PROCEEDINGS
OF THE
FIFTH SYMPOSIUM
ON THE
GEOLOGY OF THE BAHAMAS

Edited by

Roger J. Bain

Production Editor

Donald T. Gerace

Bahamian Field Station
San Salvador, Bahamas
1991

Printed in USA by Don Heuer

ISBN 0-935909-37-0

PALEOMAGNETIC DIRECTIONS OF PALEOSOLS ON SAN SALVADOR ISLAND, BAHAMAS: PROSPECTS FOR STRATIGRAPHIC CORRELATION

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ABSTRACT

Correlation of paleosols represents a unique stratigraphic problem, because they are developed over a significant paleotopography, and they are laterally discontinuous. We have applied paleomagnetic techniques to paleosols on San Salvador in an effort to obtain time-dependent correlation criteria.

To date, more than 300 core samples for paleomagnetic analysis have been collected from the island. Most samples yield moderately to very well-defined vector directions. The majority of specimens show little or no secondary components of magnetization. Those specimens containing multiple components of magnetization usually had the secondary overprints removed by 100- 200 Oersteds alternating field cleaning.

Paleomagnetic directions at various paleosol localities show moderately tight to very tight clustering (Fisher precision parameters range from 20-1,000), which suggests that the various paleosols have recorded different segments of geomagnetic history. Some locality mean directions are nearly identical, while others are statistically distinct. This suggests that different portions of geomagnetic secular variation history have been sampled, which may prove useful as a correlation tool.

Some paleosols exhibit anomalous SE and shallow magnetic directions which might be termed a geomagnetic "excursion". The "excursion" may be a record of non-dipole field behavior, perhaps related to a reversal event, or may be a combination of both normal and reversed magnetic components in a paleosol, developed during a period of formation that included a reversal event. Regardless of origin, this anomalous direction shows considerable promise as a correlation criterion.

INTRODUCTION

Paleosols are soils that formed on a past landscape, and as such are useful stratigraphic markers (Ruhe, 1965; Birkeland, 1984). They are especially useful in differentiating between episodes of limestone deposition and exposure caused by the glacio-eustatic sea level fluctuations of the Quaternary. In the Bahama and Bermuda Islands, paleosols have been used to separate limestone packages, especially eolianites, that are otherwise difficult to recognize as deposits related to individual sea level events (Sayles, 1931; Bretz, 1960; Ruhe, and others, 1961; Land and others, 1967; Harmon and others, 1983; Garrett and Gould, 1984; Carew and Mylroie, 1985; Vacher and Harmon, 1987; Vacher and Hearty, 1989). The use of paleosols as stratigraphic markers can be fraught with problems, as the paleosols are deposited over a topographically variable surface and may be laterally discontinuous. There are numerous pitfalls that can occur in the use of paleosols as stratigraphic markers (Carew and Mylroie, in press), and the development of chronostratigraphic capability for paleosol differentiation is important. Because paleosols represent a fossilized weathering front, certain geochronologic techniques, such as U/Th methods, are unsuitable. Some success has been

TABLE I – PALEOMAGNETIC DATA FROM FOUR LOCATIONS ON SAN SALVADOR ISLAND. DEMAG = DEMAGNETIZATION IN OERSTEDS. NRM = NATURAL REMANENT MAGNETIZATION. INTENSITY IS IN EMU/cm^3. GEOGRAPHIC (<u>in situ</u>) COORDINATES GIVEN AS DECLINATION (DEC) AND INCLINATION (INC). K = FISHER PRECISION PARAMETER; A_{95} = CIRCLE OF 95% CONFIDENCE; N = NUMBER OF SPECIMENS; R = RESULTANT VECTOR.

PALEOMAGNETIC ANLYSIS RESULTS FROM SAN SALAVADOR ISLAND

<u>WATLINGS QUARRY</u>

LOWER PALEOSOL

SAMPLE	DEMAG	%NRM	INTENSITY	DEC	INC
17A	120	26	2.8e^{-06}	340	43
19A	60	20	1.1e^{-06}	337	38
20A	120	36	1.9e^{-06}	347	40
21A	120	20	9.6e^{-07}	2	36
22A	120	16	7.6e^{-07}	0	39
25A	250	15	5.6e^{-07}	349	39
26A	180	34	6.2e^{-07}	346	45
26B	530	6	1.9e^{-07}	336	38
				347	40

K = 88.9 A_{95} = 5.9° N = 8 R = 7.921

UPPER PALEOSOL

SAMPLE	DEMAG	%NRM	INTENSITY	DEC	INC
27A	180	64	1.6e^{-08}	337	20
29A	180	54	2.5e^{-08}	347	27
71A	150	9	4.0e^{-08}	328	28
				337	25

K = 71.8 A_{95} = 14.7° N = 3 R = 2.972

<u>PIGEON CREEK QUARRY</u>

LOWER PALEOSOL

SAMPLE	DEMAG	%NRM	INTENSITY	DEC	INC
45A	150	36	5.4e^{-07}	355	47
48A	150	29	1.3e^{-06}	349	44
49A	150	33	1.2e^{-06}	350	44
50A	210	17	8.1e^{-08}	348	46
51A	150	42	1.3e^{-07}	347	45
				350	45

K = 1054.4 A_{95} = 2.4° N = 5 R = 4.996

UPPER PALEOSOL

SAMPLE	DEMAG	%NRM	INTENSITY	DEC	INC
58A	30	74	2.5e^{-08}	348	53
62A	150	22	3.1e^{-07}	355	47
63A	150	18	2.4e^{-07}	356	46
62B	150	23	3.8e^{-07}	350	51
63B	150	30	1.1e^{-07}	353	48
				352	49

