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Abstract

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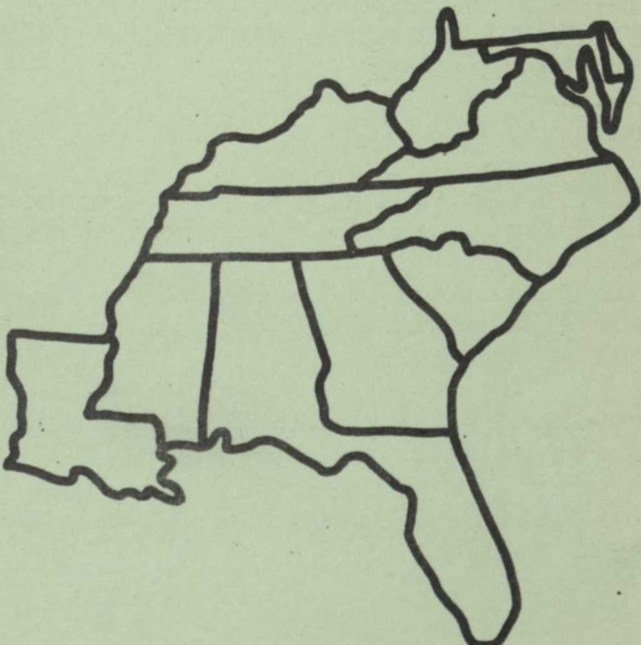
J. K. Butler

Southeastern Geology



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SOUTHEASTERN GEOLOGY

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SOME GEOLOGIC AND HYDROLOGIC FACTORS AFFECTING LIMESTONE TERRANES OF TERTIARY AGE IN SOUTH CAROLINA*

By
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ABSTRACT

Each epoch of the Tertiary period was characterized by deposition of fossiliferous marl, limestone, or coquina in the South Carolina Coastal Plain. Limestone and marl of Paleocene age occur in the subsurface in southern Beaufort County. Limestone or marl is contained in each successively younger Tertiary formation in other sections of the Coastal Plain. These include the Santee Limestone and Castle Hayne Limestone of Eocene age, the Cooper Marl of Oligocene or possibly Eocene age and unnamed limestone of Oligocene age, the Duplin Marl of Miocene age, and the Waccamaw Formation of Pliocene age. These deposits occur as thin but extensive, gently dipping beds which show some local warping.

Intensive sinkhole development typical of karst topography is uncommon over most of the limestone area, although in several areas, notably in northern Orangeburg County, the topography is characterized by numerous solution depressions typical of the doline type. Solution depressions and "Carolina Bays" mark the topography of other areas underlain by calcareous Tertiary deposits. The occurrence of the "Carolina Bay" is almost indigenous to those areas underlain by formations of middle Miocene to early Pliocene age, predominantly the Duplin Marl. The present location of karst topography is controlled in part by the Coriolis force in areas adjacent to the major stream channels and by the thickness and permeability of overburden in the interstream areas.

The solubility of the limestone aquifer separates it from most other aquifers which are comparatively insoluble. Climatic and geochemical factors are considered of primary importance in the solution process. During parts of Oligocene and Miocene time, the Santee and Castle Hayne Limestones and the Cooper Marl were exposed to subaerial and subsurface erosion, which could have developed caverns and conduits in the rock similar to those typical of a karst region. After their deposition these formations at first stored and transmitted water under water-table conditions. Subsequent artesian conditions developed when the limestones were covered by clay, marl, and siliceous phosphate of Miocene or younger age.

Solution of limestone below the water table is recognized elsewhere but not confirmed at more than normal depths in this State. The porosity and permeability of limestones in the southern part of the State appear to be greater in the upper part of the formation.

The marls of Miocene and Pliocene age are considerably thinner and less permeable than the Eocene deposits and are of minor importance as aquifers. However, their terranes have distinctive geomorphic features which have substantial significance in the genesis of the "Carolina Bay".

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* Publication authorized by the Director, U. S. Geological Survey.

INTRODUCTION

This paper presents some of the facts and conclusions drawn from analysis of geologic and hydrologic data obtained during the course of ground-water studies by the United States Geological Survey in cooperation with the Department of the Navy and the South Carolina State Development Board. The objectives include a presentation of significant features in the stratigraphy, structure, and geomorphology of the limestones of Tertiary age as they occur in South Carolina, together with a description of their terrane.

STRATIGRAPHY

Calcareous deposits of fossiliferous marl, limestone, or coquina were deposited in each epoch of the Tertiary period in South Carolina. Subsequent erosion removed part or most of these deposits and the residual material comprises the discontinuous remnants of Eocene to Pliocene age now found in parts of the Coastal Plain. Correlations of the Tertiary formations in South Carolina with those in adjacent States is shown in Figure 1. Figure 2 shows the area of exposed and buried Tertiary limestone and marl in South Carolina. Because the total thickness of Tertiary sediments is not great and because marl and limestone deposits constitute a large part of these sediments, either marl or limestone can generally be found in the greater part of the Coastal Plain within about 100 feet of the surface.

Eocene Series

Limestone of Early to Middle Eocene age crops out in the southern part of the Coastal Plain in Allendale County on the Georgia boundary and extends northeastward and eastward to Berkeley County on the Atlantic Coast. The rocks strike eastward to northeastward and dip gently to the south and southeast. The oldest (*) of these formations is the Santee Limestone, which consists of a nearly pure white to creamy yellow fossiliferous and partly glauconitic limestone containing numerous Bryozoa. As the white limestone of the Santee is so unlike other known Eocene deposits, early investigators consider it Upper Cretaceous in age. However, Charles Lyell (1845) examined the rocks in 1842 and pronounced them Eocene. Sloan (1908) used the name "Mount Hope Marl" for the typical exposures of the Santee Marl described by earlier investigators. Cooke (1936) originally placed the Santee, along with the Cooper Marl, in the Jackson group of the Eocene, but later Cooke and MacNeil (1952) decided it was equivalent to the Cook Mountain formation (upper middle Claiborne) on the basis of the included Ostrea sellaformis

(*) The "Warley Hill Marl", a formation reportedly underlying the Santee, has been revived in the stratigraphic nomenclature, but the deposit is dominantly a glaucontic sandy clay and has little significance as a limestone terrane.

			GEORGIA	SOUTH CAROLINA	NORTH CAROLINA
Pliocene			Charlton Formation	Waccamaw Formation	Waccamaw (?) Formation 1/
MIO-CENE		upper	Duplin Marl	Duplin Marl	? Yorktown Formation
MIO-CENE		middle	Hawthorn Formation	Hawthorn Formation	Calvert (?) Formation
MIO-CENE		lower	Tampa Limestone	Tampa(?) Limestone 2/	?
Oligocene			Suwanee Limestone Absent ?	Flint River Formation Cooper Marl	?
EOCENE	Jackson group		Ocala Limestone	Barnwell Formation	?
EOCENE	Claiborne group	upper	Gosport Sand	Castle Hayne Limestone	Castle Hayne Limestone
EOCENE	Claiborne group	middle	South Ga.: Lisbon Formation Northeast Ga.: McBean Formation ////////////	McBean Formation Warley Hill Marl	Santee Limestone ?
EOCENE	Claiborne group	lower	Tallahata Formation	Congaree Formation	?
EOCENE	Wilcox group		Hatchetigbee Formation Tuscahoma Sand Nanafalia Formation		?
Paleocene			Clayton Formation	Midway(?)Formation 2/	Beaufort Formation 3/

1/ May be in part Duplin. 2/ Subsurface only. 3/ Brown (1959).

Figure 1. Correlation of Tertiary formations in South Carolina and adjacent states.

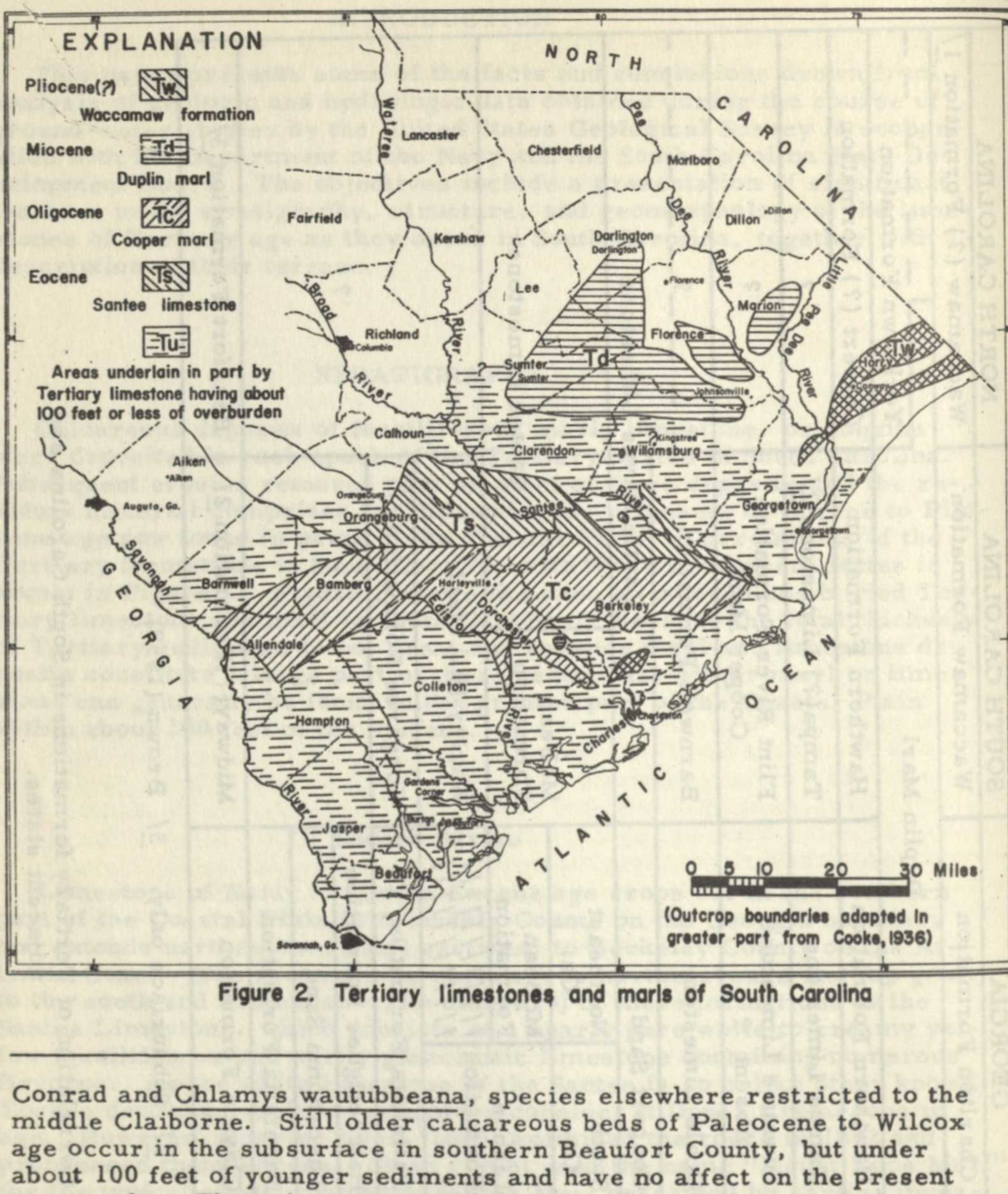

Figure 2. Tertiary limestones and marls of South Carolina

Conrad and Chlamys wautubbeana, species elsewhere restricted to the middle Claiborne. Still older calcareous beds of Paleocene to Wilcox age occur in the subsurface in southern Beaufort County, but under about 100 feet of younger sediments and have no affect on the present topography. There is some possibility that these beds remain in part calcareous for 40 to 50 miles updip and occur under a thin cover of terrace deposits in southern Williamsburg County. Even here, however, the thin calcareous deposits have little effect on the hydrology of the area.

The Castle Hayne Limestone, a buff-gray hard but crumbly fossiliferous limestone, has been recognized only in artificial exposures in South Carolina. Previously recognized only in North Carolina, where it was considered Jackson in age, Cooke and MacNeil (1952) identified the fauna of late Claiborne age in a unit overlying the Santee Limestone and underneath the Cooper Marl. Therefore, they considered this formation equivalent to the Gosport sand of Alabama (upper Claiborne), in preference to its previous Jackson dating. The areal extent and downdip thickness of the Castle Hayne are as yet undetermined. In 1952, 46 feet of the unit was exposed in the pit of the Carolina Cement and Lime Co., north of Harleyville in Dorchester County. Identification of Foraminifera apparently confirm the equivalency of the unit with deposits of Gosport age in Georgia (but in an unrestricted sense - that is, lower Jackson or upper Claiborne).

Younger deposits of Jackson age have been tentatively identified in the southwestern part of the Coastal Plain, specifically near Baldock in Allendale County. Here, a white shell limestone occurring within a few feet of the land surface is presumed to become clastic updip; its correlation with calcareous beds of Jackson age downdip has not been established.

Oligocene (?) Series

The Cooper Marl, a finely granular olive-drab to brown marl containing glauconite and Foraminifera and having phosphatic nodules in the lower part, crops out over a large part of Dorchester and Charleston Counties and in the southern part of Berkeley County. Various investigators have shifted it back and forth between the Eocene and the Oligocene. Cooke and MacNeil (1952) placed it in the lower Oligocene on the basis of somewhat tentative evidence afforded by the presence of a species of Foraminifera, Bolivinella rugosa Howe, a species found in the Red Bluff clay (early Oligocene) and the macrofossil Chlamys cocoana (Dall). Subsequently MacNeil (in Malde, 1959, p. 19) identified several pelecypods and gastropods as affinities to specie found elsewhere in deposits of middle to late Oligocene age. On the basis of additional foraminiferal evidence, other geologists have thought that the Cooper Marl might be of Jackson age (late Eocene).

Miocene Series

The lowest limestone member of the Miocene epoch occurs only in the subsurface and is recognized as similar in lithology and microfauna to the Tampa Limestone of Georgia and Florida. This limestone has been tentatively identified from test-well cuttings in Beaufort and Jasper Counties. It consists of white to gray dense phosphatic and fossiliferous limestone. After it was deposited, part of the phosphate was distributed in nodular form in alluvial deposits of Miocene to Recent age and as hard silicified layers approximately 1 to 2 feet thick on top of the Eocene or Oligocene limestone.

