PART I: COASTAL TERRACES IN FLORIDA

PART II: SINKHOLE POTENTIAL IN INDIAN RIVER, ST. LUCIE, & MARTIN COUNTIES, FLORIDA

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INFORMAL REPORT

by

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THE FLORIDA MARINE TERRACES

Changes in sea levels during Late Tertiary and Quaternary glaciation were critical to the development of the topography and other geomorphic features of Florida and the Coastal Plains of the southeastern U. S. A number of cycles of high and low sea level stages occurred which have been variously determined, described, and interpreted by different geologists. These sea level changes were either eustatic, without any appreciable changes in elevation of the land surfaces, or isostatic, accompanied by changes in elevation or depression of the land. It is generally agreed, however, that these sea level changes were so rapid with respect to any land level changes that the cycles of high and low sea levels were in general eustatic and that land levels have changed very little during the Pliocene and Pleistocene epochs.

Each cycle of sea level changes involved both depositional and erosional stages: the gently sloping former sea bottoms, now remaining as terraces, are mainly the results of deposition, and the escarpments or abrupt slopes between these terraces are mainly erosional features. Thus, the nearly flat terraces are generally bounded by two escarpments, one rising above the terrace level and the other descending from it. The base of the escarpment rising from a particular terrace area marks the approximate boundary of the old shore line of the sea which formed the particular terrace below it.

The levels of the ancient shore lines of several terraces in Florida have been discerned, traced and named. Cooke (1945) described at least eight for the entire state, Vernon (1942) found five in western Florida,

and Parker and Cooke (1944) recognized three significant ones in southern Florida. MacNeil (1949) reported the presence of four major terraces in the state, Alt and Brooks (1965) described five, and at various times Brooks (1968, 1973, 1974) discussed the possible presence of up to nine (see Chart).

Compilation of the named terraces listed by various authors yields a total of ten terraces. It can be readily seen from the attached tables (see table on the terrace map and Table·1) that not all authors recognize the existence of all terraces. Further, a single terrace may represent more than one episode of inundation (witness the Wicomico as interpreted by Brooks 1973, 1974); or a single name may include more than one terrace (e.g., the Pamlico terrace which includes the Princess Ann and the Sunderland which includes the Okefenokee). Other terraces have been named and renamed (e.g., the Hazelhurst, formerly named the Brandywine, is also a partial equivalent of the High terrace of McNeil), while still others have been discussed by elevation only rather than by name (Alt and Brooks 1965). Because of the difficulty of tracing terraces names in various sections of the Atlantic and Gulf Coastal plains, tectonism, which could elevate a younger terrace or depress an older terrace to a previously described level in a stable area, although unlikely, cannot be entirely discounted, and because of the difficulties arising from conflicting nomenclature, we suggest that the Florida terraces be referred to both by their shoreline elevations, as well as by their name.

The ten terraces named by various authors are, in decreasing order of shoreline elevation,. as follows:

Hazelhurst	270 feet	(formerly Brandywine, also part of High Terrace of MacNeil 1949)
Coharie	220 feet	(part of MacNeil's High Terrace)
Sunderland	170 feet	
Okefenokee	150 feet	
Wicomico	100 feet	
Penholoway	70 feet	
Talbot	42 feet	
Pamlico	25 feet	
Princess Ann	18 feet	
Silver Bluff	8 feet	

Although there is some controversy as to the origin of the higher terraces, particularly the 270 feet Hazelhurst, there is general agreement that all of the lower terraces are marine in origin and that they were caused by eustatic fluctuations of sea level, as described earlier.

Most workers also agree that these sea level fluctuations were caused by the advance and retreat of the great ice sheets which covered greater or lesser portions of the earth in the recent geological past. The onset of these glaciations is, therefore, pertinent to the age of the terraces. If one assumes that glacial fluctuations are restricted to the Pleistocene, one must correlate these fluctuations with the four glacial advances and four interglacial retreats of the ice sheets. The consequences of such an assumption can be readily seen in the chronological framework espoused by Cooke (1963).

The weight of the evidence accumulated in the past twenty years indicates, however, that these fluctuations began much earlier than Pleistocene time.

The onset of glaciation in Antarctica, for instance, began several million years before the glaciers started covering the northern hemisphere. Glaciation also began earlier in Greenland than in North America. Considering the amount of water involved in both of these continental ice masses, it is apparent that these glaciations have had a significant effect on the elevation of sea level. Paleoecological studies and studies of marine and land vertebrate fossils in various deposits, coupled with a more extensive use of radiometric dates, have helped to clarify the geochronology of these terraces and indicate that the sea level fluctuations clearly began before Pleistocene time.

Physiographically, the terraces represent a step-like progression of planar levels formed by sequential inundations of the Florida peninsula by a series of marine transgressions, punctuated by regressions of the sea. These terraces are increasingly lower and younger seaward. If a terrace were inundated subsequent to its formation, that terrace would have been destroyed by the erosional processes assocated with the encroaching sea. Such a sequence also implies that increasingly greater amounts of sea water have been tied up as ice in continental glaciers. This correlates well with the generally accepted view of increasingly deteriorating climates during Cenozoic, and particulary Neogene times.

The following discussion of the terraces primarly centers on their age, as this is the area of greatest disagreement by geologists.

<u>The 270' Hazelhurst terrace</u>

This highly dissected terrace, whose upper elevation seems to lie near 270 feet, lacks the distinct seaward facing scarp characteristic of the lower terraces. This has been interpreted as indicating that it is

non-marine in origin, although Cooke (1941) properly pointed out that the presence of a scarp is not a necessary criterion for a marine origin and that this may merely be an indication of the older age of the terrace and the result of extensive dissection.

MacNeil (1949) lumped all elevations above 150 feet into a single "High Terrace" and believed it to be non-marine in origin. He pointed out that one of the main features used by Cooke to determine the extent of his shoreline coincides with the boundary between the Piedmont and Coastal terranes. However, if all the glaciers presently extant in the world were to melt, sea level would rise between 200 feet and 300 feet (Alt and Brooks, 1965). Thus, the 270' Hazelhurst could well represent a former stand of sea level. Given the scant evidence available for a former shore at 270 feet, there remains considerable doubt as to whether this terrace is marine or fluvial in origin.

As late as 1963, Cooke considered this terrace to be Aftonian in age, although Vernon (1951) had tentatively recognized it as Early Nebraskan or even pre-Nebraskan. Given that there is substantial evidence that the next lower, and hence younger, 220' Coharie terrace is Late Miocene in age, the 270' Hazelhurst (if it is real) could be no younger than Late Miocene.

The 220' Coharie terrace

In his discussion of terraces MacNeil (1949) also included this terrace in his "High Terrace". Like the 270' Hazelhurst, it has no seaward facing scarp. Although he acknowledges that this terrace may have been inundated by the sea, he finds no evidence for this, and considers the terrace to subaerial in origin.

In contrast, Alt and Brooks (1965) found strong evidence for a shoreline between 215 feet and 250 feet. (Although they assign it no name, this elevation best corresponds to the 220' Coharie). Landward of this shoreline, there are distinct soils found nowhere else in the state of Florida. There is also an abrupt change in the degree of dissection of the land at this line. Cooke (1945, 1963) always considered the 220' Coharie to be Yarmouthian in age. Vernon (1951) assigned it an Aftonian age. Alt and Brooks (1965) found that the marine fossiliferous strata associated with the Coharie end at elevations of between 215 feet and 250 feet. These deposits are LateMiocene, and, hence, they assign a Late Miocene to the Coharie transgression. Such a stand does correlate well with the presumed elevation of sea level prior to the onset of the Antarctic continental glaciation. This age assignment also provides sufficient time for erosion to essentially destroy any scarp which would have been formed at that time.

The 150' Sunderland terrace

This terrace, originally named the Okefenokee by Cooke (1925), included elevations ranging from 100 feet to 160 feet. Cooke (1945) later renamed it the Sunderland and included in it elevations up to 170 feet. Because MacNeil (1949) had some reservations about correlating this terrace with the Sunderland terrace in Maryland, he revived the term Okefenokee. Various authors have used either term, although in Florida the term Okefenokee is generally preferred. The exact elevation of this shoreline is in doubt. Cooke listed its original elevation at 160 feet and later extended it upward to 170 feet. Vernon (1951) considered this 170 feet stand as minor at best and, like MacNeil (1949), thought that there had been a more definite stand at 150 feet. Cooke (1963), obviously believing that there were two stands of the sea associated with this terrace, ultimately recognized both names.

He assigned to the Sunderland a shoreline elevation of 170 feet, and to the Okefenokee an elevation of 150 feet, even though he had earlier recognized the lower level of the Sunderland at 140 feet. Brooks (1968) assigned the Sunderland (Okefenokee) elevations of between 120 feet and 140 feet, but subsequently (1973) changed it to between 140 feet and 160 feet. In his studies of the Trail Ridge, Pirkle (1970) found a lithologic break in the suite of terrace sediments at 150 feet. Thus, for the Sunderland one is left with a confusing array of elevations, ranging from a low of 120 feet to a high of 170 feet.

There is strong evidence that there were fluctuations of sea level during Sunderland time. Cooke's and Brooks' observations that there was more than one stand of sea level is supported by detailed analysis of the sediments of the Bone Valley Formation (Freas and Riggs, 1968). This formation was deposited by the Sunderland sea and has a marine Lower Member and an estuarine Upper Member. It also contains Late Pliocene vertebrate faunas. Late Pliocene vertebrates faunas have also been recovered from elevations near present sea level (Webb and Tessman, 1967), indicating two lowerings of the sea during Sunderland time.

The Yarmouthian age indicated by Cooke and many others, is inconsistent with the fossil data derived from the formations deposited by the Sunderland sea. The evidence warrants assigning a Late Pliocene age to this transgression, while recognizing that this terrace has been formed by at least two stands of sea level. If this interpretation is the correct one, as I believe it to be, it is easier to understand that the difficulty in recognizing a single level for the Sunderland shoreline reflects the complexity of a natural phenomenon rather than the absence of real evidence.

