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INTRODUCTION

Southeastern Virginia has been famous for its richly fossiliferous Yorktown Formation since Charles Lyell visited outcrops along the James River during his first trip to the United States in 1841-42. In fact, Lyell's remarks about the climatic significance of the Yorktown molluscs are quite relevant to current investigations into the paleoclimatology of the Pliocene period:

In regard to the climate of the Miocene period (Lyell considered the Yorktown Miocene in age) it is not uninteresting to observe that the fossil shells of Maryland and Virginia resemble those of Touraine and Bourdeaux more nearly than the fossils of Suffolk. It is singular that there should be so much resemblance between the Miocene shells of the Loire and Gironde and those of the James River and other estuaries of the United States which lie ten degrees of latitude farther south than the French Faluns. This circumstance may probably be accounted for by curves in the isothermal lines similar in their prolongation east and west, to those now existing as pointed out by Humboldt, in his essay on climate. (Lyell, 1845, Travels in North America, 1841-42, p. 110-111).

More recently, the Yorktown Formation and correlative deposits of the Duplin and Raysor Formations in North and South Carolina have been applied to the reconstruction of Pliocene paleoceanography of the western North Atlantic (Hazel, 1971a; Cronin, 1988) and the identification of a period of extremely high eustatic sea level (Ward and Strickland, 1985; Dowsett and Cronin, in press). The purpose of this paper is to describe the micropaleontology of some of the more important outcrops of the Yorktown Formation and the overlying upper Pliocene Chowan River Formation. The age and paleoenvironmental conditions of these formations record regional and global oceanographic events in the transgressive and regressive Coastal Plain record. Because these deposits have climatic significance beyond the outcrop area, it is all the more important to provide precise stratigraphic and geographic data that are a prerequisite for proper interpretation of the biostratigraphic and paleoclimatic results. We also describe ostracode assemblages from the upper Pleistocene Norfolk Formation which signifies another period of high sea level.

REGIONAL GEOLOGY

The U.S. Atlantic Coastal Plain is a low-lying physiographic province extending from New York to Florida and underlain by a seaward dipping wedge of Mesozoic and Cenozoic marine and continental sediments. The geologic formations underlying the emerged Coastal Plain are landward extensions of those lying offshore in basins of the continental shelf and slope (Poag, 1985). Because the Atlantic Coastal Plain is a "passive" margin of the North American lithospheric plate, its formations are only mildly deformed into basins and arches. Excellent reviews of Atlantic Coastal Plain geology are found in Gohn (1988) for the region from North Carolina to Florida and Olsson et al. (1988) for the region from Virginia to Long Island. Ward and Strickland (1985) reviewed the Tertiary stratigraphy of the Atlantic Coastal Plain with special reference to the history of transgressive-regressive cycles. The Yorktown Formation outcrops within the Salisbury Embayment and in the northern part of the Albemarle Embayment (Figure 1). Relative sea level during the maximum part of the Yorktown transgression was so high that marine deposits overlap the intervening Norfolk Arch.

YORKTOWN FORMATION

The name Yorktown Formation was introduced by Clark and Miller (1906) and since that time its fauna has been the subject of numerous paleontologic studies. Mansfield (1928, 1943) provided detailed paleontologic data on the Yorktown and divided it into two zones based on paleontologic evidence. Oaks et al. (1974) provided a discussion of the post-Miocene geology of southeastern Virginia, including a description of the Yorktown Formation. They stated that the Yorktown consists of marine clay, silt, sand, and coquina with a maximum thickness of about 12m. It is often easily distinguished from other formations by its compactness, its glauconite content, and its fauna. The maximum elevation of the York-

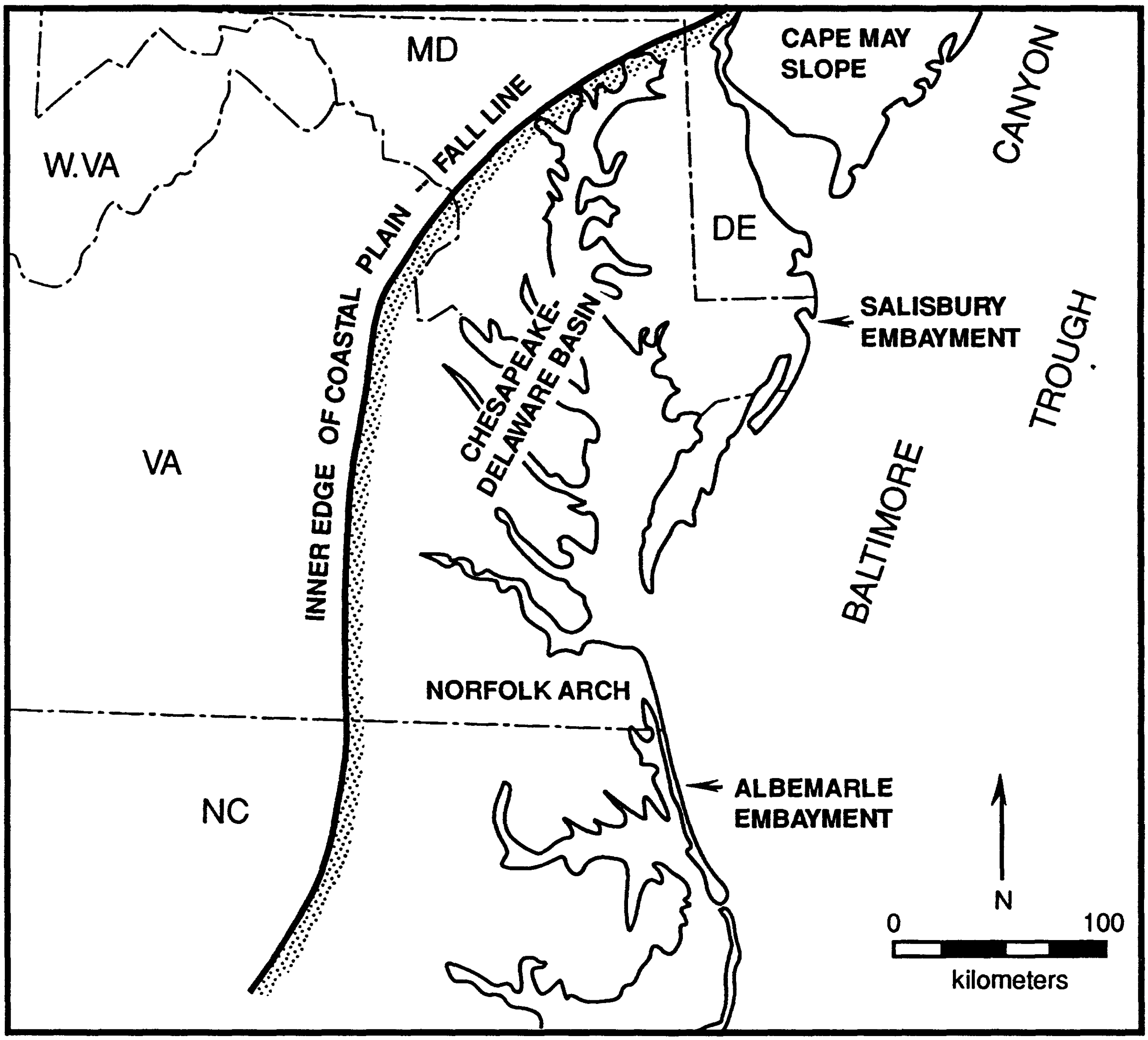

Figure 1. Map showing major geologic features of the middle Atlantic Coastal Plain of the United States.

town surface is about 40m where it occurs just west of the Fall Line (boundary between the Coastal Plain and Piedmont provinces) (Figure 1).

Despite the many studies of the Yorktown it was not until the study by Ward and Blackwelder (1980) that stratotype sections were defined formally and lithologies described. These authors distinguished the Yorktown from underlying Miocene units and they divided it into four members shown on the correlation chart in Figure 2: the Sunken Meadows (equivalent to Zone 1 of Mansfield, 1928), Rushmere, Morgarts Beach, and Moore House (together equivalent to Zone 2 of Mansfield, 1928). Ward and Blackwelder (1980) designated the section near Rushmere, Isle of Wight County (locality 8 of this report) as the lectostratotype of the Yorktown.

Biostratigraphy

Early studies of Yorktown macrofaunas established biostratigraphic evidence for correlation within the Coastal Plain and based on this evidence, most authors assigned the Yorktown to the Miocene. The development of planktic foraminifer and calcareous nannofossil biochronologic zonations in the 1960's and 1970's provided a means to correlate the York-

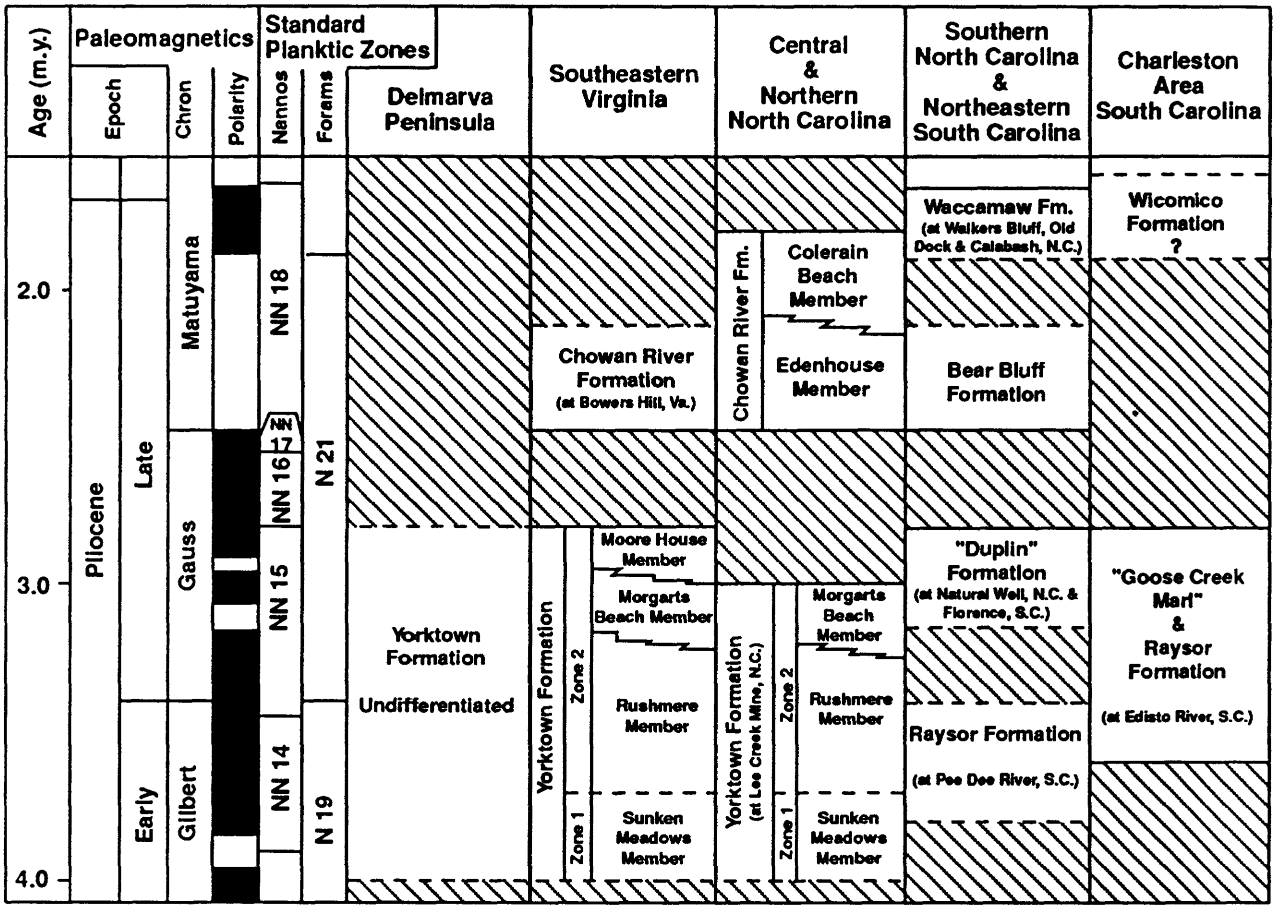

Figure 2. Correlation chart of Pliocene Formations of the Atlantic Coastal Plain (modified from Cronin et al., 1984).

town with a global time scale. Hazel (1971b) quantitatively defined an ostracode assemblage zonation of the Yorktown deposits which allowed him to correlate the Yorktown with the *Ecphora* Zone of the Jackson Bluff Formation of Florida. Hazel noted that the *Ecphora* zone contained a N18-N19 planktic foraminiferal assemblage, indicating a Pliocene age for it and probably for part of the Yorktown as well. Later studies of planktic foraminifers and calcareous nannofossils confirmed Hazel's ideas and firmly placed the entire Yorktown within the early-middle Pliocene. Akers and Koeppel (1973) found the calcareous nannofossil *Pseudoemiliana lacunosa* in the Yorktown at Lee Creek Mine, Aurora, North Carolina, indicating a maximum age of about 3.5Ma. Snyder et al. (1983) suggested that the Yorktown Formation at the Lee Creek Mine belongs to planktic Zones N19 to middle N20 and is a maximum of 4.8Ma and a minimum of 3.1Ma in age. These conclusions were based on the occurrence of 29 species and subspecies of planktic foraminifers. This age range is generally supported by Gibson's work (1983) on foraminifers. Cronin et al. (1984) found calcareous nannofossils representing zones NN13-NN15 and planktic foraminiferal zones N19-N21.

Table 1 provides additional planktic bichronologic data for localities discussed in this paper. The data generally indicate an age range of about 4.4-2.8 Ma for the Rushmere, Morgarts Beach and Moore House Members of the Yorktown.