A younger calcareous deposit of Miocene age is the Duplin Marl of late Miocene age. It is equivalent to the Choctawhatchee Formation of former usage in Florida. In South Carolina the formation consists mainly of a granular, in part porous, buff to coffee-colored sandy marl containing numerous fragments of shells. Generally less than 30 feet thick, it crops out principally in an area between Darlington, Sumter, and Johnsonville in Darlington, Sumter, Lee, Clarendon, Williamsburg, and Florence Counties. There is a small outcrop in Marion County and small patches in Berkeley and Dorchester Counties. When first deposited the formation probably occupied the entire lower Coastal Plain. The remnants now recognized represent a small part of the formation as originally deposited. The principal exposures are in bluffs along the larger rivers, although expansive flat upland inter-stream areas also are underlain by the sandy shell beds of this formation. It is the writer's opinion that perhaps a considerable amount of Miocene deposits are yet unmapped and that future exploration will show additional exposures to the northeast and southwest of those delineated to date.

Pliocene Series

During Pliocene time the Waccamaw Formation was deposited on the eroded surface of older Tertiary or Late Cretaceous formations. In the northeastern part of the Coastal Plain, in Horry and Georgetown Counties, it rests on the Peedee Formation of Late Cretaceous age, whereas to the south, in Berkeley County, it lies on either the Duplin Marl of Late Miocene age or the Cooper Marl of Oligocene age. The formation consists of blue-gray to yellow and brown sandy shell marl. Although the formation is tentatively considered Pliocene in age, some of the faunal assemblage indicates a late Miocene dating. Level surfaces characterize the area underlain by this unit and bear a resemblance to those formed by sediments of Miocene age and the terraces of Pleistocene age.

STRUCTURE

The Coastal Plain formations can generally be described as a series of sand, clay, or limestone deposits having a monoclinal or aclinal structure. They strike to the northeast and dip to the southeast and south. Resting on rocks of a much older (Precambrian to mid-Paleozoic) complex, they thicken from a featheredge on the northwest to more than 3, 500 feet along the coast.

Detailed structural features of the various Tertiary limestones between their outcrop areas and the Atlantic Coast have not been clearly defined. The most extensive limestone deposit, the Santee Limestone, occurs as a fairly extensive bed which dips 8 to 10 feet per mile to the south-southeast. Structural discontinuities may exist between the portion of this formation in the upper part of the Coastal Plain (Orangeburg and Calhoun Counties) and the extension downdip. From a featheredge in the vicinity of northern Orangeburg County the Santee thickens to the south and southeast. In the coastal area near Charleston it is approximately 200 feet thick. But farther southwest along the coast the unit either pinches out or undergoes a facies change. Originally described as Jackson in age and a facies of the Barnwell sand of earlier usage, it was later identified as a limestone facies of the McBean formation and thus as of middle Claiborne age.

The limestone occurring at depths of about 100 feet in central Beaufort County was originally considered to be the Cooper Marl and equivalent to the Ocala Limestone of Jackson age, an apparent contiguous bed occurring to the southwest in the Savannah, Ga. , area. On the basis of this age classification a structural high, or dome, was indicated in the central part of Beaufort County, from which the beds dipped in almost every direction. Subsequent updating of the Cooper Marl as Oligocene changed this situation and calls for less of a structural high than was previously indicated. The identification of upper Claiborne fauna in the limestone in northern Beaufort County further complicated the interpretation because this shows the Ocala Limestone of Jackson age occurring in the subsurface at Savannah, Ga., in apparent stratigraphic continuity with the Castle Hayne Limestone of Claiborne age in Beaufort County, S. C. Possible explanations include faulting or steepening of the dip between the two areas. Although faulting is entirely possible, consequent discontinuities in adjacent strata have not been substantiated. An additional possibility is that the limestone represents a singular lithologic unit whose deposition took place during the two time divisions.

Recent seismic refraction profiles in the area between Charleston, S. C., and Savannah, Ga., (Woollard, 1957, p. 37) indicated the presence of a structural high in the basement rocks, the "Yamacraw Ridge", and possibly this feature had some influence on the structure of the younger strata.

GEOMORPHOLOGY

Several of the landforms generally associated with limestone terranes may be found in various stages of development in South Carolina. Typical karst topography, characterized by the presence of numerous solution depressions, occurs in some but not all limestone areas in the State.

The most pronounced karst development may be found on the topographic highs on the southwest side of the major streams, where the streams cross the limestone near its thin edge. Illustrations may be found along the Santee and Savannah Rivers.

This preferred location of karst areas appears to be due, in part at least, to the stripping of thin deposits of limestone from the northeast side of the stream as it shifts laterally toward the right side of the valley wall, a phenomenon of stream scuplture which is in apparent accordance with Ferrall's law (or Coriolis force). Bluffs as high as 200 feet extend along the southwest bank of the Savannah River; and bluffs 40 to 80 feet high occur along the southwest side of the Santee River, where the limestone on the northeastern side has been extensively eroded and in many places completely removed. Doline development has progressed on the southwestern bluffs and is characterized by the occurrence of scattered jamas (a chimney-like varient of the doline type), particularly south of the Santee River.

A marked contrast in surface drainage patterns is exhibited between these areas underlain by limestones at shallow depth and those in which the limestone either is covered by a thicker or more impervious overburden or is not present at all. Areas underlain by limestone at shallow depth exhibit a retarded surface drainage pattern in which the number of surface streams per unit area is considerably less than in areas where the limestones occur at greater depth or where no limestone is present.

In some of the areas adjacent to (and generally northwest of) those now underlain by calcareous Tertiary deposits, landforms typical of limestone terranes may be found, particularly in the areas of Tertiary overlap. In these areas solution of the calcareous beds in the Upper

Cretaceous or Tertiary formations left a residue of clayey sand, the surface of which is pitted with sinkholes or other solution depressions. These solution features may be found also on the flood plains of some of the larger streams.

In areas underlain by Tertiary limestone or calcareous marl the present topography is similarly characterized by the presence of solution depressions. Some of these are representative of the so-called Carolina Bays whereas others are related to sinkhole development.

Deposits of Miocene age may be correlated with a characteristic topography. Almost all areas underlain by marls of Miocene age are very flat, exhibiting but very little relief. This flat surface is often dotted with an assemblage of so-called Carolina Bays. In fact, the occurrence of "Carolina Bays" more often than not is coextensive with those areas underlain by shallow deposits of middle Miocene to early Pliocene age. If solution phenomena are a primary factor in the origin of the bays (as considered likely by an appreciable number of geologists), then the genesis of the bays might be linked closely with these upland plains. Some of the typical bays are on the plains formed by overlapping Tertiary deposits, which now contain or at some previous time contained calcareous material. The ground water circulating through the residuum of these Tertiary deposits contains a much larger amount of calcium bicarbonate than is normally found in water from sandy sediments. Vertical and lateral movement of ground water is accentuated in these upland plains, owing to the high head developed, and the solution process is similarly accentuated.

HYDROLOGY OF LIMESTONE TERRANES

Limestone permeability is generally of two types, primary and secondary. Primary permeability is due to the pore space originally present in the semiconsolidated sediment. Secondary permeability is attributed to fractures developed in the rocks during and after consolidation and is due mainly to diastrophism. Solution of the limestone results in a marked increase in permeability, both primary and secondary.

In limestone terranes the factor of solubility plays an important part in the hydrologic regimen, whereas in most others its effect is minimal.

Swinnerton (1932, 1942) considered the following factors as most important in the limestone-solution rate: length of time solvent is in contact with solution, temperature, barometric pressure, carbon dioxide pressure, area of contact between solvent and solute, number of ions in solution, hydration of solute, polarity of solvent, volume of solute, and rate of flow. He adds that ". . . a large volume of solvent of low concentration flowing over a large area is probably more effective in producing solution than more stagnant solvents of lesser volume and contact."

Davis (1930) considered the slow movement of ground water to be the most important single factor in the solution of limestone beds and that the solution was greatest in those parts of the limestone where ground water moved very slowly.

The geochemical factors involved in limestone solution are apparently not too well understood at the present time. According to Adams and Swinnerton (1936), the partial pressure of carbon dioxide in the atmosphere is insufficient to account for the content of calcium bicarbonate in normal hard water. Explanations offered for the high calcium bicarbonate content are as follows: (1) ground water becomes enriched in CO_2 by percolation through soils where the partial pressure of this gas is known to be higher than in the atmosphere; (2) the solubility of circulating ground waters may be increased by the presence of acids generated by bacterial decomposition; and (3) the oxidation of carbonaceous matter below the water table provides the additional CO_2.

During parts of Oligocene and Miocene time, the Santee Limestone, Castle Hayne Limestone, and Cooper Marl were exposed to subsurface erosion which facilitated the development of solution caverns and conduits through the rock. Later in Miocene time these beds were covered by the clays and siliceous phosphate of the Hawthorn and younger formations. Early in the history of these formations, the circulating ground waters occurred under water-table conditions; and subsequently, when they were covered by relatively less permeable rocks, an artesian system developed downdip from the outcrop area. For short distances downdip and under a comparatively thin mantle of overlying sand and clay the limestone still functions as a water-table aquifer in which part of the recharge is facilitated by subterranean piracy of surface streams under the topographic highs. In topographically lower areas the water table is close to the surface and the rock itself is rather soft and homogeneous. Downdip, where artesian conditions predominate, the upper part of the limestone becomes indurated and more porous. In some coastal areas, where the confining bed was eroded away prior to the deposition of younger, more permeable sand and sandy clay, the aquifer is recharged by direct infiltration of rainfall. The limestone aquifers are exposed at the bottom of some of the deeper estuaries and discharge in those places.

The solution of limestone at depths considerably greater than that of the water table has been substantiated by several investigators (Moneymaker, 1948; Jordan, 1950; Kaye, 1957). To date, studies of ground water in limestone aquifers in South Carolina have not confirmed the existence of solutional activity at depths greater than about 300 feet. However, the data obtained are by no means complete, and solution could be active at greater depths. In the Beaufort area the limestone is most permeable in the uppermost 25 feet of the formation. At greater depths, the limestone becomes less porous and the rock appears to be more nearly of a soft marl than a compact limestone. It also becomes less permeable at depth, as indicated by the smaller yields of wells drilled below the upper 25 feet of formation. But the relation of permeability to depth is not uniform throughout even small areas; for example, the permeability of the limestone in the vicinity of Gardens Corner, Beaufort County, is appreciably less than it is at similar depths in Burton, 9 miles to the south. The distance from Gardens Corner and Burton to points of natural discharge is approximately the same. Ten miles southwest of Burton, an area farther from natural discharge, the formation becomes appreciably more permeable. Still higher permeabilities are thought to exist at greater distances to the southwest. Thus M. A. Warren of the Geological Survey (oral communication, 1957), as a result of studies in the Savannah area, thought that the aquifer was increasingly permeable to the southwest. The transmissibilities definitely increase southwestward from Beaufort to Savannah, but here the effect of artificial discharge from wells might be decisive. The amount of water pumped from the aquifer in the Savannah area is several times that pumped at Beaufort, but the wells are deeper and penetrate a greater thickness of the aquifer. The amount of water pumped in the Burton area is likewise greater than that pumped at Gardens Corner. Therefore the relation of local permeability to depth and to the distance to areas of discharge is complicated by several factors, whose degree of influence is not definitely understood at this time.

Some of the factors affecting the hydrology of the Eocene limestone to the south are similarly applicable to the Miocene marls or limestones in the northern half of the Coastal Plain. In this area the Duplin Marl occurs as a rather thin, almost flat series of deposits. Its ground-water movement has received little attention, and not much is known concerning its permeability, porosity, and other hydrologic factors. However, water levels in wells tapping this formation in Sumter County have been recorded at elevations higher than the top of the formation and at levels dissimilar to those in the overlying sands. Although the Duplin is closer to land surface in this northern area than is the older limestone to the south, its intake and discharge may be slower than those of the Eocene limestone because its permeability is less. Solution depressions are evident on the ground surface, but there is no karst topography. Water presumably discharges in streams and springs at the lower altitudes.

The Waccamaw Formation, tentatively assigned to the Pliocene epoch, contains some sand and shell beds which function as aquifers. The blue-clay beds in the formation probably function as aquicludes for some of the older sands. The aquifers in this formation are utilized in the development of small water supplies for domestic use. Generally, the water occurs under water-table conditions. Part of the terrane differs from that typical of limestone areas, probably because of the blanketing effect of the overlying Quaternary material. Because of this the terrane appears as a very flat plain, broken in some areas by very low ridges of old shore features. Where the terrane does reflect subsurface solution, some of the surface depressions heretofore attributed to the solution of deeper Cretaceous beds may have been formed as a result of solution in the overlying Pliocene deposits.

CONCLUSIONS

Deposits of fossiliferous marl, limestone, or coquina were laid down during each epoch of the Tertiary period in South Carolina. Many of these now crop out at the surface, although some are found only in the subsurface. The structure of these beds is generally flat to monoclinal, with gentle dips to the south and southeast. Some discordance of structure may be present in the extreme southern part.

The present terrane is affected by the nature of these deposits, in large measure owing to their solution by circulating ground waters. However, typical karst topography is not common in most of the limestone areas, although in several of them subsurface solution is indicated by the presence of dolines and of the depressions referred to in the literature as "Carolina Bays." The bays occur frequently in those areas underlain by sandy and calcareous beds of Miocene to early Pliocene age. The most prominent karst development is found on the southwest side of the major streams.

Ground-water movement from the topographically high areas updip to those of low elevation downdip has increased both the primary and secondary porosity of the limestone, principally in the upper part of each formation. The proximity of areas of discharge, either natural or by pumping, is likely to have some effect on the permeability, although the evidence is not conclusive. The solution of limestone at depths considerably greater than that of the water table, although confirmed in other areas, is not known to have appreciable application to the South Carolina Coastal Plain.

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BASES FOR COASTAL CLASSIFICATION

By

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ABSTRACT

A preliminary examination of 14 coastal classification schemes leads to a list of 17 types of basic information on which such schemes can be constructed. (Additional types of basic information may be added in the future). A chart of classificatory schemes shows the extent to which each worker has used, or ignored, the available types of information.

Several classifications, made or revised during the last 15 years, are outlined briefly. These include those of Shepard, Cotton, Fleming and Elliott, Valentin, Tanner, Price, and Guilcher.

INTRODUCTION

The classification of shorelines has long been a major problem in geomorphology. Although many people have devised classifications, no single scheme currently available has had wide acceptance as being thoroughly satisfactory. In view of the tremendous importance of coastal forms and processes, this is surprising.

The present note is the result of an effort to survey the status of coastal classificatory studies. It does not pretend to be either thoroughly historical or comprehensive. It does present, however, some of the systems which have been devised in the last few decades. It also attempts to show to what extent these various schemes have covered the subject. This concept is developed in Table 1, which is based on a list of 17 types of information which might conceivably be used in studying coasts. (It is possible that additional types of information might be found useful).

The basic ideas included in the table can be listed as follows:

Structure: stability or instability of the coast.

Structure: type, such as old mountains, young mountains, coastal plain, etc.

Motion: horizontal (advance and retreat).

Motion: vertical (emergence and submergence).

Agency: that agency now shaping the coast.

Agency: that agency which formerly shaped the coast, if different from the present agency.