The 90' - 100' Wicomico terrace

MacNeil (1949) considered this terrace to represent a true peak of marine transgression, but also felt that it was one of the least sharply defined of the recognized shorelines. He further considered it to have occurred in two stages. In their investigation of the Florida terraces, Alt and Brooks (1965) found a clear separation in the soils above and below this shoreline. They also remark that the landward side exhibits highly developed karstic erosion, in contrast to the much less eroded seaward side. Because of this topographic difference and because of the voluminous sand deposits associated with this stand of the sea, they concluded that this terrace represented a prolonged episode of inundation. While investigating the lithology of terrace deposits, Pirkle (1970) also found a clear break in sedimentation at 100 feet of elevation.

Age estimates of this terrace vary widely. Early workers considered this terrace Sangamonian. By the sixties, age estimates had been revised upwards, and Cooke (1963) assigned it a Yarmouthian age, although DuBar (1968) still held to a Sangamonian age. Alt and Brooks (1965) considered this terrace to have been formed by a stand of the Pliocene sea, as the terrace is underlain by a series of Pliocene formations (including the Caloosahatchee Formation). After detailed work on the Caloosahatchee, Brooks (1973) concluded that a portion of this formation (the Bee Branch Member) indicated a water depth of between 90 feet and 100 feet and that it was correlated to the Wicomico stand of sea. He assigned it to the Aftonian on the basis of fossils. Although there is no detailed discussion of the problem, his chronological chart of sea level stands shows two Wicomico transgressions: an earlier one which he places in the pre-glacial Pleistocene and a later one in the Aftonian. A year later (1974), in his detailed discussion of the

geology of Southern Florida, he indicates that Units 1 and 2 of the Caloosahatchee are separated by a distinct unconformity, yet both units indicate a water depth of between 90 feet and 100 feet. Because of the age of the Caloosahatchee fossils, he considered this unconformity to have been caused by the lowering of sea level associated with the Nebraska glaciation, and hence that the 90' to 100' stand was both pre- and post-glacial. MacNeil (1949) also noted two sets of geomorphic features associated with the Wicomico stand of sea. If, as detailed work seems to indicate, there were two 90' to 100' stands associated with the Wicomico sea, it would explain why the shoreline is poorly defined. The second transgression would tend to rework and mask many of the features created during the first stand of the sea.

The 70' Penholoway and 40' Talbot terraces

Considered minor terraces by most authors, these terraces are best developed in Central Florida. Many authors considered these terraces to have been formed by the withdrawal of the Wicomico sea. Since the 1960's, their age generally has been recognized as Yarmouthian and are considered as having been formed by minor fluctuations of the sea during this interglacial.

The 25' Pamlico and 18' Princess Ann terraces

The Pamlico terrace is one of the best developed terraces in Florida and is readily discernible in South Central Florida. Its acceptance has been virtually unanimous. As one of the lower, and hence younger, terraces, it has suffered little dissection. There is, however, no concensus regarding its age. Because early workers had assumed that all terraces corresponded to glacial Pleistocene events, they apparently ran out of interglacials and found themselves forced to relegate the Pamlico to a warmer interval of the last ice age, the Wisconsin. Field work in the early sixties led most

workers to reassign this terrace a Sangamonian age. Radiometric dates of associated deposits indicate that this stand is approximately 230,000 years old. Whether this date represents a Late Yarmouthian or an early Sanganomian age depends on one's interpretation of glacial geochronology. The Princess Ann terrace, described by Wentworth in 1930, and included in the Pamlico by Cooke (1931), has largely been ignored by most workers. However, detailed stratigraphy of South Florida strata (Brooks, 1974) seems to indicate that the Coffee Mill Hammock Formation was deposited at a time when sea level stood between 18 feet and 20 feet higher than present. This stand of the sea appears distinct from the Pamlico stand as this stratum bears a radiometric date of 120,000 BP. This date would indicate that a transgression occurred during the Sangamonian, some 100,000 years after the Pamlico maximum. Thus, stratigraphic and radiometric evidence would seem to vindicate Wentworth's recognition of the Princess Ann terrace at 18 feet, although the proximity in elevation between the above two terraces would certainly explain why this terrace is not often recognized.

The 8' Silver Bluff terrace

This youngest of all the terraces is recognized around the Florida peninsula by most workers, and corresponds to an 8' stand of sea level. Cooke (1945) considered it to be mid-Wisconsin in age. MacNeil (1949) associated it with a post-Wisconsin climatic optimum between 6000 BP and 4000 BP. Such an interpretation is also favored by Fairbridge (1974), but is contested by Brooks (1974), who points out that lagoonal deposits associated with the Silver Bluff are too old to date by C14 radiometric methods and hence must be at least Sangamonian in age.

Marine Terraces In Southern Florida

The four main terraces recognized in southern Florida are: (in order from the most recent to the oldest, and with range of elevation above present sea level).

1. the Silver Bluff from sea level to about 10 feet;
2. the Pamlico from about 10 feet to 25 feet;
3. the Talbot from 25 feet to about 42 feet; and,
4. the Penholoway from 42 feet to 70 feet.

A less well defined terrace, the Wicomico, occurs from between 70 feet to 100 feet, and extends into southern Florida as part of the Highlands Ridge.*

The zones of junctions between each of these terraces are not often easily recognized scarps. Where well defined, they usually consist of hills and ridges of sand, which in most instances may have been old beaches or dunes. Other features of these ancient shorelines between terraces are elongated depressions which are sloughs and ponds, cypress and bay swamps, and marshes.

The seas that formed both the Talbot and Penholoway terraces occurred during the Yarmouthian interglacial stage and the terraces and scarps left by them have become variously altered. Both of these seas deposited marine sands directly over parts of the Caloosahatchee and the Tamiami formations,

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*The Princess Ann shoreline near 18 feet is largely ignored by most workers although it seems to be real and correlates with the deposition of the Coffee Mill Hammock Formation 120,000 years ago during the Sangamonian.

but do not seem to have deposited material over younger strata than these. The Miami Oolite, the Anastasia and the upper part of the Fort Thompson Formation were developing at this time and only thin sands of the Talbot sea overlie these contemporary strata. The Talbot and Penholoway terrace sands are usually thicker and less calcareous than the younger Pamlico terrace sands. The old shorelines between the Talbot and Pamlico terraces are difficult to trace except between the Istokpoga Basin and Highlands Ridge. It seems certain, however, that the Caloosahatchee River valley was flooded by the Pamlico sea and that an island of land existed south of it in Hendry, Lee, and Collier counties during that time.

The Pamlico was laid down perhaps as early as the Late Yarmouthian, but certainly by the Sangamonian interglacial stage and before the last glacial stage, the Wisconsin. The Pamlico sea covered all of southern Florida up to the 25' level. By this time, most or all of the Fort Thompson Formation that floors most of the Lake Okeechobee and the northern part of the Everglades; the Miami oolitic limestone which floors most of the southern Everglades and forms the Miami Rock Ridge; and, the Anastasia coquina, which forms most of the northern part of the Atlantic Coast Strip, had all been formed. This means that the Pamlico sea did much to alter these strata and soils and form the present land features of southern Florida. It particularly initiated the conditions which formed the Everglades-Lake Okeechobee Basin. It reshaped the early strata and the older sand terraces as well as depositing materials of its own.

After the Sangamonian interglacial the sea receded and a low sea level stage occurred during the Wisconsin glacial period, which may have been as much as 450 feet lower than present sea level. This low sea level

caused the erosion and solution of the bare rock and some shifting of the marine sands. The exposed Miami oolite, Anastasia coquina, Fort Thompson Formation, and Tamiami limestones and sandstones were variously corroded and eroded, forming many of the uneven surface features which now exist.

One of the most distinctive of these erosional features that were formed following the periods of high sea levels was the cutting of channels out of the Everglades-Lake Okeechobee Basin to the sea. Most of these channels were cut through the Miami oolite ridge that flanks the eastern and southern parts of this basin. Some channels were cut deeply, down through the Miami oolite and into the Tamiami Formation underlying it, while others were shallow. Most of these channels have been partly filled with sands and marls, but many still remained sufficiently low to act as drainage channels from the Everglades, and some are now rivers, canals, and transverse glades.

During Recent time, the sea level has fluctuated, but in general is rising more than falling. It is probably rising slowly at the present time (Davis, 1940; Cooke, 1935; Brooks, 1973; Hicks, unpublished data).

Another important event, apparently spanning Late Wisconsin to Recent time, was the formation of a freshwater marly mud layer over a great part of the floor of the Everglades and some adjacent regions. This marl is the Lake Flirt marl and rests on top of the Pamlico sands, but in the central and northern parts of the Everglades it is a thin deposit directly on top of those limestones that are not covered by Pamlico or Recent sands.*

* White (1970) offers evidence that where it underlies the Everglades peat, the Lake Flirt marl is largely an insoluble residue of the underlying limestones.

The Lake Flirt marl is important because it is relatively impermeable and retards the seepage of water into the rock strata over which it lies. It thus prevents most of the underground drainage of water from the peat and marl soils into the rock strata which floor a great part of the Everglades. It is doubtful that the Everglades marshes would have developed without a marl layer over the rock floor, as surface and soil water would have drained off rapidly through some of the underlying porous rock strata. Some of the drainage canals have been cut through this marl and into the more permeable layer of rock, increasing underground drainage locally and markedly affecting the surface and groundwater levels.

The distribution of sand and other materials of the marine terraces were altered by the general leveling of the surface which seems to have been more prevalent than increases in degree of relief. Along with these processes, sands, marls, and organic soils were deposited and accumulated over large areas, some of which were formerly bare of soils. Many of the present shoreline beaches, dunes, ridges, swales, lagoons, bays, islands, and other characteristic features were formed, and the present soil and topographic conditions were established. Most notably, the organic and marl soils were formed and the present drainage conditons which make possible the Everglades marshes and swamps were established by alterations in topography.