Paleoclimatology

Lyell was one of the first to comment on the climatic significance of the Yorktown fauna, and Hazel (1971b) was the first to quantitatively analyze the Yorktown faunas for paleotemperature reconstruction. By comparing the ostracode fauna from the Yorktown to the modern fauna from the continental shelf off eastern North America, Hazel was able to estimate the similarity of Yorktown paleoclimatology to the climate of today. He estimated that the earliest Yorktown (Sunken Meadows Member), *Pterygocythereis inexpectata* ostracode Zone, was deposited during

Table 1. Planktic foraminiferal species in the Yorktown Formation[1].

Locality[2]	MH	Rice's Pit				M.B.		YP
Taxon/Sample[2]	1	2	3	4	5	6	7	8
Dentoglobigerina altispira	0	1	1	0	0	0	0	0
Globigerina apertura	0	1	1	0	1	0	1	0
Globigerina bulloides	1	1	1	1	1	1	1	1
Globigerina falconensis	1	1	1	0	1	0	1	0
Globigerina woodi	1	0	1	1	1	0	1	0
Globigerinella aequilateralis	1	1	1	1	1	1	0	1
Globigerinoides obliquus	0	1	1	1	1	0	0	1
Globigerinoides ruber	0	1	1	1	1	1	1	1
Globigerinoides sacculifer	1	1	1	1	1	1	1	1
Globorotalia puncticulata	0	0	0	1	0	0	1	0
Globorotalia tumida	0	0	0	0	1	0	0	1
Neogloboquadrina acostaensis	1	1	1	1	1	1	1	1
Neogloboquadrina atlantica	1	0	0	0	0	0	0	0
Neogloboquadrina spp.	0	1	0	1	1	0	1	0
Orbulina	0	1	0	0	1	0	0	0
Sphaeroidinellopsis	0	1	0	0	0	1	0	0

[1] Presence indicated by '1', absence indicated by '0'.
[2] MH=Moore House Locality: 1, 78TC133; Rice's Pit Locality 2: 89HD12; 3, 89HD13; 4, 89HD14; 5, 89HD16; MB= Morgarts Beach Locality 6: 89HD8; 7, 89HD9; YP= Yadkins/Deep Creek Pit Locality 8: 89HD10.

a mild temperate climate with annual bottom water temperatures (BWT) ranging from below 12.5°C during winter to below 20°C during summer. The middle Yorktown ostracode fauna indicates a warm temperate climate with winter BWT between 12.5-15°C and summer BWT near 20°C. Maximum temperatures were reached in the middle and upper parts of the *Orionina vaughani* ostracode Zone in the middle and upper Yorktown when summer temperatures averaged between 20-25°C, and cool-water species were conspicuously absent.

Cronin and Dowsett (in press) applied factor analytical techniques to analyze the ostracodes from the Yorktown Formation and obtained the February and August BWT's given in Table 2. The occurrences of 59 temperature-sensitive ostracode genera used to develop an ostracode transfer function in eleven Yorktown samples, are given in Table 3. The paleotemperature history of the Rushmere, Morgarts Beach and Moore House Members based on results from 7 samples from localities 1 and 7, is plotted in Figure 3. The Sunken Meadows Member, not shown in Figure 3, had a February BWT of about 10.1°C, and an August BWT of 12.1°C. February BWT fluctuated between about 11°C and 16°C during the rest of the Yorktown transgression, with a peak of 16°C obtained from a sample from locality 7. Modern winter BWT's at similar depths at the latitude of the Yorktown Formation (37°N) average about 5.5°C.

Table 2. Yorktown paleotemperature estimates.

Locality	Sample	Aug. Temp.	Feb. Temp.	Communality [1]	Number of ostracode specimens
7	78TC126	17.4	11.2	0.71	290
7	78TC127	17.9	12.4	0.68	273
7	78TC129	18.0	16.1	0.46	379
1	88TC10	19.5	11.1	0.44	311
1	78TC132	19.6	15.8	0.69	316
1	78TC133	19.3	15.2	0.63	464
1	78TC134	20.8	13.0	0.69	380

[1]Communality measures howsimilar the fossil assemblage is to the modern assemblages that were used to derive the transfer function equations. A value of 1.0 indicates complete similarity. See Cronin and Dowsett (in press).

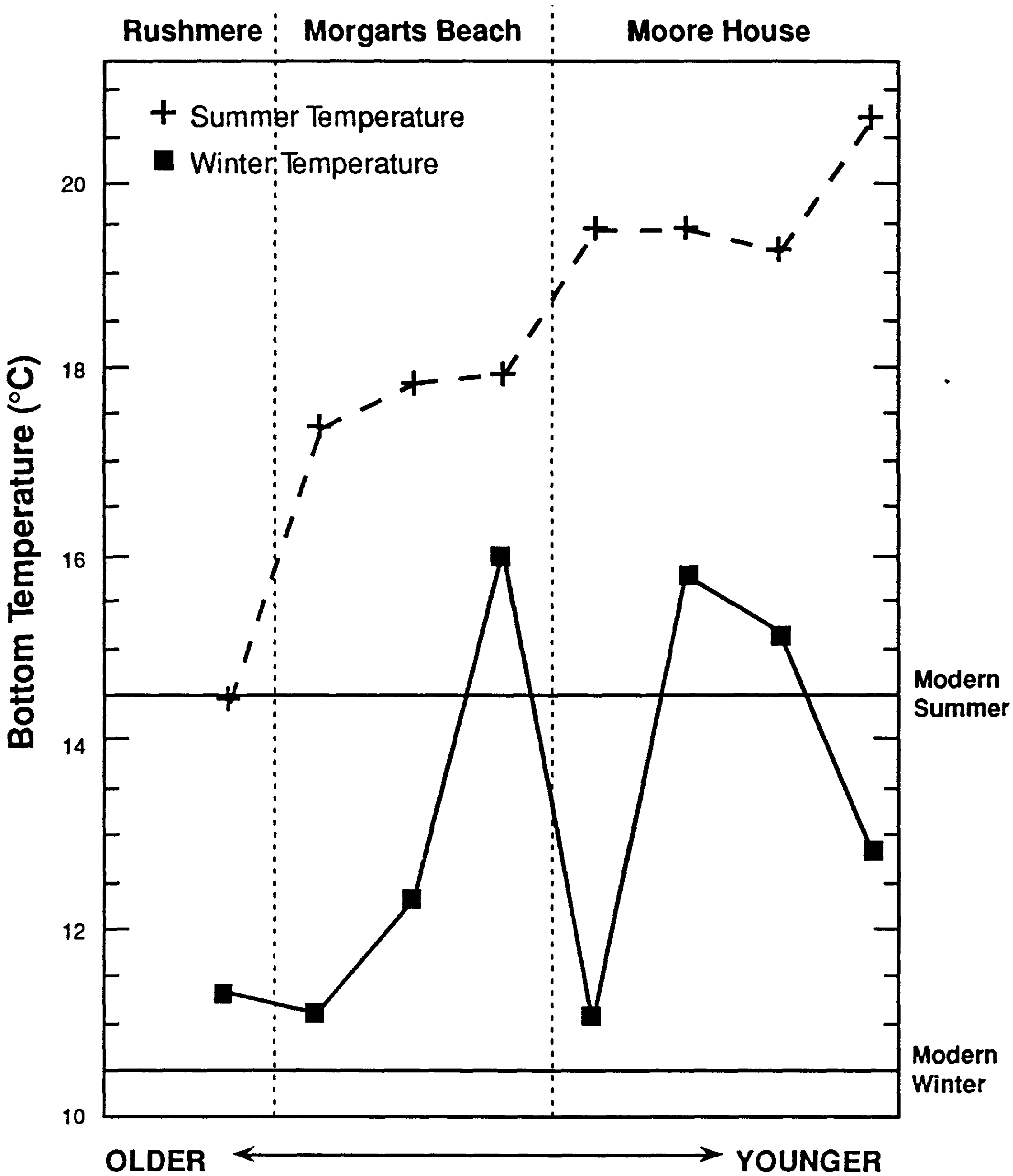

Figure 3. Yorktown Formation paleotemperatures based on Cronin and Dowsett (in press).

August BWT's show a general increase during Yorktown history as they rose from about 14.5°C to almost 21°C during the deposition of the Moore House Member. The warmest temperatures were obtained from a sample from the Moore House Member at locality 1. Modern August BWT's offshore at similar depths average about 14.5°C. Thus, the Yorktown Formation was deposited during a time when summer and winter temperatures were substantially warmer than those off the southeastern Virginia coast today and these differences most likely signify the enhanced influence of the Gulf Stream during the middle Pliocene (Cronin, 1988).

Table 3. Ostracodes in the Yorktown Formation.

Locality	Locality 8	Locality 7			Locality 1				Locality 2		
Genera[1]/Sample[2]	1	2	3	4	5	6	7	8	9	10	11
Acanthocythereis	0	0	0	0	0	0	0	0	0	0	0
Actinocythereis	37	4	3	6	5	11	3	6	8	3	4
Aurila	0	0	0	0	0	1	7	0	0	0	0
Baffinocythere	0	0	0	0	0	0	0	0	0	0	0
Bairdoppilata	0	0	0	0	0	0	0	0	0	0	0
Bensonocythere	0	22	16	13	13	6	13	13	35	31	19
Campylocythere	0	0	5	4	0	0	4	10	15	11	11
Caudites	0	0	0	0	0	0	0	0	0	0	0
Climacoidea	3	15	10	16	20	19	14	25	31	23	24
Cushmanidea	0	0	0	0	1	0	0	0	0	1	0
Cythere	0	0	0	0	0	0	0	0	0	0	0
Cytherelloidea	0	0	0	0	0	0	0	0	0	0	0
Cytheropteron	5	5	1	6	5	1	0	1	6	7	3
Cytherura	8	5	10	14	14	25	31	22	2	8	5
Echinocythereis	0	0	0	0	0	0	0	0	0	0	0
Elofsonella	0	0	0	0	0	0	0	0	0	0	0
Eucythere	0	0	3	0	2	2	1	1	3	7	4
Finmarchinella	0	3	0	0	0	0	0	0	0	0	0
Hemicythere	0	0	0	0	0	0	0	0	0	0	0
Hermanites	0	0	0	0	0	0	0	0	0	0	0
Hulingsina	6	72	58	46	60	61	95	95	54	49	53
Jugocythereis	0	0	0	0	0	0	0	0	0	0	0
Leptocythere	2	0	0	0	0	0	0	0	0	0	0
Loxoconcha	6	31	23	28	19	33	53	36	49	36	29
Loxocorniculum	0	0	0	0	0	0	0	0	0	0	0
Macrocyprina	0	0	0	0	0	0	0	0	0	0	0
Malzella	3	34	46	102	40	45	80	65	126	134	86
Muellerina	9	49	50	58	26	35	55	44	63	98	73
Munseyella	0	0	0	0	0	0	0	0	0	0	0
Neocaudites	0	0	0	0	0	0	0	0	0	0	0
Neonesidea	0	0	0	0	0	0	0	0	0	0	0
Normanicythere	0	0	0	0	0	0	0	0	0	0	0
Orionina	1	11	8	5	10	0	0	0	53	63	39
Palmenella	0	0	0	0	0	0	0	0	0	0	0
Paracytheridea	0	13	9	28	9	22	32	16	7	40	25
Paradoxostoma	0	1	0	1	0	2	4	4	0	0	2
Paranesidea	0	11	18	15	0	15	15	5	15	17	12
Patagonacythere	0	0	0	0	0	0	0	0	0	0	0
Pellucistoma	0	0	0	0	0	0	0	0	0	0	0
Peratocytheridea	0	0	0	0	2	4	1	12	2	1	7
Phlyctocythere	0	0	0	0	0	0	0	0	0	0	0
Pontocythere	0	0	4	0	0	0	0	0	0	0	0
Propontocypris	0	1	0	1	0	3	4	1	0	0	0
Protocytheretta	6	2	2	10	0	0	0	0	2	0	0
Pseudocytheretta	4	0	0	0	75	0	0	0	52	34	21
Pterygocythereis	8	0	0	0	0	0	0	0	0	0	30
Puriana	0	4	1	5	0	3	4	1	20	31	0
Radimella	0	0	0	0	0	0	0	0	0	0	0
Robertsonites	0	0	0	0	0	0	0	0	0	0	0
Sahnicythere	0	0	0	0	1	0	0	0	0	1	0
Sarsicytheridea	0	0	0	0	0	0	0	0	0	0	0
Sclerochilus	0	0	0	0	0	0	0	0	0	0	0
Semicytherura	0	0	0	0	0	0	0	0	0	0	0
Tetracytherura	7	7	6	20	5	13	15	18	15	31	17
Thaerocythere	2	0	0	0	4	15	32	2	3	0	1
Triebelina	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis	0	0	0	0	0	0	0	0	0	0	0
TROPICAL TAXA	0	0	0	1	0	0	1	3	0	0	0
ARCTIC TAXA	0	0	0	0	0	0	0	0	0	0	0

[1]See Cronin and Dowsett (in press) for details on 59 taxonomic categories used in transfer function.

[2] Samples: 1=78TC112, 2=78TC126, 3=78TC127, 4=78TC129, 5=88TC10, 6=78TC132, 7=78TC133, 8=78TC134, 9=88TC11, 10=88TC12, 11=88TC14

DESCRIPTION OF LOCALITIES

In the following discussion, we describe briefly the geology and paleontology for each locality and show its location on a topographic map. Each outcrop is drawn diagrammatically showing general lithologic characteristics and the name of the formation/member. The most important aspects of the planktic foraminiferal and ostracode assemblages are described. In addition, molluscan data from published sources are given for easier identification of the units in the field.

