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Cover photo: *Diploria strigosa*, the common brain coral, preserved in growth position at the Cockburn Town fossil coral reef site (Sangamon age) on San Salvador Island. Photo by Al Curran.

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CHARACTERISTICS AND ORIGINS OF JOINTS AND SEDIMENTARY DIKES OF THE BAHAMA ISLANDS

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ABSTRACT

Joints and sedimentary dikes are common features in bedrock of the Bahama Islands. Joints may be filled, lined, or unfilled and may be randomly or preferentially oriented. Randomly oriented joints and dikes are generally of local extent, short, confined to surficial beds, and are apparently caused by local, surficial processes. Those which exhibit preferential orientation occur on a deposit scale and are generally long, sinuous, commonly bifurcate, and cut multiple beds. These may be tens of meters in length, transect bedrock vertically to subvertically, and may extend more than 6 meters below present sea level. Joints and dikes commonly exhibit orientations which are generally either parallel or at high angles to depositional strike.

Dikes developed during glacial periods when sea level was low, pluvial conditions persisted over the area, and deposits were exposed to subaerial diagenesis. Caliche fills joints near the surface, but where joints have been sheltered by depth, grainstone and spar fillings occur. Petrography, mineralogic composition, and isotopic signatures (carbon and oxygen) of sedimentary fillings indicate subaerial, freshwater environments of deposition associated with well-developed soils and vegetation. A radiocarbon date of 20,200 B.P. for caliche-dike material corresponds to the maximum extent of late Wisconsin glaciation.

Major dikes probably originated as joints induced by gravitational settling aided by sporadic seismic vibrations. Soon after formation, joints became filled with sedimentary materials. Joints and dikes are common in lump-like deposits of platform margins while rare in the more stable, sheet-like deposits of platform interiors. Occurrence of joints and sedimentary dikes are, therefore, an indicator of the platform margin.

INTRODUCTION

The term joint is used to describe fractures that exhibit no evidence of offset by shear (Secor, 1965; Verbeek and Grout, 1983). Joints may also be called fissures (Newell and Rigby, 1957), but when filled by sedimentary processes become sedimentary dikes.

Sedimentary dikes in the geologic record are described by several authors and are branded by numerous names. All joints filled by sedimentary material from above are referred to as neptunian dikes (Shrock, 1948; Wilson, 1975), but more specific names are given with adjectives describing the infilling material such as clastic dikes (Smith, 1952), sandstone dikes (Fairbridge, 1946), and caliche dikes (White and others, 1984).

To date, little has been done to describe or interpret the origin of joints and sedimentary dikes which occur in Late Pleistocene deposits of the Bahamas. No paper has specifically addressed the question of the origin of joints and sedimentary dikes in the Bahama Islands, and materials other than caliche fillings have not been reported. The purpose of this paper is to describe the spectrum of fillings, occurrences, and orientations of joints and sedimentary dikes in the Bahamas Islands and offer an interpretation of their origin.

CLASSIFICATION OF JOINTS

Joints may be filled (dikes), lined, or unfilled; they may be long, preferentially oriented, and cut multiple beds, or they may be short, randomly oriented, and confined to surficial beds. The state of filling and preference of orientation provide the basis for classification and identification of joint types. To facilitate description, "filled", "lined", and "unfilled" joints are labeled types "F", "L", and "U" respectively with the letters "p" for preferred and "r" for random orientation attached. The classification scheme is summarized in Table 1.

Classification of Joint Types		Orientation	
		Preferred	Random
Filling Extent	Filled	Fp	Fr
	Lined	Lp	Lr
	Unfilled	Up	Ur

Table 1. Classification of joint types.

JOINT AND DIKE ORIENTATIONS

Length-weighted orientations of joints and dikes were measured at 19 locations (Fig. 1) using pace and compass techniques. To obtain orientation data on long, sinuous joints and dikes, orientations were measured along joint-strike approximately every five meters. The orientations are graphically displayed in azimuthal orientation diagrams (Fig. 2). All but 3 of the 19 locations tested for orientation preference of joints proved to be statistically preferred (= 0.05).

Joints and dikes measured at most locations exhibit preferred orientations which generally transect deposits either approximately parallel or at high angles to platform margins. This relationship between joint and dike orientation and platform-margin orientation is demonstrated in Figure 3 by a frequency curve of the departure of orientation from tangents to platform margins.

JOINT DEVELOPMENT

Many processes may cause joints. Some causes may be inferred from joint occurrence or presence of still active processes. Generally, the processes responsible for random joint development are different from causes which produce joints of preferred orientation.