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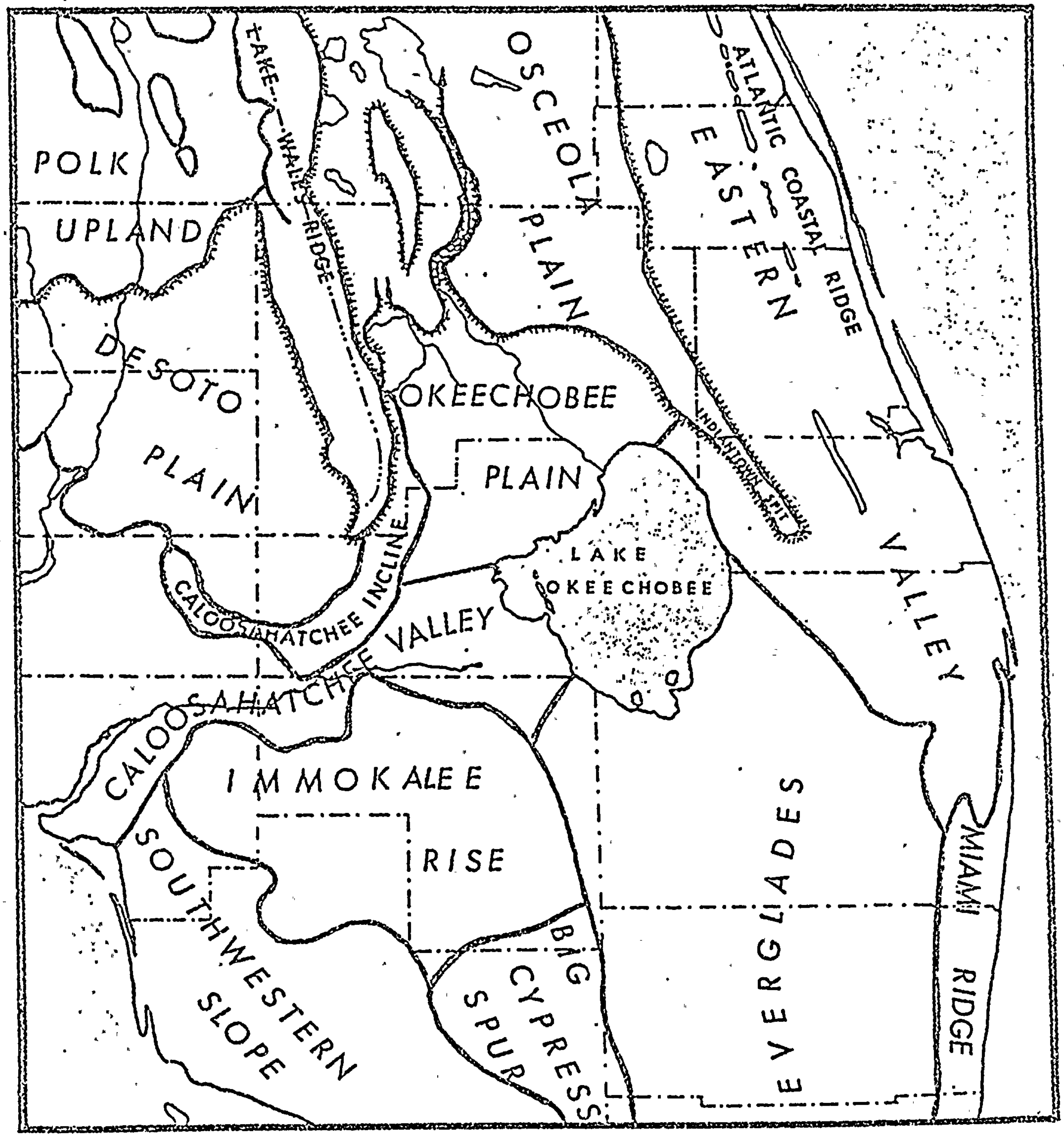
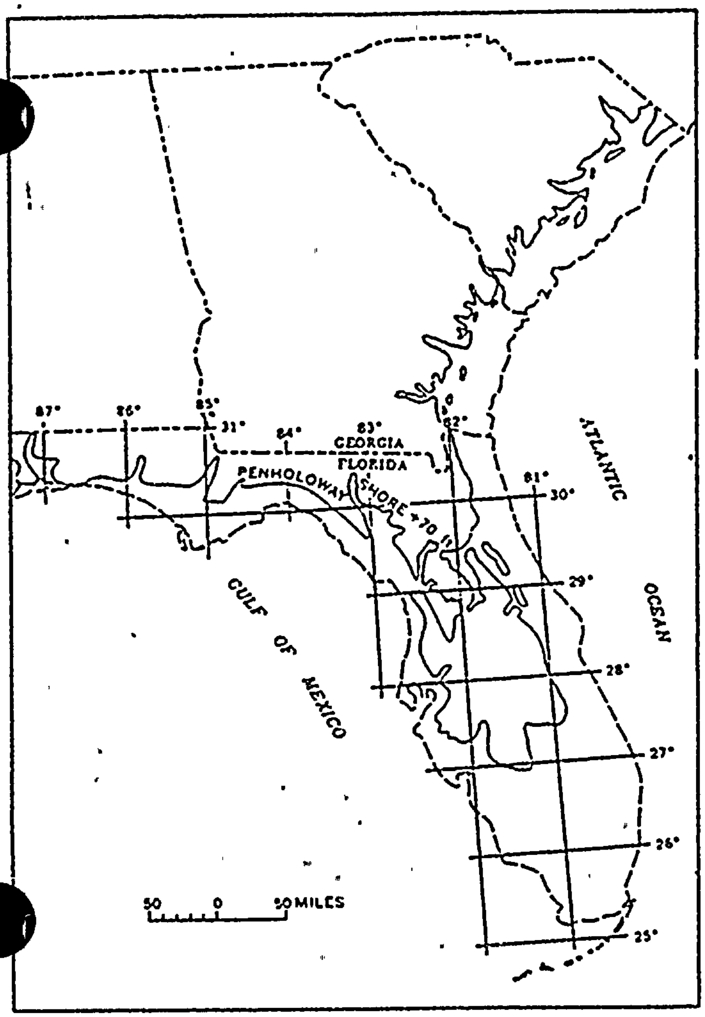
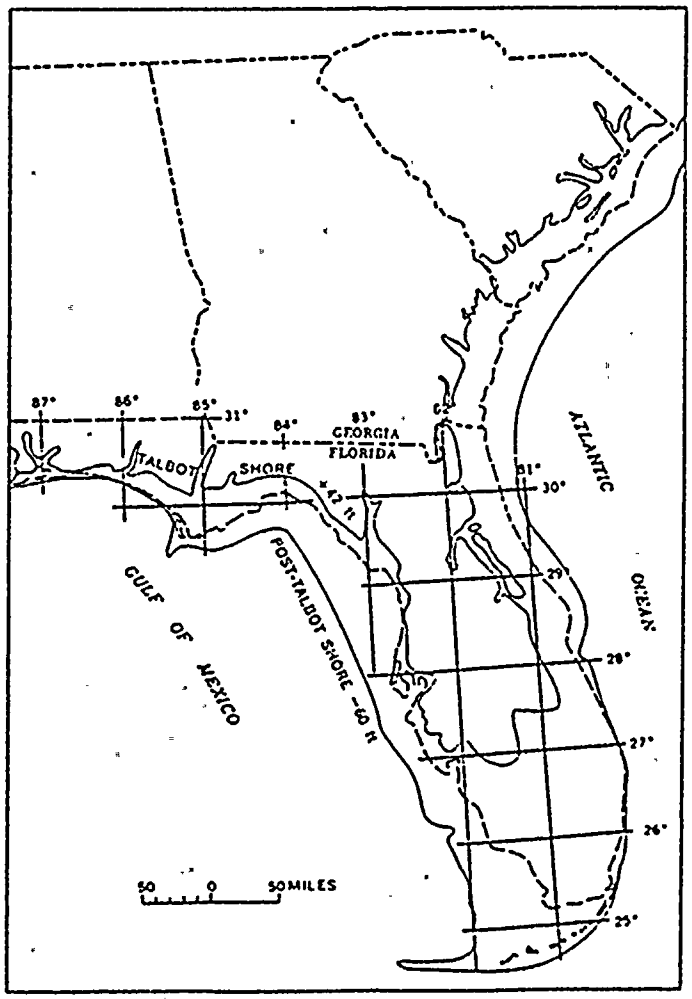


Physiographic divisions of the landscape in portions of central and southern Florida modified from White (1970) by J. F. Mims.

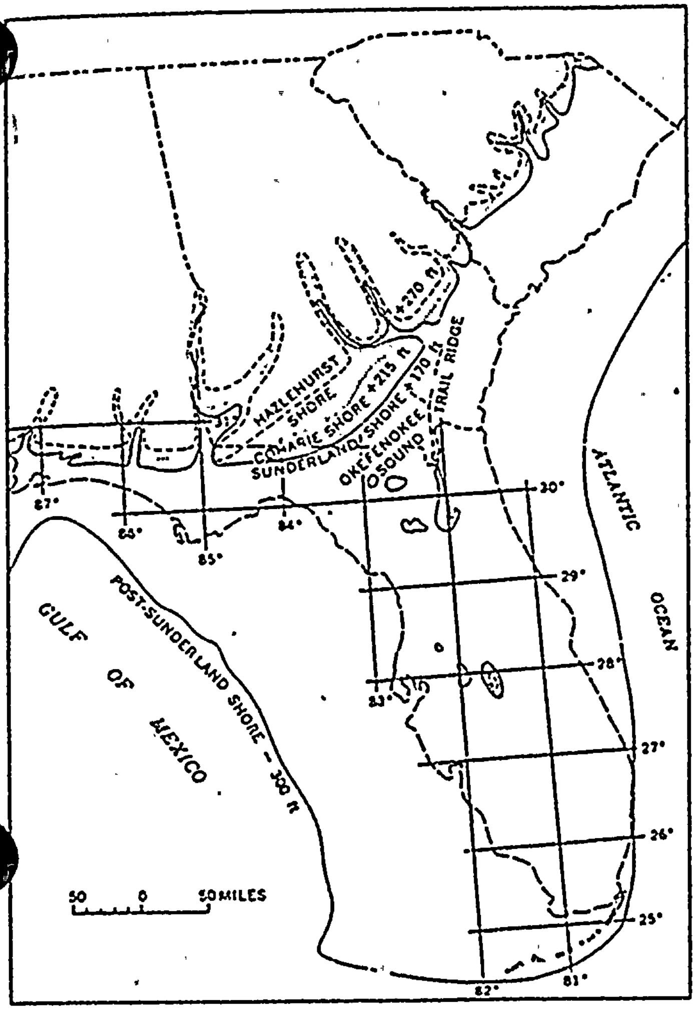
(Brooks, 1974).



