-level and commonly show keystone vugs. However, the voids reported in this paper are not related to these low-elevation beach deposits. They appear instead in a high eolian ridge, more than 600 m inland and several tens of meters above today's sea-level.

Subaerial keystone vugs

I have found keystone vugs on the northwestern side of a roadcut located near Gregory Town, in the northern part of Eleuthera (lat. 25°24'02"N, long. 76°33'20"W, Fig. 2 and 5a). This roadcut is perpendicular to a NW-SE oriented, Late Pleistocene (U1) ridge which stands some 620 m away from the windward shoreline of the island and 43 m above present sea-level. The ridge consists of well sorted, medium-grained, peloidal-ooidal limestone (Fig. 3). The good sorting coupled with the presence of typical wind-induced sedimentary structures (steep foresets, large-scale trough cross-bedding; Fig. 4) and meteoric vadose cements identify the ridge as an eolian deposit.

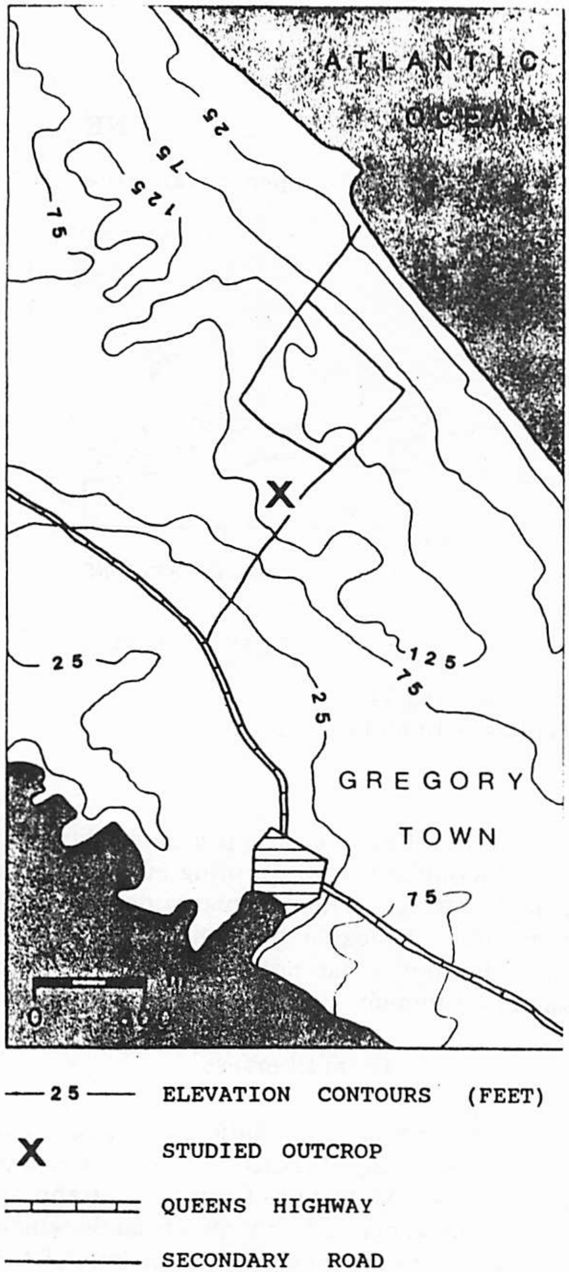


Fig. 2. Situation map of studied outcrop.

The observed keystone vugs appear in low-angle backsets on the NE (windward) side of the dune (Fig. 4). They form thin (1-2 cm) and discontinuous horizons in which the rock texture may be slightly coarser. In cross section, the voids have an elongate or a subcircular shape (Fig. 5b). The linear vugs are parallel to bedding and range from 5 to 10 mm in length and 0.5 to 1 mm in height. The subcircular voids are less common and may reach 1 mm in diameter. The keystone vugs do not seem to be interconnected and it is difficult to obtain a perfect impregnation of the samples. The fabric selectivity of the voids appears well, in thin section (Fig. 5c). Indeed, the grains are not cut or dissolved along the void's edges.