Materials: bedrock (outcrops and exposures).

Materials: sediments in transit (quartz sand, shell hash, clay, etc.).

Energy type: wave, tidal, current.

Energy level: high, moderate or low.

Geometric pattern: straight, curving, indented, irregular, etc.

Coastal equilibrium: degree of balance between sediment drift and wave energy.

Transverse profile: presence or absence of the equilibrium profile (taken at right angles to the coast).

Erosion-versus-deposition.

Stage (or age): the maturity or cycle concept.

Climate:

Ecology: Organisms.

It is obvious that some of these overlap, and many others are more or less closely related. Yet each permits a certain methodology in the study of coastal areas, and each is capable of being used in worthwhile studies.

THE CLASSIFICATIONS

An early, simple classification was that of Suess (1888, 1906), who separated straight coasts, having structures essentially parallel with the shoreline, and irregular coasts, having structures at some obvious angle with the shoreline. Davis (1898) distinguished between emergent and submergent coasts, crediting the basic idea to an observation by Dana (1849). Gulliver (1899) and Johnson (1919) expanded this idea to the four-part scheme so well known by American geologists: submergent, emergent, compound, and neutral. Davis also (1898, 1912) developed the concept of the cycle in coastal development, with various stages (or ages) such as youth and maturity. In this cycle, the notion of the "graded condition" of the coastal profile was important. He described a graded profile as being an essentially smooth one, with cliffed headlands and bar-bridged bays in continuous alignment. Cotton (1954) has reviewed these early efforts, along with the contributions of others, such as Richthofen (1886) and DeMartonne (1909).

The Johnson classification was so widely taught in the United States that its influence is being shaken off only with great difficulty. It is still defended, in some quarters, because it is logical, simple, easy to teach, and easy to remember. Unfortunately, it neither classifies nor explains, as detailed studies of many coastal types, in more recent years, have shown.

Shepard (1948) presented two classifications which can be summarized as follows:

Shepard (I)

Classification of coastal types; a regional approach.

A. Coasts with young mountains (i. e., less than about 5×10^7 years old).

B. Coasts with old mountains (i. e., more than about 5×10^7 years old).

C. Coasts with broad coastal plains, including deltas and alluvial plains (i. e., the southern and eastern coasts of the U. S.).

D. Glaciated coasts.

Shepard (II)

Classification of shorelines; a detailed approach.

I. Primary or youthful coasts and shorelines, configuration due primarily to nonmarine agencies.

A. Shaped by terrestrial erosion and drowned by deglaciation or

TABLE I

Basic types of information used.	Structure: Stability	Motion: Horizontal	Motion: Vertical	Agency: Present	Agency: Former	Materials: Bedrock	Materials: In Transit	Energy Type	Energy Level	Transverse Profile	Coastal Equilibrium	Geometric Pattern	Erosion/Deposition	Stage (age)	Climate	Ecology
Structure: Type				7	5,13							0,13				
Structure: Stability			6			12	12	12	12	12		12				
Motion: Horizontal			8	8												8
Motion: Vertical				8						1,2,3		1,2,3		1,3		8
Agency: Present					4								4,7			9
Agency: Former												13	4			
Materials: Bedrock							12	12	12	12	11	12				
Materials: In Transit								10	10	10	11	12				10
Energy Type									10	10		12				10
Energy Level										10	11	12				10
Geometric Pattern											1,11	12		1,3		
Coastal Equilibrium												1,11		1		
Transverse Profile																
Erosion/Deposition																
Stage (or age)																
Climate																

0. Suess, 1888
1. Davis, 1898, 1926
2. Gulliver, 1899
3. Johnson, 1917
4. Shepard, 1948(a)
5. Shepard, 1948(b)
6. Cotton, 1954
7. Fleming & Elliott, 1954
8. Valentin, 1954
9. Price, 1954
10. Price, 1955
11. Tanner, 1958
12. Price, 1959
13. Guilcher, 1958

profile (taken at right angles to the coast).

Erosion-versus-deposition.

Stage (or age): the maturity or cycle concept.

Climate:

Ecology: Organisms.

It is obvious that some of these overlap, and many others are more or less closely related. Yet each permits a certain methodology in the study of coastal areas, and each is capable of being used in worthwhile studies.

THE CLASSIFICATIONS

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D. Glaciated coasts.

Shepard (11)

Classification of shorelines; a detailed approach.

I. Primary or youthful coasts and shorelines, configuration due primarily to nonmarine agencies.

A. Shaped by terrestrial erosion and drowned by deglaciation or down-warping.

1. Drowned river valley coasts (ria coasts); either dendritic or trellis forms.
2. Drowned glacial erosion coasts; fjords and glacial troughs.

B. Shaped by terrestrial deposition agencies.
1. River deposition coasts.
a. Deltaic coasts.
b. Drowned alluvial plains.
2. Glacial deposition coasts.
a. Partially submerged moraines.
b. Partially submerged drumlins.
3. Wind deposition coasts; prograding sand dunes.
4. Vegetation extending the coast; i. e., mangrove coasts.

C. Shaped by volcanic activity.
1. Coasts with recent lava flows.
2. Shorelines due to volcanic collapse or explosion.

D. Shaped by diastrophism.
1. Fault scarp coasts.
2. Coasts due to folding.

II. Secondary or mature coasts and shorelines, configuration primarily the result of marine agencies.

A. Shorelines shaped by marine erosion.
1. Sea cliffs straightened by wave erosion.
2. Sea cliffs made irregular by wave erosion.

B. Coasts and shorelines shaped by marine deposition.
1. Shorelines straightened by building bars across estuaries.
2. Coasts prograded by wave and current deposits.
3. Shorelines with offshore bars and longshore spits.
4. Coral reef coasts.

Cotton (1954)

The original classification (Cotton, 1918) appears in the form of a diagram or flow-sheet, which can be read in several different ways. It can be summarized as consisting of four initial coastal classes(1, resulting from volcanic accumulation; 2, resulting from either regional movement or marginal warping; 3, resulting from faulting; 4, resulting from glacial erosion below sea level), compounded by a sequence of later events (1, uplift or subsidence; 2, retrogradiation or progradiation, the latter due to either alluviation or wave action). However, if this is drawn in chart form, not all of the pigeon-holes are filled (i. e., Class I, resulting from volcanic accumulation, is not considered to have been uplifted but only stable or depressed). A slightly simpler approach given by Cotton, follows:

A. Coasts of stable regions (all are compound).
1. Recently submerged.
2. Previously emerged.
3. Miscellaneous (volcanic, fjord-wall, etc.).

B. Coasts of mobile regions (all are compound).
1. Recently submerged.
2. Recently emerged.
3. Fault and monoclinal coasts.
4. Miscellaneous (volcanic, fjord-wall, etc.).

Fleming and Elliott (1954)

This simple scheme is based essentially on the concepts of dominant agency, and erosion-versus-deposition:

A. Glacial.
   1. Erosional.
   2. Depositional.
B. Alluvial.
   1. Erosional.
   2. Depositional.
C. Young orogenic.
   1. Erosional.
   2. Depositional.
D. Biogenous.

Valentin (1954)

The notions of coastal advance or retreat, and of coastal form, are fundamental for this classification. Valentin considered first the horizontal and vertical motions which combine to cause a shift in shoreline position, then developed a picture of the form which might be expected as a result. A simplified version of his chart includes the following:

I. Advancing coasts.
   A. Emerged coasts; sea-floor coasts.
   B. Constructional coasts.
      1. Organic.
         a. Plant: mangrove coasts.
         b. Animal: coral coasts.
      2. Inorganic.
         a. Marine.
            (1) Weak tidal effects: bay-and-dune coasts.
            (2) Strong tidal effects: tidal-flat-and-island-chain coasts.
         b. Alluvial: delta coasts.
II. Retreating coasts.
   A. Submerged coasts.
      1. Glacial.
         a. Eroded.
         b. Deposited.
      2. Fluvial.
         a. Young folded.
         b. Old folded.
         c. Flat lying.
   B. Retrograded (destroyed) coasts; cliffed coasts.

Price (1954)

A simple, early classification by this author is tailored to fit the coasts around the Gulf of Mexico:

A. Alluvial.
B. Karst.
C. Young orogenic.
D. Biogenous.
   1. Carbonate (molluscs and corals).
   2. Swamp or marsh (mangrove ridge; grass or reed).

Price (1955)

This somewhat overwhelming classification consisted of three charts (each of which is rather involved), accompanied by a list of terms, notes, and sketches. Although very elaborate, the chart does not cover all shoreline types. The dominant considerations are energy type, energy level, transverse profile, and materials in transit. Deltas are treated in detail in one of the two auxiliary charts, and only briefly in the main scheme.

I. Smooth, well-aligned shorelines.
   A. Wave-dominated.
      1. Medium to high energy (ramp gradients 1.5 to 5.0 feet per mile): beach ridges, cuspate forelands, fan deltas, stream deltas, barrier chains, lagoons.
      2. Zero to low energy (ramp gradients up to 1.5 feet per mile); perched beach ridges and storm ridges on pocket beaches.
   B. Current-dominated.
      1. Low to medium energy (ramp gradients 0.8 to 2.5 feet per mile): chenier plain.
      2. Zero energy: marsh, swamp, or mangrove barrier ridge.
   C. River-dominated: deltas.
II. Irregular shorelines.
   A. Tide dominated.
      1. Medium to high energy: cross-channels, tidal networks, funnel estuaries, ria coasts.
      2. Zero to low energy: marsh, mangrove barrier ridge, drowned karst, abandoned delta, multilobate deltas, funnel estuaries, unfilled drowned valleys.
   B. Organic: reefs.

Tanner (1958)

The relationships between coastal equilibrium, on the one hand, and bedrock materials, materials in transit, energy level, and geometric pattern, on the other hand, underlie this classification. In chart form, the log of mean annual breaker height (in cm; B) can be plotted against the log of mean annual drift (in m^3; L) to yield an equilibrium line which can be approximated by either

$$B = 0.634L - 1.66$$

or

$$L = 1.577B + 2.62.$$

If a given coast falls on or close to this line, a stable version of the equilibrium form (similar to Davis' "graded condition") should appear. If a coast falls off of the line, to either side, the equilibrium form should shift position, geographically, or even be destroyed. These basic ideas can be summarized in simplified form:

A. Sub-equilibrium coasts: equilibrium form has not developed yet.
   1. Equilibrium conditions do not exist because energy level is too low and drift "load" is too small; essentially the "zero energy" shoreline; mean annual breaker height probably less

than one centimeter.

2. Equilibrium conditions do exist; waves will, in due time, shape the coast.
3. Equilibrium conditions do exist; tectonic instability precludes an equilibrium shoreline.

B. Equilibrium coasts. Wave energy, beach sand prism characteristics, map geometry, and drift "load" are so precisely adjusted to each other that the equilibrium form is maintained.

1. Stable equilibrium; shoreline does not shift either landward or seaward.
2. Shifting equilibrium.
   a. Prograding. (By various means; see under "D", below).
   b. Retrograding. (Decrease in drift "load" or increase in wave energy).

C. Eroded coasts. Wave energy markedly exceeds that necessary to carry the drift "load" which is available; active wave erosion, and a landward shift of part or all of the shoreline. The shape of the shoreline will depend on bedrock materials present.

D. Constructed coasts. Wave energy is markedly less than that necessary to carry the drift "load" which is available.

1. Excess load is supplied by non-marine agencies.
   a. Streams (deltas).
   b. Glaciers.
   c. Volcanoes.
2. Excess load is supplied by marine agencies.
   a. Waves, by drift.
   b. Waves, from offshore.
   c. Other marine agencies.
3. Excess load is due to a down-shore diminution in wave energy, without any absolute increase in drift "load".

Price (1959)

For the Institute in Marine Geology, held at Florida State University in the summer of 1959, Price undertook a rearrangement of his previous classifications. The revision required 24 pages of text, prepared for and circulated to participants in the conferences, and included five different tabulations, based respectively on: I. Large-scale features; II. Wave energy; III. Deltas; IV. Progradation; and V. Smoothness-versus-irregularity (geometric pattern). These separate schemes are summarized below:

Large-scale features

I. Unstable coasts.
   A. Isostatic: coasts formerly glaciated ("Atlantic" or "discordant" types).
   B. Tectonic: young, orogenic coasts ("Pacific" or "concordant" types).

II. Moderately stable coasts.
   A. Narrow steep coastal plains off mountains of dying orogeny.
   B. Others?

III. Coasts largely stable, chiefly progradational.
   A. Broad, gently sloping wave-dominated coastal plains, with sandy alluvium.

1. Off an old mountain chain. (Eastern U. S., New Jersey to Georgia).
2. Off continental interior or distant low highlands. (Texas coast).

B. Narrow coastal plains and alluvial valley mouths on old plateau coasts.
1. Deltaic. (French West African coast).
2. Chenier plain. (Guiana coast of South America).
3. Marshy alluvial valley mouth. (Amazon estuary).

C. Broad limestone coastal plains.
1. Drowned karst, zero wave energy coast. (Florida coast near Cedar Keys).
2. Barrier-bordered, medium wave energy coast. (Florida coast near Tampa).
3. Barrier-bordered, high wave energy coast. (Atlantic coast of Florida).

Wave energy

I. Tide dominated; zero wave energy.
II. Wave dominated.
A. Low wave energy.
B. Medium wave energy.
C. High wave energy.

Deltas

I. Leaf fan deltas.
A. Digitate. (Belize sub-delta of Mississippi river).
B. Lobate. (Mississippi river delta complex).
C. Arcuate. (Brazos-Colorado river delta, Texas).
II. Cuspate.
A. Beach plain. (Rhone).
B. Barrier. (Apalachicola river delta, Florida).
III. Multilobate. (Ganges; Irriwaddy).

Prograding coasts

I. Strand plains. Deltas; beach plains and chenier plains; barrier-and-lagoon plains; marsh and swamp.
II. Sediment dams. Transverse (paired natural levees); Longitudinal (ridges, tidal levees, reefs, etc.).
III. Settling basins. Deltaic levee flanks; coastal lagoons; reef lagoons.

Smoothness-versus-irregularity

I. Irregular coasts.
A. Tide dominated: initial (no equilibrium profile).
B. Tide dominated: depositional.
1. Deltaic.
2. Volcanic.
C. Tide dominated: erosional (tide channeled).
II. Smooth coasts.
A. Wave dominated OR tide dominated.
1. Initial. (Drowned plain).