Locality 1. Yorktown, Virginia.

This outcrop is located on the south bank of the York River behind the Moore House residence within the Yorktown National Park. It had been informally referred to as the type locality by early workers and is the type locality of the Moore House Member of Ward and Blackwelder (1980). The outcrop had gradually become more covered by vegetation and debris such that only a small portion of the cliff was exposed (Ward and Blackwelder, 1980); however recent storms have exposed fresh sediment almost to mean tide level.

The Moore House Member represents the final regressive phase of the Yorktown Formation. The underlying Morgarts Beach Member, now exposed at the base of the section at Moore House, is also exposed at localities 7 and 8. Ward and Blackwelder (1980, p. D45) described the lithology of the Moore House Member as an "orange fragmental shell hash, extremely calcareous but containing some fine quartz sand; bryozoa and molluscan fragments abundant." The maximum thickness of the Moore House Member in outcrop is 6m.

Planktic foraminiferal assemblages from the Moore House and Morgarts Beach members (Table 1) are dominated by *Globigerina bulloides, G. woodi, G. falconensis, Globigerinoides sacculifer, Globigerinella aequilateralis, Neogloboquadrina acostaensis,* and *N. atlantica.* Although this fauna suggests a middle Pliocene age, no diagnostic species are present that can provide an unequivocal age in millions of years.

The Moore House Member represents the upper part of the *Orionina vaughani* ostracode assemblage Zone of Hazel (1971b). The ostracode assemblage (Table 3, samples 78TC132, 133, 134, 88TC10) is dominated by the genera *Hulingsina, Malzella, Muellerina, Paracytheridea, Thaerocythere,* and *Cytheridea.* Summer BWT's peaked at about 20-21°C during deposition of the Moore House (see Paleoclimatology above).

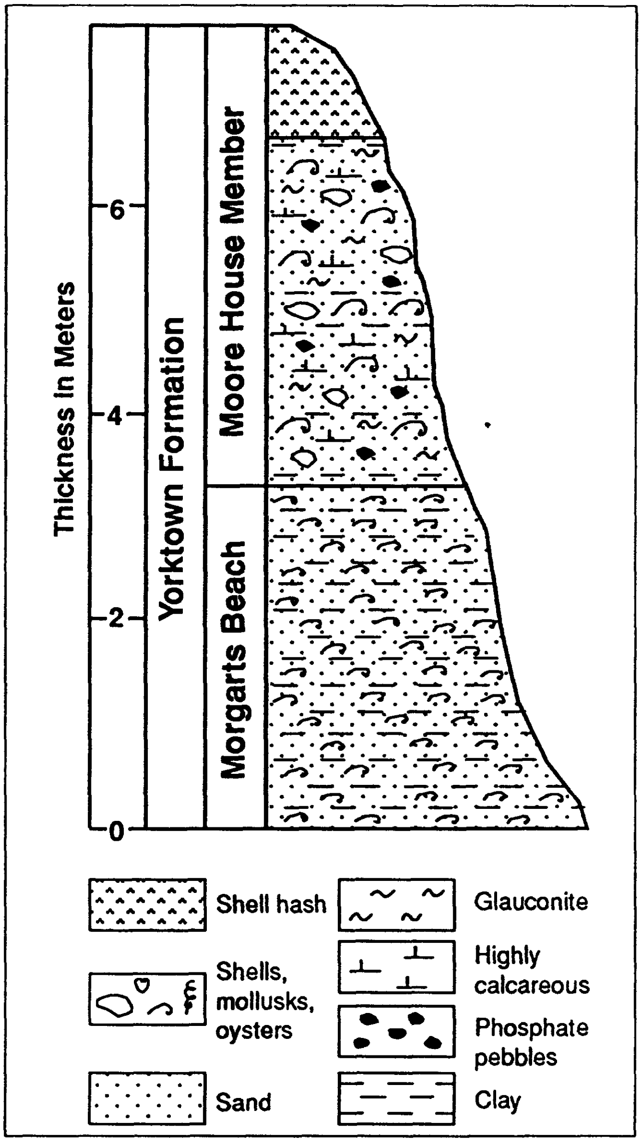

Figure 4. Stratigraphic section of the Moore House Locality, Yorktown, Virginia. Geology after Ward and Blackwelder (1980).

Locality 2. Rice's Pit, Virginia.

The Rice's Pit section was formerly a sand and gravel pit but it is now the Kenneth E. Rice Memorial Museum and Fossil Pit. This section represents a slightly deeper water facies of the Morgarts Beach Member of the Yorktown Formation, deposited in middle to perhaps outer shelf environments. Hazel (1971b) described the section as consisting of "buff to gray clayey sand, becoming less fossiliferous towards the bottom of the pit".

Planktic foraminifers are common and well preserved throughout the exposure and support the interpretation of outer shelf deposition. Assemblages

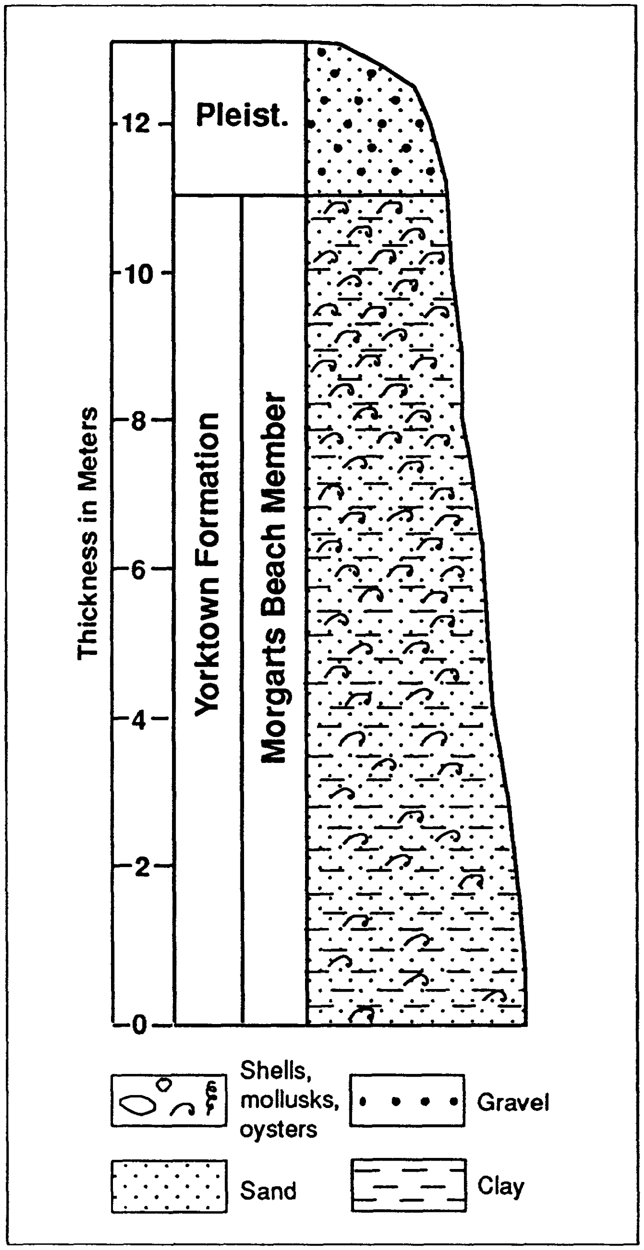

Figure 5. Stratigraphic section of Rice's Pit Locality. Geology after Hazel (1971b).

are dominated by *Globigerina bulloides* but also contain *Globorotalia puncticulata, Sphaeroidinellopsis,* and *Dentoglobigerina altispira* (Table 1). These taxa indicate an age between 4.4 and 3.0 Ma.

The ostracodes contain greater proportions of *Malzella* than any modern samples examined and also high proportions of *Orionina, Pseudocytheretta, Muellerina, Hulingsina,* and *Bensonocythere* (Table 3, samples 88TC11, 12, 14). The annual range of bottom water temperatures, as calculated by the ostracode transfer function, was between 12°C and 18°C, slightly cooler than the inshore facies of the Yorktown.

Locality 3. Gomez Pit, Virginia.

This locality exposes the late Pliocene Chowan River Formation, which is overlain by late Pleistocene deposits referred to by various authors as the Tabb, Norfolk, Acredale, and Kempsville Formations. The top of the Chowan River Formation may or may not be visible depending on digging activity in the pit. A detailed description of the Gomez Pit and the confusing stratigraphic terminology for upper Pleistocene units is given in Mixon et al. (1982), and Wehmiller et al. (1989).

This outcrop shows two main facies of the Norfolk complex: first, a lower sand, with occasional boulders and discontinuous *Crassostrea* (oyster) bioherms and second, an overlying quartzose sand containing well-preserved beds of in situ *Mercenaria* and extremely well-developed serpulid and bryozoan bioherms.

Corals from the Norfolk complex in the Norfolk, Virginia area have yielded uranium series ages of 80,000 to 60,000 years (Cronin et al., 1981; Szabo, 1985). Three specimens from the upper beds of the Gomez Pit yielded ages of 79,000±5,000, 69,000±4,000 and 67,000±4,000 years. Amino acid racemization studies indicate that two aminozones exist, the lower zone represented by the oyster bioherm and the beds just below it, and the upper zone represented by the serpulid bioherm down to about 2 1/2 m below it. Wehmiller et al. (1989) postulated that the two aminozones, which are both situated within the Sedgefield Member of the Tabb Formation, represent the last two interglacial periods, about 200,000 and about 125,000-75,000 years ago respectively. They favor the interpretation that the upper aminozone represents isotope substage 5e rather than substage 5a, and that the lower zone represents isotope stage 7. Electron spin resonance data from these two units generally support the amino acid data that stages 5 and 7 are represented here (Wehmiller et al., 1989). Cronin et al. (1981), Szabo (1985) and Cronin (1988) believed the upper beds correlate with substage 5a rather than substage 5e.

The ostracode assemblage from the *Crassostrea* facies, located within the lower aminozone, consists of a typical brackish water lagoonal assemblage, which includes *Cyprideis, Cytheromorpha curta, Cytherura neusensis,* and *Hulingsina* sp. The ostracodes from the upper aminozone include a more diverse assemblage, including *Campylocythere laeva, Bensonocythere* spp., *Hemicythere villosa, Peratocytherideа setipunctata, Hulingsina* spp., *Climacoidea (Proteoconcha)* cf. *tuberculata, Paracytheridea altila, Neolophocythere subquadrata, Cytherura reticulata, Cytherura howei, Cytherura* spp., *Loxoconcha matagordensis, Loxoconcha* sp. A, *Paradoxostoma* sp., *Sahnia* sp., and *Pontocythere* sp.

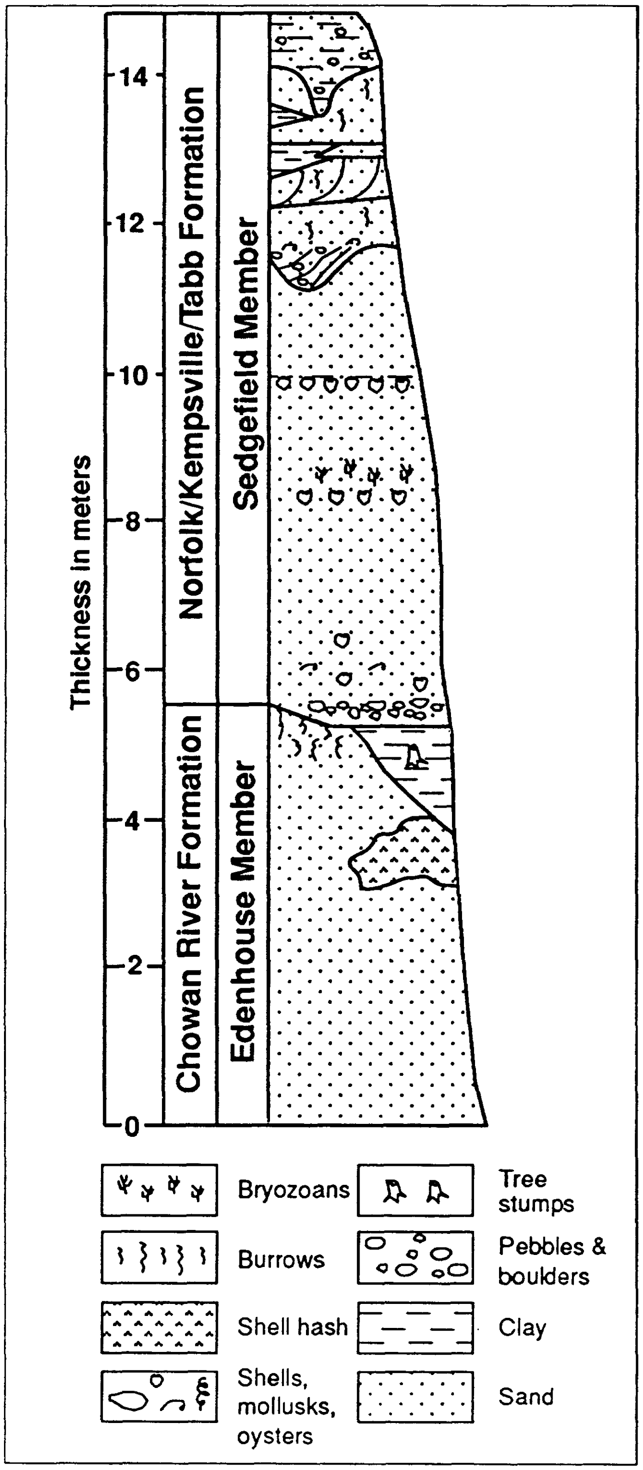

Figure 6. Stratigraphic section of the Gomez Pit Locality, Virginia. Geology after Wehmiller et al. (1989)

This assemblage indicates inner shelf paleoenvironments near a coast and normal or near normal marine salinities. The assemblage is typical of late Pleistocene faunas, such as those from the Kempsville and Norfolk Formations in nearby pits described by Valentine (1971). It is not clear from the ostracode assemblages whether a gap of 100,000 years occurred between the lower and upper aminozones (see also table 4).