Random Joints

Randomly oriented joints (types Fr, Lr, and Ur) are typically short (<1m long), discontinuous, and confined to surficial beds. They are produced by local and chiefly surficial processes, and are minor features on an outcrop scale. Causes of randomly oriented joints commonly may be inferred by their occurrence. The surficial breakup of thin, brittle beds may produce numerous, randomly oriented joints (Fig. 4) by mechanical processes which include collapse from cavitation, impact of storm debris, and disruption by organisms. The interconnection of randomly oriented joints with large rhizocretions may indicate jointing by the wedging of plant roots. The radiating intersection of other joints with solution pits suggests contraction of case-hardened bedrock surrounding the pits (Fig. 5). Random joints may also be produced by desiccation in muddy sediments (Reeves, 1976) and possibly by the force of crystallization (Shinn, 1969) forming polygonal patterns.

Preferred Joints

Joints which exhibit preferred orientations (types Fp, Lp, and Up) are prominent features on an outcrop scale (Figs. 6, 7 and 8). They are typically sinuous, cut multiple beds, may be tens of meters in length, commonly bifurcate, and generally dip vertically to subvertically. Joints exposed on the vertical walls of a blue hole on Gibson Cay in the Middle Bight area of Andros Island transect bedrock to a depth of at least 6 meters below present sea level. Their widths vary from a centimeter to a few centimeters, with one exception being a dike exhibited in the Cockburn Town fossil reef on San Salvador which attains widths up to 20 centimeters. Orientations are generally

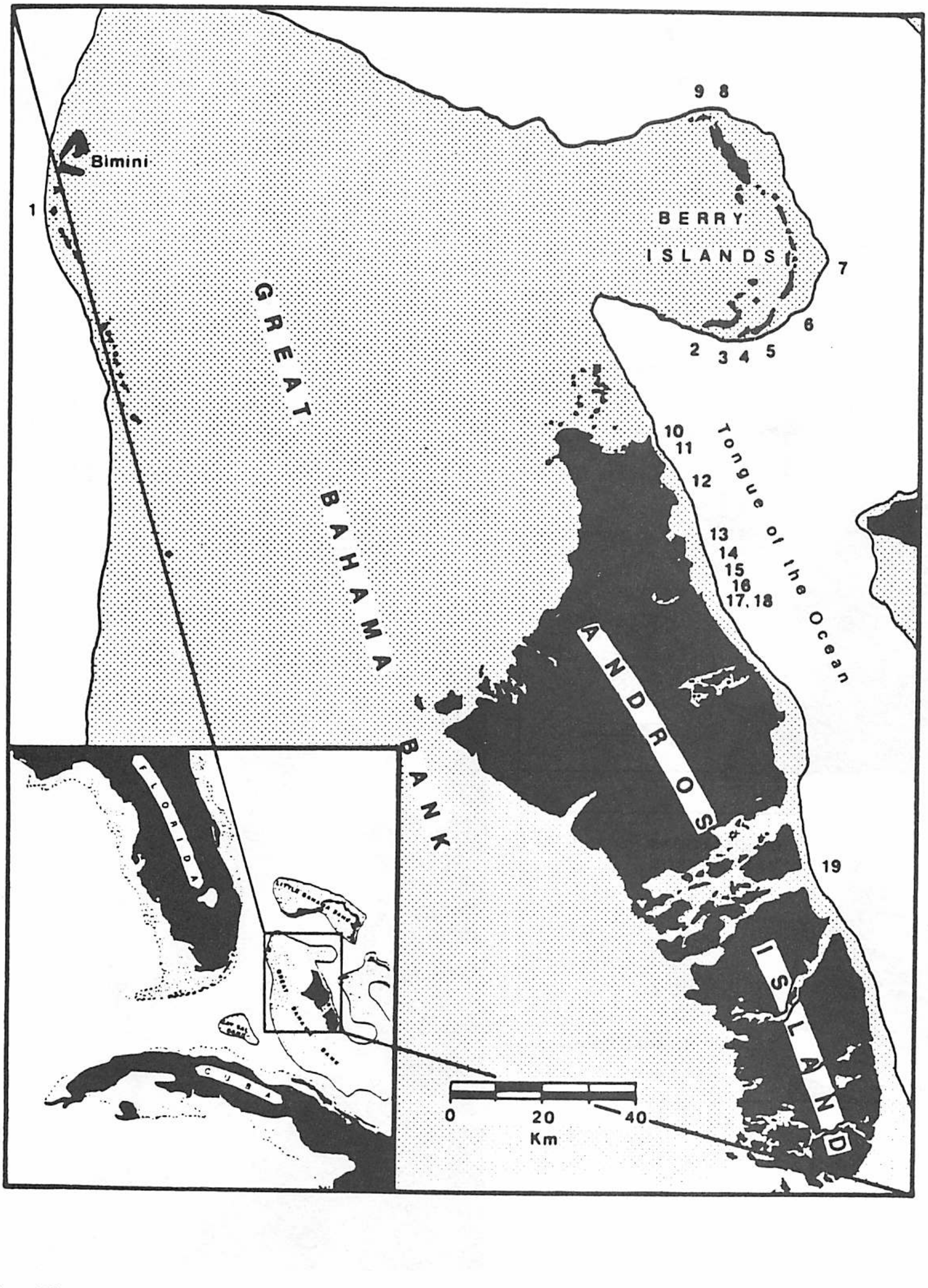

Fig. 1. The Great Bahama Bank and locations mentioned in text from Gun Cay, south of Bimini (1) through the Berry Islands (2-9) and Morgans Bluff (10) south to Gibson Cay (19) of Andros Island.