K = 449.7 A_{95} = 3.6° N = 5 R = 4.991

<u>THUMB BEACH</u>

SAMPLE	DEMAG	%NRM	INTENSITY	DEC	INC
69A	120	22	1.9e^{-06}	350	66
70A	189	9	–	355	57
71A	120	18	1.2e^{-07}	339	45
72A	180	9	6.3e^{-08}	340	56
72B	60	61	5.4e^{-08}	339	40
				344	53

K = 52.4 A_{95} = 10.6° N = 5 R = 4.924

<u>OWL'S HOLE</u>

SAMPLE	DEMAG	%NRM	INTENSITY	DEC	INC
2A	120	17	7.3e^{-08}	5	56
3A*	150	9	1.6e^{-07}	16	42
7A	180	8	1.7e^{-08}	0	35
8A*	270	1	4.7e^{-08}	13	36
9A+	150	26	2.9e^{-06}	30	40
11A+	150	15	1.5e^{-06}	22	47
15A	220	20	2.0e^{-04}	31	42
119	110	10	5.9e^{-06}	357	44
120	110	16	9.6e^{-06}	359	44
				13	44

K = 50.0 A_{95} = 7.4° N = 9 R = 8.840

<u>ANOMALOUS DIRECTIONS</u>

PIGEON CREEK QUARRY

SAMPLE	DEMAG	%NRM	INTENSITY	DEC	INC
54A	150	37	3.2e^{-08}	108	29
56A	180	32	2.1e^{-08}	130	43
162A	270	27	9.9e^{-09}	128	22
163A	350	35	1.8e^{-08}	118	23
				120	30

K = 36.0 A95 = 15.5° N = 4 R = 3.917

OWL'S HOLE

SAMPLE	DEMAG	%NRM	INTENSITY	DEC	INC
4A	80	3	2.3e^{-08}	132	13
4B	200	1	1.3e^{-06}	136	10
12A	90	3	1.4e^{-06}	104	26
13A	90	3	1.4e^{-06}	126	28
				125	20

K = 25.5 A_{95} = 18.6° N = 4 R = 3.882

*SAMPLES CHANGE FROM REVERSED TO NORMAL DIRECTIONS DURING AF CLEANING

+SAMPLES CHANGE FROM ANOMOLOUS (SOUTHEAST, SHALLOW) TO NORMAL DIRECTIONS DURING AF CLEANING

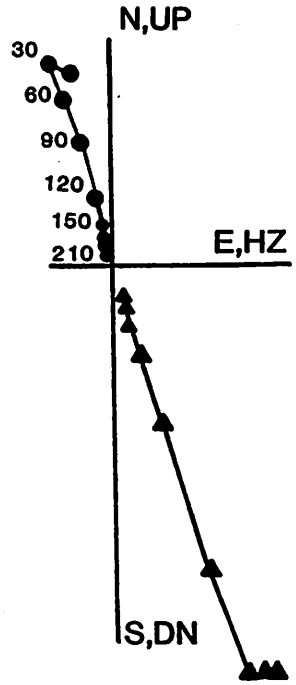

Fig. 1. Vector diagram showing demagnetization experiments that isolate characteristic directions. Dots are declinations plotted in N–E–S–W plane. Triangles are inclinations plotted in vertical plane (UP–D–HZ): standard convention for inclination is positive downward. Demagnetization in oersteds. Notice the linear magnetic decay towards the origin and the lack of secondary components.

achieved using aminostratigraphy of land snails (Carew and Mylroie, 1987; Vacher and Hearty, 1989), but this technique depends on the fossils being present and unaltered.

Paleomagnetic methods have been utilized on paleosols from San Salvador Island, Bahamas, as a possible tool for recognition of unique aspects of a paleosol that would allow its correlation over a broad geographic area. An initial sampling program was conducted in the early 1980's, and the results of that study suggested that certain paleosols were magnetically reversed (Mylroie and others, 1985; Carew and Mylroie, 1985). Further work undertaken to substantiate the preliminary data resulted in modification of the original interpretations, and raised concern that the technique might not be reliable in the carbonate environment (Stowers and others, 1989). In December 1988, a major effort was undertaken to examine the paleomagnetic characteristics of the paleosols on San Salvador in order to sort out the conflicting results from the earlier analyses. In addition, the new project was designed to examine subtle aspects of the paleomagnetic record that might lead to the identification of a unique paleomagnetic signature for each suite of paleosols on San Salvador Island. This work is still in progress, but the preliminary results presented here are interesting and encouraging.

METHODS

Samples were collected from layers within 15 paleosol outcrops at various localities around the island. Cores were drilled using a hand-held gasoline-powered drill, equipped with a one inch inside diameter, diamond-tipped core barrel. Normally, 6-10 samples were collected from each paleosol layer in outcrop.

Magnetic remanence was measured for standard samples (2 cm core length) using either a 2-G two axis cryogenic magnetometer or a Schonstedt SSM-1A spinner magnetometer. In order to remove secondary components of magnetization, the large majority of specimens were subjected to stepwise alternating field (AF) demagnetization. After each cleaning treatment the magnetic direction of the specimen was remeasured and then cleaned at the next AF intensity, and so on. Between 6 and 14 cleaning steps were used in order to define the various magnetic components.

For comparison, two samples were cleaned using thermal demagnetization. This technique involves heating and cooling the specimen in field-free space in order to unblock and randomize (demagnetize) magnetic components with blocking temperatures up to the heating temperature. Remanence was measured after each heating step.

RESULTS

Laboratory Analyses

Of the approximately 300 samples collected, 102 have now been analyzed in the laboratory. Initial remanence intensities vary considerably from layer to layer and range from 10^{-3} to 10^{-8} emu/cm^3. To a large extent, specimens yielded very well defined single component remanence directions (Fig. 1). Coercivity spectra for the majority of samples are relatively narrow with most of the remanence being lost by about 200 Oersteds. The two thermally demagnetized samples retained directional stability up to 550° C (Fig. 2), which is suggestive of a magnetite carrier of remanence.