In summary, there is conflicting evidence as to whether the uppermost fossiliferous beds at the Gomez pit signify a high sea level during isotope substage 5a, about 75,000 yr BP, or during substage 5e, about 125,000 yr BP. The resolution of the age of these upper Pleistocene deposits has significance for problems of sea level history during the last interglacial period.

Table 4. Locality 3 Ostracodes from the Norfolk complex, Gomez Pit, Virginia.

Aminozone 1, *Crassostrea* Facies (87TC6,7,12,13):
Bensonocythere hazeli
Cyprideis mexicana
Cytheromorpha curta
Cytherura neusensis
Hulingsina sp. A
Hulingsina rugipustulosa
Leptocythere nikraveshae
Neolophocythere subquadrata
Paracytheridea altila
Paracytheroma stephensoni
Perissocytheridea brachyforma

Aminozone 2, Serpulid, *Mercenaria* Facies, Lower Part (87TC14):
Campylocythere laeva
Cytheromorpha curta
Cytherura nucis
Cyprideis mexicana
Eucythere sp.
Hulingsina sp. A
Leptocythere nikraveshae
Paracytheroma stephensoni
Paradoxostoma sp.
Peratocytheridea bradyi
Pseudocytheretta sp.
Perissocytheridea brachyforma
Puriana rugipunctata

Aminozone 2, Serpulid, *Mercenaria* Facies, Upper Part (87TC16,17,18):
Actinocythereis captionis
Bensonocythere hazeli
Bensonocythere valentinei
Bensonocythere sapeloensis
Campylocythere laeva
Climacoidea (Proteoconcha) nelsonensis
Cytherura reticulata

Table 4. Continued.

Cytherura wardensis
Cytherura howei
Cytherura neusensis
Cytherura spp.
Cytherura forulata
Hemicythere villosa
Hulingsina rugipustulosa
Hulingsina spp.
Loxoconcha matagordensis
Loxoconcha sperata
Loxochoncha sp. A
Malzella floridana
Neolophocythere subquadrata
Paracytheridea altila
Paradoxostoma sp.
Peratocytheridea setipunctata
Pontocythere sp.
Propontocypris edwardsi
Sahnia sp.
Tetracytherura choctawhatchensis

Locality 4. Yadkin Pit, Virginia.

The pit near Yadkin is an important outcrop because it exposes in ascending order fossiliferous beds of the Yorktown, Chowan River, and Norfolk Formations. Hazel (1971b, p. 11) described the Yorktown beds (Hazel's Unit 1) as a "blue clayey sand; macrofossils very common". The Chowan River unconformably overlies the Yorktown with an irregular contact and consists of reddish, clayey sands, containing nodules, mudballs, and well-preserved *Corbicula densata*. The Norfolk Formation is a gray clayey sand often containing iron-cemented concretions and, in some parts of the pit, rare macrofossils.

Ostracode assemblages from the Yorktown at Yadkin Pit include abundant *Malzella conradi, Muellerina, Paranesidea, Orionina, Paracytheridea mucra, P. altila, Protocytheretta* sp., *Campylocythere laeva, Actinocythereis dawsoni, Climacoidea (Proteoconcha), Loxoconcha,* and *Hulingsina*. The overlying Chowan River Formation contains the following ostracodes: *Hulingsina* spp., *Peratocytheridea, Pseudocytheretta, Climacoidea (Proteoconcha) multipunctata, Actinocythereis dawsoni, Bensonocythere* spp., *Puriana mesacostalis, Malzella conradi, Muellerina, and Tetracytherura similis.*

Hazel (1971b) correlated ostracode assemblages quantitatively from the Yorktown and Chowan River Formations at the Yadkin pit (Hazel referred to both units as the Yorktown but his unit 2 was reassigned to the Chowan River Formation by Blackwelder, 1981). Hazel found that the assemblage from the Yorktown clustered tightly with assemblages from locality 2 (Rice's Pit), and the assemblage from the Chowan River was much younger and correlated with beds outcropping on the Chowan River (our localities 5 and 6). The ostracodes from both formations

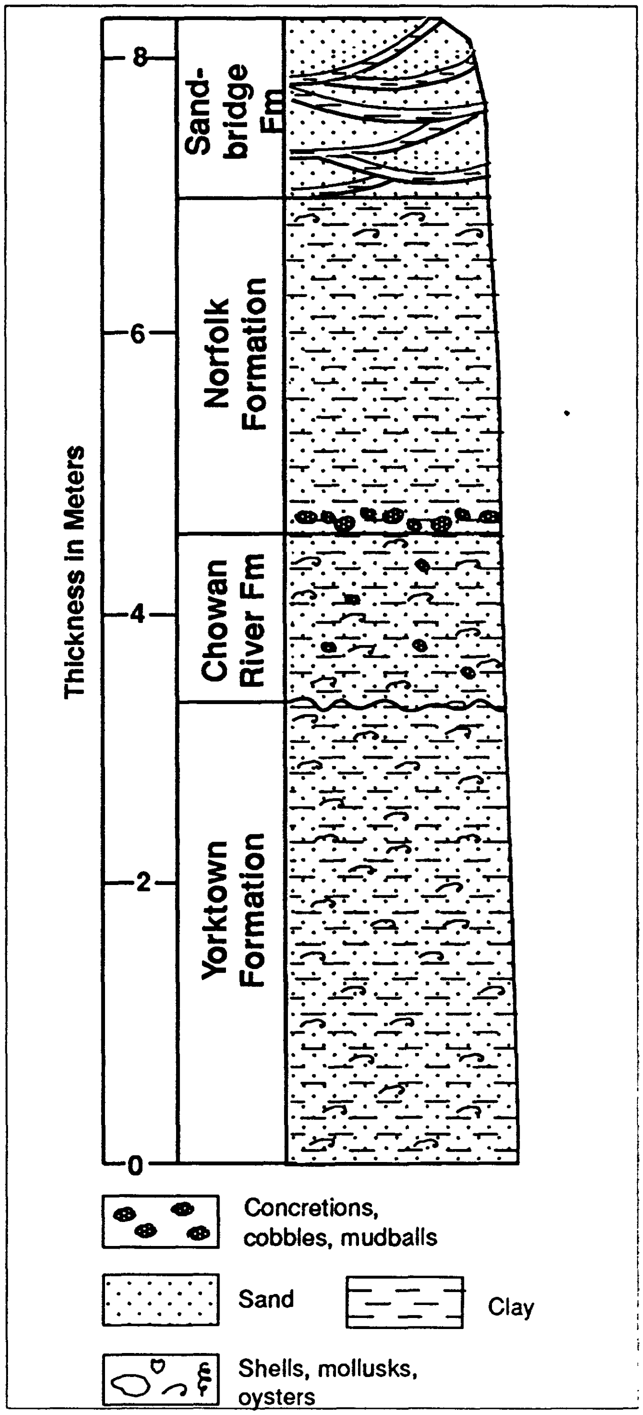

Figure 7. Stratigraphic section of Yadkin Pit, Virginia. Geology after Hazel (1971b).

indicate warm temperate bottom water (Hazel, 1971a) but there is clearly a depositional hiatus between the two units.

Paleomagnetic analysis of the Chowan River Formation at Yadkin by Joseph E. Liddicoat (written communication, 1981) gave a reversed magnetic signal, which together with the biostratigraphic data suggests an early Matuyama age. The Chowan River Formation near Bowers Hill, Virginia is also reversely magnetized.

Planktic foraminifers from the Chowan River Formation at Yadkin Pit are common and well preserved. The presence of *Globigerinoides obliquus* and the absence of *Sphaeroidinellopsis*, combined with reversed magnetism restricts the age of the Chowan River to 2.47- 1.88 Ma. Several specimens tentatively assigned to *Dentoglobigerina altispira* were also found at Yadkin Pit. These specimens are low trochospiral and not at all like the *D. altispira* obtained from the underlying Yorktown Formation at Rice's Pit. If these are indeed *D. altispira*, and they are not reworked, the age of the Chowan River could fall within the Kaena or Mammoth reversed subchrons.

Locality 5. Edenhouse, North Carolina.

Blackwelder (1981) proposed the name Chowan River Formation for fossiliferous beds overlying the Yorktown Formation in southeastern Virginia and northeastern North Carolina. Localities 5 and 6 represent the type localities of the two members of the Chowan River Formation: the Edenhouse Member and the overlying Colerain Beach Member respectively. The Edenhouse Member consists of shelly burrowed sands, including the mollusks *Argopecten, Astarte, Abra, Corbicula, Cyclocardia, Parvilucina, Nucula,* and *Crassatella*. Corals from the Edenhouse Member near Mount Gould, North Carolina were dated at about 1.9Ma using the helium-uranium technique (Blackwelder, 1981). Although it is not clear how accurate this technique is, the age is consistent with the reversed paleomagnetic data and the biostratigraphy.

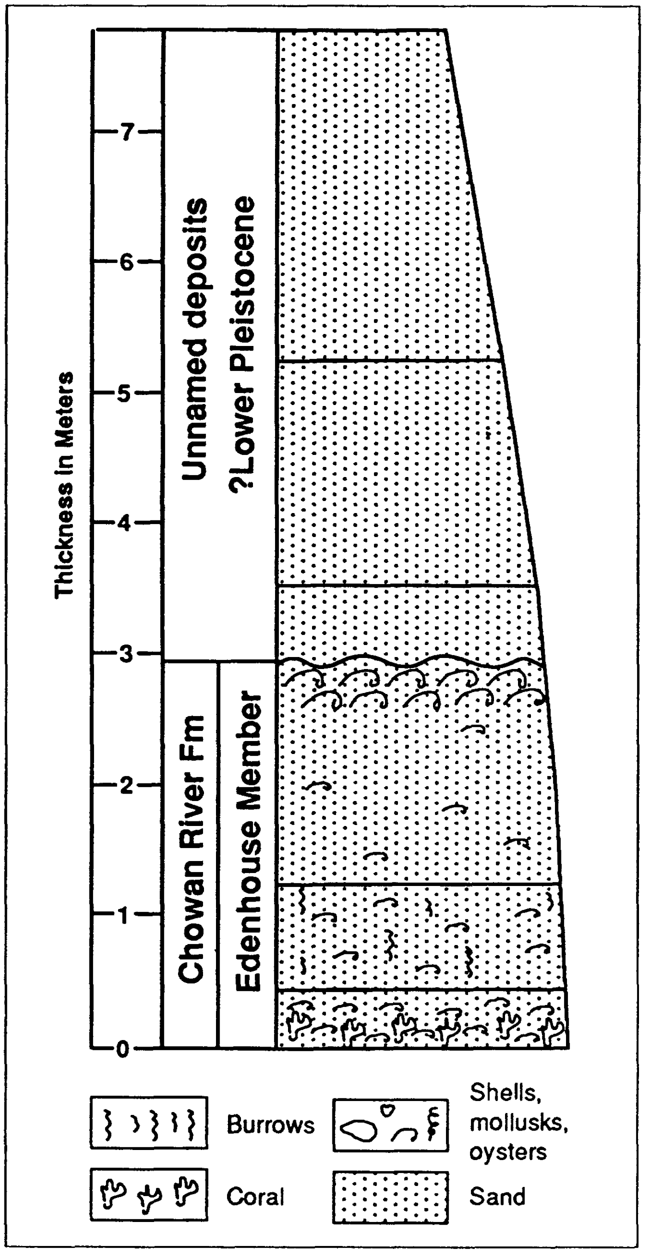

Figure 8. Stratigraphic section of the Edenhouse locality, Edenhouse, North Carolina. Geology after Blackwelder (1981)

Locality 6. Colerain Beach. North Carolina.

The Colerain Beach Member of the Chowan River Formation overlies the Edenhouse Member at the Colerain Beach Club. The Colerain Beach Member consists of cross-bedded sands and silts containing lenses of fossils near the top of the unit. The following mollusks occur: *Rangia, Corbicula,* and *Mercenaria*. The ostracodes (including *Cyprideis* and *Cytheromorpha curta*) and mollusks indicate a brackish water estuarine environment for the uppermost beds at this section. Blackwelder (1981) state that the Colerain Beach Member represents the regressive phase of the late Pliocene Chowan River marine inundation.

The Edenhouse Member at this locality contains a diverse mid-outer shelf ostracode assemblage, differing from the Colerain Beach Member in having more common *Thaerocythere,* and *Muellerina* and in the presence of *Echinocythereis*. The Colerain Beach

Member also contains *Actinocythereis captionis, Orionina vaughani, Bensonocythere whitei, Malzella evexa, Paracytheridea altila, Thaerocythere, Campylocythere, Cytheridea, Hulingsina, Protocytheretta, and Climacoidea (P.) multipunctata.*

Locality 7. Morgarts Beach, Virginia.

This section exposes the Rushmere and Morgarts Beach Members of the Yorktown Formation. Ward and Blackwelder (1980, p. D41) described the lithology of the Morgarts Beach Member as a "Gray fine slightly sandy clay (tan where weathered) containing abundant small shell (*Mulinia*) throughout". The contact with the underlying Rushmere member is conformable and sometimes gradational. The Morgarts Beach Member contains mollusks indicating deposition behind barrier islands in water of normal marine salinity.