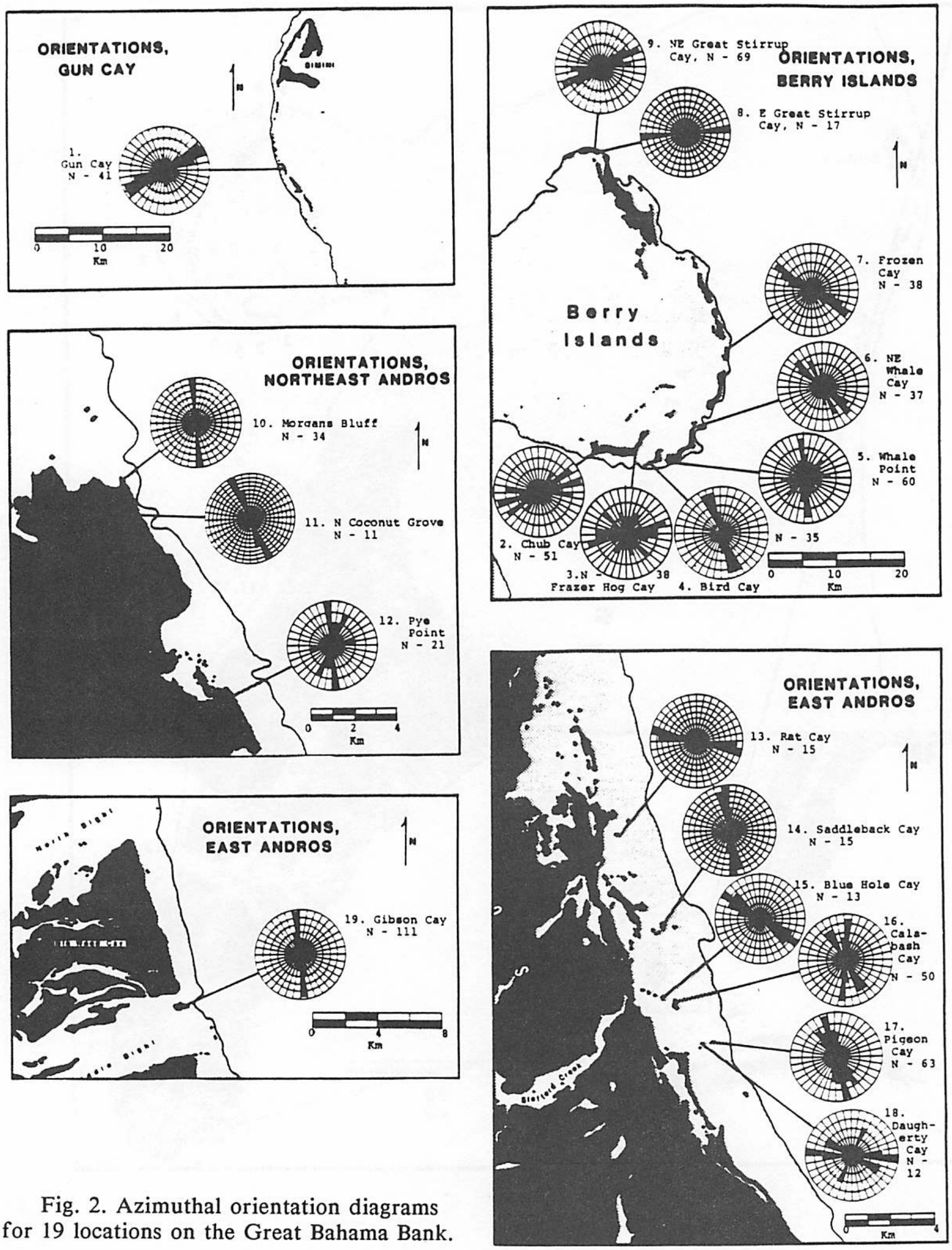

Fig. 2. Azimuthal orientation diagrams for 19 locations on the Great Bahama Bank.