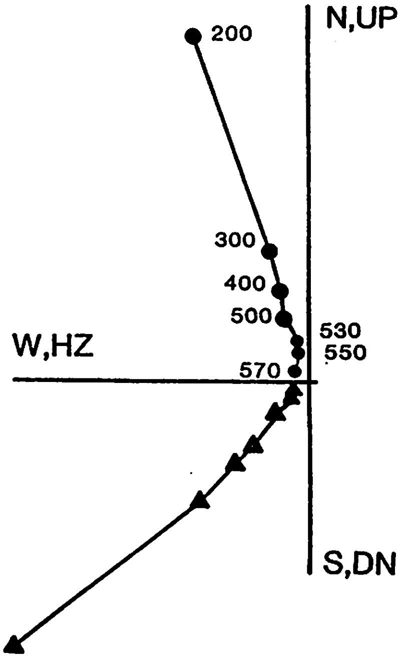

Fig. 2. Thermal demagnetization diagram of sample 26B. Plot begins at 200°C (40% original intensity) to show details of demagnetization at high temperature.

Where multi-component vectors were observed, AF cleaning to 200 Oersteds was usually sufficient to remove the secondary components (Fig. 3). Using Fisher statistics, mean paleomagnetic vector directions and circles of 95% confidence were calculated for each paleosol layer (Table 1). Statistical comparisons of mean directions were made using the technique of McFadden and Lowes (1981).

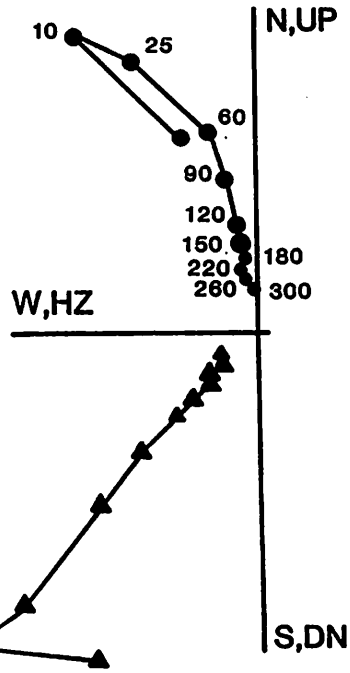

Fig. 3. Sample 26A displays three components of magnetisation. Two low coercivity components are removed by 10 and 60 OE: the characteristic direction is isolated by the 60 OE cleaning level. Note that the lowest coercivity component (0–10 OE shows an anomalous southeast, shallow inclination.

Field Sites

Watlings Quarry

The mean directions for the two Watlings Quarry paleosols (Fig. 4) show separate mean directions with overlapping circles of confidence (Fig. 5). Despite this overlap, the directions are statistically different at the 95% confidence level. The fact that different directions have been obtained for each paleosol suggests that mean directions may be a useful distinguishing criterion. However, it should be noted that the upper paleosol direction is based on only 3 samples and more samples are needed to verify the statistical distinction between the two paleosols.

Thumb Beach

The Thumb Beach data display moderately tight clustering of individual directions as indicated by the relatively high precision parameter (K = 52.4, Table 1). These samples were collected from a calcrete-lined paleo-solution pit that contains several different layers (Figs. 6 and 7). The stratification within this pit is believed to indicate separate soil accumulation events (Mylroie, 1988, p. 22-23). Temporally protracted deposition is supported by the up to 26° variation in directions. Unfortunately, poor drilling conditions precluded collection of enough samples for good statistical control.

Pigeon Creek Quarry

At Pigeon Creek Quarry (also known as Quarry E), there are two paleosols that occur above and below the fossil tidal delta deposits (Fig. 8). Toward the west end of the quarry, these two paleosols appear to merge.

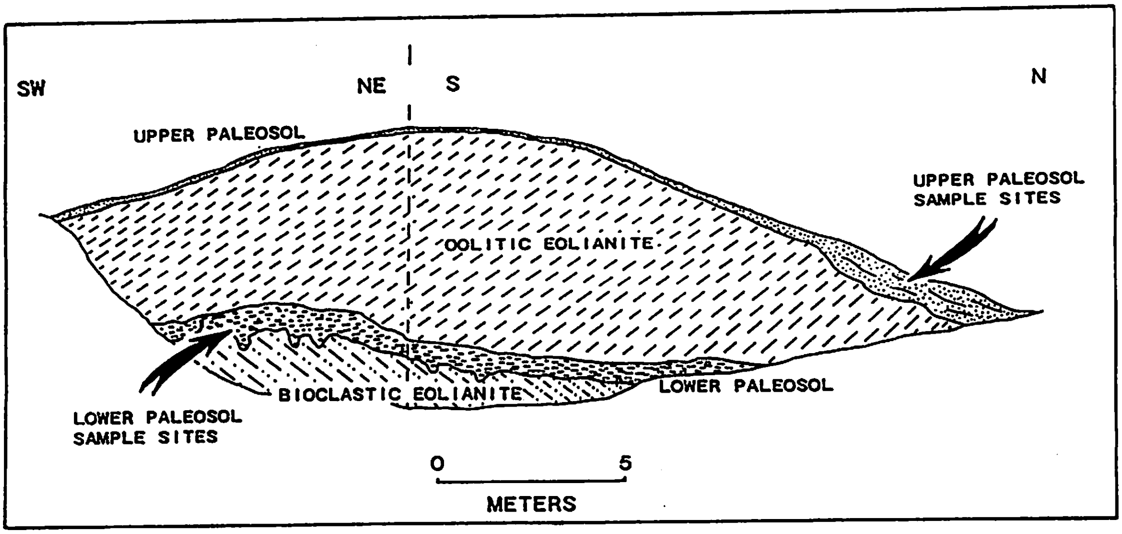

Fig. 4. Cross section of Watlings Quarry showing stratigraphy and sample locations.