Planktic foraminifers are especially abundant in the Morgarts Beach member of the Yorktown Forma-

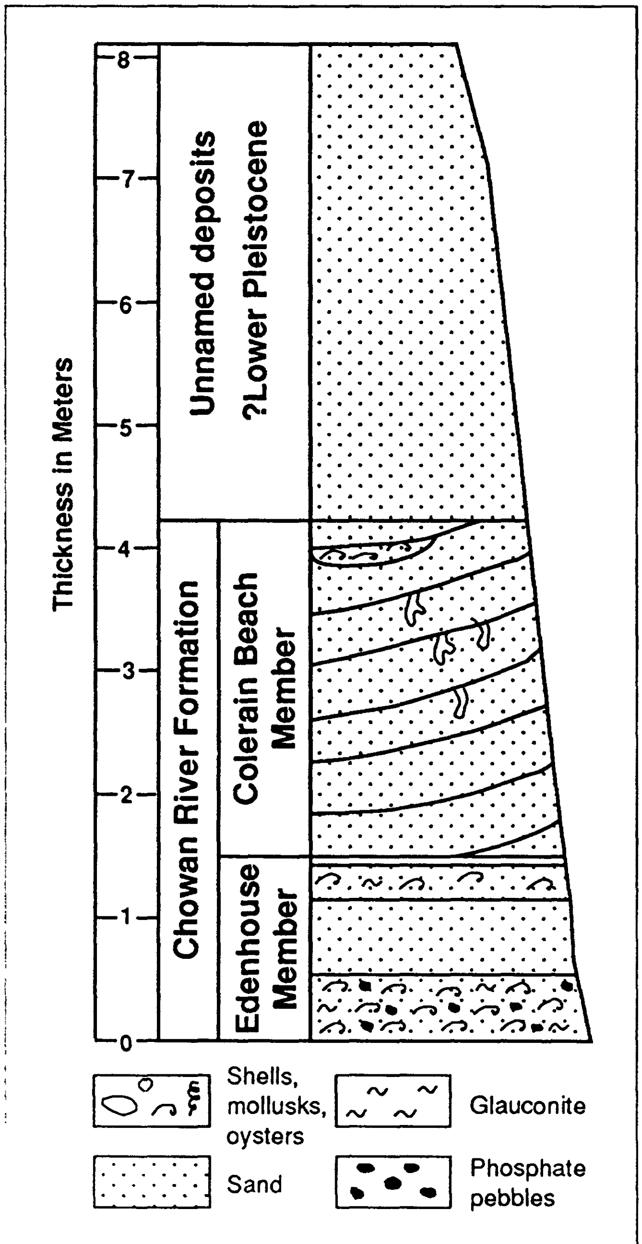

Figure 9. Stratigraphic section of the Colerain Beach locality, North Carolina. Geology after Blackwelder (1981).

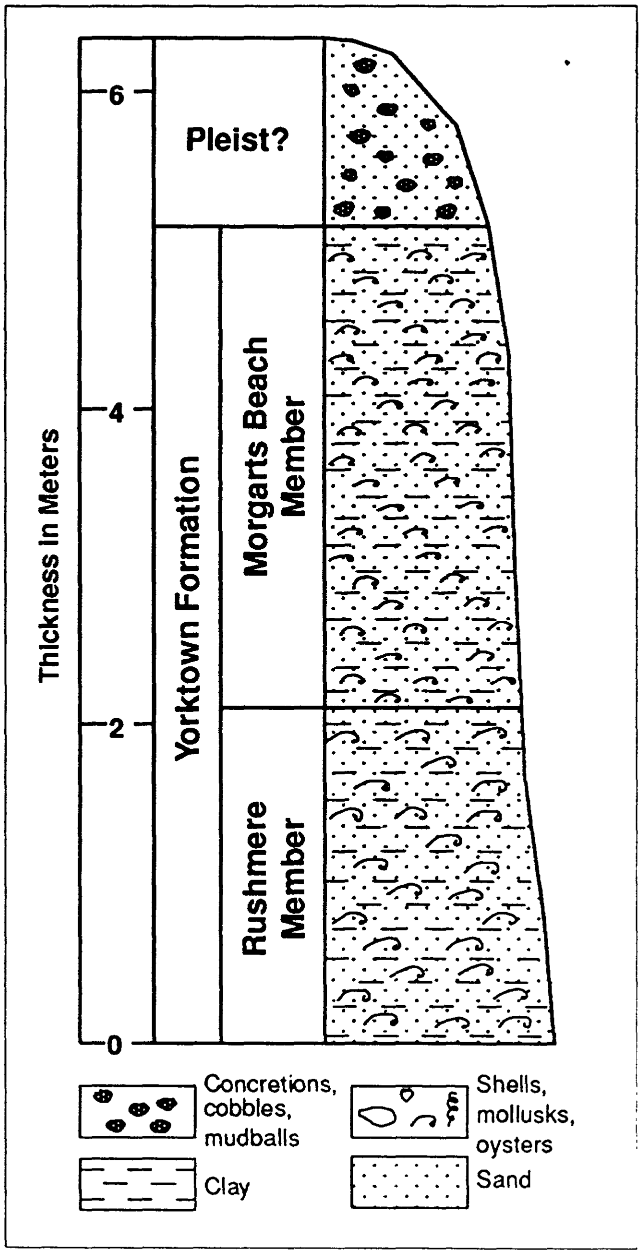

Figure 10. Stratigraphic section of the Morgarts Beach locality, Virginia. Geology after Ward and Blackwelder (1980).

tion at this locality. The fauna is dominated by *Globigerina bulloides* but contains other globigerinids and *Globorotalia tumida*. The underlying Rushmere Member, while containing a less diverse fauna, does contain the stratigraphically important genus *Sphaeroidinellopsis* (last appearance at 3.0 Ma in the deep-sea record; Dowsett, 1989). The data at this and other sections (Rice's Pit) leads us to tentatively place the boundary between the Morgarts Beach and Moore House Members at 3.0 Ma.

Application of the ostracode transfer function to assemblages from the Morgarts Beach Member at this locality (Cronin and Dowsett, in press) gave February BWT's of 11.1 to 12.4°C and August BWT's of 17.4 to 17.9°C (samples 78TC126 and 78TC127 in Table 3).

Locality 8. Rushmere, Virginia.

The exposure at locality 8 at Burwell Bay, near Rushmere, Virginia is the type locality of the Yorktown Formation and of the Rushmere Member, and it also exposes the overlying Morgarts Beach and Moore House Members (Ward and Blackwelder, 1980). The Rushmere Member at this locality consists of a blue-gray, fine, sandy clay, containing very abundant mollusk shells, echinoderms, foraminifers, and ostracodes. The Rushmere overlaps sediments of the Sunken Meadows Member of the Yorktown throughout the region and represents the greatest transgression of the Yorktown Formation. Fossiliferous marine deposits of the Rushmere occur as far inland as Skippers, Greensville County, Virginia where they overlie granite saprolite.

The Rushmere Member contains a diverse marine fauna with subtropical and tropical influence, especially in southerly regions of its outcrop belt (Ward and Blackwelder, 1980). Ostracode assemblages are dominated by *Malzella, Muellerina, Pterygocythereis, Protocytheretta, Pseudocytheretta, and Tetracytherura.*

Locality 9. Cobham Wharf, Virginia

Locality 9 is the type locality of the middle upper Miocene Cobham Bay Member of the Eastover Formation, and this outcrop also exposes the Sunken Meadows and Rushmere Members of the Yorktown Formation. The Cobham Bay Member is described in detail by Ward and Blackwelder (1980) and consists of fine-grained, well-sorted sand containing open-marine, subtropical molluscs. It is unconformably overlain throughout much of its outcrop area by either the Sunken Meadows or Rushmere Members of the Yorktown.

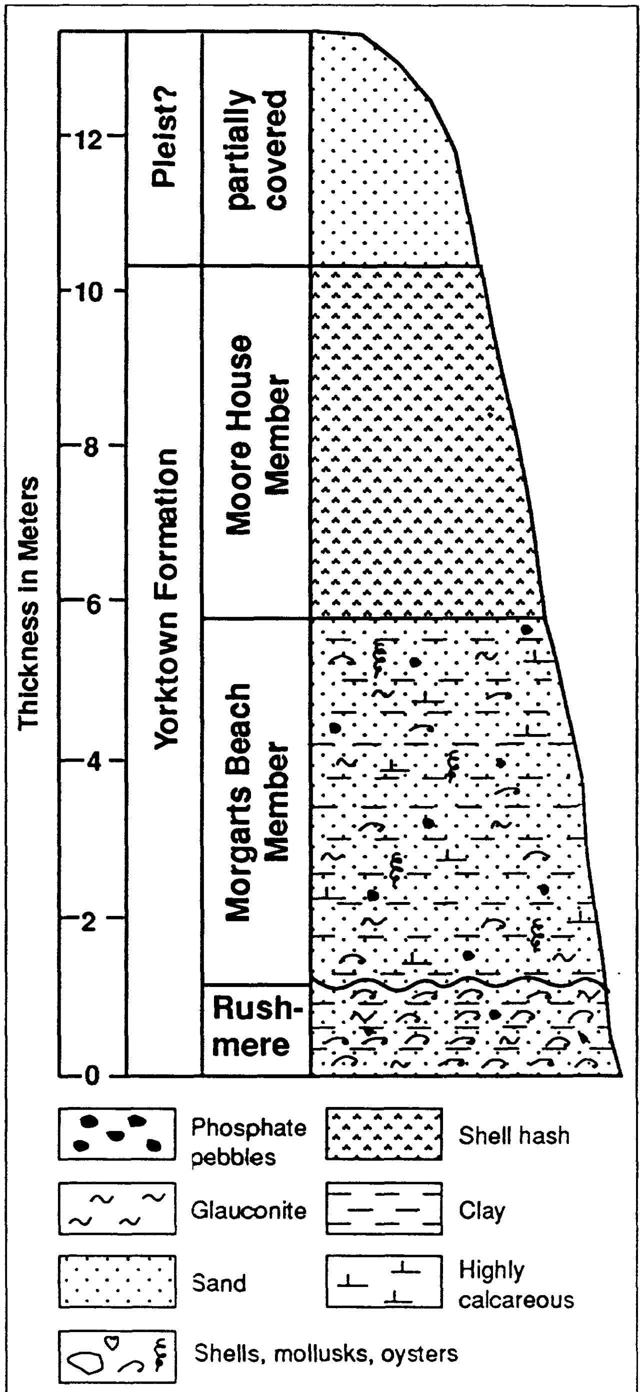

Figure 11. Stratigraphic section of the Rushmere locality, Virginia. Geology after Ward and Blackwelder (1980).

The age of the Cobham Bay Member is late Tortonian and radiometric dates of 8.7±0.4Ma and 6.46±0.15Ma are available from this unit (Ward and Blackwelder, 1980). Molluscan assemblages suggest that the Cobham Bay Member can be correlated to the Arca Zone of Florida, which Akers (1972) dated

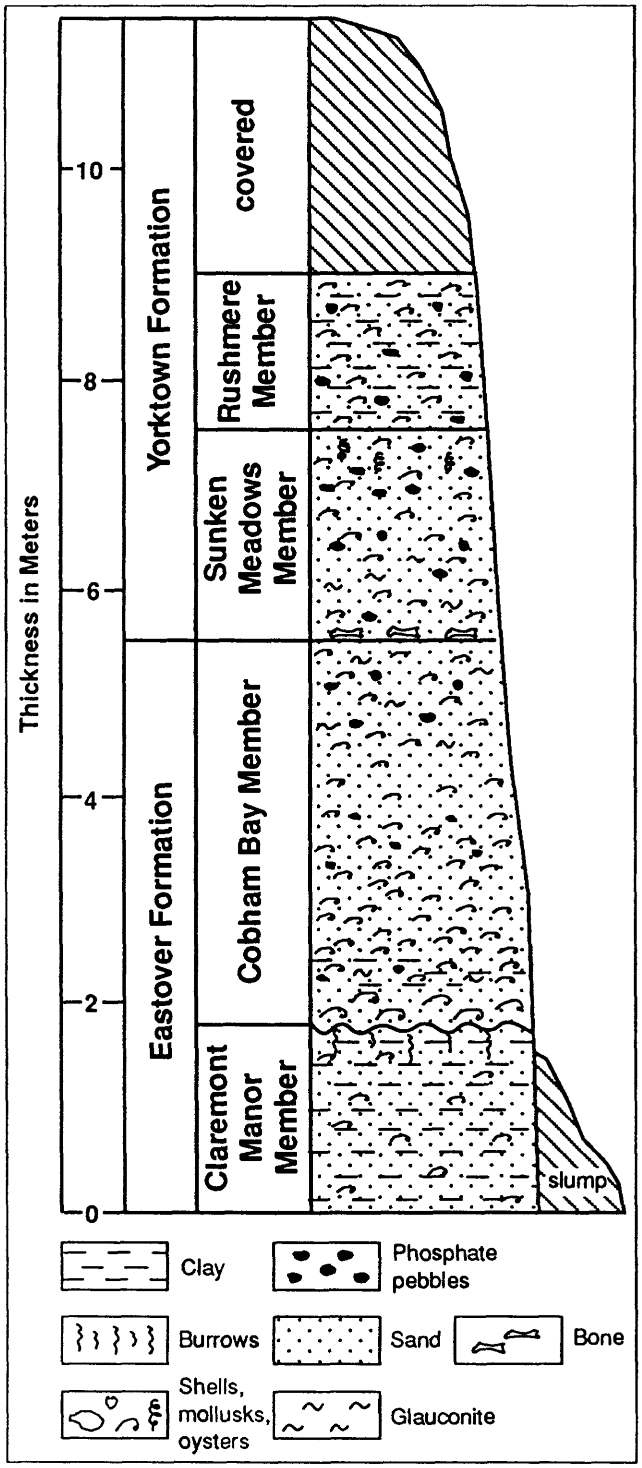

Figure 12. Stratigraphic section of the Cobham Wharf locality, Virginia. Geology from Ward and Blackwelder (1980).

as planktic foraminifer Zone N17 (about 7.0-5.5Ma). The ostracodes from the Cobham Bay Member were described by Forester (1980).