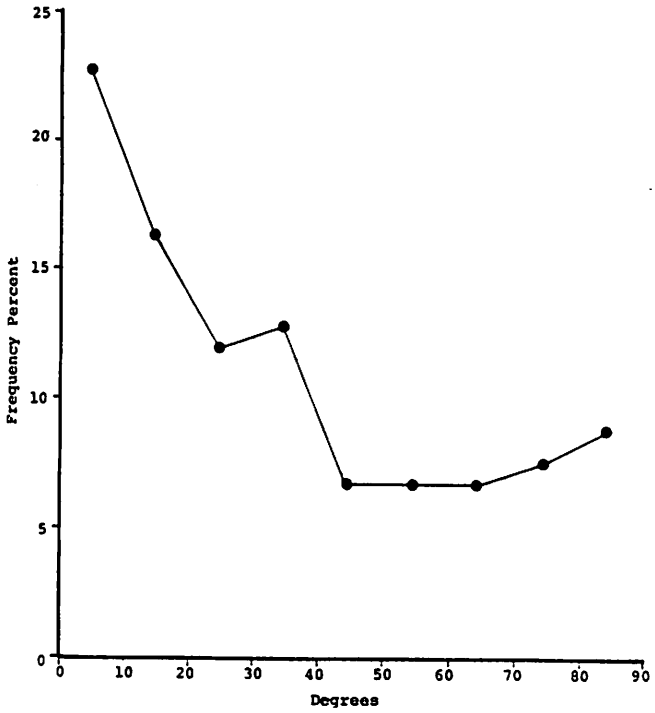

Fig. 3. Frequency curve of departure of joint and dike orientations in degrees from tangents to platform margins for measurements from locations of statistically preferred orientations. Lines connect midpoints of 10 degree intervals compiled from 623 measurements.

either parallel or at high angles to depositional strike (Figs. 2 and 3). Those oriented parallel to strike commonly exhibit greater widths than those at high angles.

The causes of these features are not as readily apparent as causes of minor joints except where joints have developed as a result of coastal erosion through undercutting which has led to partial collapse of wave-carved ledges, or where steep margins of deposits exhibit listric joints which define incipient, seaward slumps (Fig. 7). Many other processes have been identified as causing joint development (see Dionne and Shilts, 1974), but only mass movement and seismic activity are likely to have initiated major joint development in the Bahamas.

Mass movement. Deposits in which joints most commonly occur are generally lump-like deposits which have relatively large topographic relief and/or bulk thickness. Gravitational forces acting on such deposits could cause them to settle prior to extensive cementation when deposits are relatively poorly-cemented and weak (for example, Heron and others, 1971).

Seismic activity. Vibrations produced by sporadic seismic activity is a likely trigger of joint development. Seismic activity further south in the Caribbean is known to have jarred neighboring Florida many times (Lane, 1983). Vibration of loosely cemented, lump-like deposits would likely aid gravitational forces, inducing settling, and resulting in joint development (for example, Reimnitz and Marshall, 1965).

Geologic Controls. Joint development by gravitational forces (mass movement, perhaps triggered by seismic activity) is most likely to occur where relief and bulk of deposits are greatest. Topographic relief as a control of jointing has been recognized by Chapman (1958), and clastic dikes oriented parallel to hillslopes have been observed by others in the Carolinas (Heron and others, 1971). In the Bahamas, jointing occurs in dunes, barrier-island complexes, and reefs which generally develop parallel to depositional strike, itself controlled by the orientation of platform margins. It is the seaward margins of platforms where sediments have accumulated into elongate, lump-like deposits and where joints and dikes are most common. The scarcity of joints and dikes in sheet-like deposits distant from platform margins and some deposits which are close to platform margins may stem from a lack of deposit relief, lack of bulk thickness, or greater stability of underlying bedrock.

Joint development primarily parallel to the margins of deposits represents extension in the direction of least confinement as outlined by topography. Joints may also develop at high angles to the margins but the extension is more confined. For this reason, joints at angles other than parallel to depositional strike are less common than those which are parallel (Fig. 3). Local variations of stress may explain random orientations such as those obtained for Frazer Hog Cay of the Berry Islands, and Pye Point of east Andros Island.

DEPOSITION OF FILLINGS

Sheltering by depth appears to determine the type of dike which develops. Caliche is most common for joints exposed to subaerial processes, grainstone fillings may occur below caliche, and sparry calcite fillings may occur below grainstone. Presumably, grainstone fillings occur where deposition is sheltered by depth from caliche processes, and sparry calcite is deposited if joint space is sufficiently deep and sheltered from both caliche processes and grain infall. These relations are depicted in Figure 9.

Processes responsible for the filling of joints include: (1) accretion, (2) mechanical infilling, and (3) micritization of host rock. Accretionary deposition is indicated in caliche dikes by lamination of caliche material resulting from the addition of caliche layers of differing textures (Fig. 10) and in sparry calcite dikes by dense, sparry calcite radiating from joints walls and coarsening to fill joint space (Fig. 11). Mechanical infilling, by the washing or falling of clasts or particles from the surface into joints, is indicated by the incorporation of grains and clasts derived from external sources such as black pebbles (Fig. 12). Alteration by micritization may be responsible for some of the micritic caliche fill via the assimilation of grains into the caliche matrix as indicated by floating texture (Fig. 13), ghost grains, and partially assimilated grains.