2. Tectonic. ("Pacific" or "concordant" shoreline).
B. Wave dominated.
1. Prograded.
2. Eroded.

Guilcher (1958)

This simple essentially structural classification offers little that is new, but rather sticks with the methodology of the older, more nearly descriptive, efforts:

I. Ria coasts.
II. Fjord coasts.
III. Glacial lowland coasts.
IV. Unglaciated lowland coasts.
V. Coasts dominated by structure.
  A. Longitudinal structure. ("Pacific" or "Dalmatian").
    1. Direct tectonic influences; i. e., recent faulting.
    2. Indirect tectonic and lithologic influences; i. e., ancient folding or faulting.
  B. Transverse structure. ("Atlantic").
    1. Direct tectonic effects.
    2. Indirect tectonic and lithologic effects.
  C. Oblique structure.
  D. Arcuate structure.
  E. Rectangular structure.
  F. Discordant structure; contraposed coasts.
  G. Volcano coasts.
    1. Circular or lobate.
    2. Caldera.

CONCLUSIONS

Fourteen classifications have been either listed or summarized. The basic ideas which each of these schemes contributes to coastal classification work are given in Table 1. From a study of the table one can observe that certain studies have concentrated on one or two points only, whereas others have been very broadly conceived.

It is apparently yet too early to rank the bases of classification. Not enough information appears available to permit one to exclude, for example, "Climate"; certainly climate is important. Nor can one give relative status to many of the other types of information which might be used.

Perhaps most surprising is the list of ideas which have been used little or none at all: materials deposited (sand, clay, shell hash, calcilutite, peat, etc.); bedrock materials (consolidated, unconsolidated; soluble, insoluble; finely-fractured, coarsely-fractured; etc.); climate; organisms present. And of course there is the possibility that additional pertinent ideas, included to date in none of the schemes listed, may be revealed in future work.

Obviously coastal classification is not a simple matter. The diversity of methods of attack is evidence that many workers in this field are not yet satisfied with the products of previous investigations. The uncertainty involved in evaluating the various devices is evidence that much work still remains to be done.

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CASE HISTORY STUDIES OF HOW GEOLOGY AND HYDROLOGY INFLUENCE NUCLEAR REACTOR SITE LOCATIONS IN FLORIDA

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ABSTRACT

Three different projects concerning site location studies for proposed nuclear reactors to be located in different parts of Florida are discussed. One project involved a generalized and detailed study of the geologic and hydrologic factors of importance in evaluating a pre-selected area near Pierce, Fla., about 35 miles east of Tampa. A second project involved a similar study of the Ft. Pierce area on the lower east coast. A third project was to find the most favorable sites, geologically and hydrologically, in the broad area including Dixie, Levy, Citrus, and Marion counties.

Favorable geologic and hydrologic factors influencing the safety factors inherent in a given site location were used to evaluate the various possible reactor site locations. These factors were:

1. Quantity and quality of surface and ground water available at any location.
2. Topography and drainage characteristics.
3. Population affected in the event of accidental spillage of radioactive liquids or solids to the ground.
4. Porosity and permeability of the soil and bedrock at each locality.
5. Downstream hazard in the event of radioactive contamination of surface or ground water.
6. Possible protection the soils may afford toward radioactive decontamination due to their clay content.
7. Radioactive dilution potential of surface and ground water in each area.

Several areas in Citrus and Levy counties are identified as having the most favorable geologic and hydrologic characteristics from the standpoint of safety. To these advantages, engineering and economic factors were added to give an overall rating in each general area.

INTRODUCTION

During the past year the writer had the opportunity to work on three projects concerning site location studies for proposed nuclear reactors to be located in different parts of Florida. One project involved a generalized and detailed study of the geologic and hydrologic factors of importance in evaluating a pre-selected area near Pierce, Florida (about 35 miles east of Tampa) for inherent safety factors of the surroundings in the event of accidental spillage of radioactive liquids to the ground. A second project involved a similar study of the Ft. Pierce area in St. Lucie County. A third project was to study these same factors and select a broad area in Florida which possessed recognized inherent safety factors due to favorable geology, hydrology, sparse population distribution, and then combine these with engineering and economic factors to obtain an overall rating of five specific areas within the broad area, which included Dixie, Levy, Citrus and Marion counties.

Certain details of this study can be revealed in the case of the Tampa area since the land has already been purchased for the reactor site location. A somewhat similar situation exists in the Ft. Pierce area. However, in order to avoid the temptation of using detailed information in the Citrus - Levy - Dixie - Marion County area for land speculation in anticipation of locating a nuclear reactor at a particular place, the writer is not at liberty to identify the best site location areas in detail. It is believed that within these limitations, there is growing interest as to what geologic and hydrologic factors enter into an engineering analysis of the feasibility of a nuclear reactor site, and how these same factors affect a safety analysis of the site and surroundings. Geologic and hydrologic factors are only two among many factors that bear upon the engineering feasibility and safety analysis of a proposed nuclear reactor facility. It is also believed that a certain amount of publicity as to the scope and amount of work involved in attempting to evaluate carefully the safety factors will help to alleviate the fears of the general public concerning nuclear reactor hazards and inform the public how these hazards are being met.

TAMPA AREA REACTOR NEAR PIERCE

Figure 1 shows the general site location for the Florida West Coast Nuclear Group project. Figure 2 shows the area immediately surrounding the site, which lies near the divide between the Alafia and Peace River systems. Figure 3 shows the topographic map of the site and surrounding area. The abundance of ponds and marshes suggests the generally slow percolation of surface water down to the Floridan aquifer. A large portion of this area is saturated with fresh ground water from the surface to depths of many hundreds of feet. Figure 4 shows the site located on the 1959 geologic map of Florida. The Bone Valley Formation forms the bedrock in this area.

General Geology and Hydrology of the Area

Figure 5 shows the long-time average flow of rivers in Florida in cubic feet per second. There is a small amount of stream flow in the site area. Figure 6 shows the general structural geology in central Florida. Note the southeastward dip of the rocks, the thick limestone aquifer (Floridan aquifer) overlain by Hawthorn, Bone Valley, and Tamiami Formations which contain lenses of clay and sand and act as semi-permeable aquicludes. Figure 7 shows the Florida Stratigraphic Nomenclature Chart. The formations important to this study (named from oldest to youngest in age) are the Inglis, Williston, and Crystal River Limestones; the Suwannee Limestone; the Tampa Formation; Pleistocene formations, and Recent formations. The Pleistocene and Recent sand terrace remnants are not shown on the geologic map in the

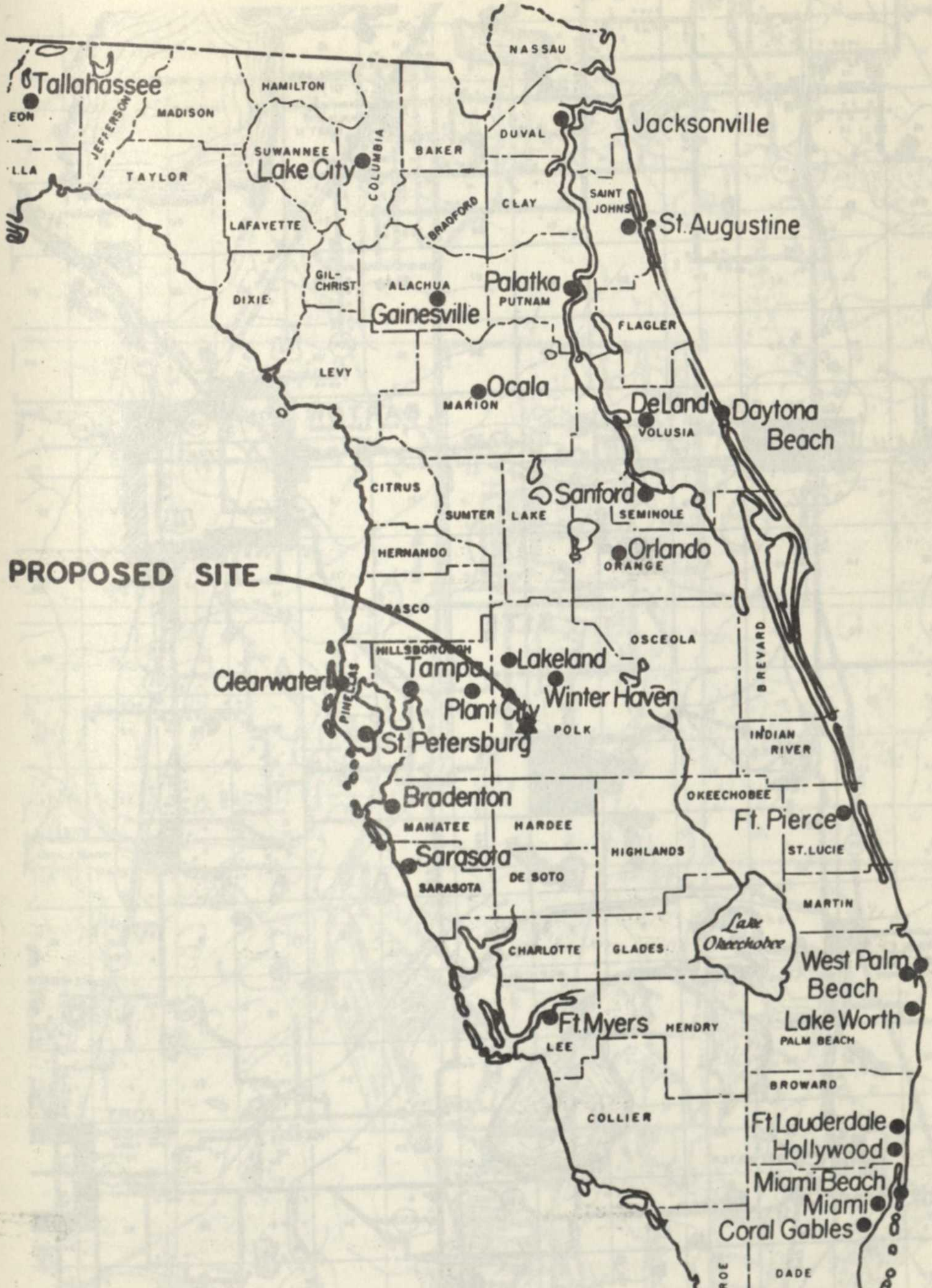

Figure 1. General site location for the Florida West Coast Nuclear Group project.

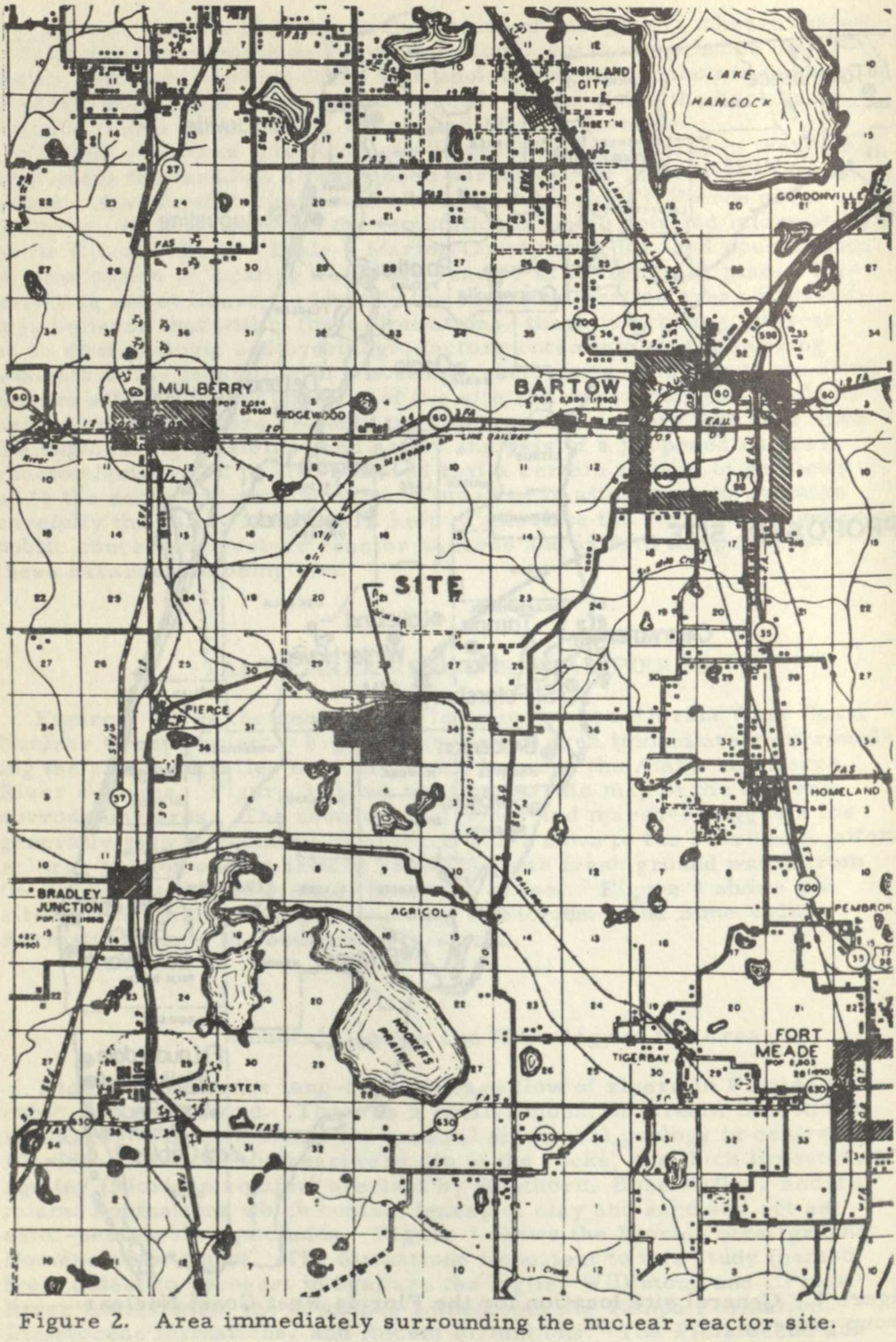

Figure 2. Area immediately surrounding the nuclear reactor site.