DISCUSSION

The Yorktown Formation represents a major marine transgression during the middle Pliocene. Further, the stratigraphic break between the Yorktown and the Chowan River Formation signifies subsequent emergence during a period of low relative sea level. The following hypothesis, adapted from Cronin (1988) and Dowsett and Cronin (1989, in press), explains most of the available age and paleoenvironmental data for these units. The Yorktown indicates a middle Pliocene period of global warmth when continental ice volume was low and global sea levels high (Dowsett and Cronin, 1989, in press; Sarnthein and Fenner, 1988). The warm paleoceanographic conditions inferred from the Yorktown faunas indicate that the paleo-Gulf Stream flowed past eastern North America during this warm interval (Hazel, 1971a; Cronin, 1988). The unconformity between the Yorktown and Chowan River Formations signifies a major period of emergence and erosion (DuBar et al., 1974) due to increased northern hemisphere ice volume and concommitant lower eustatic sea-level. Similar changes are recorded in deep-sea cores in the North Atlantic (e.g. Shackleton et al., 1984). Although the present elevation of Yorktown deposits records only relative sea level positions, in a stable area such as the Coastal Plain most of the sea level signal was probably glacio-eustatic. The subsequent late Pliocene transgression that deposited the Chowan River Formation did not reach the elevation of the Yorktown, and the Chowan River faunas indicate slightly cooler marine climates.

Dowsett and Cronin (1989, in press) studied microfaunas from deposits of the Duplin Formation in North and South Carolina, a unit correlative with the Yorktown. The Duplin Formation represents the marine transgression that cut the Orangeburg Scarp, a Pliocene shoreline that gives an excellent indication of Pliocene relative sea level. By subtracting estimated tectonic upift of the scarp since 3.0 Ma, Dowsett and Cronin estimated eustatic sea level about 3.4-3.0Ma was as much as 25-35m higher than it is today. Such a sea level rise is consistent with the depositional pattern of the Yorktown Formation, which is farther inland than other Neogene and Quaternary marine units. The Yorktown Formation was therefore most likely deposited during a period of reduced continental ice in both polar regions. This hypothesis can be tested by additional geochronologic study of the Yorktown Formation, especially the most landward exposures, and of the Pliocene marine deposits in other relatively stable coastal regions.

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We greatly apprectate the permission of the following people for access to the outcrops described here: James Haskett, Chuck Rafkind, Diane Depew (National Park Service, Yorktown Va.), Mrs. Mary Rice (Rice's Pit), Dave Basnight (Gomez Pit), McArn Bell (Edenhouse, N.C.), James White (Colerain Beach, N.C.), Melvin Lyles, W. Barnham (Morgarts Beach), Margaret Barr (Rushmere, Va.), and Wallace Cahoon (Yadkin Pit). R.Z. Poore and Laurel M. Bybell reviewed the manuscript. Drs. Aliashraf Mamedov and Olga Borisova provided helpful comments on the stratigraphy and paleontology of the Yorktown. We are grateful to Dr. John Wehmiller, University of Delaware, for information on the Gomez Pit and to Cynthia Schneider for assistance in the field.

This paper represents part of an integrated program conducted by the USGS whose main objective is to reconstruct the Northern Hemisphere during the middle Pliocene, a period of extreme warmth based upon various paleontologic and geologic evidence. This project is part of a broader program in the USGS directed at Global Change. The results of this reconstruction will provide climate modelers with a means to test the predictive powers of general circulation models used to project future climate change.

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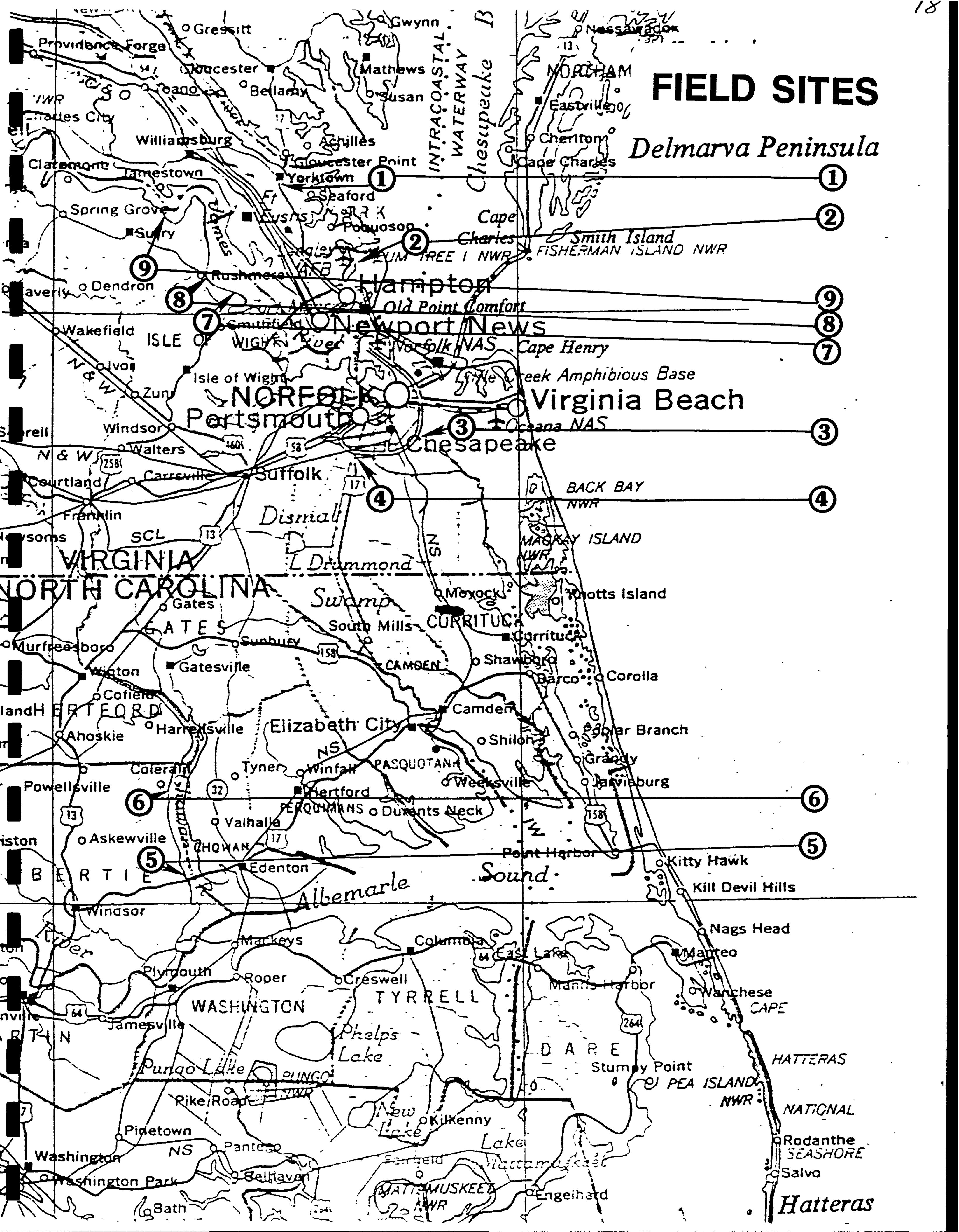
APPENDICES

Area and quadrangle maps with localities indicated.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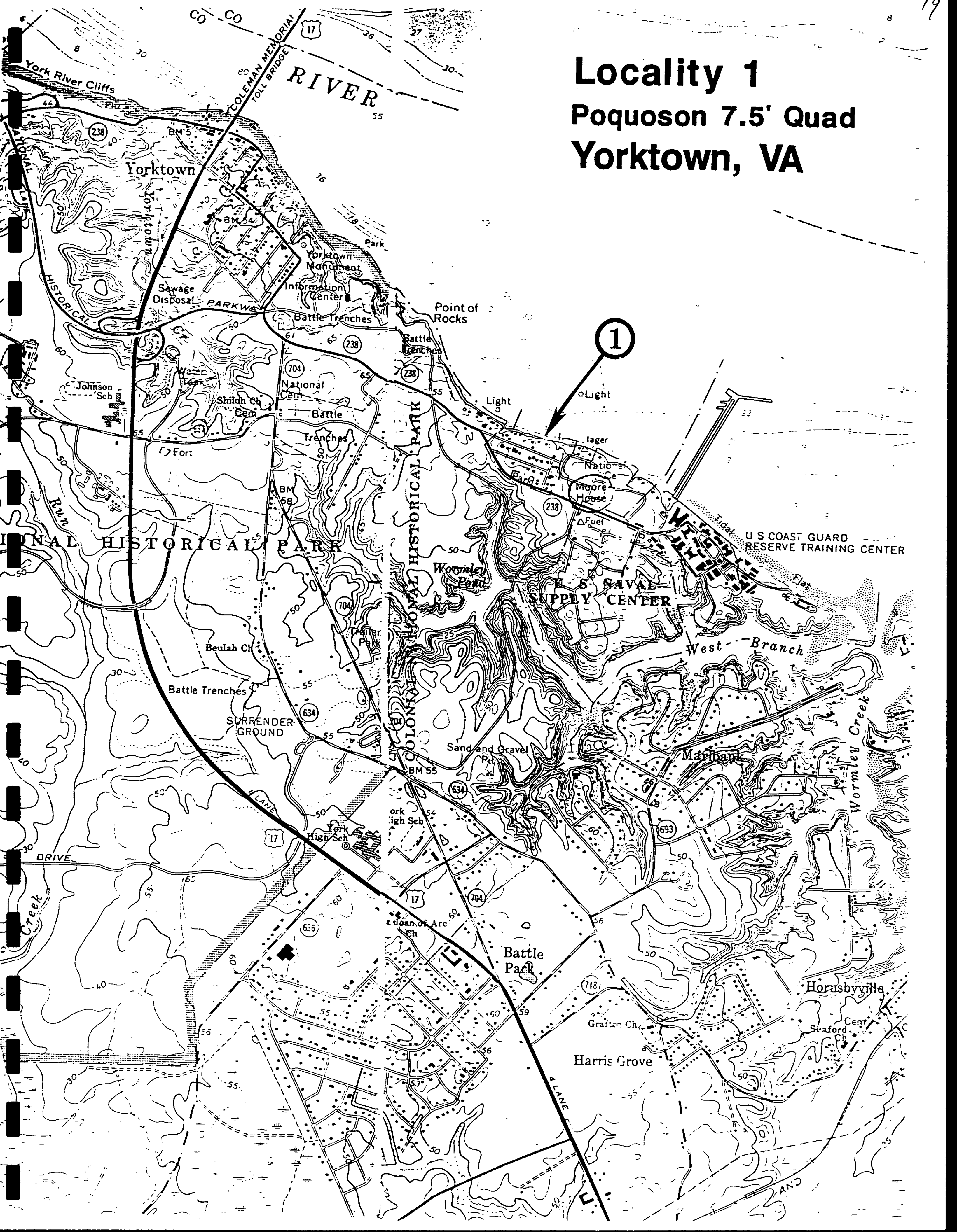
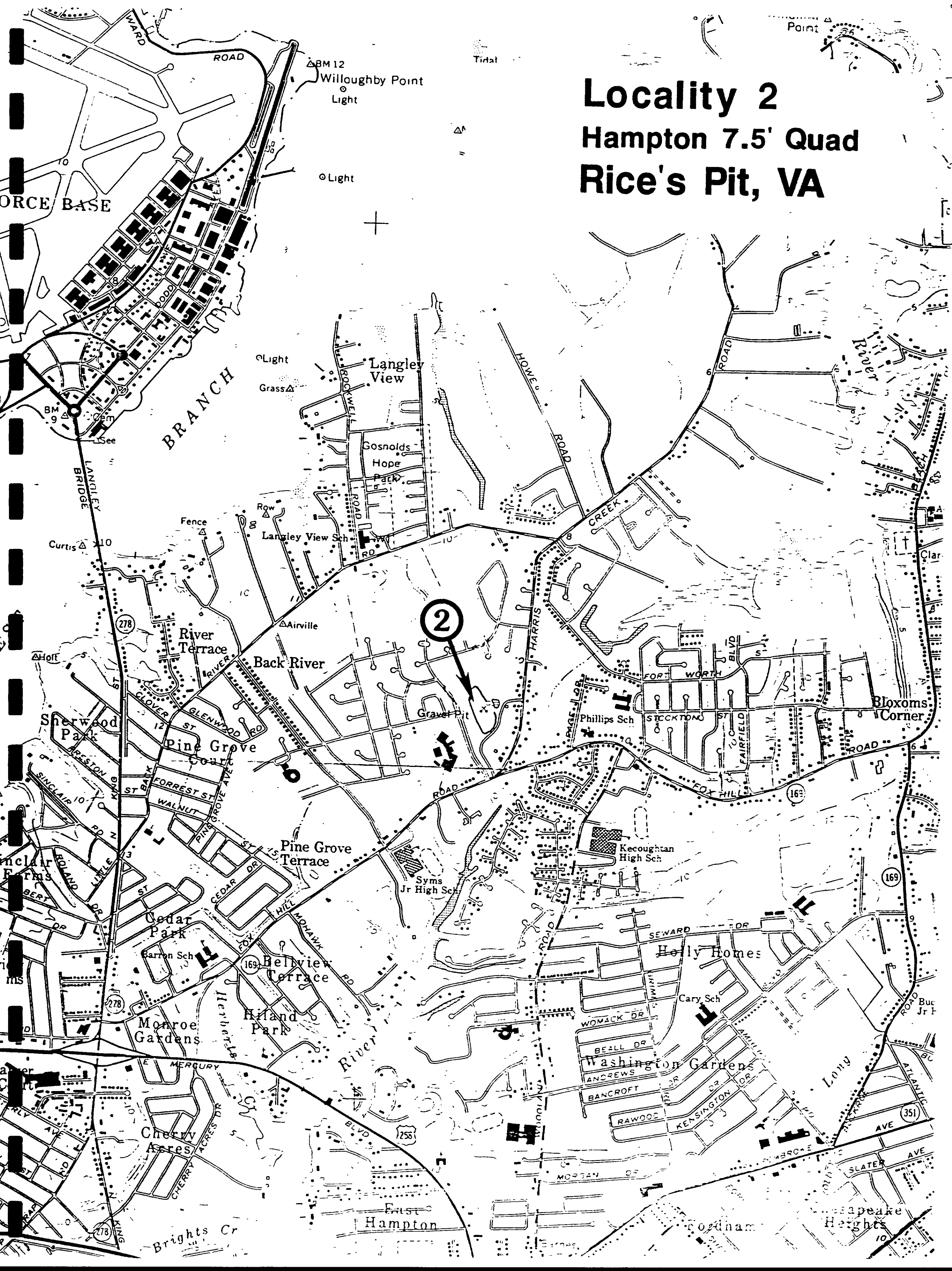
Delmarva Peninsula
Gressitt
Gwynn
Nassawadox
Providence Forge
Gloucester
Mathews
NORTHAM
Bellamy
Susan
Eastville
Charles City
Williamsburg
Achilles
Cheriton
Gloucester Point
Cape Charles
Claremont
Jamestown
Yorktown
INTRACOASTAL WATERWAY
Chesapeake B
1
1
Seaford
Spring Grove
Poquoson
Cape Charles
Surry
Smith Island
2
2
FISHERMAN ISLAND NWR
9
Rushmere
Dendron
Hampton
9
8
Old Point Comfort
8
Waverly
7
Smithfield
Newport News
Wakefield
ISLE OF WIGHT
Norfolk NAS
Cape Henry
7
Ivor
Isle of Wight
Creek Amphibious Base
Zuni
NORFOLK
Virginia Beach
Windsor
Portsmouth
Oceana NAS
3
3
Walters
Chesapeake
N & W
Courtland
Carrsville
Suffolk
BACK BAY NWR
4
4
Franklin
Dismal
SCL
MACKAY ISLAND NWR
VIRGINIA
L. Drummond
NORTH CAROLINA
Swamp
Moyock
Knotts Island
Gates
GATES
South Mills
CURRITUCK
Currituck
Murfreesboro
Sunbury
CAMDEN
Shawboro
Winton
Gatesville
Barco
Corolla
Cofield
HERTFORD
Camden
Harrellsville
Elizabeth City
Poplar Branch
Ahoskie
Shiloh
Grandy
Colerain
Tyner
Winfall
PASQUOTANK
Powellsville
Weeksville
Jarvisburg
6
Hertford
6
PERQUIMANS
Durants Neck
Valhalla
Askewville
CHOWAN
Point Harbor
5
5
Kitty Hawk
Edenton
BERTIE
Sound
Kill Devil Hills
Albemarle
Windsor
Nags Head
Mackeys
Columbia
Manteo
East Lake
Plymouth
Roper
Creswell
Manns Harbor
Wanchese
WASHINGTON
TYRRELL
CAPE
Jamesville
Phelps Lake
DARE
HATTERAS
Pungo Lake
PUNGO NWR
Stumpy Point
PEA ISLAND NWR
Pike Road
New Lake
Kilkenny
NATIONAL
Pinetown
Lake Mattamuskeet
Rodanthe
Washington
Pantego
SEASHORE
Fairfield
Salvo
Washington Park
Belhaven
MATTAMUSKEET NWR
Engelhard
Bath
Hatteras