All dikes are developed in a freshwater, near-surface, or subaerial environment. Petrographically, this is confirmed by features in all three types of fillings.

Caliche forms beneath soils when carbonate constituents on or in the soil are leached by slightly acidic rain water which upon evaporation, becomes supersaturated and precipitates low-magnesium calcite (Kornicker, 1958; Multer and Hoffmeister, 1968; Robbin and Stipp, 1979). Many features which occur in the caliche fillings of joints are themselves indicators of the near-surface environment. These include black pebbles, rhizoliths, leached and vuggy porosities, and iron-oxide staining. Black pebbles are thought to be produced from the discoloration of rock fragments by the decay of organic matter along the shores of hypersaline lakes (Ward and others, 1970) or blackened by brush fires (Shinn and others, 1984). Rhizoliths, produced by the precipitation of micrite around roots, commonly mark the presence of paleosols among eolian calcarenites (Bird, 1972). The leached and vuggy porosities are types which commonly result from dissolution near the surface of bedrock in the freshwater vadose environment (Longman, 1980; Harris and others, 1985). Iron-oxide staining is also an indicator of surface to near-surface diagenesis as this is where intense weathering and oxidation is active (Pettijohn and others, 1972).

Petrography of grainstone dikes also indicates a history of joint filling under vadose conditions as suggested by staining, micritization, and dissolution of filling components and the host-rock interface. Stained and micritized grains and clasts (Fig. 14) were probably derived from the surface by infall as a result of storm wash or winds and by collapse from higher portions of joint walls. Pore waters led to cementation of the components by blocky spar and later exposure to vadose dissolution led to the development of vuggy porosity.

Sparry calcite dikes indicate deposition in a freshwater environment on the basis of crystal morphology. Extensive intergranular cementation, interlocking crystals of equant calcite that coarsen toward pore centers, and bladed calcite of dikes are typical of freshwater cements (Longman, 1980). Freshwater precipitation is also suggested by the occurrence of trigonal prism outlines of crystals and thorn-shaped vacuole inclusions (Fig. 11) which are commonly formed in meteoric environments but rarely developed in marine environments (Binkley and others, 1980; Chafetz and others, 1985). Banded coloration which pervades spar (Fig. 15) may be caused by inclusions of amorphous organic and iron pigments responsible for a similar effect in caliche crusts (Multer and Hoffmeister, 1968) and variations in banding are possibly due to alternations of wet and dry periods (Robbin and Stipp, 1979).

Mineralogic and isotopic data also indicate deposition in a freshwater environment. The average mode-mole percent magnesium calcite content of fillings, determined by x-ray diffraction (Fig. 16), is 2.1%. The low-magnesium content is typical of carbonate precipitated in the freshwater environment (Chafetz and others, 1985). Isotopically (Fig. 17), samples exhibit a relatively narrow range of delta ^{18}O (-3.33°/oo to -5.97°/oo), typical of limestones altered by subaerial diagenesis (Allan and Matthews, 1977; 1982). Delta ^{13}C values for caliche crust, caliche filling, and sparry

Fig. 4. Random joints (type Ur) in thin, brittle bed on Calabash Cay, Andros Island. →

← Fig. 5. Random joints (type Ur) radiating from solution pit in case-hardened bedrock on Gibson Cay, Andros Island.

Fig. 6. Preferred caliche dike (d; joint type Fp) cutting bedding on Gun Cay, south of Bimini. →

← Fig. 7. Lined, listric joint (type Lp) defining seaward slump on Whale Cay, Berry Islands.

Fig. 8. Preferred, unfilled joint (type Up) in Holocene dune on High Cay, San Salvador. Note narrowing and pinch-out with depth.

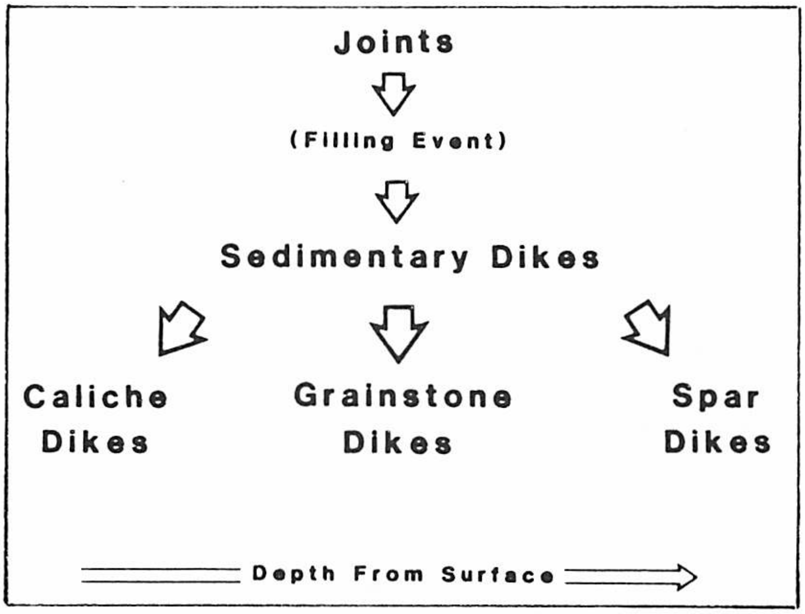

Fig. 9. Relation of dike types with depth from the surface.