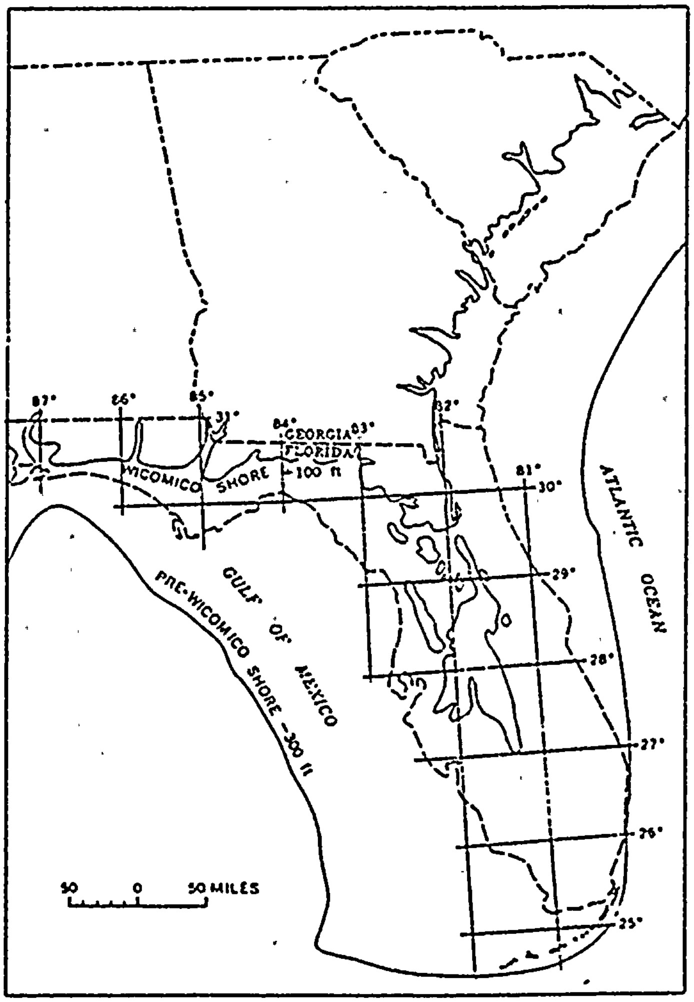
—Shoreline of the Penholoway sea in the Southeastern States. (After Cooke, 1939, fig. 14.)



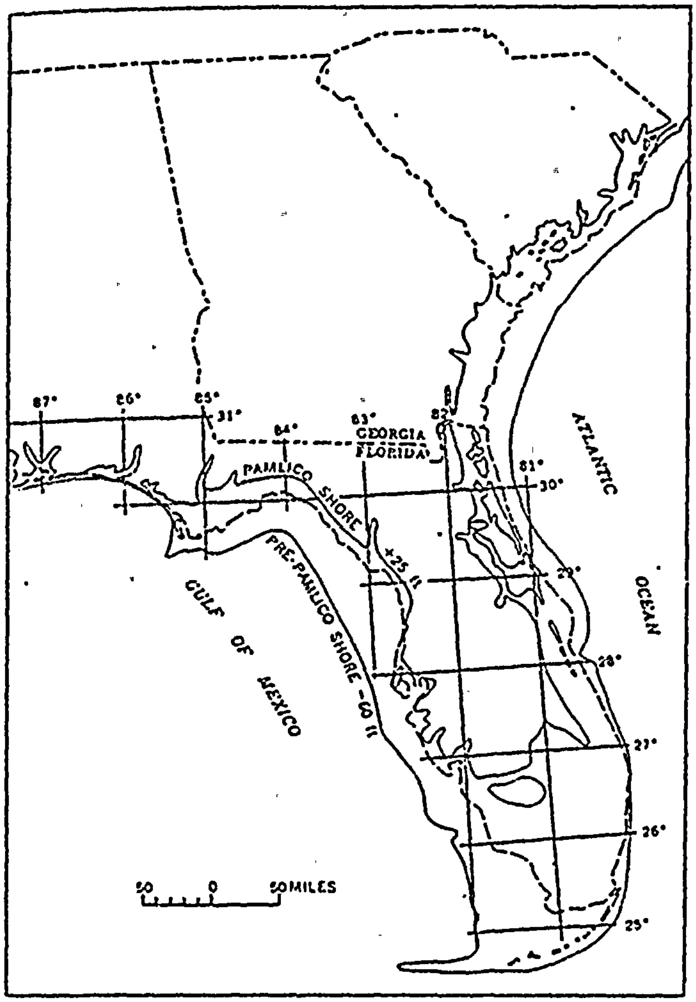
—Shoreline of the Talbot sea in the Southeastern States. (After Cooke, 1939, fig. 15.)



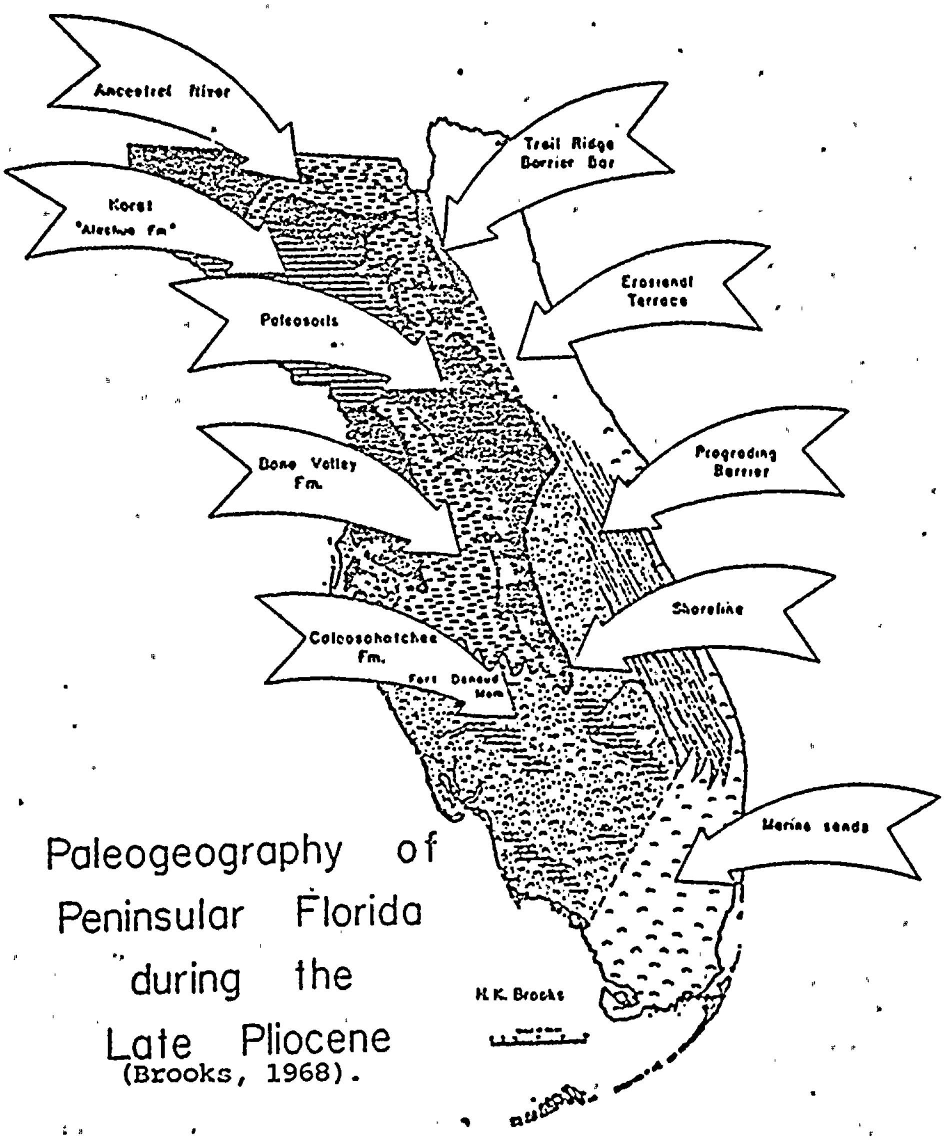
—Early Pleistocene shorelines in the Southeastern States, much generalized and in part conjectural. (After Cooke, 1939, fig. 12.)



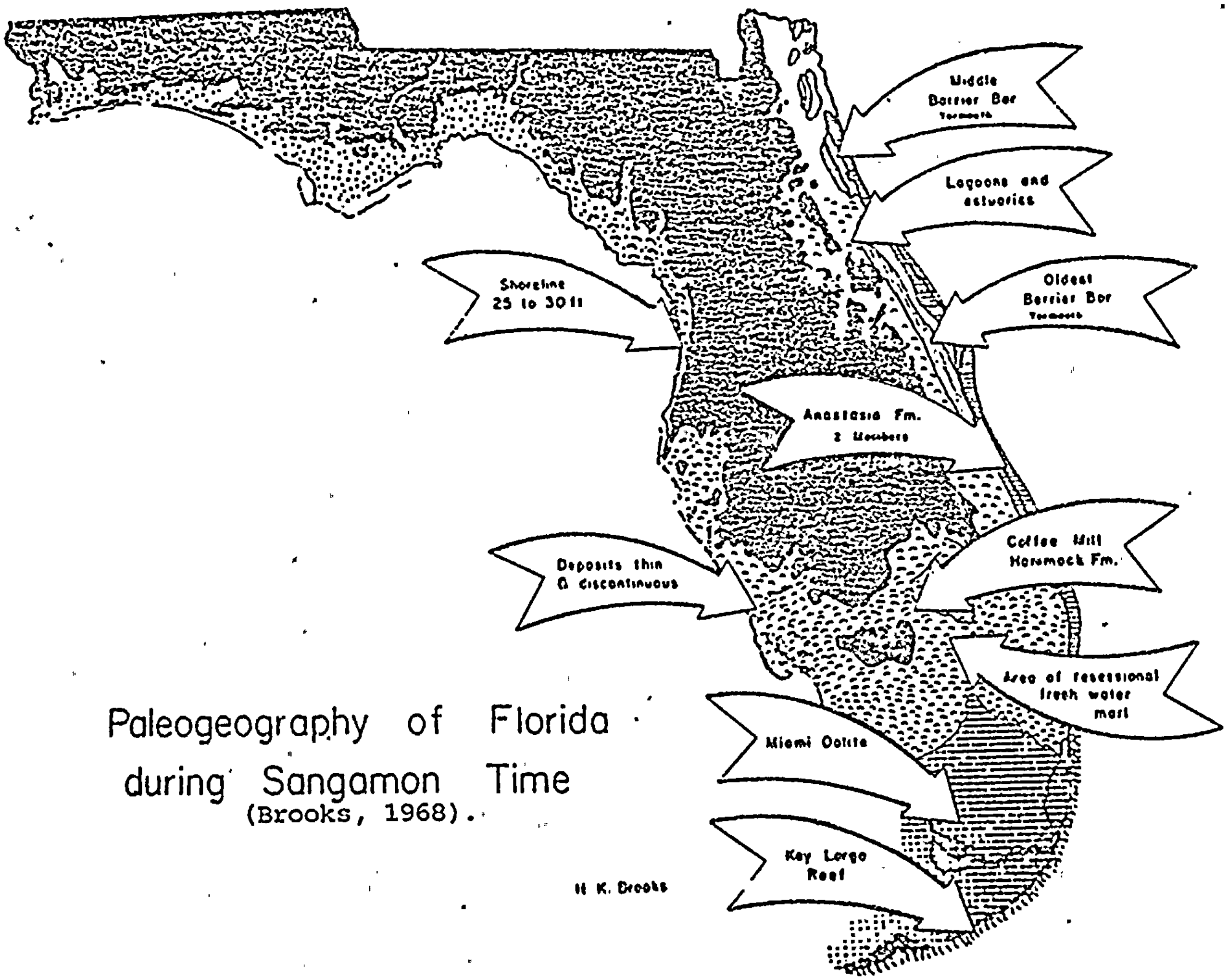
—Shoreline of the Wicomico sea in the Southeastern States. (After Cooke, 1939, fig. 13.)