GENERAL PERCENTAGES

Grains	53.8 %
Primary porosity	11.6 %
Secondary porosity	7.5 %
Cement	27.2 %

GRAIN PERCENTAGES

Peloids	58.1 %
Ooids	27.9 %
Bioclasts	2.1 %
Others	11.9 %

Fig. 3. Petrographic composition of the Late Pleistocene limestones containing the studied keystone vugs.

DISCUSSION

In order to explain the formation of the described keystone vugs by beach-swash action, one has to suppose (1) that sea-level was much higher during the Late Pleistocene than today, (2) that Eleuthera has been uplifted since that time, or (3) a combination of both. Consultation of eustatic (Cronin 1983) and subsidence (Mullins and Lynts 1977) curves for the area indicate that (1) sea-level was never more than 4-8 m higher during the Late Pleistocene than it is now, and (2) that the Bahama Platform has been subsiding at an approximate rate of 1.6 cm/1000 yrs since the Oligocene. Hence, the origin of the elevated keystone vugs observed on Eleuthera cannot result from fair-weather swash-zone action. Three alternative mechanisms are discussed in the following part of this section : (1) storm-swash action, (2) decay of organic matter, and (3) rainfall effect.

Storm swash action

Wanless et al. (1989) first proposed this mechanism to explain the occurrence of keystone vugs 25 m above today's sea-level, in a Pleistocene ridge on Providenciales, Caicos Islands. According to these authors, the ridge and the associated voids were formed when catastrophic swells broke onto an unprotected platform and

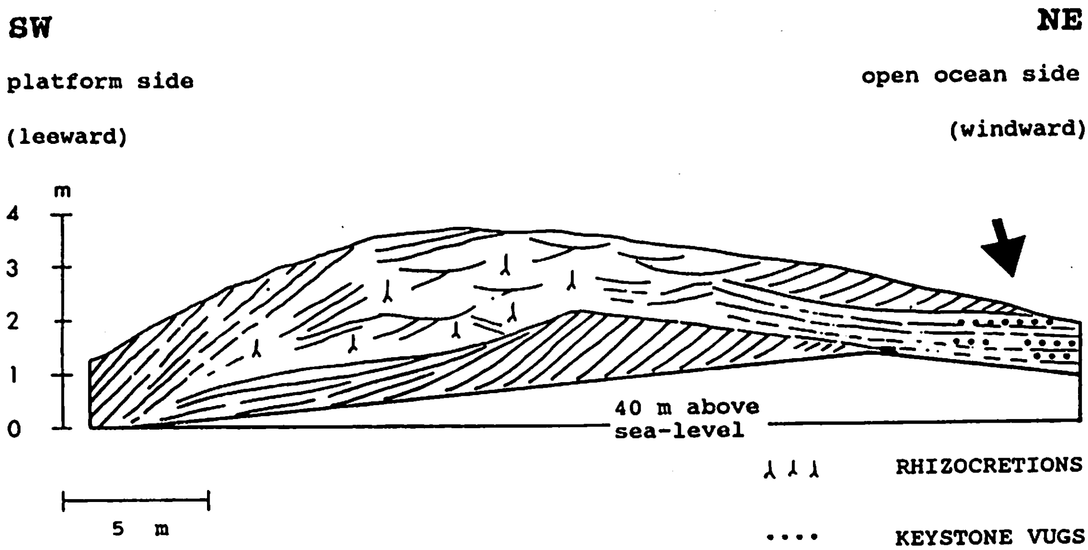


Fig. 4. Sketch of studied outcrop showing keystone vugs location and typical eolian sedimentary structures.

initiated surges to very high elevations.

Similarly, Smith and Dawson (1990) reported sandy horizons apparently deposited by 4-19 m high tsunami floods, interlayered within Holocene estuarine mud on the Western Coast of Scotland. Moreover, in the Pacific Ocean, earthquake-induced tsunami waves may be as high as 50 m when they reach the shore (Barnes-Svarney 1988).