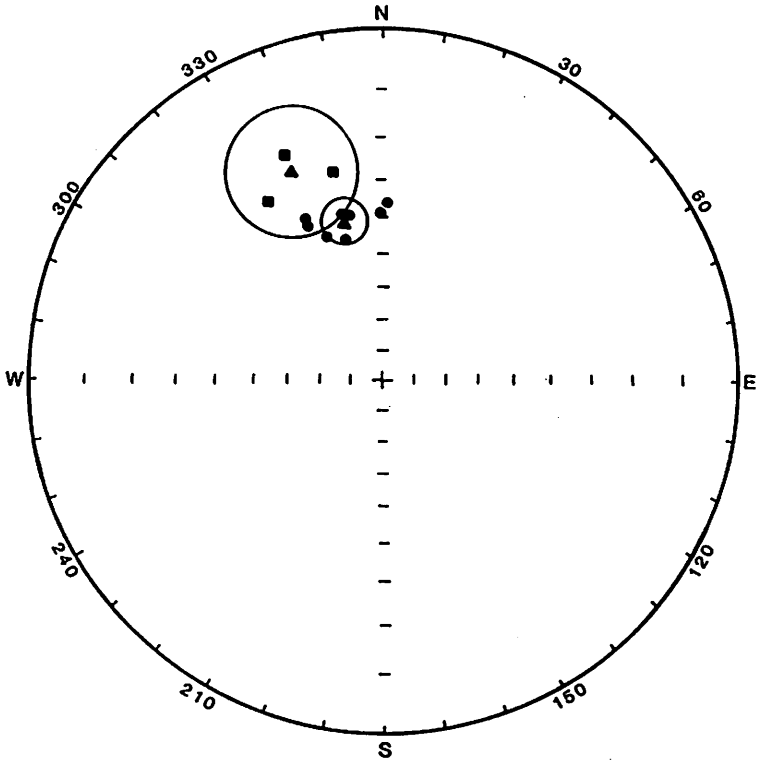

Fig. 5. Paleomagnetic directions for Watlings Quarry. Mean directions shown by triangles with circles of 95% confidence. Lower paleosol directions shown by dots; upper paleosol directions shown by squares. Upper and lower mean directions are statistically different at 95% confidence.

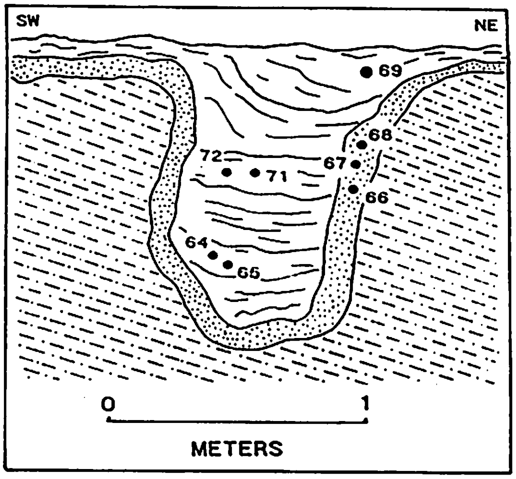

Fig. 6. Cross section of sampled paleo-solution pit at thumb beach. Dot pattern is calcrete lining of the pit; wiggly lines the pit infill. Eolianite shown as dashed lines. Individual core sample locations numbered.

Five samples have been analyzed from each horizon and they cluster very tightly (K = 450 and 1054, Table 1). Although the two mean directions differ by only 4°, they are statistically distinct. The directions from the samples taken on the western side of the quarry (numbers 53-55) are anomalous: southeast and shallow positive (Fig. 9; Table 1). This anomalous direction could be the result of a nondipole field related to a polarity transition, or a combination of two populations of magnetic carriers with opposite polarities.

Owl's Hole

The approximately 15 cm thick lower paleosol in Owl's Hole is a composite of several paleosol laminations (Figs. 10 and 11). Relatively tightly grouped (K = 50) normal directions were isolated from 9 specimens. However, 4 specimens yielded an anomalous SE shallow vector (declination = 125°, inclination = 20°; Fig. 12), similar to the anomalous directions obtained at Pigeon Creek Quarry. The anomalous directions were observed in samples 4, 12 and 13, which were collected from 2 separate paleosol layers, but within a relatively small area (Fig. 11). The fact that most of the samples from the same strata produced normal directions, and the fact that the

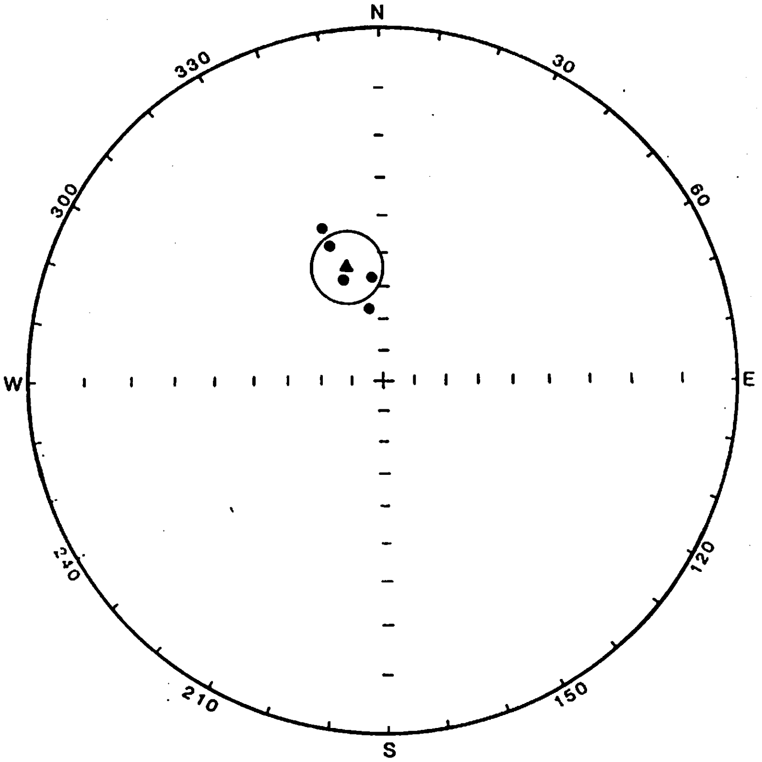

Fig. 7. Paleomagnetic directions for thumb beach.