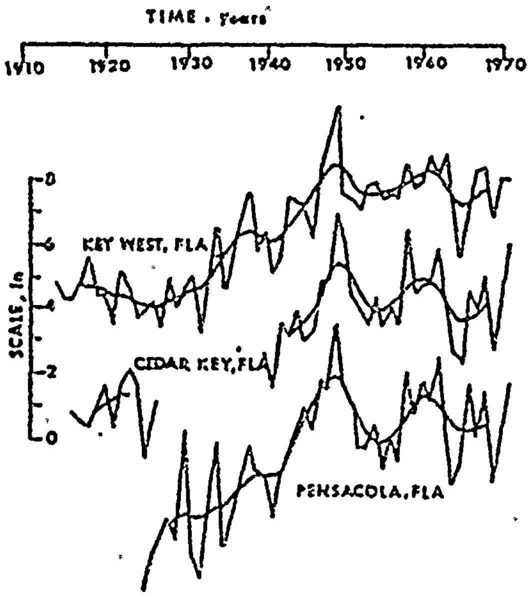
—Shoreline of the Pamlico sea in the Southeastern States. (After Cooke, 1939, fig. 16.)



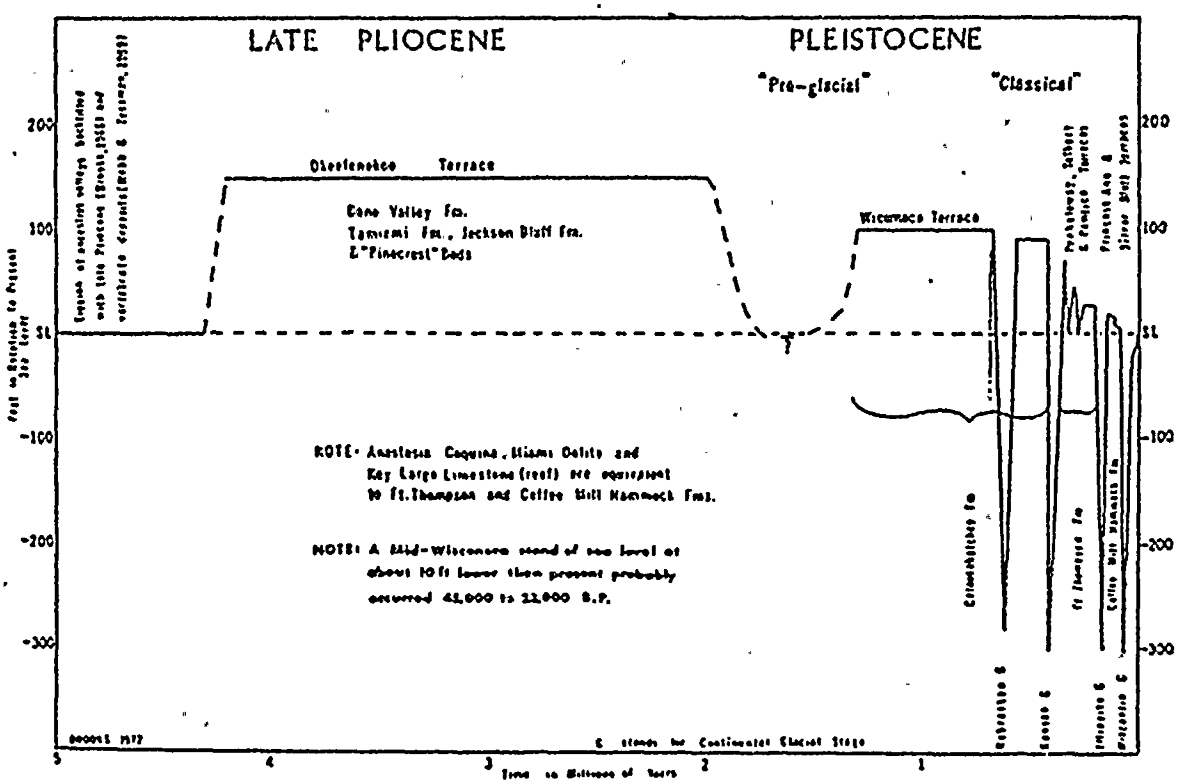
Paleogeography of
Peninsular Florida
during the
Late Pliocene
(Brooks, 1968).



Paleogeography of Florida during Sangamon Time
(Brooks, 1968).



Recent changes in Sea Level as Recorded By Tidal Gauges in Eastern Gulf of Mexico (modified from Hicks, unpublished)



Glacial Eustatic Sea Level Chronology Based upon Stratigraphic Evidence in Florida (Brooks, 1968)

UTHOR	Co[illegible], 44	[illegible]			Brin[illegible] 66)	[illegible]COLS, 65	[illegible]	[illegible]	[illegible]	
CENT			Silver Bluff 8'-10'							RECENT
		SILVER BLUFF Late Wis. or Rec. Bermesexly								Late. WISCONSIN
	Pamlico 25'	Pamlico 25'	Pamlico 25-35'	Pamlico 25'	Silver Bluff 6'		Princess Ann 18'			mid. WISCONSIN
										Early WISCONSIN
PLEISTOCENE	Talbot 42' Penholoway 70' Wicomico 100'	Talbot 42' Penholoway 70' Wicomico 100'	Wicomico 100'	Wicomico 100'	Pamlico 25'		Pamlico 25'	Silver Bluff 6-8 (90000 BP) Princess Ann 18 (120000 BP)	Silver Bluff 6-8' (90000 BP) Princess Ann 18' (120000 BP)	SANGAMON
										ILLINOIAN
	Sunderland 170' Coharie 215'	Sunderland 170' Coharie 215'	Okefenokee 150'	Okefenokee 150'	Talbot 42' Penholoway 70' Wicomico 100' Okefenokee 150 Sunderland 170 Coharie 215'	25-30' NORMAL INTERGLACIAL STAND	Talbot 40' Penholoway 70'	Pamlico 25' (230000 BP) Talbot 40' Penholoway 70'	Pamlico 25'-30' Talbot 40'-50' Penholoway 70'	YARMOUTH
						PLIOCENE OR PLEISTOCENE				KANSAN
	Brandywine 270'	Brandywine 270'	HIGH TERRACE NOW MARINE	Coharie 220'	Hazelhurst 270' (=Brandywine)	? 45'-55' 70'-80'	Wicomico 90'-100'	Unnamed 90' stand	Wicomico 90'-100'	AFTONIAN
										NEBRASKAN
						?		Wicomico 100'	Wicomico 90'-100'	PRE GLACIAL PLEIST. PLEISTOCENE
LIOCENE						90-100'	Okefenokee 120-140' (Late Plio)	Okefenokee 140-160' (Late Plio)	Okefenokee 120'	PLIOCENE
IOCENE	--					215'-250'		Upper Miocene 200'		MIOCENE

PART II: SINKHOLE POTENTIAL IN INDIAN RIVER, ST. LUCIE, AND MARTIN COUNTIES, FLORIDA

- GENERAL
- SINKHOLE POTENTIAL IN FLORIDA
- PRESENT-DAY SOLUTION IN THE DEEP AQUIFER?
- SOLUTION AND SINKHOLE POTENTIAL IN THE SURFICIAL AQUIFER

GENERAL

Sinkhole or karst topography in Florida is generally limited to those areas where limestone is at or near the surface and the overlying Hawthorn Formation has been removed by erosion, or where sinkholes and/or other solution features extend to the underlying limestone through a substantially thinned-out Hawthorn.

Where the clastic Hawthorn Formation is present the first cycle of solution probably was started by water in the permeable beds of the Hawthorn moving downward to the limestone below. The solution of limestone along vertical intersecting joints and fractures enlarge these vertical openings from mere tubes to large shafts.

Sinkholes, natural wells, or solution pipes are natural openings that normally extend from the land surface to a highly permeable or cavernous zone in the underlying limestone. In general, sinkholes are caused by solution and by collapse of the roof of underground channels or caverns. Roughly cylindrical natural wells or vertical shafts and pipes are formed by solution along joints or fractures in the vadose zone in the limestone, the solution rate being roughly the same from the top to the bottom of the shafts. Most of the natural wells terminate at the level of a lateral, or horizontal, channel and often extend through several levels. Whereas some of the lateral channels are now above the zone of saturation, and may have been modified by vadose water, it is generally agreed that they were formed chiefly by phreatic solution. Notably, the lowest historical position of the water table in the limestone is indicated by the deepest natural wells (Pohl, 1955; Merrill, 1960; Stringfield, 1966).