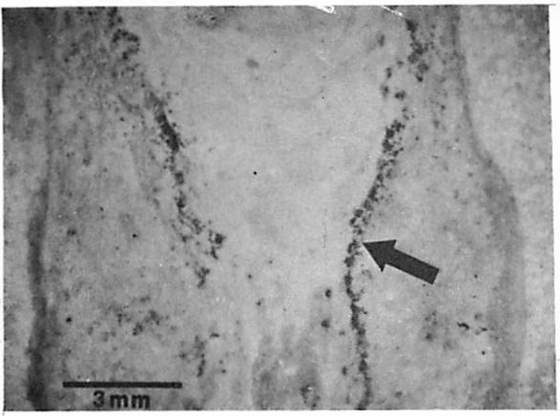

Fig. 10. Laminated micrite in caliche dike. Note dark pigment of residual organics (arrow) between layers. Polished slab.

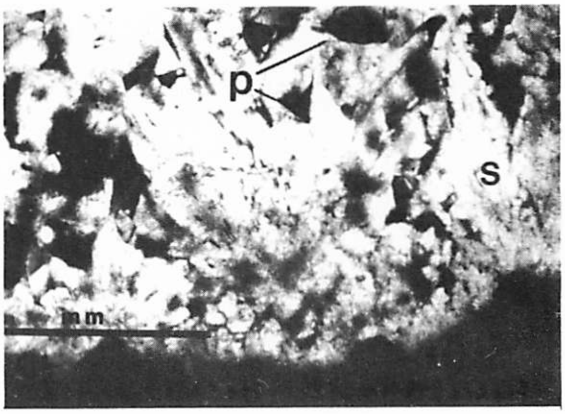

Fig. 11. Flower spar(s) radiating from wall of sparry calcite dike. Note trigonal prism outlines (p) of crystals. Photomicrograph, crossed polars.

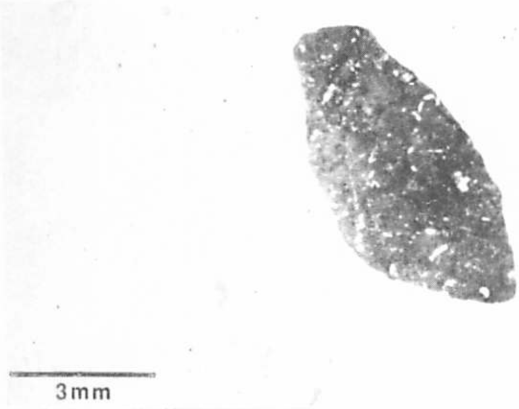

Fig. 12. Black clast in caliche dike. Polished slab.

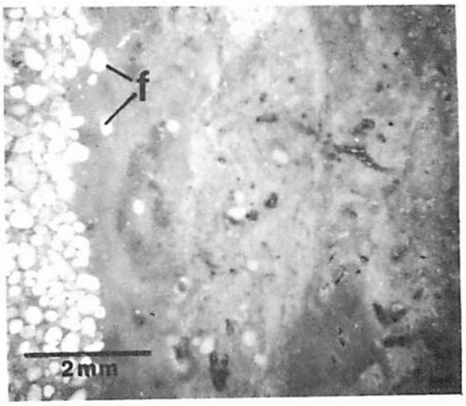

Fig. 13. Floating texture (f) exhibited by grains and clasts in caliche dike. Polished slab.

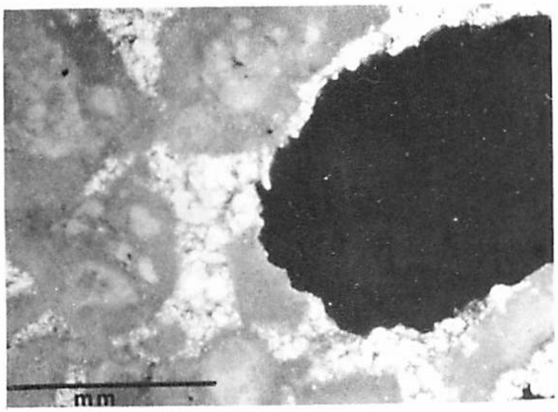

Fig. 14. Stained and micritized grains and clasts of grainstone dike cemented by spar. Note large vug (black). Photomicrograph, ordinary light.