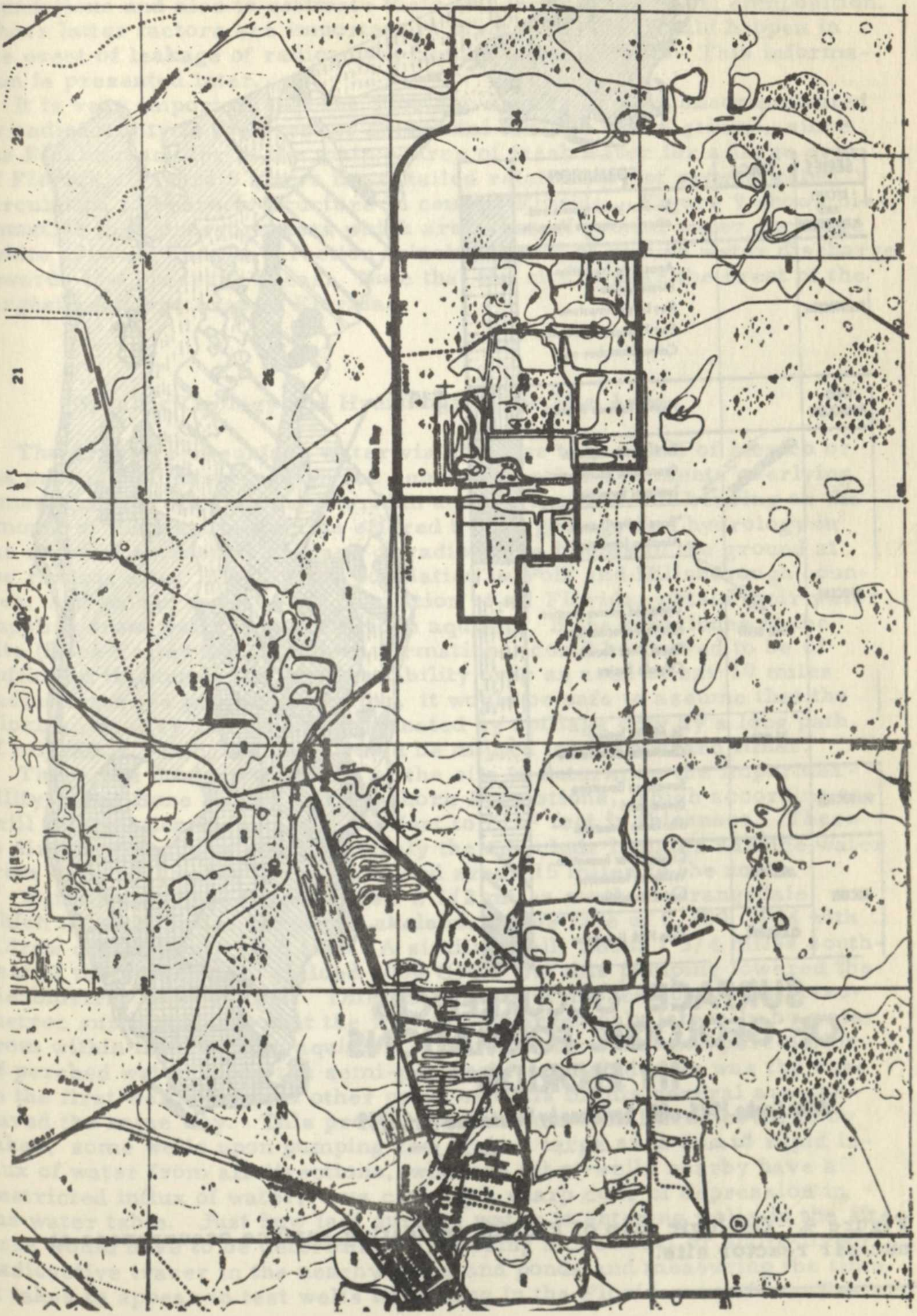

Figure 3. Topographic map of nuclear reactor site and immediate area.

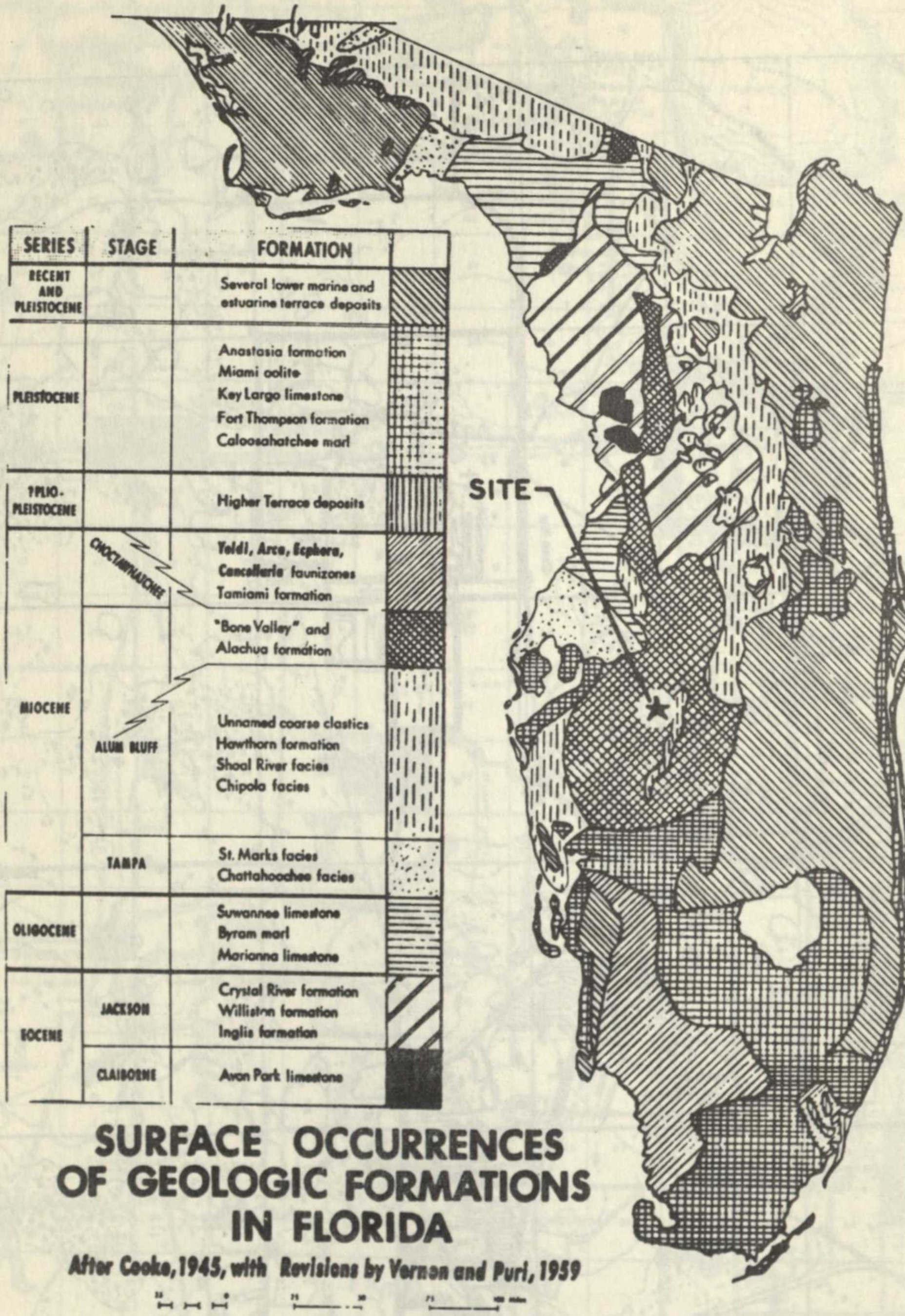

Figure 4. Geologic map of Florida indicating surface occurrences at nuclear reactor site.

site area, but they characterize much of the soil. Drilling was done to locate these soils and to evaluate their characteristics for supporting foundations and also to estimate their mineral and chemical composition. These latter factors are important in predicting what would happen in the event of leakage of radioactive liquids to the ground. This information is presented later.

It is very important that the Floridan aquifer remain uncontaminated by radioactivity in the event of accidental leakage to the ground, since the Floridan aquifer is the main source of fresh water for a large area of Florida. Figure 8 shows the detailed relationship of ground water circulation to bedrock structure in central Florida. Figure 9 shows piezometric high pressure areas which are areas of ground water recharge (white arrows) and the direction (black arrows) of ground water discharge towards low pressure areas. Note that the site is near the crest of the largest recharge area in Florida.

Specific Geology and Hydrology of the Site Area

The drainage of surface water via streams to the Gulf of Mexico or via percolation down through the semi-permeable sediments overlying limestone bedrock into the Floridan aquifer has a direct bearing on the amount of inherent protection offered by the geology and hydrology in the event of accidental spillage of radioactive liquids to the ground at the reactor site. Most of the population in Polk and Hillsborough counties, and indeed most of the population of all Florida, obtain their water supplies from wells in the Floridan aquifer. If the aquicludes at the site (Bone Valley and Hawthorn formations) could be proved to be of sufficient thickness and impermeability over an area of say 10 miles radius from the proposed reactor, it would be safe to assume that the Floridan aquifer could be contaminated by spillage only by a long path of migration during which it would be diluted many thousand times.

There are no deep well data at the site to determine the impermeability of the Bone Valley and Hawthorn Formations, which according to drill information range from 105 feet to 215* feet in thickness. There is direct evidence of how effectively the aquiclude isolates surface water from deep well water in the Lakeland area, 15 miles to the north.

Water was pumped from a well 2 1/2 miles south of Orangedale, which is seven miles north of Lakeland, at the rate of 6, 500 GPM with a draw down of only 11. 6 feet. A similar well, about 1 3/4 miles southeast of the above well, yielded 4000 GPM, but this pumping lowered the piezometric level 69 feet. This sharp cone of depression in the piezometroc surface means that the well is recharged only laterally by water from within the Floridan aquifer, rather than by downward percolation of perched water above the semi-permeable aquiclude, as was the case in the first well. Several other pairs of wells in this general area behaved the same way. This proves that within a small area covered by lakes, some wells upon pumping can drain a large area due to rapid influx of water from all directions, whereas other wells nearby have a restricted influx of water, thus causing a sharp cone of depression in the water table. Just how fast surface water is entering wells in the site area would have to be determined by placing a chemical or short-lived radioactive tracer in the nearby lakes and ponds and measuring the time it takes to appear in test wells bottoming in the Floridan aquifer. Tests

* Personal communication, Florida Geological Survey, Tallahassee.

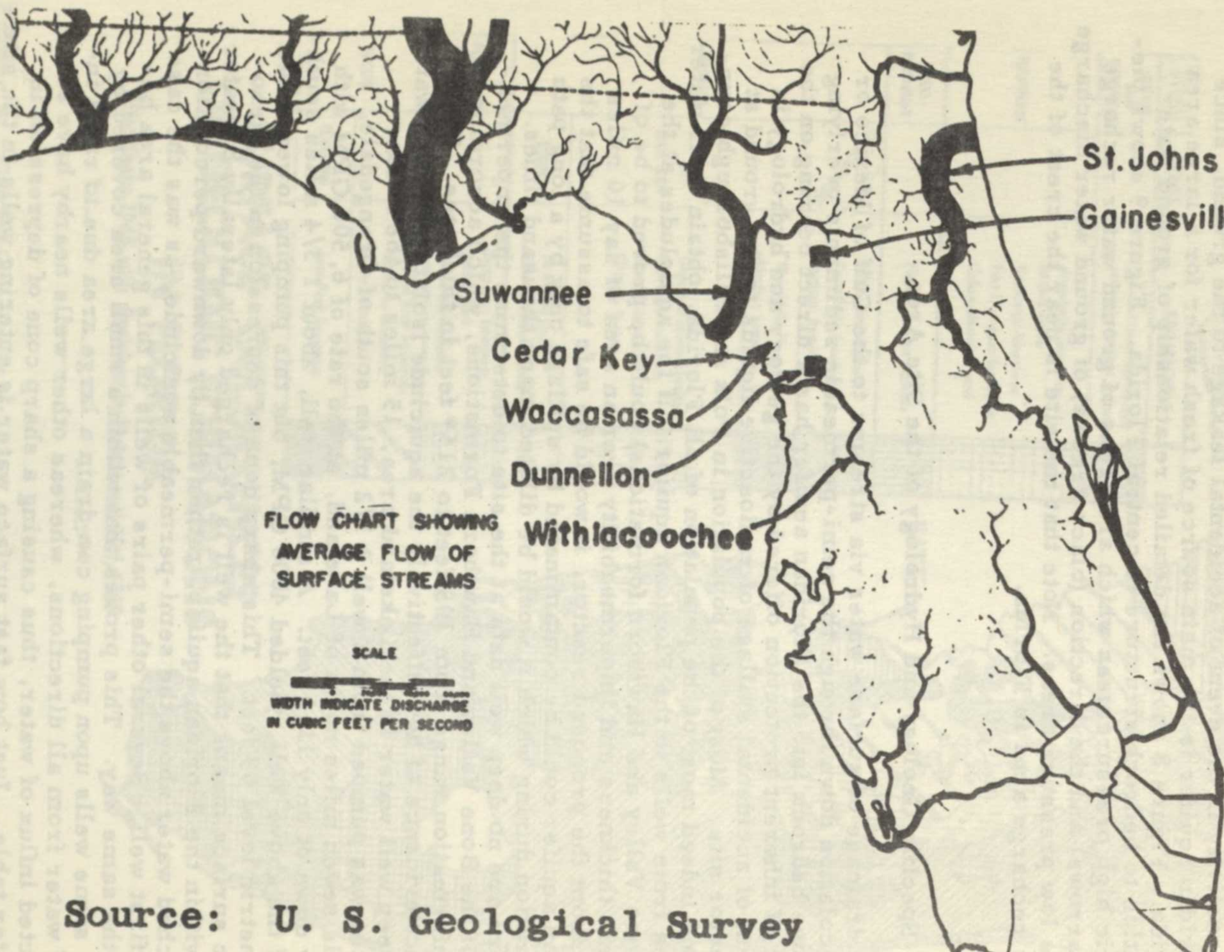

Figure 5. Long time average flow of rivers in Florida.