As part of the Hawthorn Formation was removed by erosion in Florida, more and more of the surface drainage went underground into solution channels. In the areas where the Hawthorn is present, and the top of the Floridan aquifer is relatively high, as on part of the Ocala Uplift, sinkholes extend from the surface through the Hawthorn into the underlying limestone.

Most of these sinks are now partly filled with unconsolidated material, some of which is relatively permeable. In the areas where the Hawthorn was overlain by unconsolidated sands, the sands slumped into the sinks and formed the sloping walls of the sink. The slope depends to a large extent on the thickness and angle of repose of the unconsolidated material. Some of the material may have been removed by solution and caving before the material at the surface collapsed into the underlying solution cavity.

As stated by Sellards (1914), sinks generally are not known to form in areas of artesian flow. The artesian aquifer, the Floridan aquifer, is overlain by relatively impermeable beds and the water in cavities is under artesian pressure. Along the border between the flowing and non-flowing areas, the artesian water forms artesian springs in some places where the aquifer is at or near the surface and the artesian pressure is sufficient to force water to a point of discharge at the surface. Most of these springs flow through channels and sinkholes apparently formed when the seas stood at a lower level and when the top of the zone of saturation in the limestone was at a lower level.

The areas in which the sinks are forming today are generally those in which 1) the limestone is near the surface, 2) the water level in the limestone is near the surface, and 3) the material overlying the limestone is too weak to prevent collapse into the underground cavity (see below).

When the water level in the limestone is high, as in a rainy season, a cavity having a weak roof may be filled with water, which will give some support to the roof. During prolonged drought, however, when the water level declines, the support is withdrawn and the roof of the underground cavity may collapse. The same condition may be brought about by extensive well pumpage and the consequent cone of depression created in the potentiometric surface.

Erosion and solution of the Hawthorn seems to have started in the Late Miocene* and Early Pliocene in north-central Floida, where the Bone Valley Formation is deposited in shallow sinks in the Hawthorn Formation in Polk and Hillsborough counties (Cathcart, 1963). Sinkholes were also formed after deposition of the Bone Valley and prior to deposition of the Pleistocene sand. Since that time advances and recessions of the sea have affected the sinkhole topography and solution in the limestone to such an extent that in many areas it is difficult to interpret both historical and present conditions.

*My own research shows that sinkhole formation began in older rocks as early as the Late Oligocene (Patton, 1969, 1971).

SINKHOLE POTENTIAL IN FLORIDA

After deposition in the sea, most of the water-bearing formations of the Floridan aquifer were raised above sea level, and solution cavities formed in the limestone and other carbonate rocks before they were resubmerged in the sea and covered by overlying formations. The longer the emergence, the greater the opportunity for cavern development; conversely, where the limestones are relatively quickly buried, as in the study area, the opportunity for cavern formation is substantially reduced.

This is important in view of the following considerations: 1) most of the solution takes place in the phreatic zone, although some enlargement and modification occurs through vadose processes; 2) maximum solution, however, takes place in the upper phreatic zone, or near the phreatic-vadose interface (Davis, 1930; Bretz, 1942; Swinnerton, 1932); 3) limestone is dissolved most rapidly in the zone <u>between the highest and lowest positions</u> occupied by the water table in its seasonal, or historical, fluctuations (Piper, 1932; and see Kaye, 1957).

Therefore, fluctuations in base level engendered by eustatic rises and falls in sea level can, and do, play a major role in the formation of cavernous zones (and ultimately karst conditions) in limestone terranes by significantly increasing the vertical range of the most active solution zones.

It has been our observation, as well as that of others (S. Windham, Fla. Bureau of Geology, pers. comm.), that these primary conditions are met where the water-bearing limestones are structurally or erosionally high and relatively near the surface so that fresh water can enter the system and

begin to develop cavities (N.B. Deep solution is less where the limestone is bare at the surface, that is, where it lacks a thin, permeable clastic cover). For example, in Orange County, where surface altitude is generally about 100 feet, recorded cavities in the limestone of the Floridan aquifer are reported as follows (Lichtler, 1963, written communication to V. Stringfield; in Stringfield, 1966, p. 80):

Depth below mean sea level (feet)	Number of reported cavities	
	At least 1 foot in vertical dimension	At least 10 feet in vertical dimension
0–100	14	5
100–200	12	2
200–300	11	3
300–400	23	2
400–500	5	1
500–1,000	0	0
1,100–1,200	2	0
1,200–1,300	2	0
1,300–1,400	1	0

Thus, in Florida, experience indicates that the requirements for the development of an active karst topography include the following:

1) the presence of a dense soluble limestone in an erosionally or structurally high area, where the opportunity exists for active solution to take place;

2) a history of base level fluctuation, which creates a larger and more vertically extensive cavernous system;

3) a comparatively thin sequence (empirically, 100' or less, but this is variable, depending somewhat on the coarseness of the constituent sediment particles) of permeable clastics covering the limestone;

4) a potentiometric surface below the water table, a situation resulting in a loss of upward pore pressure in the clastics and loss of buoyancy in in the limestone, combining to create downward stress on the system;

5) and, obviously, zones of weakness and/or openings at or near the top of the limestone, increasing the potential for ultimate collapse.

As displayed in the accompanying sinkhole potential map, the study area is located in one of the least likely areas for sinkhole development. In view of the criteria listed above, this is due to the fact that 1) the water-bearing limestones of the Floridan aquifer in that region were never significantly emergent, precluding the formation of extensive cavernous zones; 2) they were relatively quickly buried by a thick sequence of impermeable Hawthorn sediments; 3) considering the thickness of the Hawthorn sequence, Late Neogene sea level fluctuations probably never reached down to the underlying limestones; 4) the potentiometric surface is, and was, considerably above the artesian system, creating considerable upward pressure in the overlying sediment; and, 5) there is little or no leakage, natural or artificial, through the overlying sediments to reduce that pressure (see below).

PRESENT-DAY SOLUTION IN THE DEEP AQUIFER?

There may be solution by deep circulation of artesian water in areas where there are favorable structural conditions, such as recharge of the aquifers at high altitudes or discharge from a deep basin at a lower altitude (Stringfield, 1966). Where hydrologic and structural conditions are not favorable for circulation of groundwater, large cavities such as those in the Ocala or Avon Park would have to form before the formations are deeply buried. As discussed in the previous section, in southern Florida such favorable conditions did not obtain, the soluble limestones of the Floridan aquifer were never structurally high, circulation of fresh groundwater did not occur to any great extent (in fact, apparently not all of the connate salt water

was flushed out), and the limestones were rather quickly buried under thick accumulations of mostly impermeable clastic sediments.

For any substantial solution by deep circulation to be currently ongoing, two conditions are generally required: 1) recharge and 2) opportunity for discharge at submarine outcrops or through springs and upward leakage into overlying formations. The latter condition is controlling for purposes of this discussion. The discharge at submarine outcrops is controlled by the relation of the fresh water head and the back pressure from the salt water. In areas where the pressure of the salt water is greater than the artesian head at the submarine outcrop, no discharge occurs. Upward leakage depends on the permeability and thickness of the overlying beds and the hydrostatic head of water in the aquifer in the overlying formations (Stringfield, 1966).

In the study area there are no submarine outcrops of the artesian aquifer, and the overlying Hawthorn Formation constitutes an effective impermeable cap, which prevents upward leakage from the aquifer. Both of these factors preclude significant present-day circulation through, and solution in, the deeply buried Floridan aquifer. Thus, modern solution and collapse of the limestones of the Floridan aquifer and its possible surface expression through hundreds of feet of overlying sediments may be effectively discounted.

SOLUTION AND SINKHOLE POTENTIAL IN THE SURFICAL AQUIFER

Although there is extensive solution in the calcareous formations comprising the surfical aquifer in southeastern Florida, it is not of the type that lends itself to the formation of sinkholes. Solution was most

active when sea level was below its present level and, like today, is usually initiated in small depressions or pits in the surface of the limestone. Water stands in the depression and dissolves the limestone until it is flushed from the depression during and after rains. These gradually became deeper, without visible outlets along the sides and bottom. On a modern surface these depressions ("cow wells" in the West Indies; "potholes" in Florida) in some places become so numerous and closely juxtaposed that they almost constitute a "karrenfeld" in karst terminology (Sweeting, 1972). They later became tubes which enlarged into holes of different shapes and sizes, some several feet deep. Those formed during ancient sea level stands are now mostly filled with permeable sand. Parker and Cooke (1944) report that in large areas of southern Florida at least one-fourth of the total volume of limestone of the shallow aquifer is now occupied by solution holes, generally filled with sand. Although solution in the shallow aquifer has been intense, typical sinkhole or karst topography has not resulted. One reason is that the limestone extends to the land surface and solution has occurred throughout the aquifer in relatively small channels instead of concentrating in large channels which might cause sinkholes (Stringfield, 1966). Another, related, reason is that, unlike the older, higher limestones which are highly fractured, the surficial limestones in the study area are not so broken, preventing the more selective, concentrated movement of groundwater in major fractures or joints that results in larger cavern formation. Additionally, the younger formations tend to be more permeable, again allowing more diffuse percolation through the system, further reducing the opportunity for formation of large solution cavities. Thus, the samll diameter, shallow

depth, and lack of extensive interconnectness of the solution features in the surfical aquifer greatly reduces the probability of any sinkhole formation in the study area.*

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*At present, sea level is near the top of the aquifer, and the water table ranges from sea level along the coast to a miximum of about 10 feet above sea level several miles inland (Stringfield, 1966). Sea level is not likely to drop precipitously (!), but if groundwater were to be pumped vigorously in a localized area, sand could be flushed from the cavities, surface drainage would be underground, and the water table would decline to the bottom of the aquifer. These conditions <u>might</u> destabilize the system, but 1) since the decline might be compensated for by saltwater intrusion, and 2) the factors listed in the last paragraph above would still obtain, I doubt whether such pumpage would have much effect in causing local sinkhole formation.