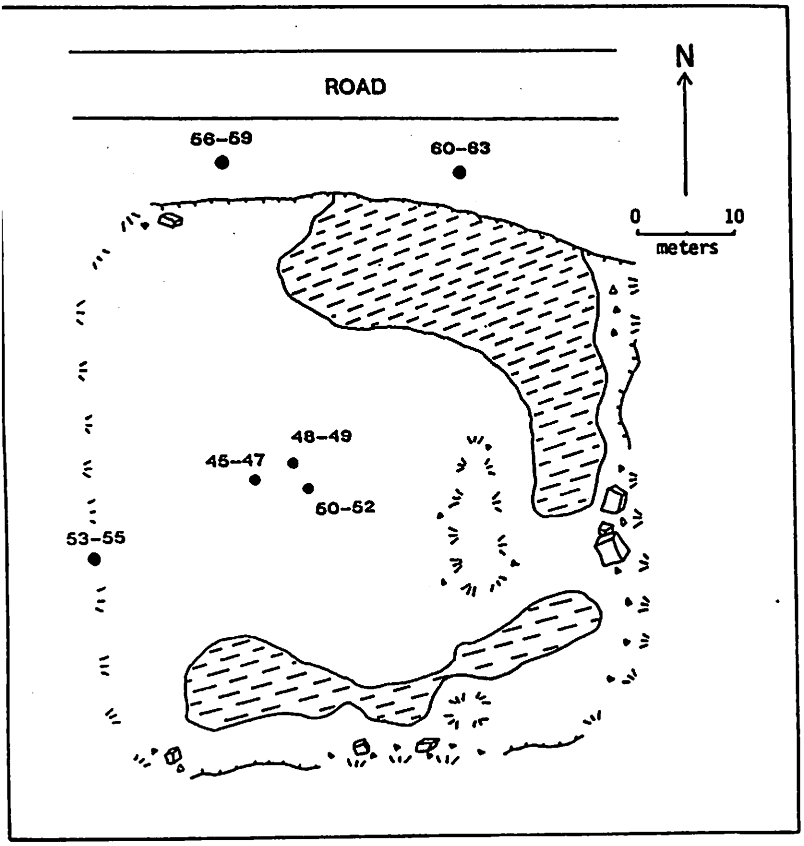

Fig. 8. Sketch map of Pigeon Creek Quarry. Site areas given by numbered dots. Diagonal dashes are shallow tidal ponds. Hachures denote a vertical quarry wall about 2 meters high. Slopes shown by short diverging lines. The paleosol sampled at 60–63 and 56–59 sweeps down the slope at 53–55 and joins the paleosol surface sampled at 45–52, which then goes underneath the tidal delta deposits below the paleosol sampled at 56–59 and 60–63. Here, as at Watlings Quarry, the paleosols have merged.

anomalous samples came from the same area, suggests the possibility of a localized diagenetic remagnetization or overprint. However, it should be noted that 2 samples (9 and 11) cleaned to normal directions from an initially SE shallow direction, and two samples (3 and 8) cleaned up from an originally reversed direction (Fig. 13). Regardless of the origin of the anomalous and reversed components, the magnitization process appears to be more pervasive rather than restricted.

DISCUSSION

The locality mean paleomagnetic directions for San Salvador paleosols are, for the most part, statistically distinct. These directions are also different from the present dipole field (Fig. 14). This suggests that the directions preserved in the paleosols record secular variation. The distribution of directions within the lower Watlings Quarry and the Thumb Beach suites is somewhat elongate (Figs. 5 and 7). This could be the result of small differences in the timing of magnetization, and could be a record of geomagnetic secular variation. It is also possible that these directions contain an unresolved secondary component which contaminates the signal.

Paleomagnetic field tests for stability, such as the fold test and reversal test, are not available and stability of the remanence can not be demonstrated at present. However, a conglomerate test and a paleosol block tilt test are planned. If these tests yield positive results, it can be concluded that the samples have been stable since before the time the paleosol clasts were eroded from outcrop, or since before the paleosol block slumped away from a sea cliff. As the length of time since erosion or slumping is likely to be rather short (a few thousand years), these tests would not be very robust. Nevertheless, these tests will yield at least a marginal indication of the duration of magnetic stability.

As the various paleosol localities record different directions, there is a possibility that a correlation tool can be developed. From the current data set, only the lower Watlings Quarry