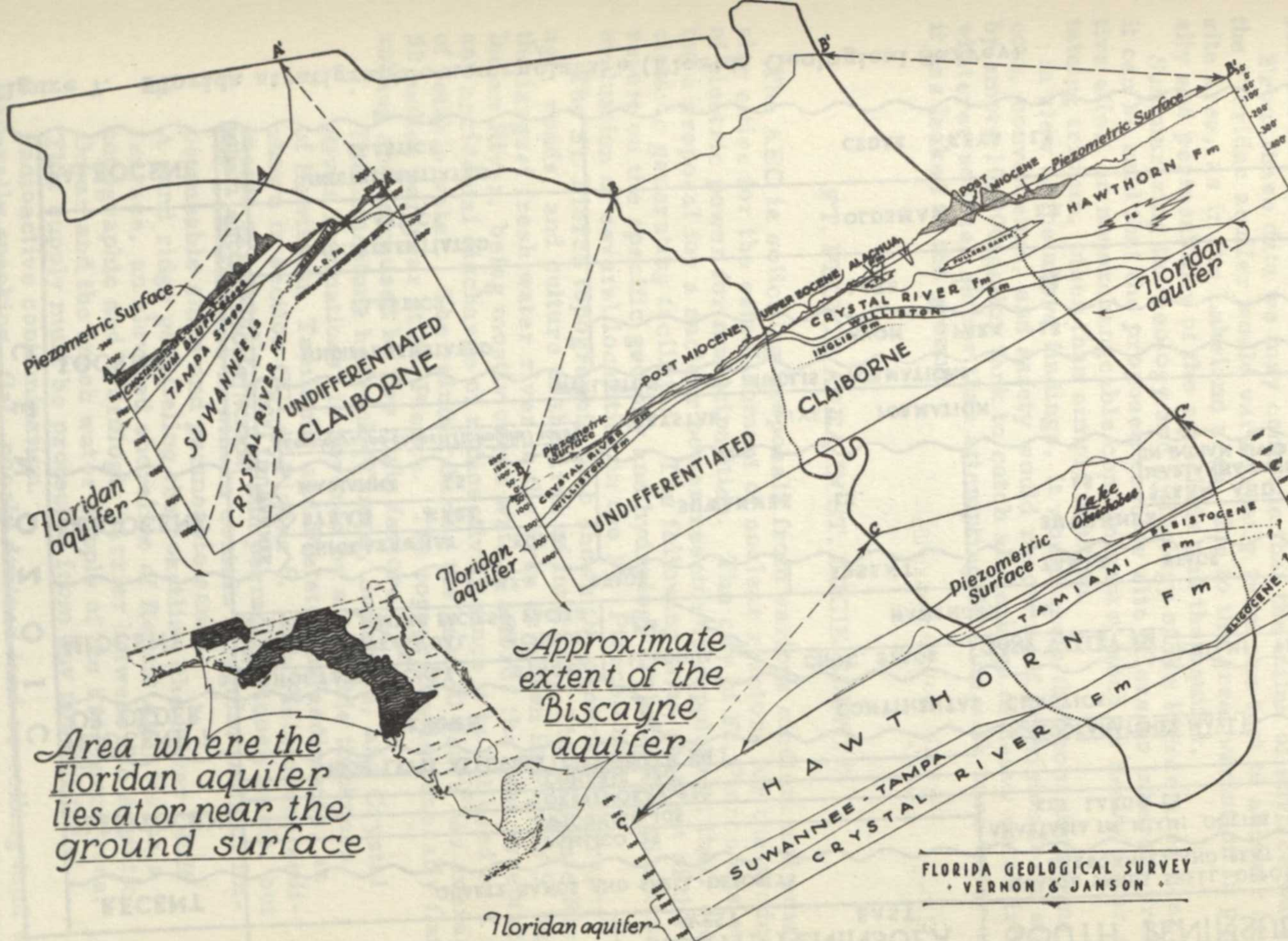

Figure 6. Geologic cross-sections of Florida.

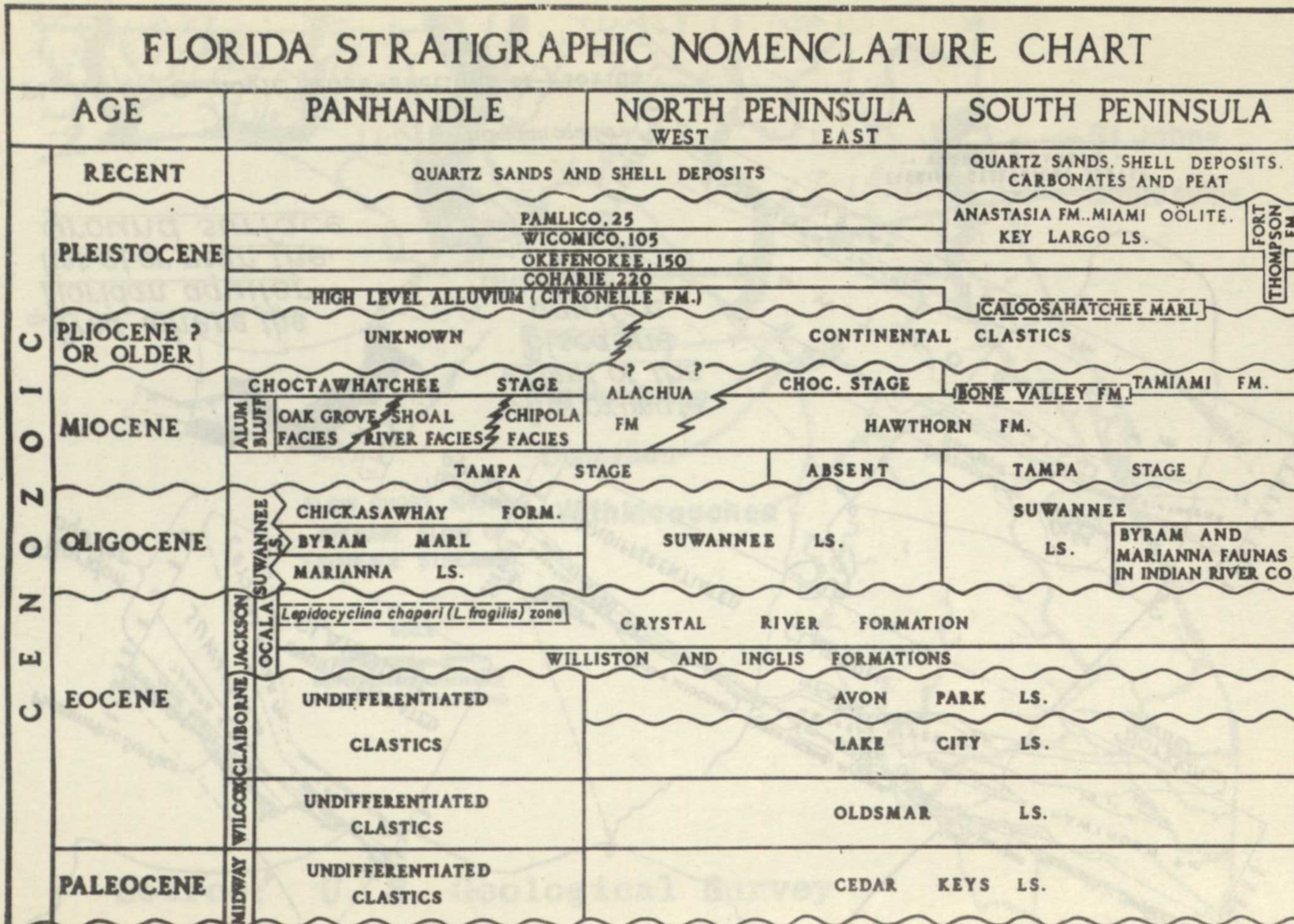

Figure 7. Florida stratigraphic nomenclatture (Florida Geological Survey).

of this nature are now in progress. Similar experiments in the Gainesville area proved that pond water percolated downward 500 feet and laterally 1 1/2 miles to reach deep wells supplying city water within 10 hours (Reichert, 1958). However, the protective aquiclude in the Gainesville area ranges from 0 - 50 feet in thickness, as compared with 105 - 215 feet at the Pierce area.

From these data we may conclude that the influx of surface water to the Floridan aquifer would vary greatly from one test to another at the site area, as in the Lakeland area, due to the great variation in porosity and permeability of the aquiclude and the aquifer.

Summarizing the geology and hydrology of the Pierce area near Tampa, it can be said that the proposed reactor site offers no inherent protective effect on nonexchangeable contaminants, such as heavy water containing tritium, other than simple dilution.

In view of the above findings, it would seem that considerations of cost, convenience, and safety would recommend provision for a standby empty 10,000 gallon tank to catch all leakage of heavy water from whatever source, rather than attempting dilution with pure water after it has leaked to the ground.

FT. PIERCE AREA IN ST. LUCIE COUNTY

The AEC is soliciting proposals from various medium and small size cities for the establishment of nuclear reactors for the production of electric power for municipalities. The city of Ft. Pierce has submitted a proposal for a nuclear power reactor to supplement their steam-electric generating facilities. The following is an abstract of the writer's report on the specific geology and hydrology of the area and a hazards evaluation of several localities in the Ft. Pierce area.

The Ft. Pierce topographic map shows the general topography, drainage, roads, and culture of the area of interest. The St. Lucie River is the largest fresh water river in the area as shown in Figure 5, but the Indian River, being mostly ocean water, affords the best receptacle for any accidental discharge of radioactivity since it is not used as a source of potable water. The rainfall during the past 40 years has averaged 53 inches per year at Ft. Pierce. The topography is generally flat to rolling and is caused by two main factors.

1. The limestone bedrock (Tampa, Suwannee, and Crystal River Formations) is covered by a variable thickness of Hawthorn, Tamiami, and Pleistocene sediments, as shown in section CC' of Figure 6. The Pleistocene sediments are mostly porous and permeable loose sands, but the Tamiami and Hawthorn contain irregular beds of impermeable clays and permeable sands.
2. A sand ridge paralleling the coastline (the Silver Bluff terrace, an elevated shoreline of Recent Age) forms a topographic and hydrologic barrier between the Atlantic Ocean and the fresh water supply of the Ft. Pierce area. This supply must be protected from any possibility of radioactive contamination.

Generally speaking, flat, poorly drained land or rolling land with numerous ponds and lakes indicates a high water table resting on impermeable clay beds at a relatively shallow depth. Well-drained flat or

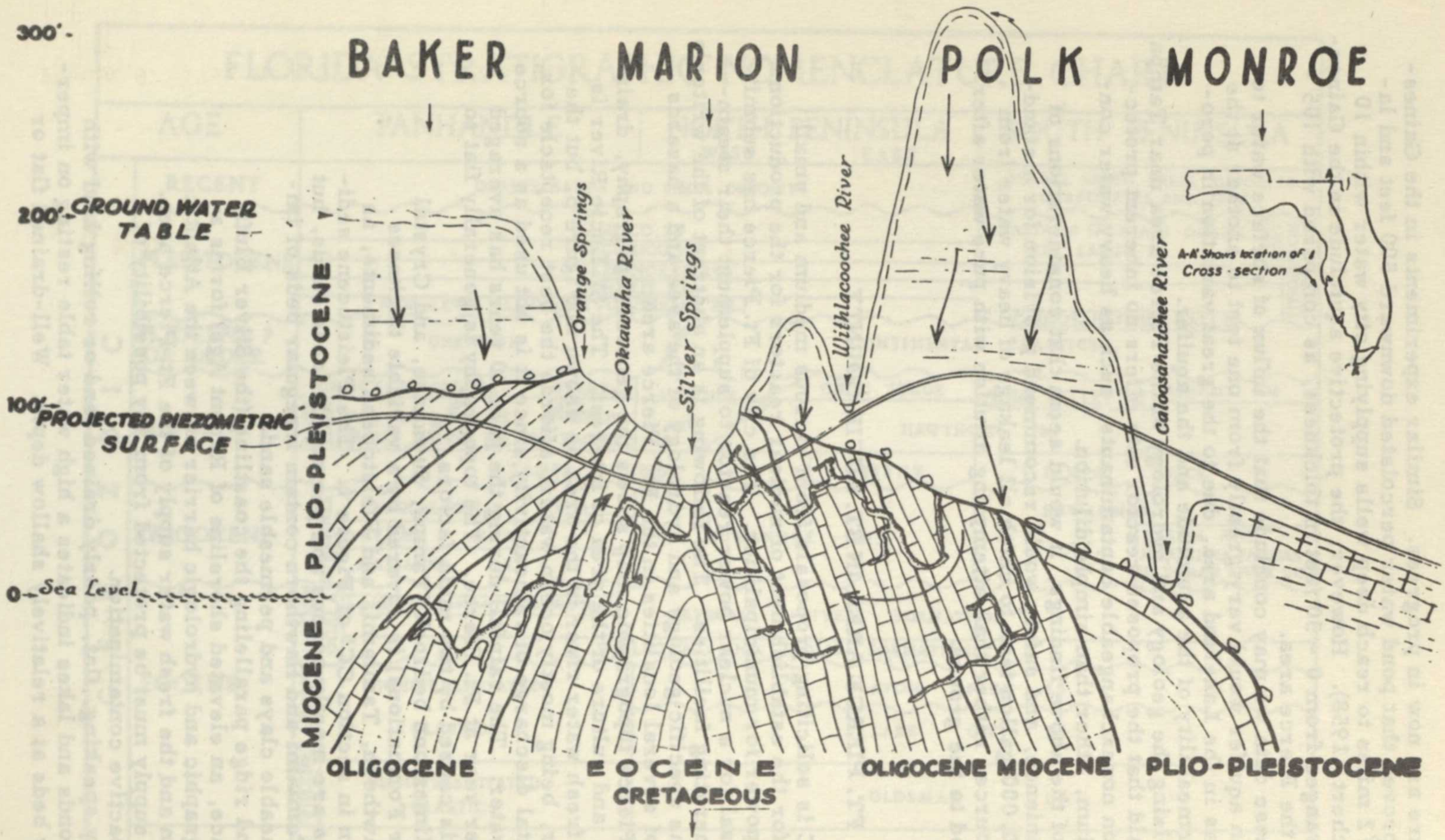

Figure 8. North-South geologic-hydrologic cross-section of Florida, showing piezometric surface. Vertical exaggeration is 3500 to 1 as compared to horizontal scale. This exaggeration emphasizes the dip of the strata, topography, and piezometric surface. Source, R. O. Vernon, Florida Geological Survey.

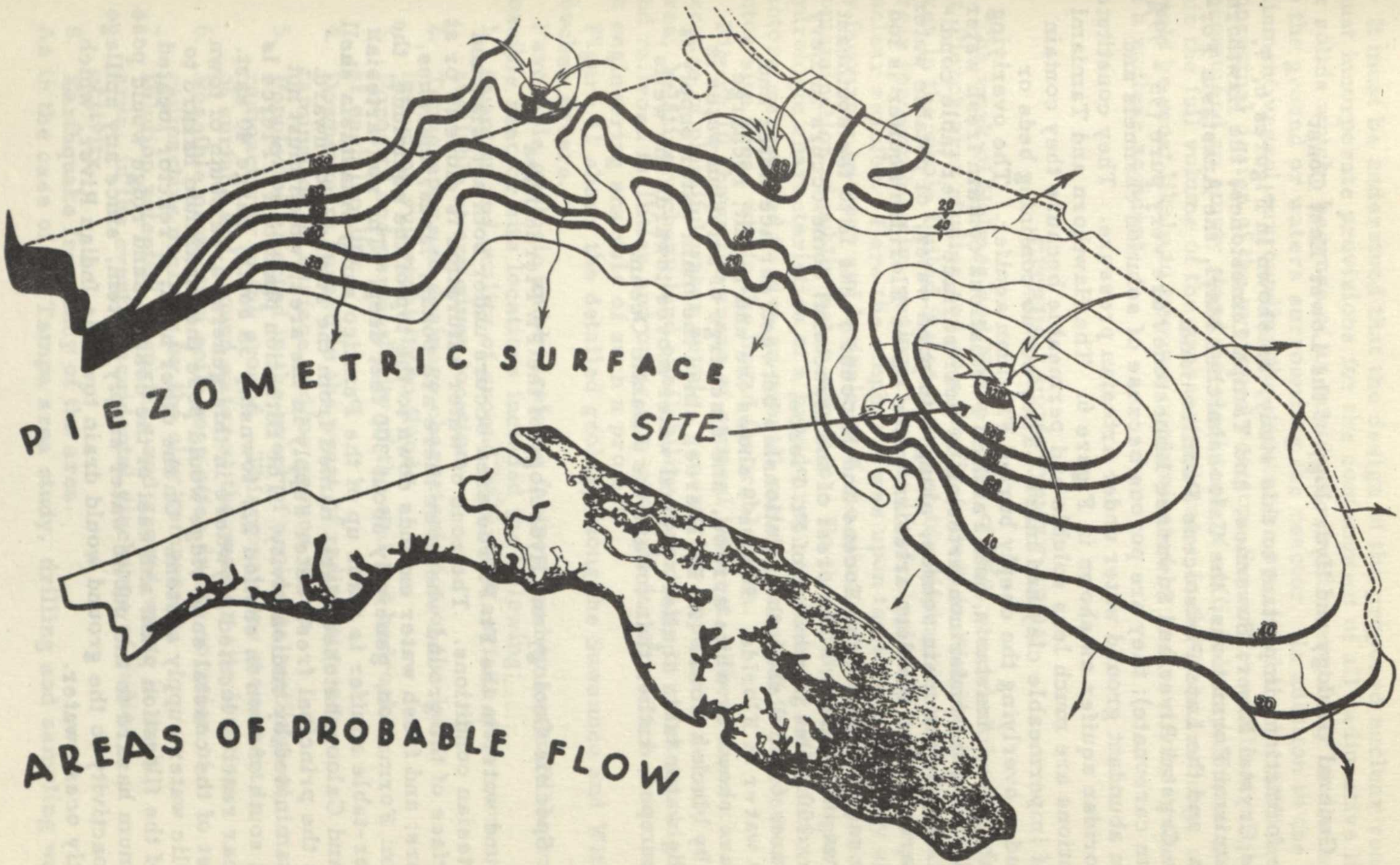

Figure 9. Piezometric map of ground water. Source, Florida Geological Survey.

rolling land indicates a deeper water table in thicker, porous sands.