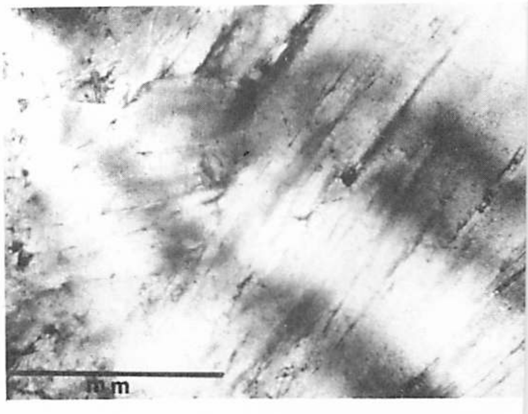

Fig. 15. Bladed spar of sparry calcite dike with pervasive, banded coloration. Photomicrograph, ordinary light.

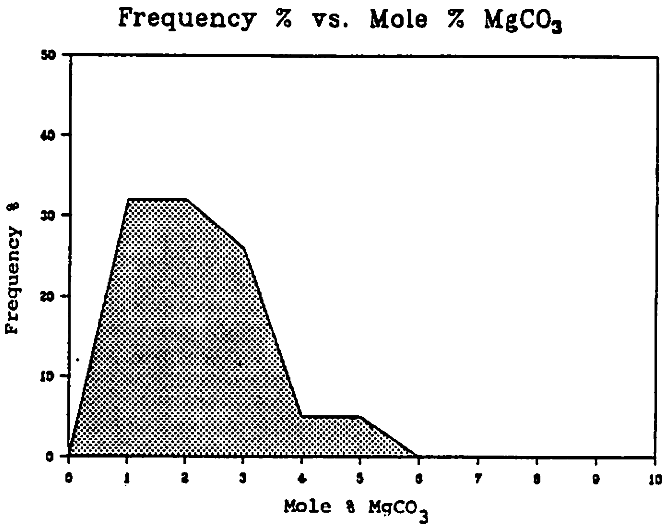

Fig. 16. Frequency curve of mode-mole percent magnesium calcite content of 19 samples of joint fillings.

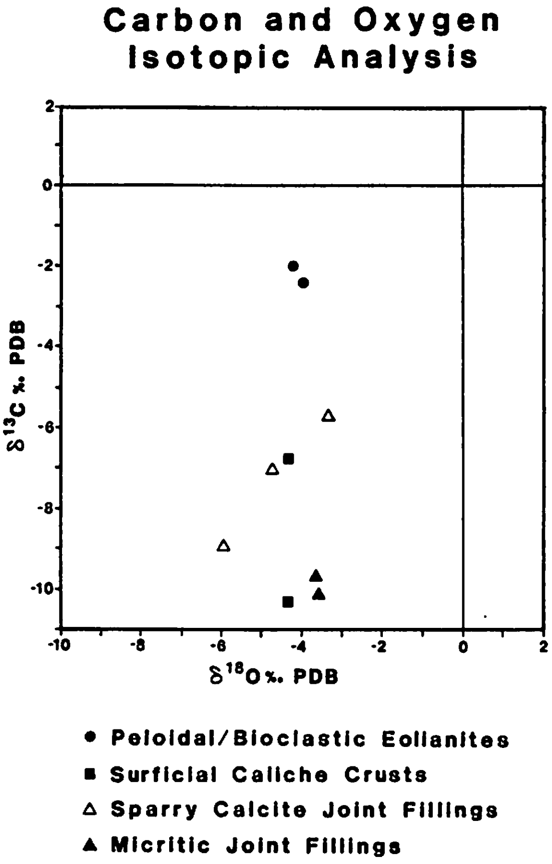

Fig. 17. Carbon and oxygen isotopic signatures of joint fillings, caliche crusts, and bedrock.

calcite filling exhibit marked negative values, as low as -10.35°/oo, while delta ^{13}C values for host eolianite is much less negative, only -2.05°/oo and -2.45°/oo. The ^{13}C values of the host eolianite is typical of Pleistocene limestones (James and Ginsburg, 1979), however, the highly negative delta ^{13}C values of crusts and fillings indicate that organic carbon derived from soils has been a dominant factor in their formation (Hudson, 1977; Allan and Matthews, 1977; 1982).

A radiocarbon date of 20,200 B.P. for a sample of caliche filling is approximately equivalent to the maximum extent of late Wisconsin glaciation and accompanying sea level depression (Shackleton and Opdyke, 1973), a period when deposition in the subaerial environment was extensive. Carew and Mylroie (1985) claim that pluvial (high precipitation) conditions may have existed in the latitudinal belt of the Bahamas during this period as a result of compression of climatic belts, a climatic change which caused extensive vegetation and soil formation. Amino acid racemization ages for *Cerion* sp., a terrestrial gastropod from paleosols in San Salvador, cluster at around 20,000 B.P. (Mylroie and others, 1985). Thick vegetation and soil formation would result in accelerated development of caliche which formed crusts and filled joints during this period.