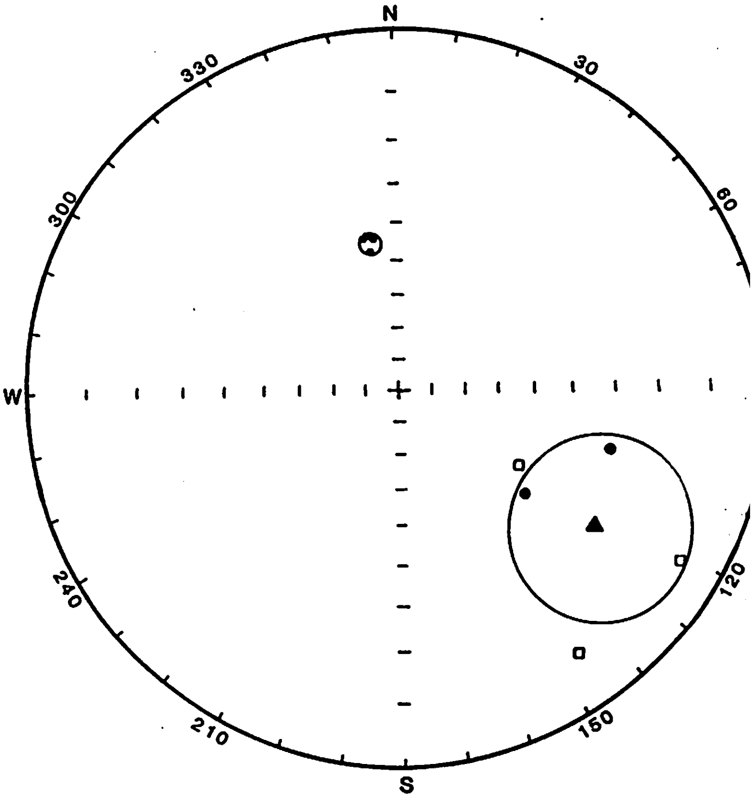

Fig. 9. Paleomagnetic directions for Pigeon Creek Quarry. Mean directions are shown by triangles with circles of 95% confidence. Southeasterly directions are anomalous and occur in an isolated pocket of paleosol of uncertain affinity (either upper or lower paleosol). Dots are cleaned characteristic directions. Open squares are NRM (Uncleaned) directions.

and Pigeon Creek Quarry paleosols may record the same direction. A statistically valid test of directional similarity is not possible because the McFadden and Lowes (1981) test requires that the precision parameters for the two localities be the same and this is not the case.

Perhaps the most promising finding pertaining to correlation is the occurrence of an anomalous SE shallow direction. This anomalous direction is problematic at present because it is not confined to a well established stratigraphic position. The SE directions at the Pigeon Creek Quarry locality occur at the location of the apparent merging of two paleosols. The SE directions at Owl's Hole are contained within a layer that generally yields normal paleomagnetic directions. Two possible explanations for these anomalous results are: a) these paleosol layers were formed over a long period of time that encompassed both transitional and normal geomagnetic fields, or b) the SE directions represent a partial overprint acquired during a transitional field. At present, these two hypotheses are not easily distinguished.

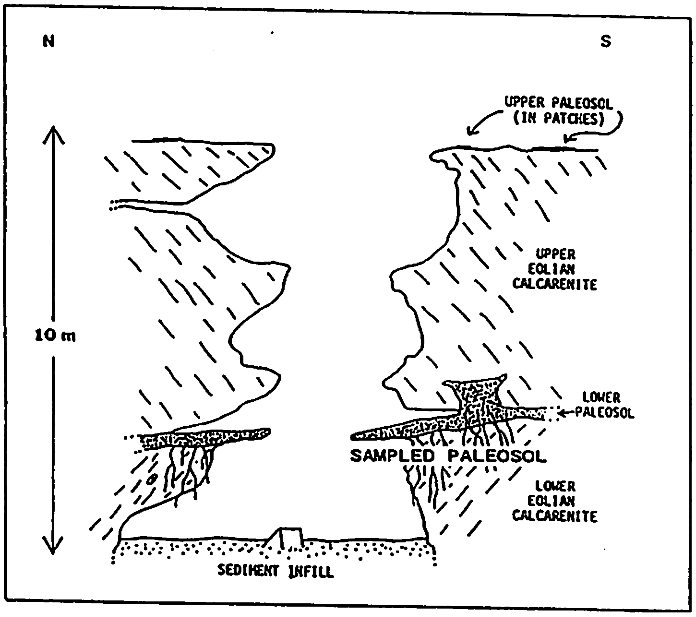

Fig. 10. Cross section of Owls Hole showing the paleosol horizon within the pit that was extensively sampled.

The fact that the Owl's Hole kappa value is relatively low (K = 25.5) suggests that the soil was formed over a long period of time during which substantial geomagnetic secular variation occurred, and this favors hypothesis "a". However, the Pigeon Creek Quarry locality has two paleosols with very high kappa values (K = 450-1,000) and a very small directional difference. As this implies a very short period of time during which the remanence was imparted, the SE directions would more likely represent a post-depositional event. It is also possible that the Pigeon Creek SE directions are part of a third paleosol that was superimposed on the paleotopography, and that the discontinuous nature of the paleosols in the quarry floor obscures the geologic details.

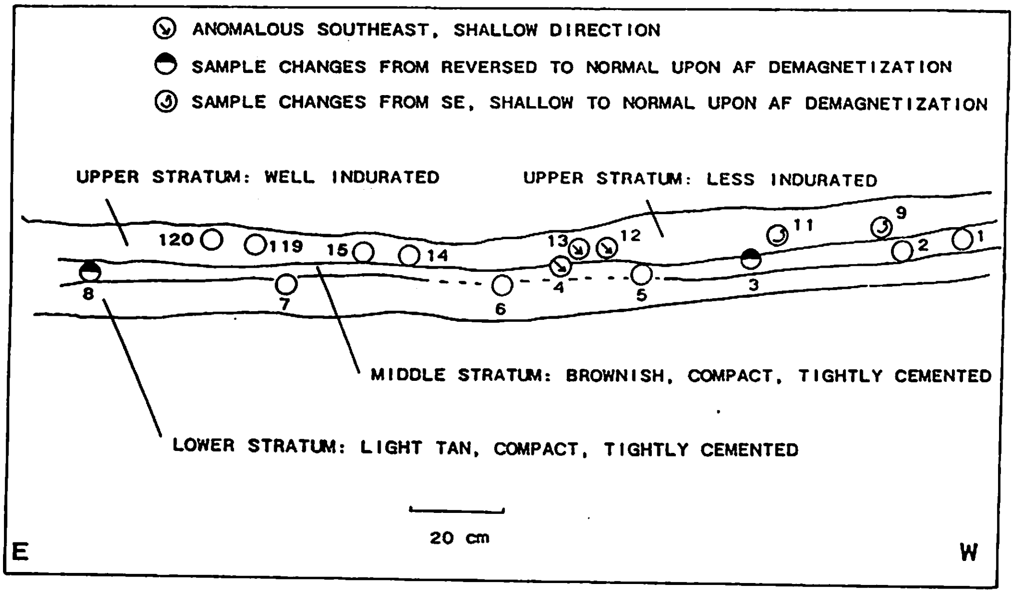

Fig. 11. Cross section sketch of the Owls Hole sample localities in the lower paleosol. Circles indicate the approximate location of the core samples. Circles with symbols or shading denote anomalous directions or anomalous secondary components as indicated in the legend.