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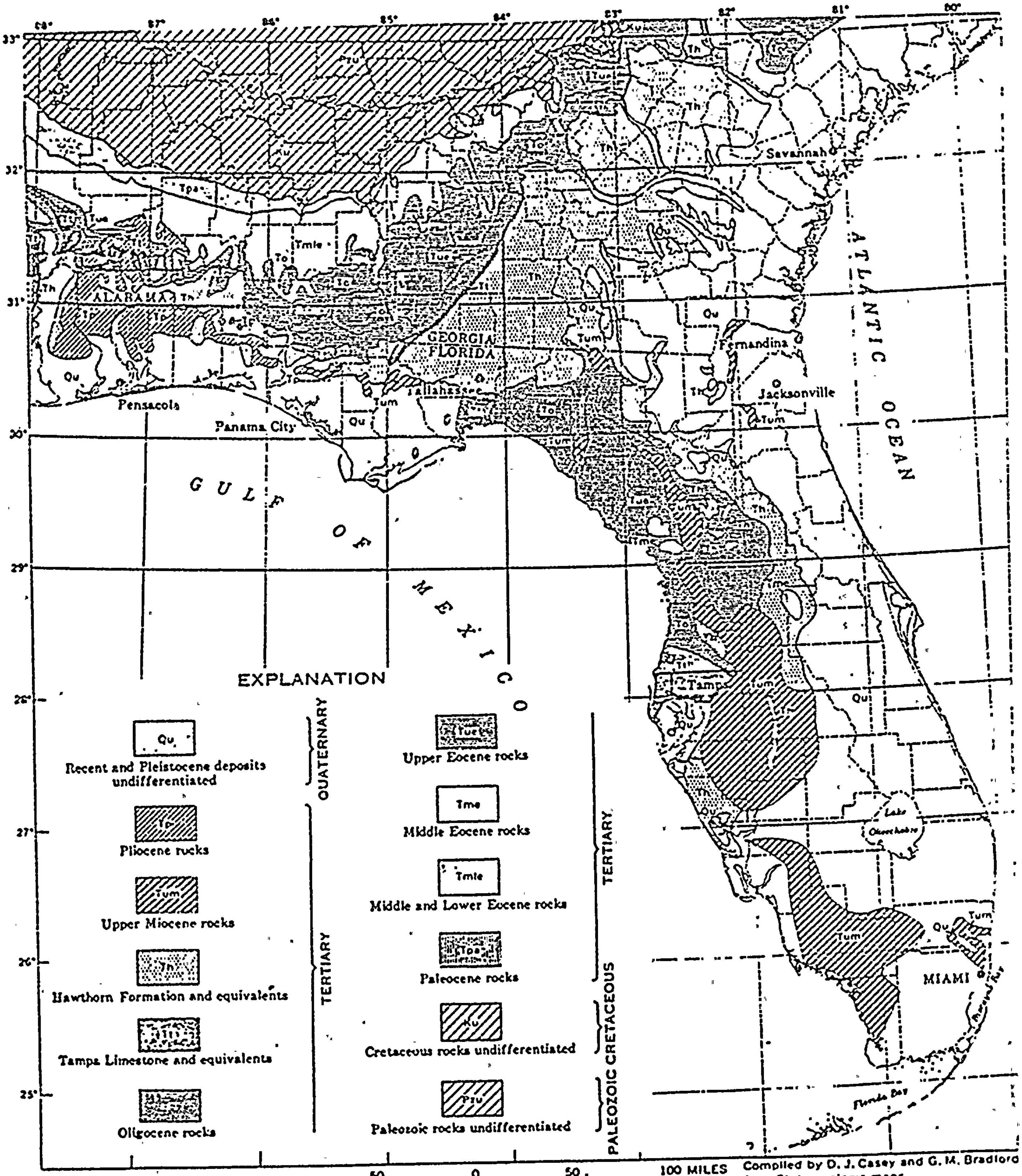
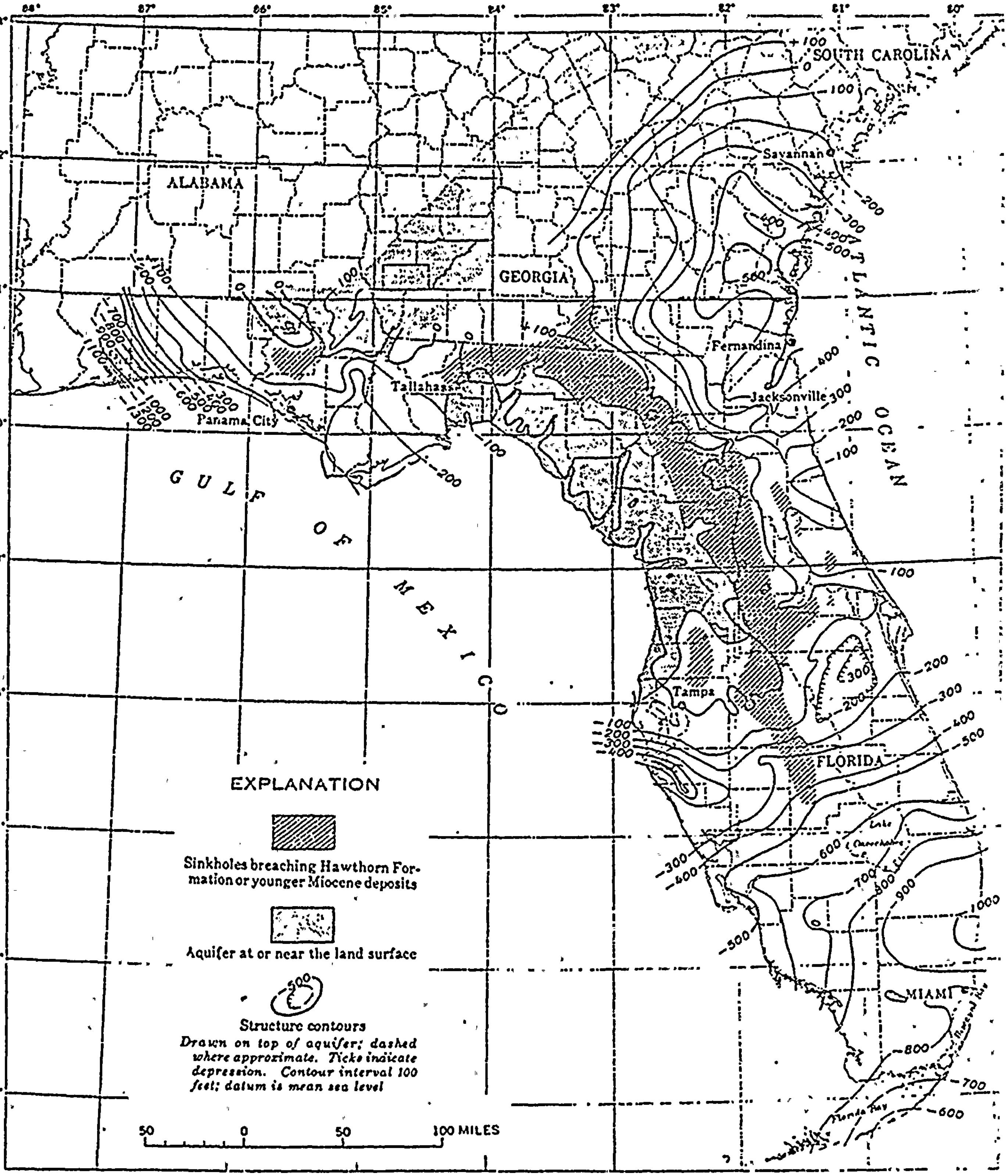
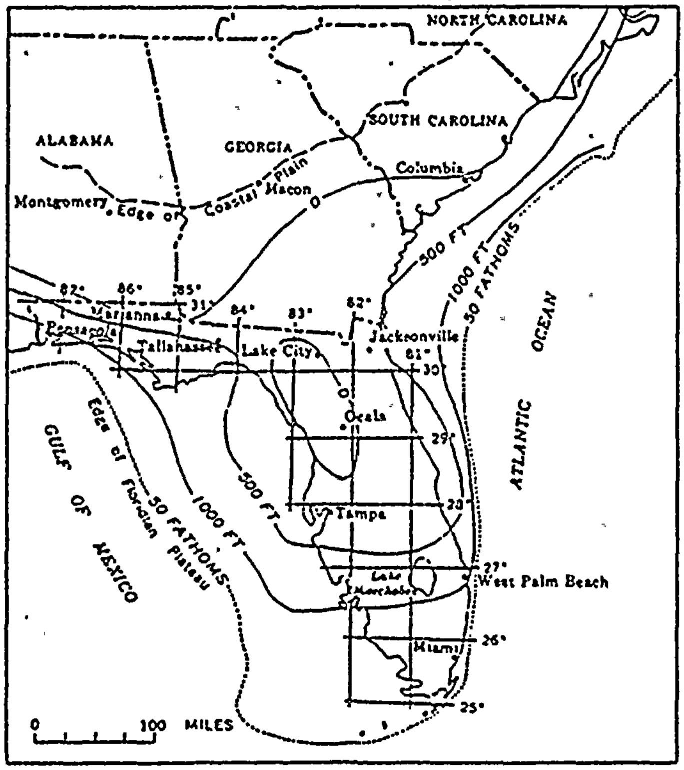


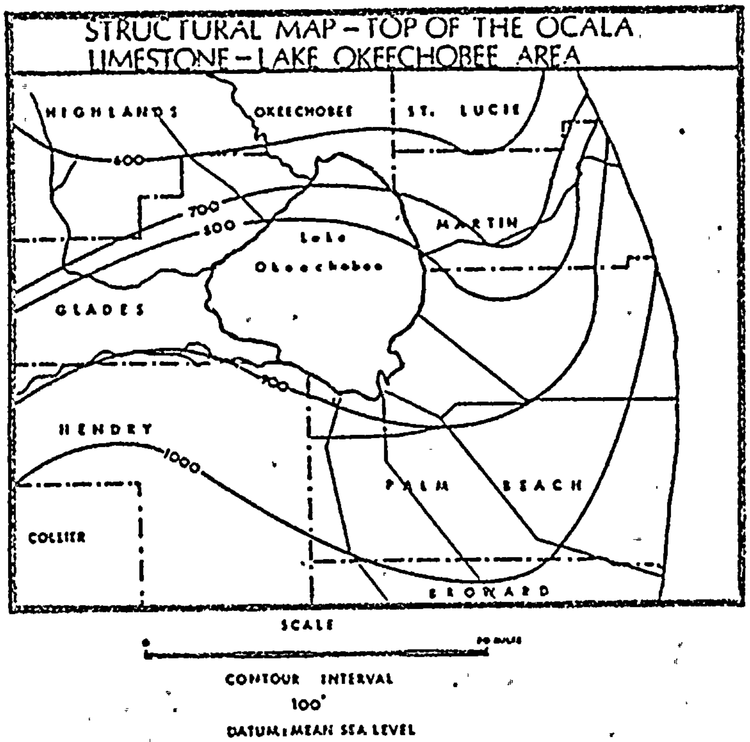
–Generalized geologic map of the Coastal Plain of the Southeastern States.
(Stringfield, 1966).