The elevated keystone vugs observed on Eleuthera could result from such catastrophic waves, or exceptionally strong storm-floods. However, their clear association with eolian sedimentary structures does not agree very well with this hypothesis.

Decay of organic matter

Two slightly different void-forming mechanisms are discussed under this label. In the first case, megapores form directly by the degrading of buried psammophitic plant fragments. In the second case, vugs result form biogenic gas production during the decay of organic matter.

If the first explanation were correct, (1) the observed keystone vugs should be better interconnected, and (2) dune cementation should have been exceedingly rapid for the voids to be preserved because degrading of organic matter occurs at a very fast rate in oxidizing environments.

Tebbutt et al. (1965) presented biogenic gas production as a void-forming mechanism in peritidal settings. Their explanation certainly appears more probable than the "burying and decay" idea but it has not been verified in an eolian environment.

Rainfall effect

Two similar explanations are suggested under this heading. According to the first one (Bain 1985), keystone vugs form by air trapping in rainstorm-generated slurries of sands which flow down from the dune face to the base of the dune. The second model proposes that the infiltration of rain through dry (eolian) sands results in vugs formation by air trapping.

The value of these hypotheses is enhanced by experimentation (Kindle 1936, Bain 1985) and direct observation. Indeed, voids formed by rain infiltration have been observed in the coastal dunes of North Florida (Emery 1945) and in a subaerial dam spillway in Indiana (Stieglitz and Inden 1968).

The above discussion shows that the elevated keystone vugs described in this paper are not related to an intertidal environment and probably formed by air trapping in dune sands after a series of heavy tropical rainstorm. Further experiments and more observations in actual sediments, Holocene dunes and Pleistocene

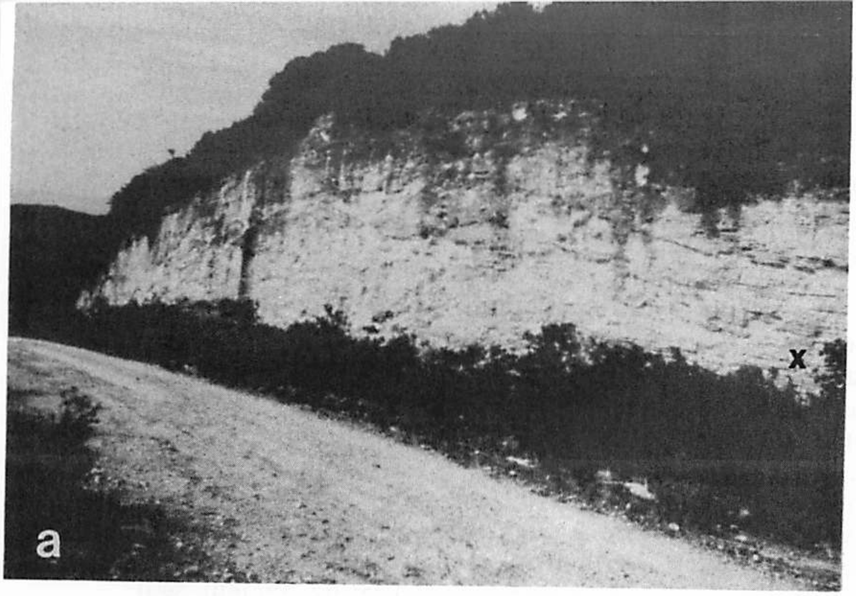
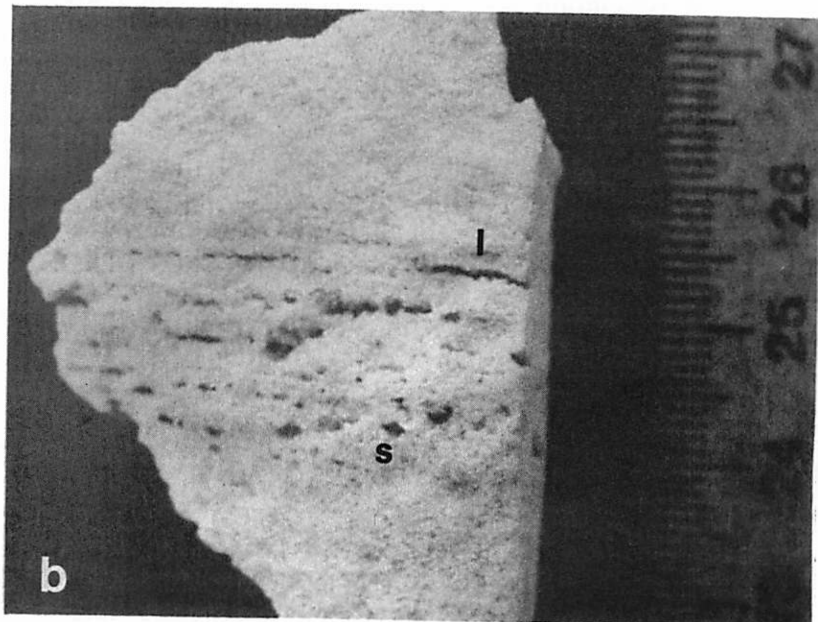