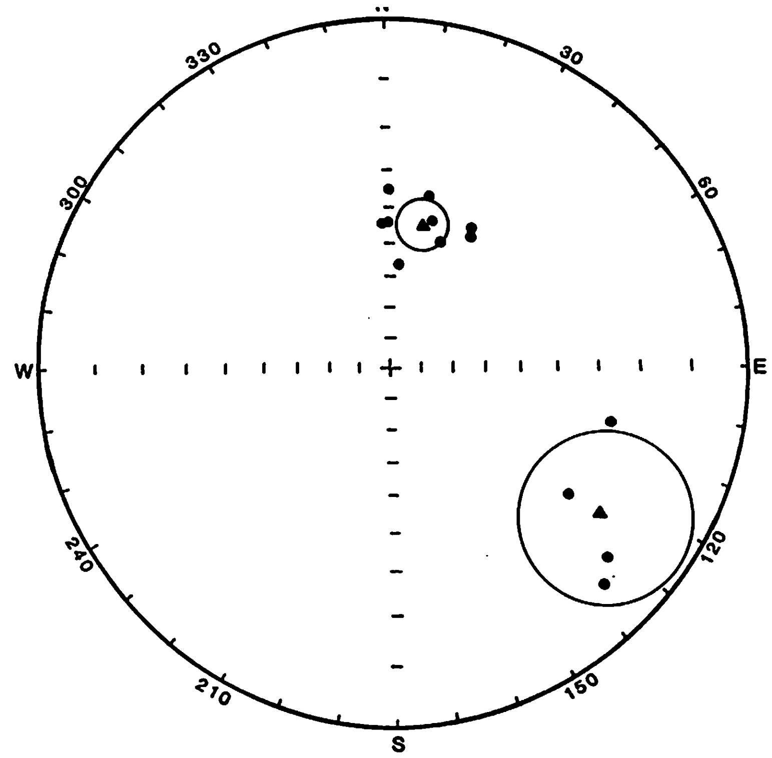

Fig. 12. Paleomagnetic directions for the Owl's Hole paleosol. The southeasterly direction is anomalous.

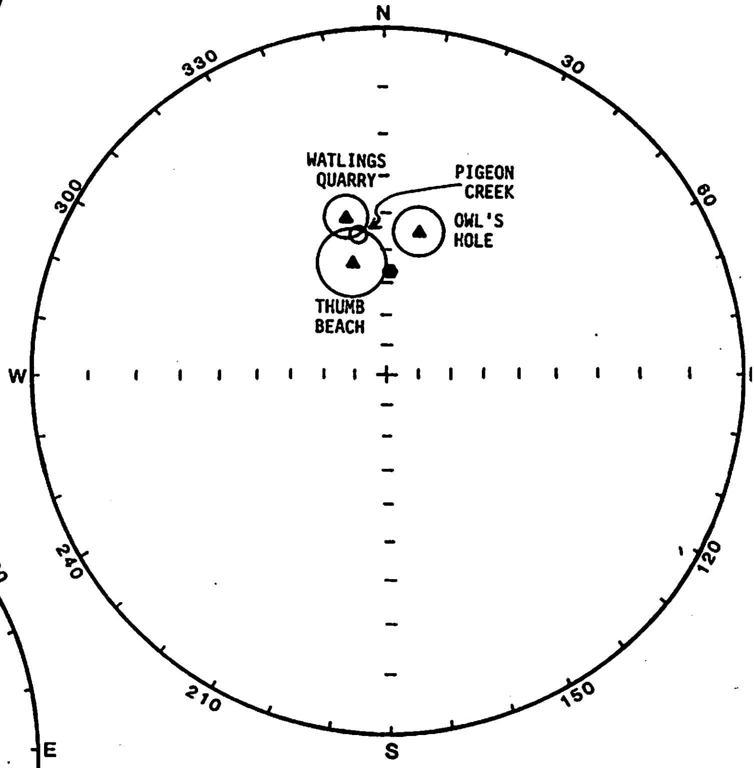

Fig. 14. Mean paleomagnetic directions and 95% confidence circles for the four paleosol localities. All directions are statistically different at 95% confidence, with the possible exception of Watlings Quarry and Pigeon Creek Quarry. Hexagon represents the present dipole field.