Locality 1
Poquoson 7.5' Quad
Yorktown, VA



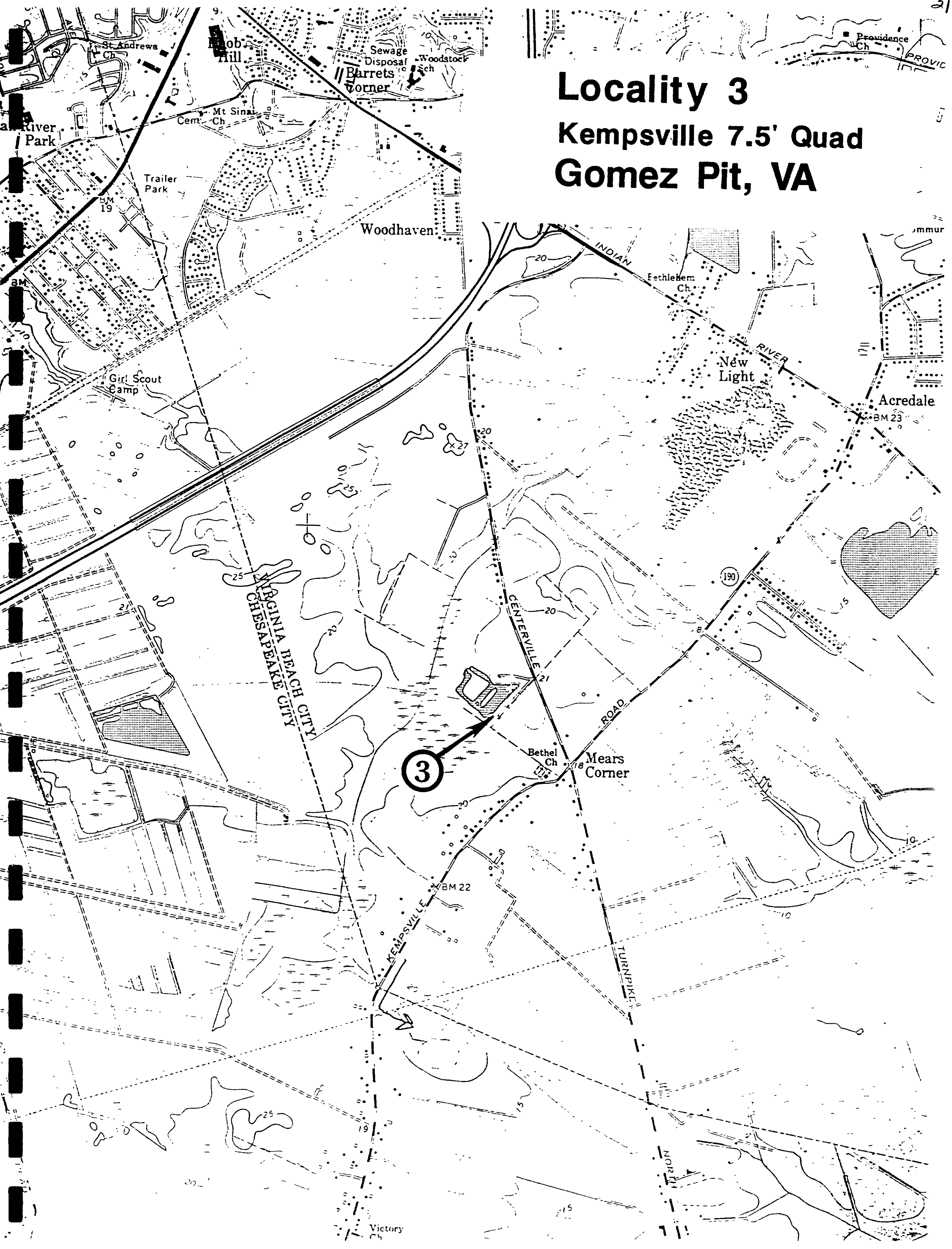
Locality 2
Hampton 7.5' Quad
Rice's Pit, VA



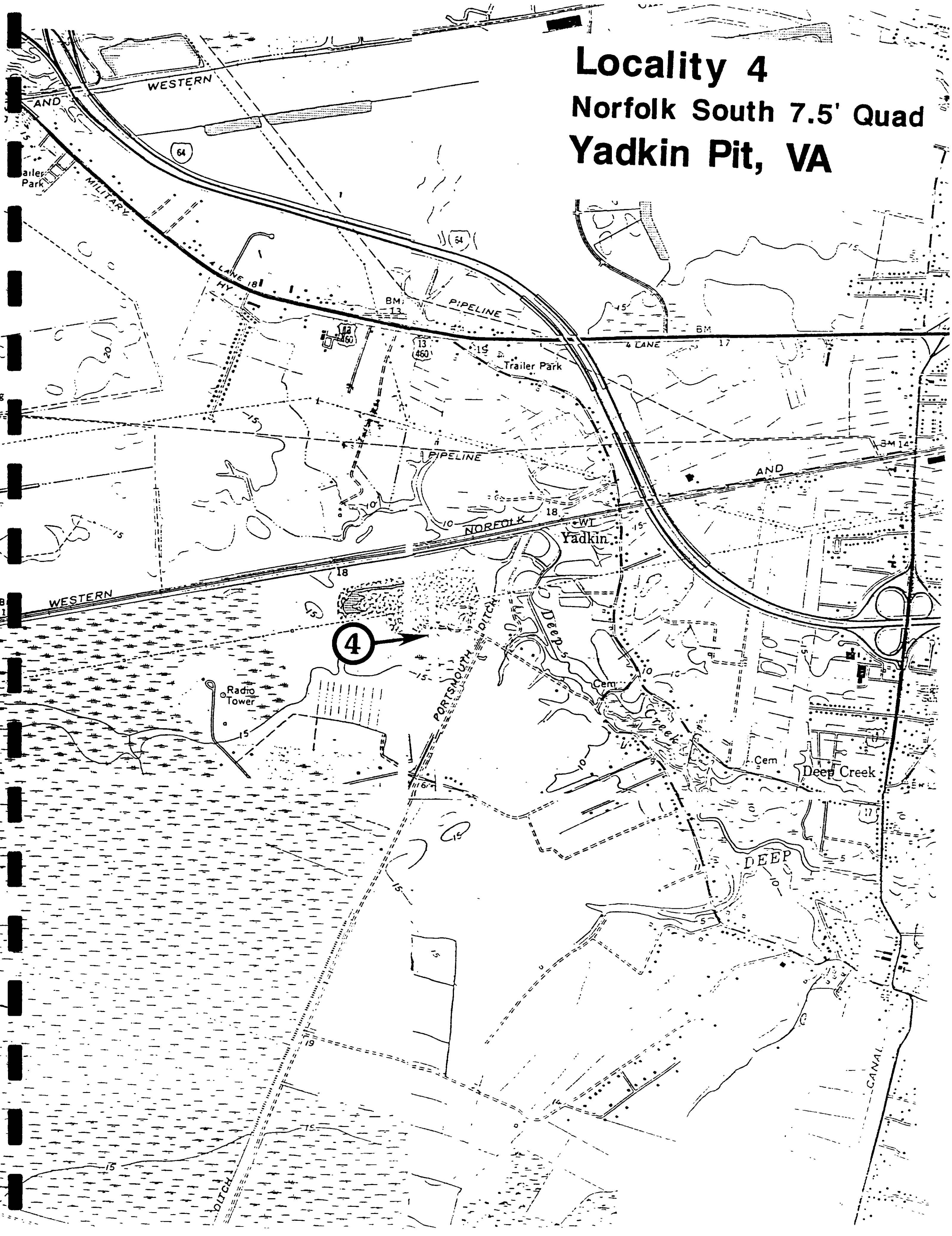
Locality 3

Kempsville 7.5' Quad

Gomez Pit, VA



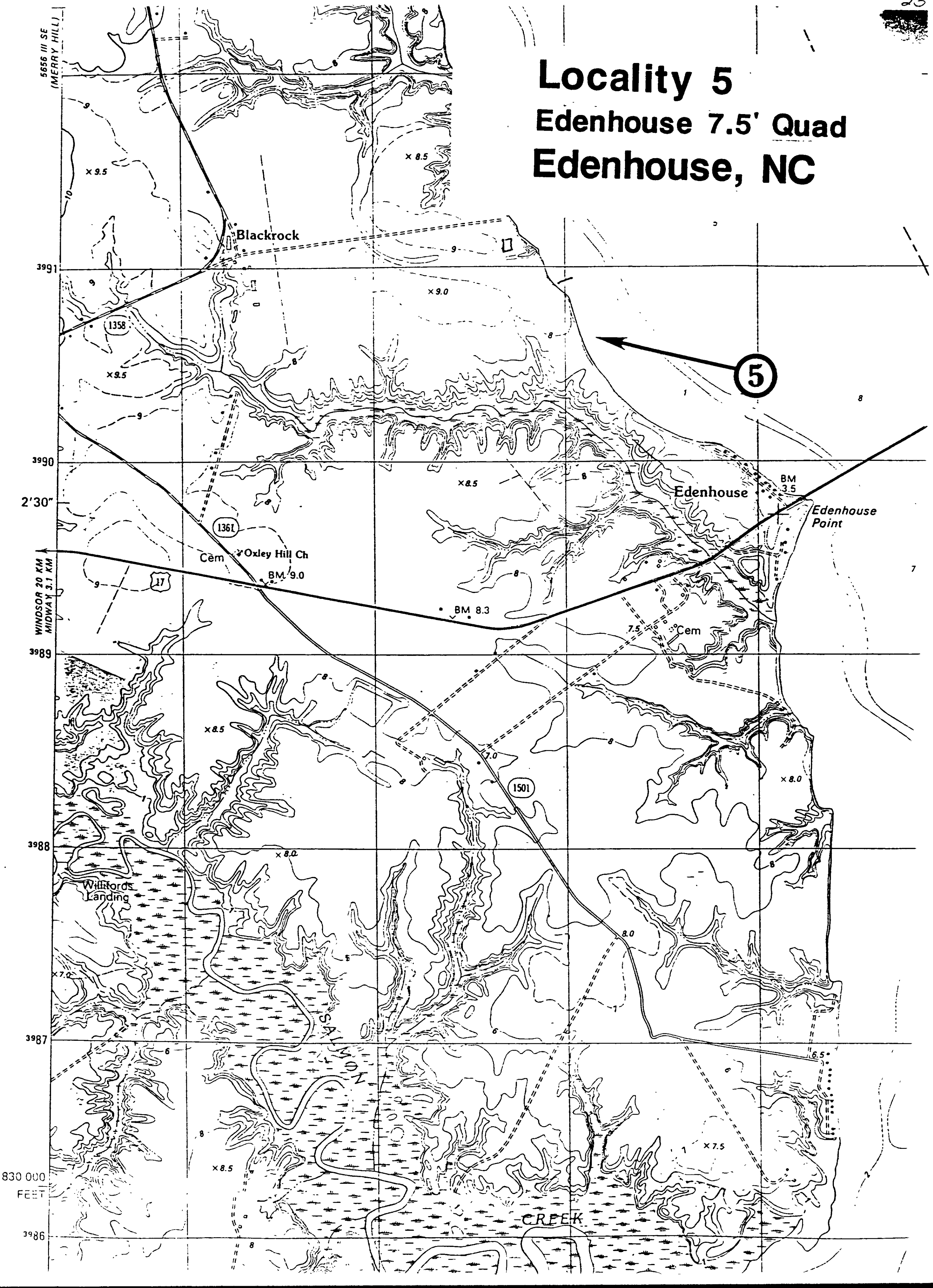
Locality 4
Norfolk South 7.5' Quad
Yadkin Pit, VA