General Geology and Hydrology of the Lower East Coast

The formations important to this study, as shown in Figures 6, 7, are the Crystal River, Suwannee, and Tampa Limestones, the Hawthorn and Tamiami Formations, the Caloosahatchee Marl, the Anastasia Formation, and the Late Pleistocene Pamlico sand.

The Crystal River and Suwannee Limestones are very pure (95 - 99% calcium carbonate); they are porous because of solution channels and contain abundant ground water under artesian pressure. They constitute the Floridan aquifer as shown in Figure 6. The Hawthorn and Tamiami Formations are much less soluble and permeable because they contain beds of impermeable clay and marl. They act as confining beds or aquicludes overlying the deeply buried Floridan aquifer. The overlying Calooshatchee, Anastasia, and Pamlico Formations contain fresh water at shallow depths under non-artesian or near surface water table conditions. This is the main source, along with pond water, of potable water in the area, since the deep artesian water in the Floridan aquifer is too saline.

The regional dip of the Eocene and Miocene rocks is to the southeast as shown in Figure 6. The crest of the structural dome occurs in Levy County, 200 miles northwest of Ft. Pierce.

Figures 6 and 8 show the relationship between surface water and ground wat er in Florida. Figure 9 shows the end result; recharge areas are shown by white arrows, and discharge of artesian water is shown by black arrows. At Ft. Pierce, since the main water supply is from the water table aquifer, ground water moves towards the wells being pumped, rather than toward the Atlantic Ocean.

Specific Geology and Hydrology of the Ft. Pierce Area

Ground water in the Ft. Pierce area occurs under both artesian and non-artesian conditions. The zone of water saturation is close to or at the surface of the ground wherever there are ponds, lakes, marshes, or rivers; and fresh water extends down to the top of the aquiclude, the Tamiami Formation, generally about 300 feet deep. The non-artesian or water-table aquifer is made up of the Pamlico sand, Anastasia shell beds, and Caloosahatchee Marl, named from the surface downward. This is the principal fresh water supply in the area, which must not be contaminated by radioactivity. The filtration plant of Ft. Pierce is located south of town in section 22, township 35 south, range 40 east. A nuclear reactor located anywhere in this general area south of town and west of the coastal sand ridge would pose the maximum hazard to the public water supply system. On the other hand, a reactor located north of the filtration plant and east of the coastal sand ridge would pose a minimum hazard to the public water supply system, since any spillage of radioactivity to the ground would drain towards Indian River, which is mostly ocean water.

Safety Precautions

It must be understood that the design of the proposed nuclear reactor must incorporate provisions for the containment of all radioactive liquids or solids which, because of an accident, could conceivably be discharged to the ground or waters surrounding the reactor. In addition to the containment vessel surrounding the reactor as specified by the AEC in their conceptual design of the proposed reactor, the writer would strongly recommend an empty stand-by steel tank of sufficient capacity to contain the full volume of the pressurized water in the primary loop, which would be most likely to become contaminated by radioactivity in the event of a nuclear accident.

CITRUS-LEVY COUNTY AREA

The work of Holmes and Narver, Inc. (1959) preceded the Pierce and Ft. Pierce area studies and was the first study in Florida and perhaps even in the whole United States aimed at identifying the most favorable areas topographically, geologically, and hydrologically for a high power nuclear reactor. Here the emphasis was upon the inherent safety afforded by favorable geology and hydrology of the site against gross radioactive contamination of public water supplies. To these inherent geologic and hydrologic characteristics of a broad area, engineering and economic factors were added to give an overall rating to each of five selected reactor site areas within the broad favorable area.

Figure 10 shows the areas of general interest. These were chosen because of plentiful water supply, general low population density of the area, relatively cheap land availability, proximity to markets, highway and railroad facilities and other non-geologic factors which enter into an engineering analysis of such a project.

Figure 11 shows the detailed geology along the Suwannee and Withlacoochee Rivers.

Favorable geologic and hydrologic factors used to evaluate the various possible reactor site locations included the following:

1. Quantity and quality of ground water and surface water available at any given location.
2. Topography and drainage characteristics of the land, including vulnerability to floods.
3. Porosity and permeability of the soil and bedrock at each locality.
4. Downstream hazard in the event of radioactive contamination of surface and/or ground water.
5. Population affected in the event of accidental spillage of radioactivity to the ground. This considers movement of surface and ground water at the reactor site location.
6. Possible protection soils may offer due to sorption of radioactive nuclides by the clay component.
7. Dilution potential of surface and ground water in each area, in the event of accidental discharge of radioactivity.
8. Earthquake frequency of the area.

As in the case of the Tampa area study, drilling and sampling was

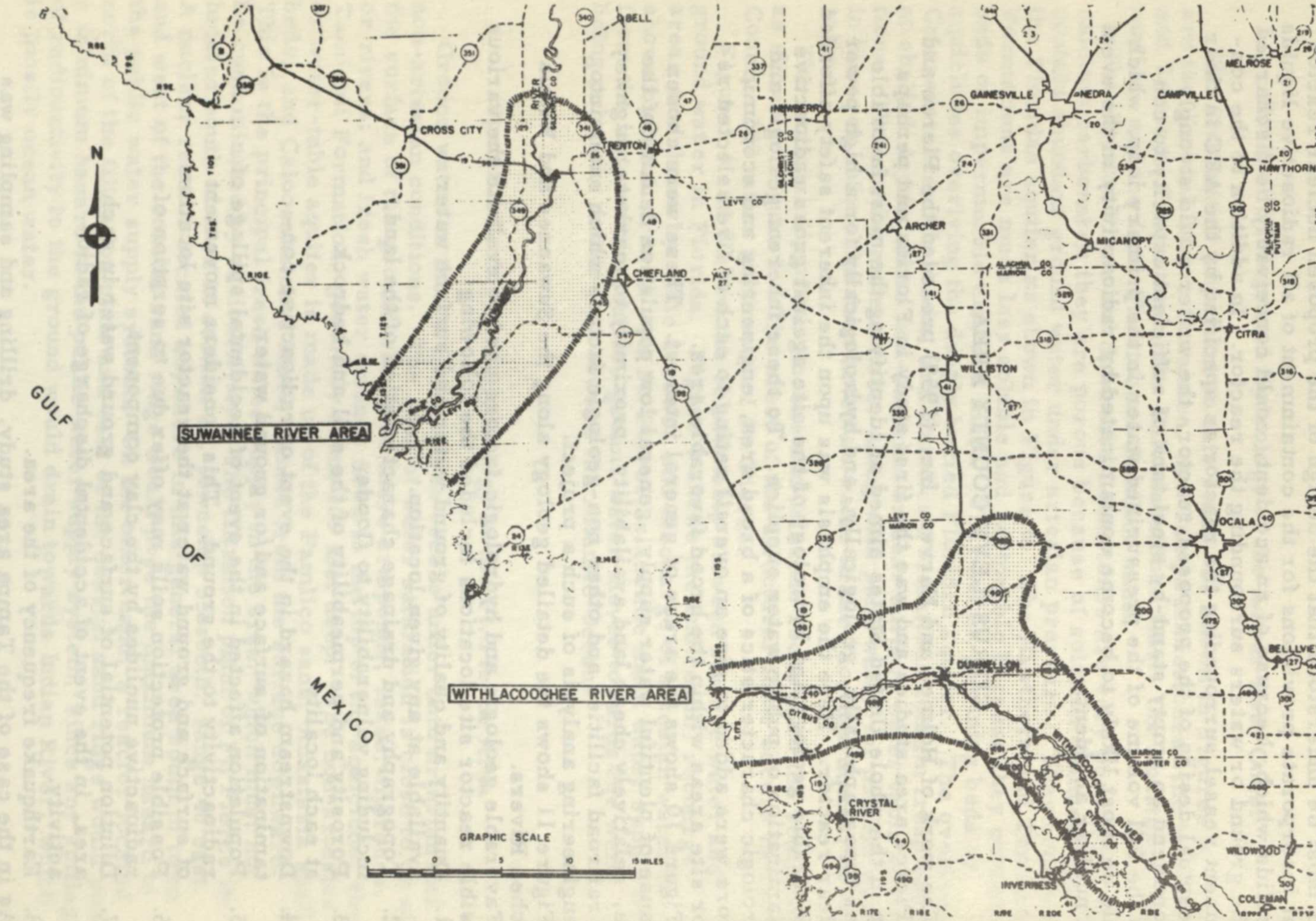

Figure 10. General site areas, Citrus and Levy Counties.

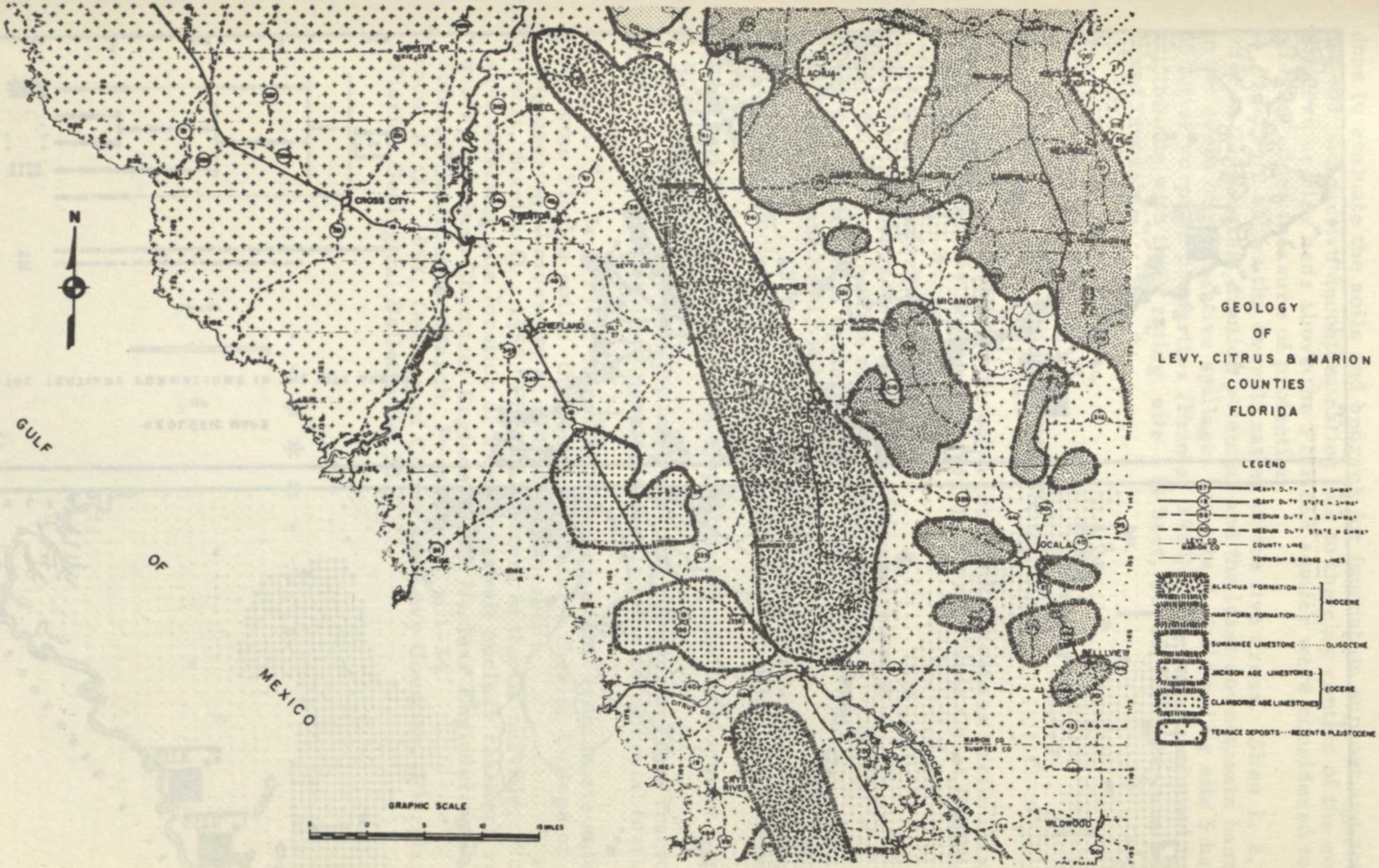

Figure 11. Detailed geology of the Citrus and Levy Counties, (Vernon, 1951).