CONCEPTUAL MODEL OF DEVELOPMENT

The sum of the above data allows the construction of a conceptual model of joint and subsequent dike development. The model depends first upon the deposition of lump-like deposits such as barrier island complexes, dune complexes, and reefs during relative highstands of sea level. Deposition may then cease due to sea level fall and early cementation of deposits may then be initiated. Outer surfaces would begin to become case-hardened and colonized by vegetation (Fig. 18a). At this time, disruption by roots and expansion or contraction of the thin, cemented outer surface may result in type Ur (unfilled and random) joint development.

When lowstands of sea level occur (during glacial episodes), cementation and alteration progress. When gravitational settling aided by sporadic seismic vibration occurs, adjustments of deposits to more stable

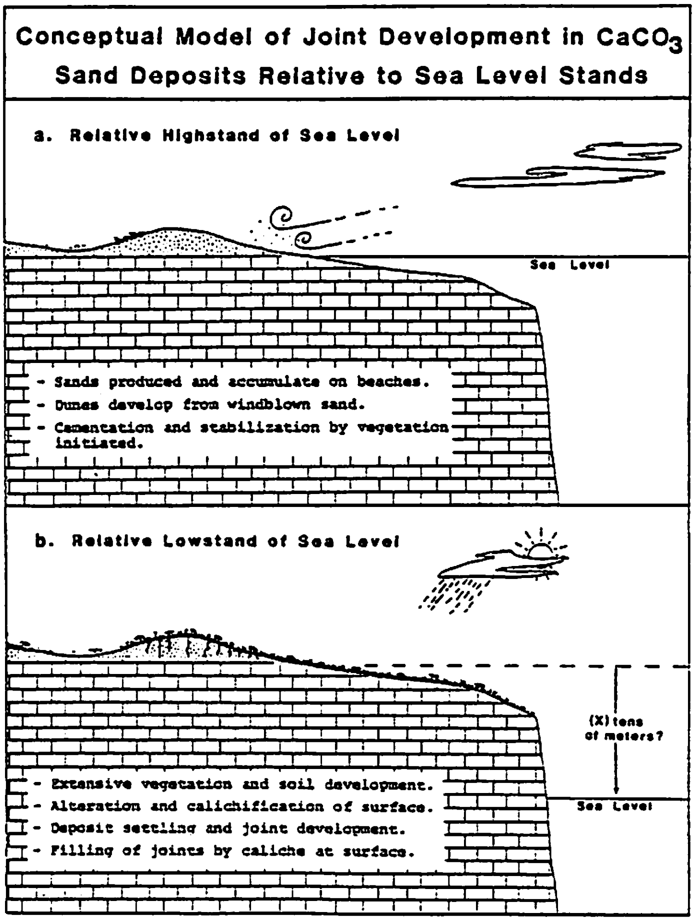

Fig. 18. Conceptual model of joint and dike development relative to a) highstands of sea level, and b) lowstands of sea level.

positions are accomplished by joint development. By this time the bulk of deposits are at least loosely cemented so joints cut multiple beds, forming perpendicular to directions of least confinement. Orientations are largely determined by deposit configuration and thus type Up (unfilled, preferred orientation) joints develop approximately parallel or at high angles to elongate, lump-like deposits of platform margins (Figs. 2 and 3).

Accompanying the lowstand of sea level, pluvial conditions lead to extensive vegetation and soil development. Surficial zones of deposits undergo advanced alteration and calichification, and joints are filled with sedimentary materials in a near-surface, freshwater, diagenetic environment (Fig. 18b). Joint types Ur and Up may accrete material on joint walls to become lined joint types Lr and Lp, and upon complete filling become types Fr and Fp (dikes).

CONCLUSIONS

Joints of the Bahama Islands occur on both local and deposit scales. Joints on local scales are generally randomly oriented and confined to surficial beds while joints which develop on deposit scales generally exhibit preferred orientations and cut multiple beds. When filled, joints become sedimentary dikes with the type of sedimentary filling determined by degree of isolation from subaerial processes. Dikes developed in a freshwater, diagenetic environment, probably during relative lowstands of sea level when subaerial deposition was extensive.

Random joints develop from surficial instability caused by surface contraction, expansion, or root disruption of brittle beds; while major joints of preferred orientation develop from gravitational settling of large portions of deposits probably aided by sporadic, seismic vibration. This joint-producing mechanism is most effective on lump-like deposits like those which develop on platform margins and, indeed, this is where joints and dikes in the Bahamas are most common.

Because major joints tend to develop either parallel or at high angles to depositional strike, joints and dikes of this type may be useful indicators of the platform margin. In addition, filling materials are informative records of diagenesis of deposits.

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