Locality 5

Edenhouse 7.5' Quad

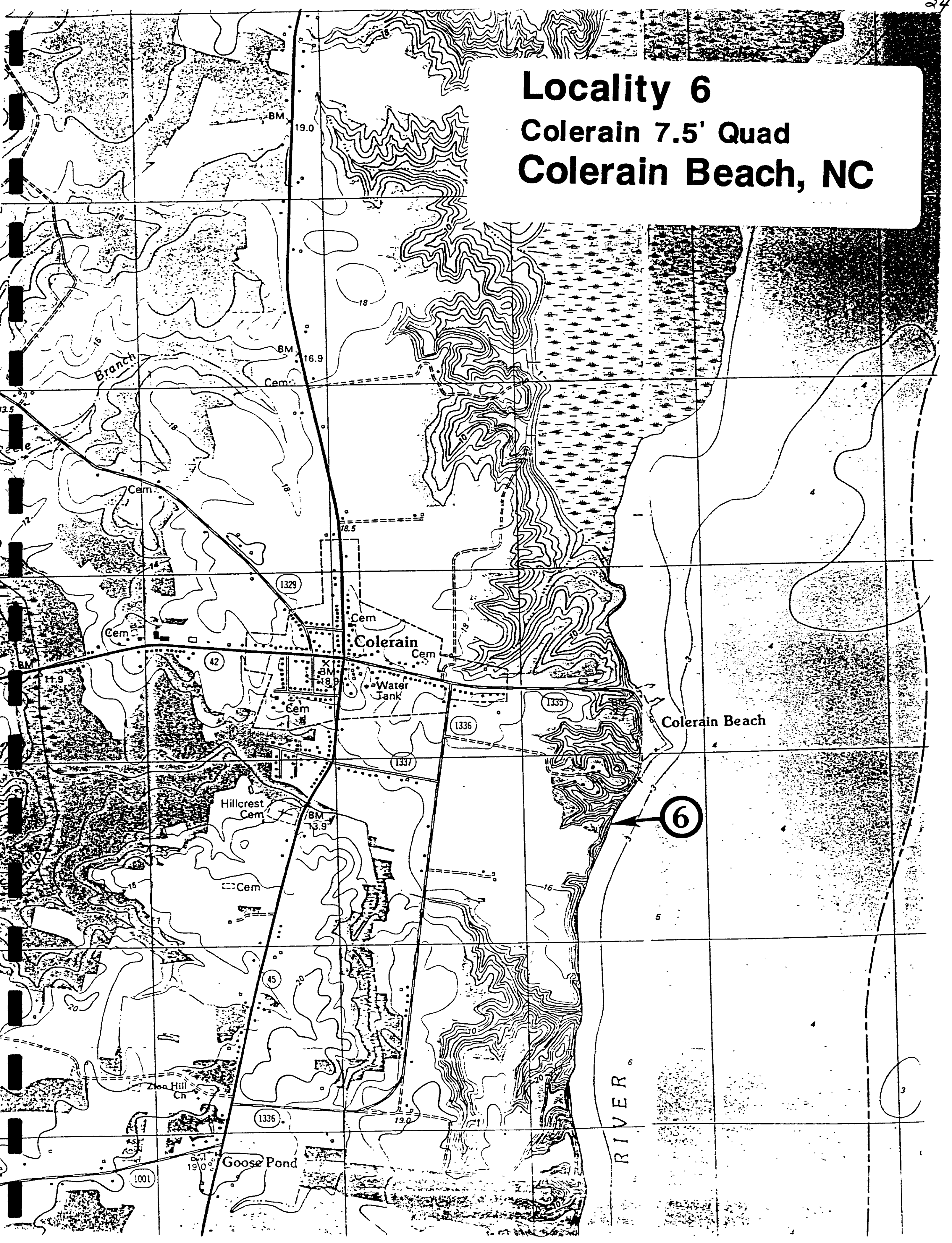
Edenhouse, NC



Locality 6

Colerain 7.5' Quad

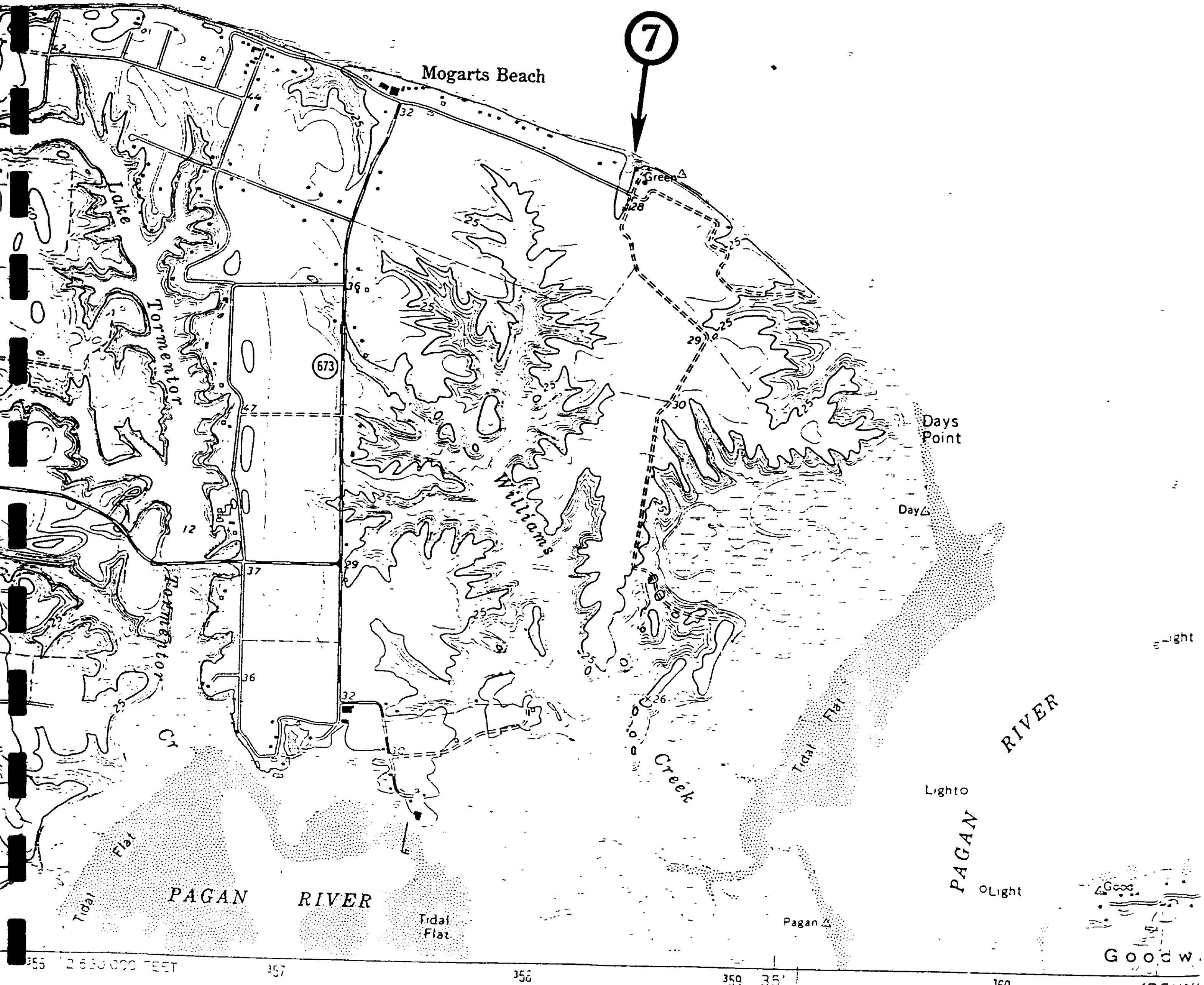
Colerain Beach, NC



Locality 7

Mulberry Island 7.5' Quad

Morgart's Beach, VA



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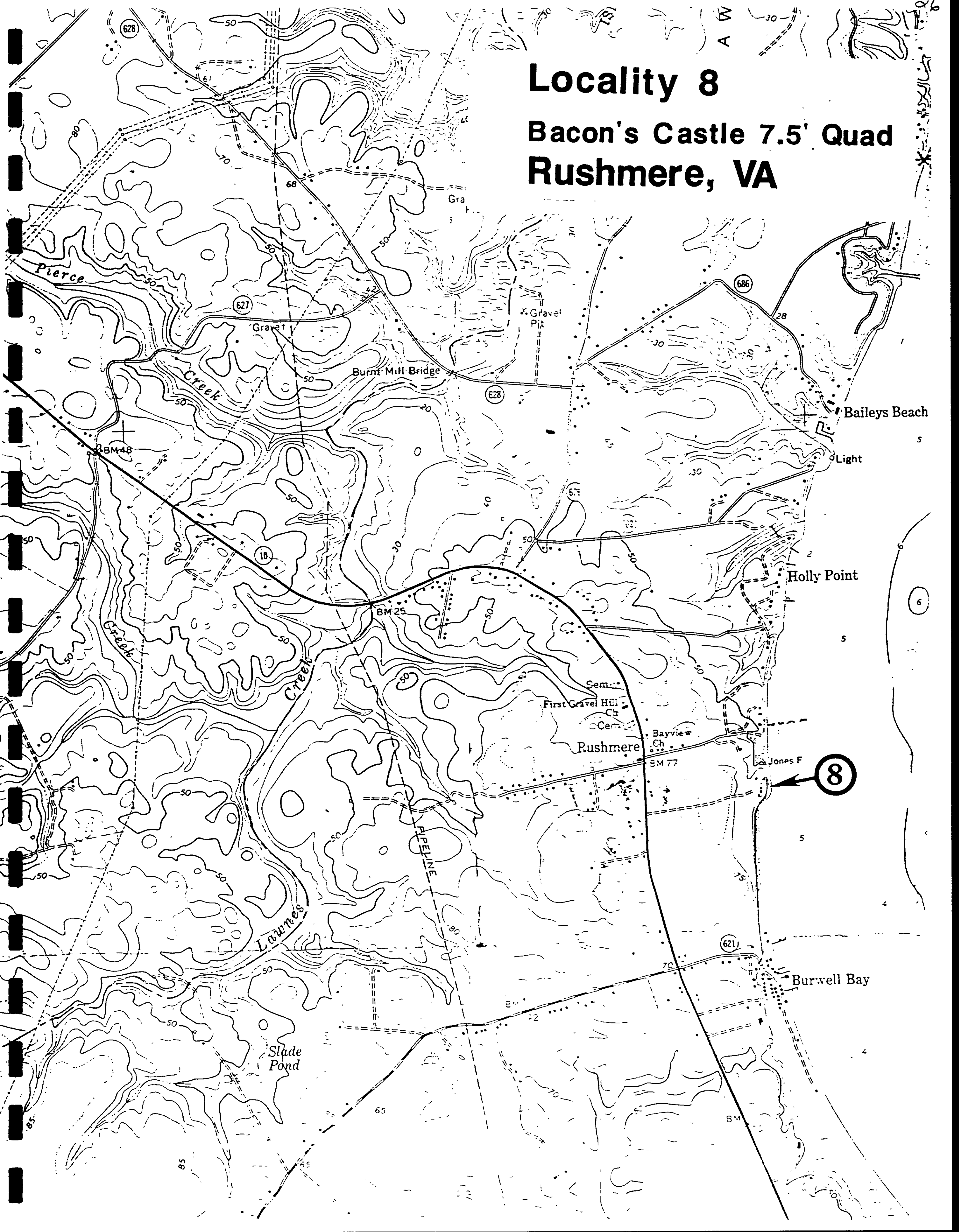
USC&GS, and USCE
photogrammetric methods from aerial photographs

Locality 8

Bacon's Castle 7.5' Quad

Rushmere, VA



Locality 9

Surry 7.5' Quad

Cobham Wharf, VA