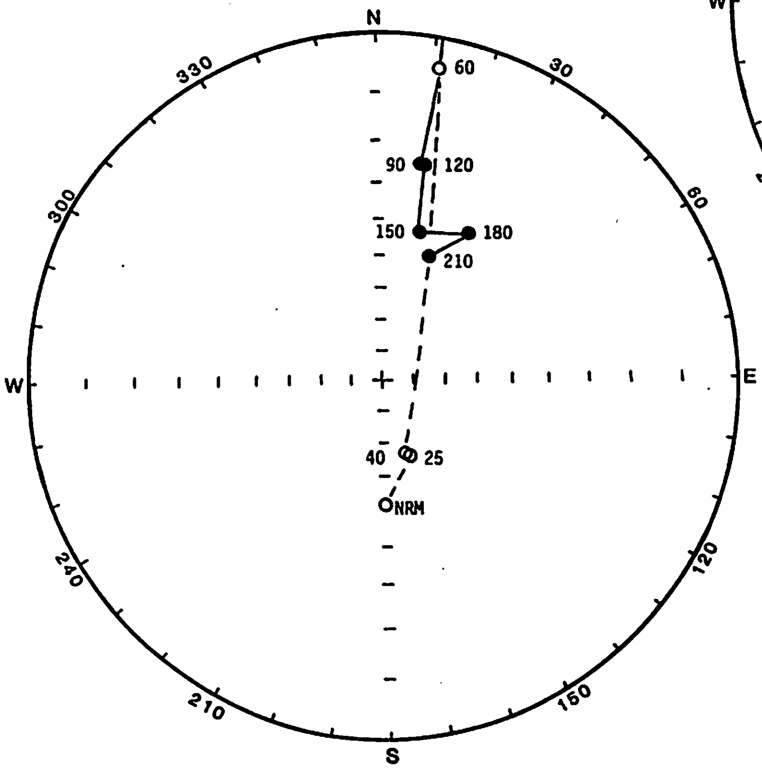

Fig. 13. Demagnetization path for sample 3A, Owls Hole. Note that the sample's NRM direction is reversed and cleans to normal direction during AF demagnetization. Dots are normal directions (lower hemisphere). Open circles are reversed directions (upper hemisphere).

The paleomagnetic data acquired to date do not yield any unique interpretation with stratigraphic utility. Considerable work needs to be done, especially with respect to stability, magnetic carriers, and the origin of the magnetization. Although no geological constraints can be derived from the paleomagnetic data at present, the magnetic properties of the paleosols suggest that useful correlation criteria may ultimately emerge.

CONCLUSIONS

Paleosol samples from San Salvador Island generally contain well defined paleomagnetic directions. Internal consistency within sites and statistically different mean directions between sites suggests that secular variation correlation among paleosols may be possible. An anomalous southeast, shallow paleomagnetic direction, observed at two localities, holds considerable promise as a time stratigraphic indicator.

ACKNOWLEDGMENTS

The authors thank Dr. Donald T. Gerace, Executive Director of the Bahamian Field Station, for support of this research. Discussions with Mark Boardman, Don McNeil and Len Vacher were helpful in this project. Field and laboratory assistance from Cynthia Burris, Janet Coker, Jonathan Harris, and Leslie Sontag is appreciated.

REFERENCES CITED

Birkeland, P. W., 1984, Soils and Geomorphology, London, Oxford University Press, 372 p.

Bretz, J. H., 1960, Bermuda: a partially drowned, late mature Pleistocene karst: Geological Society of America Bulletin, v. 71, p. 1729-1754.

Carew, J. L., and Mylroie, J. E., 1985, Pleistocene and Holocene stratigraphy of San Salvador Island, Bahamas, with reference to marine and terrestrial lithofacies at French Bay, in Curran, H. A., ed., Guidebook for Geological Society of America, Orlando Annual Meeting Field Trip #2, Fort Lauderdale, FL, CCFL Bahamian Field Station, p. 11-61.

Carew, J. L., and Mylroie, J. E., 1987, A refined geochronology for San Salvador Island, Bahamas, in Curran, H. A., ed., Proceedings of the Third Symposium on the Geology of the Bahamas, Fort Lauderdale, FL, CCFL Bahamian Field Station, p. 35-44.

Carew, J. L., and Mylroie, J. E., in press, Some pitfalls in paleosol interpretation in carbonate sequences: Carbonates and Evaporites.

Garrett, P., and Gould, S. J., 1984, Geology of New Providence Island, Bahamas: Geological Society of America Bulletin, v. 95, p. 209-220.

Harmon, R. S., Mitterer, R. M., Kriausakul, N., Land, L. S., Schwarcz, H. P., Garrett, P., Larson, G. J., Vacher, H. L., and Rowe, M., 1983, U-series and amino-acid racemization geochronology of Bermuda: Implications for eustatic sea- level fluctuation over the past 250,000 years: Paleogeography, Paleoclimatology, Paleoecology, v. 44, p. 41-70.

Land, L. S., Mackenzie, F. T., and Gould, S. J., 1967, The Pleistocene history of Bermuda: Geological Society of America Bulletin, v. 78, p. 993-1006.

McFadden, P. L., and Lowes, F. J., 1981, The description of mean directions drawn from Fisher distributions: Royal Astronomical Society Geophysics Journal, v. 67, p. 19-33.

Mylroie, J. E., editor, 1988, Field guide to the karst of San Salvador Island, Bahamas: Port Charlotte, FL, Bahamian Field Station, 108 p.

Mylroie, J. E., Carew, J. L., and Barton, C. E., 1985, Paleosols and karst development, San Salvador Island, Bahamas: Program of the 1985 National Speleological Society Annual Convention, Frankfort, Ky, June 19-23, 1985, p. 43.

Ruhe, R. V., 1965, Quaternary Paleopedology, in Wright, H. E. and Frey, D. G., eds., The Quaternary of the United States, INQUA Reviews Volume, Princeton University Press, p. 755-764.

Ruhe, R. V., Cady, J. G., and Gomez, R. Z., 1961, Paleosols of Bermuda: Geological Society of America Bulletin v.72, p. 1121-1142.

Sayles, R. W., 1931, Bermuda during the Ice Age: American Academy of Arts and Sciences, v. 66, p. 381-468.

Stowers, R. E., Mylroie, J. E., and Carew, J. L., 1989, Pleistocene stratigraphy and geochronology southwestern San Salvador Island, Bahamas, in Mylroie, J. E., ed., Proceedings of the Fourth Symposium on the Geology of the Bahamas: Port Charlotte, FL, Bahamian Field Station, p. 323-330.

Vacher, H. L., and Harmon, R. S., 1987, Unpublished 1987 Penrose Conference fieldguide to the geology of Bermuda, 48 p.

Vacher, H. L., and Hearty, P., 1989, History of Stage 5 sea level in Bermuda: review with new evidence of a brief rise to present sea level during substage 5A: Quaternary Science Reviews, v. 8, p. 159-168.