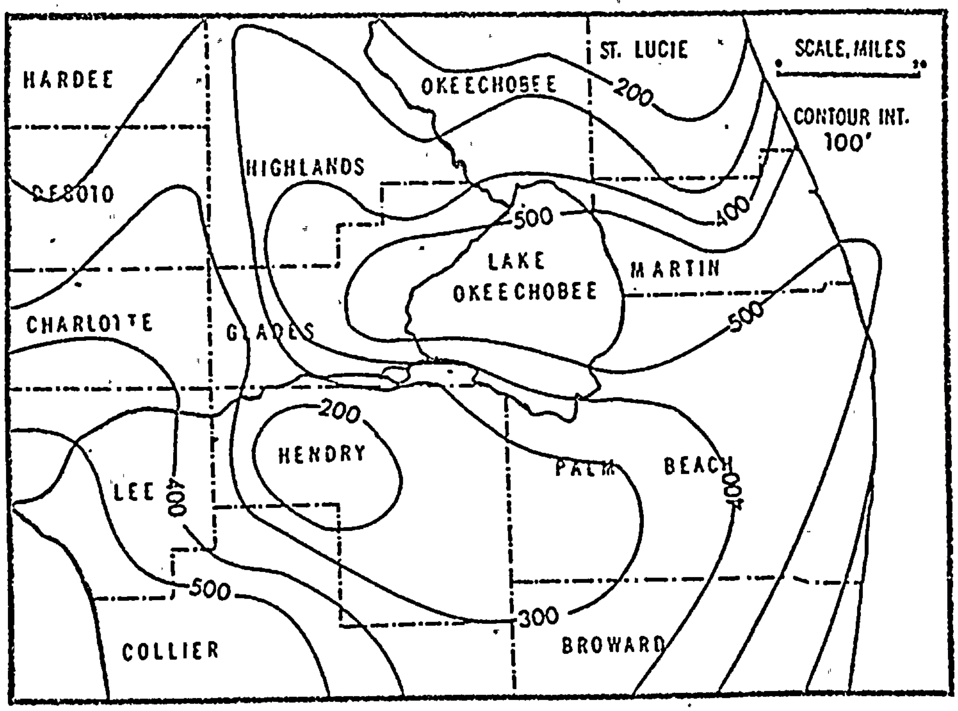
–Contour map of top of principal artesian aquifer. (Florida, from Vernon, 1955; Georgia, from Warren, 1944.) (Stringfield, 1966).



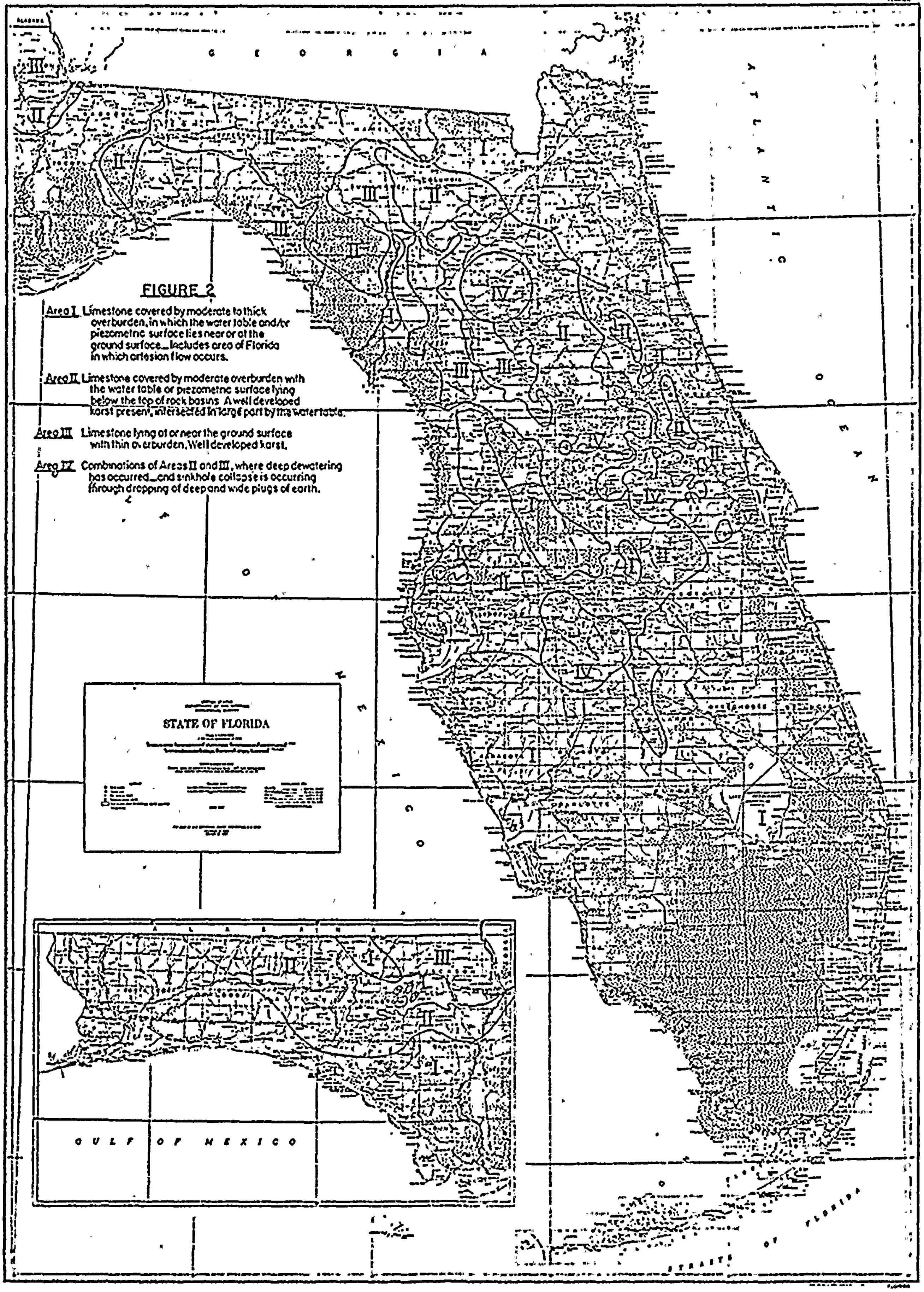
. —Sketch map of Florida and adjacent States showing Floridian Plateau and top of Eocene formations. (From Cooke, 1945, p. 6.)



Structural contour map based on top of the Ocala Limestone in the area of Lake Okeechobee. The datum is sea level and the contours are 100 feet intervals below the datum. Drawing by J. F. Mims.



Isopachous map showing thickness of the Hawthorn Formation under Lake Okeechobee. Contour lines represent thickness in increments of 100 feet. The apparent thinning southwest is probably due to more of the Miocene section being included in the Tampa Formation. Drawing by J. F. Mims. (Brooks, 1974).



G E O R G I A
ATLANTIC OCEAN
FIGURE 2
Area I. Limestone covered by moderate to thick overburden, in which the water table and/or piezometric surface lies near or at the ground surface. Includes area of Florida in which artesian flow occurs.
Area II. Limestone covered by moderate overburden with the water table or piezometric surface lying below the top of rock basins. A well developed karst present, intersected in large part by the water table.
Area III. Limestone lying at or near the ground surface with thin overburden. Well developed karst.
Area IV. Combinations of Areas II and III, where deep dewatering has occurred and sinkhole collapse is occurring through dropping of deep and wide plugs of earth.
STATE OF FLORIDA
GULF OF MEXICO
STRAITS OF FLORIDA

NAME	ELEVATION	AGE
Hazelhurst	270 feet	Late Miocene
Coharie	220 feet	Late Miocene
Sunderland*	170 feet	Late Pliocene
Okefenokee*	150 feet	Late Pliocene
Wicomico	100 feet	Aftonian
Penholoway	70 feet	Yarmouthian
Talbot	42 feet	Yarmouthian
Pamlico	25 feet	Sangamonian 4
Princess Ann	18 feet	Sangamonian
Silver Bluff	8 feet	Sangamonian

* Presently combined and referred to as Okefenokee Terrace

Cooke(7) (78), who did much of the original detailed delineation and correlation of terrace surfaces in Florida, states that he sees no evidence of tilting or warping of the Pleistocene shorelines and terraces. White(79) used terrace correlations and other geomorphic evidence to examine the possibility of westward tilt in peninsular Florida. He concluded that there was no evidence to support late (post-Pleistocene) tilting.

(REF: SEE REF 98 PAGE 2.5-86B)

2.5.1.1.4 Structural Geology

Opinions concerning the structure of the basement complex underlying peninsular Florida are still developing and are based on limited data, mostly obtained from petroleum exploration wells. Geophysical studies, primarily gravimetric (Figure 2.5-22 and 2.5-23), aerial magnetic (Figure 2.5-24), and seismic reflection surveys indicate the basement surface is undulatory, 0
however, data is insufficient to indicate whether elevation differentials 4
are the result of erosion or warping.

Martin and Case(31) suggest that steep northwest-trending gravity (See 0
Figure 2.5-22) and magnetic gradients that transect southern Florida may be indicative of a crustal boundary or a major basement fault.

The following discussion describes the major structural features affecting peninsular Florida. Figure 2.5-8 shows the major published structural features throughout peninsular Florida.

There are a number of regional geologic structures in the subsurface of the Atlantic and Gulf Coastal Plain which occur within 200 miles of the site. These structures may be grouped according to age of formation as follows: The Applin Feature (Precambrian or early Paleozoic); the