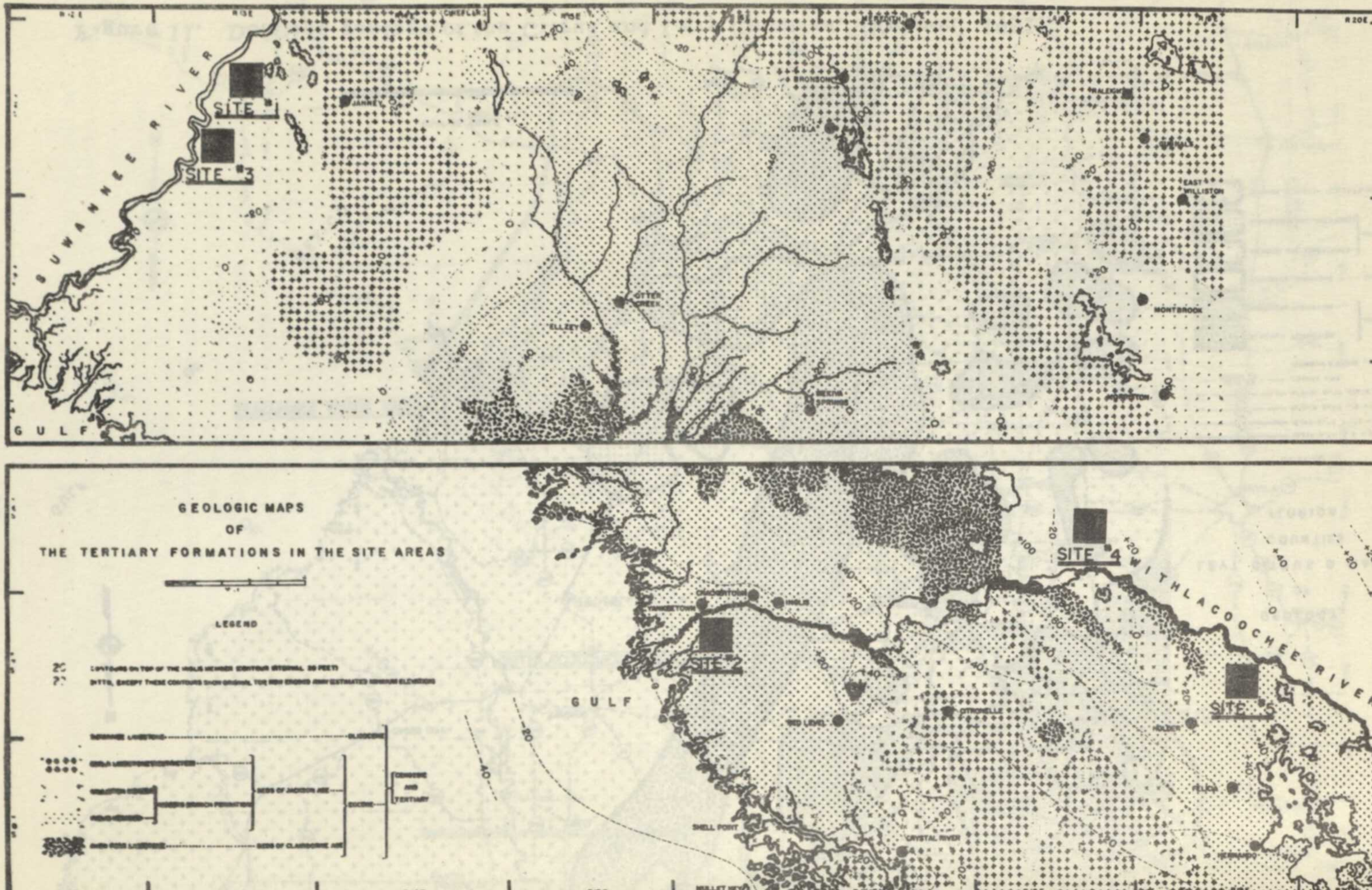

Figure 12. Five sites in the Citrus-Levy County area.

done to evaluate the soils and bedrock for foundation support and potential for radioactive decontamination due to the clay content of the soils. Impervious clay beds above the Floridan aquifer were considered to offer an added measure of protection.

Figure 12 shows the overall rating of the five areas. Sites 1, 2, 3 offered the greatest dilution potential and the least downstream hazard in the event of radioactive spillage, but site 4, followed by site 5 had soils of better sorption properties (Printz, 1960). Sites are numbered in accordance with their rating; site 1 is best, but all five sites are considered favorable.

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A DERIVATION OF EARLE'S FORMULA FOR THE CALCULATION OF TRUE DIP

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ABSTRACT

A useful formula for true dip calculation (Earle, 1934) has special value for areas of low dip such as the coastal plains where solutions by descriptive geometry or by graphical methods may be awkward. A minor error is corrected in the derivation of the formula.

INTRODUCTION

One of the problems that forever confronts the field geologist is the computation of dip and strike problems. He is further confronted constantly with the problem as to which is the best method to use. Numerous works have been published on the solution of dip and strike problems. Should a descriptive geometric method be used, or is a trigonometric solution more suitable? Each method has its advantages and disadvantages. The geometric solution is of interest, but it value is impaired because no formula is deduced, and the field geologist will have to repeat the solution for every individual set of data. The trigonometric solution is by far the more accurate of the two methods, and hence has a greater value.

A practical and useful formula by which true dip calculations may be made is that which appears in "Dip and Strike Problems Mathematically Surveyed," by K. W. Earle (1934). It is especially useful in areas of low dip, such as parts of the Gulf Coastal Plain, where dips are in the magnitude of 30 to 40 feet per mile (less than 1/2 degree). In these areas solutions to dip and strike problems by the usual descriptive geometry or by graphical methods may be awkward and not within the limits of accuracy dictated by the nature of geological observations. This formula of Earle's has been used by the writer many times in the field, and also has been found to have merit for teaching application as well.

The only error that was found in the derivation was the absence of ($\pm$) sign preceding the second member of Equation I, the reason being explained in the derivation.

FORMULA OF EARLE

Given: A bed crops out at A, B, and C, points of known elevation and position whose respective heights are h_1, h_2, and h_3 (Figure 1). Points B' and C' (Figure 2) are projections onto the horizontal plane through A, the highest point. Let the horizontal distance between A and B' be c and between A and C' be d. Let the angle between the bearings AB' and AC' be θ.

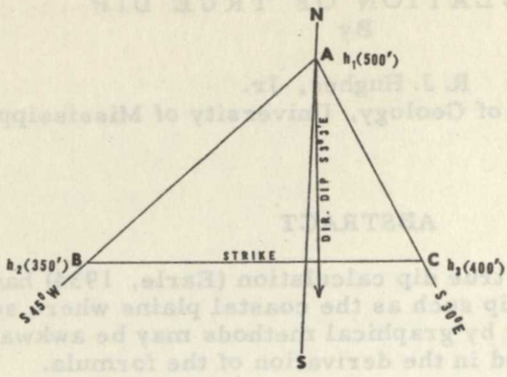


Figure 1

Solution: The apparent dip from A to B is $\tan^{-1}\left(\frac{h_1-h_2}{c}\right)$,

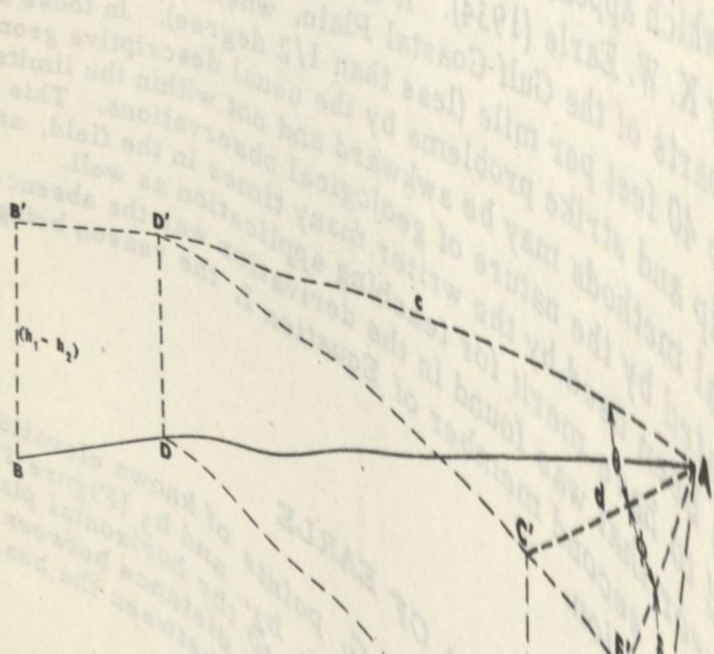
whereas the apparent dip from A to C is $\tan^{-1}\left(\frac{h_1-h_3}{d}\right)$,

The true dip at an angle $\emptyset$ from AC is, therefore, given by:

$$\text{Tan}\ \emptyset = \pm \left\{\frac{d(h_1-h_2)}{c(h_1-h_3)} - \cos\theta\right\} \text{cosec}\ \theta \qquad \text{Eq. I}$$

and

$$\text{Tan}\ \delta = \left(\frac{h_1-h_3}{d}\right) \sec \emptyset \qquad \text{Eq. II}$$



Should any two of the heights, be the same, e. g., $h_1 = h_2$, then $\tan \phi = -\cot \theta$; the direction of dip is, therefore, at right angles to AB, or AB is the strike.

In this case $\tan \delta = \left(\frac{h_1 - h_3}{d}\right) \operatorname{cosec} \theta$ Eq. III

If $\theta = 90^{\circ}$, $\tan \phi = \left\{\frac{d(h_1 - h_2)}{c(h_1 - h_3)}\right\}$ Eq. IV

with a corresponding alteration in the value of δ.

DERIVATION

Let $\overline{AC}' = d$; $\overline{AB}' = c$; $\overline{BB}' = h_1 - h_2$; $\overline{CC}' = h_1 - h_3$; $\theta = \angle C'AB'$; $\phi = \angle E'AC'$; $\overline{DD'} = \overline{CC'}$ (Figure 2).

whence $\angle AE'C' = 90^{\circ}$ (definition of dip)

$$\sin \angle AC'D' = \cos \phi \quad \text{(right triangle)} \quad (1)$$

$$\sin \angle AC'D' = \frac{\overline{AD}'}{\overline{C'D'}} \sin \theta \quad \text{(sine law)} \quad (2)$$

$$\overline{C'D'} = \sqrt{\overline{AD}'^2 + d^2 - 2\overline{AD}'d \cos \theta} \quad \text{(cosine law)} \quad (3)$$

$$\overline{AD}' = c\left(\frac{h_1 - h_3}{h_1 - h_2}\right) \quad \text{(similar triangles AD'D and AB'B)} \quad (4)$$

so

$$\cos \phi = \sin \angle AC'D' \quad (1)$$

$$= \frac{\overline{AD}'}{\overline{C'D'}} \sin \theta \quad \text{from (2)}$$

$$= \frac{\overline{AD}' \sin \theta}{\sqrt{\overline{AD}'^2 + d^2 - 2\overline{AD}'d \cos \theta}} \quad \text{from (3)} \quad (5)$$

$$\cos \phi = f \quad (6)$$

$$\sec \phi = \frac{1}{\cos \phi} = \frac{1}{f}$$

$$\tan^2 \phi = \sec^2 \phi - 1 = \frac{1}{f^2} - 1$$

$$= \frac{\overline{AD}'^2 + d^2 - 2\overline{AD}'d \cos \theta}{\overline{AD}'^2 \sin^2 \theta} - 1 \quad \text{from} \quad (5)$$

$$\tan^2\phi = \frac{\overline{AD}'^2 + d^2 - 2\overline{AD}'d\cos\theta - \overline{AD}'^2\sin^2\theta}{\overline{AD}'^2\sin^2\theta}$$

$$= \frac{\overline{AD}'^2(1-\sin^2\theta) + d^2 - 2\overline{AD}'d\cos\theta}{\overline{AD}'^2\sin^2\theta}$$

$$= \frac{d^2 - (2\overline{AD}'\cos\theta)\,d + \overline{AD}'^2\cos^2\theta}{\overline{AD}'^2\sin^2\theta}$$

$$= \pm\left\{\frac{(d - \overline{AD}'\cos\theta)^2}{\overline{AD}'^2\sin^2\theta}\right\}$$

$$\tan\phi = \pm\left(\frac{d - \overline{AD}'\cos\theta}{\overline{AD}'\sin\theta}\right)$$

$$= \pm\left(\frac{d - \overline{AD}'\cos\theta}{\overline{AD}'}\right)\operatorname{cosec}\theta$$

$$= \pm\left(\frac{d}{\overline{AD}'} - \cos\theta\right)\operatorname{cosec}\theta$$

and from (4)

$$\tan\phi = \pm\left\{\frac{d(h_1 - h_2)}{c(h_1 - h_3)} - \cos\theta\right\}\operatorname{cosec}\theta \qquad (7)$$

thus checking Eq. I.

Use (+) sign if $\frac{d(h_1 - h_2)}{c(h_1 - h_3)} > \cos\theta$

Otherwise use (−) sign.

Let dip = $\angle E'AE = \angle\delta$

but $\overline{E'E} = h_1 - h_3$ by construction

therefore $\tan\delta = \frac{h_1 - h_3}{\overline{AE}'}$

but $\overline{AE}' = \overline{AC}'\cos\phi = d\cos\phi$

therefore $\tan\delta = \frac{h_1 - h_3}{d\cos\phi} = \left(\frac{h_1 - h_3}{d}\right)\sec\phi$ checking Eq. II (8)

or $\tan\delta = \frac{h_1 - h_3}{d}(\tan^2\theta + 1)$ where $\tan\phi$ is found from (7)

ILLUSTRATIVE EXAMPLE

Given: Three points A, B, and C, on a dipping stratum whose elevations are 500 ft, 350 ft., and 400 ft., respectively (Figure 1). The distance from A to B is a half mile S 45° W, and from A to C is a quarter of a mile in a direction S 30° E.

Required: True dip in direction and amount.

Solution:

$$\text{Tan } \emptyset = \left\{\frac{440(500-350)}{880(500-400)}\right\} \qquad \text{from Eq. I}$$

$$= \left\{\frac{(150 \times 440)}{(880 \times 100)} - \cos 75^{\circ}\right\} \text{cosec } 75^{\circ}$$

$$= (0.75 - 0.2588) \times 1.0353$$

$$= 0.491 \times 1.0353$$

$$= 0.508$$

therefore $\emptyset = 26^{\circ}57'$ Ans.

Solving for δ or angle of dip

$$\tan \delta = \frac{100 \sec 26^{\circ}57'}{440 \times 3} \qquad \text{Eq. II}$$

$$= \frac{10 \times 1.1218}{44 \times 3}$$

$$= \frac{11.28}{132}$$

$$= 0.084$$

therefore $\delta = 4^{\circ}48'$ Ans.

A quick graphical solution of the above problem shows the angle of dip to be 4°57' S 2° E. By comparing these values with those of the trigonometric solution it is seen that there is a variation. The difference of 0°9' in the angle of dip is especially noticeable in areas of very low dip geology, as mentioned previously. For example, if the dip were 35 feet per mile, the difference of 0°9' would mean a difference of 13.8 feet per mile, or an error of 39 per cent.

ACKNOWLEDGMENT

The author wishes to express his sincere appreciation to Dr. Frederic H. Kellogg, Dean, School of Engineering, for proof reading the manuscript and for checking the formulae.

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