Fig. 5a. View of studied outcrop. X indicates the position of keystone vugs. The sea is visible in the background. Height of outcrop is 4 m between road level and the upper bushes.

Fig. 5b. Detailed picture of the described keystone vugs showing their linear (l) and subcircular (s) morphology.



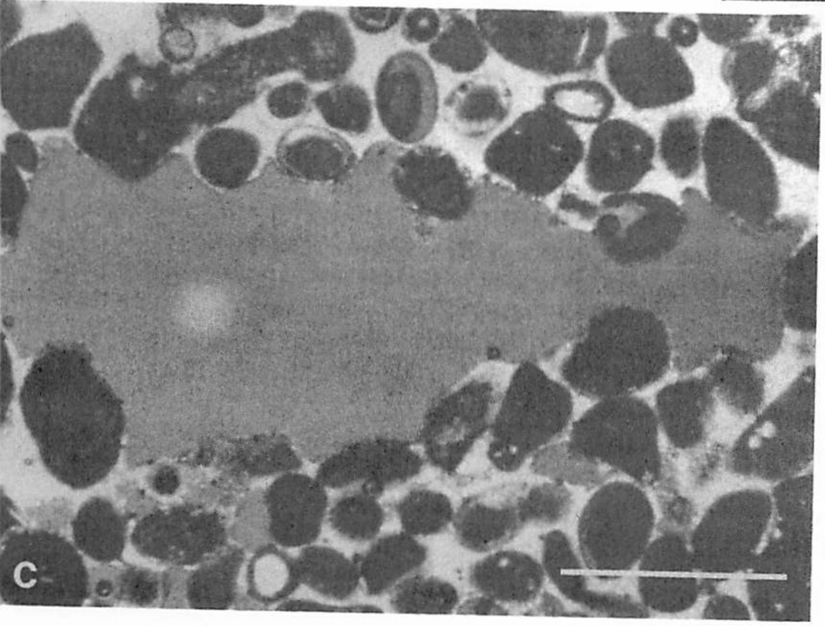


Fig. 5c. Microscopic view of an elongate void (scale bar: 0.5 mm). Notice the fabric selectivity of the gap.

eolianites are needed to strengthen this hypothesis.

CONCLUSION

The occurrence of elevated keystone vugs in a high Pleistocene dune on Eleuthera attests that, although their mode of formation is still debatable, these voids are not always related to an intertidal setting. In ancient sequences, keystone vugs should be used as a sea-level indicator, only when they are included in a typical sedimentary sequence and when they appear in association with characteristic trace and body fossils.

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