From:	J Sevilla [qmakeda@chesapeake.net]
Sent:	Sunday, March 28, 2010 12:08 AM
To:	Steckel, James
Cc:	Allison Fisher; Michael Mariotte; Paul Gunter; Peter Vogt; Peter Saar; dspowars@usgs.gov; larsencurt@msn.com; Arora, Surinder
Subject:	CC3 FSAR- NRC/Steckel-request action on plausible earthquake fault 1.25 miles or closer, south of CCNPP-Docket 52-016
Attachments:	Kidwell_1997JSR.pdf; Sevilla Resp to UniStar Oppo- Attachment 1- Review of CCNPP appeal-Curt Larsen.pdf; PSC 9218 - Sevilla resp to UniStar Oppos- Attachment 2 - Emails on Fault.pdf; Nuclear 2009 appeal Vogt refs.pdf; Sevilla Resp to UniStar Oppo- Attachment 1- Review of CCNPP appeal-Curt Larsen.pdf
Importance:	High

To: James Steckel, NRC
From: June Sevilla
<u>Subject:</u> Request NRC action on Plausible Earthquake Fault at Calvert Cliffs - scientific information for CC3 FSAR consideration, Docket No. 52-016
SRP Section: 02.05.04 - Stability of Subsurface Materials and Foundations
Application Section: 2.5.4

Jim,
The attached documents regarding a plausible earthquake fault near CCNPP are pertinent to the soil and foundation infrastructure upon which Calvert Cliffs Unit3 is to be built. Since our discussion during the March 17th tele-conference was about the FSAR, you indicated that my forwarding this fault information to you, would include your passing on the information to the appropriate NRC staff as well as consider them in your analysis of the areas within your jurisdiction before the FSAR is released. Since the plausible fault a.k.a "Moran's Landing Fault" was discovered at Calvert Cliffs just 1 1/4 miles south of CCNPP, with possibility of the fault running much closer to CC3, it warrants immediate investigation and consideration in the FSAR for CC3.

When I brought up this subject during public comment discussion, NRC staff admitted that liquefaction is a siesmic consideration. This is also reflected in your meeting agenda, per NRC email below, where two sections specifically address liquefaction and seismic issues in particular. Item 02.05.04-14, Section 2.5.4.8 is of great concern since it states that "*liquefaction is not a concern for this site*", possibly because to the best of my knowledge, Moran's Landing Fault was neither recognized nor considered in CC3's application whatsoever. Your agenda included:

"02.05.04-14 : Section 2.5.4.8 presents liquefaction potential analysis results and concludes that liquefaction is not a concern for this site. However, the data also show that the upper soil layer (Terrace Sand) does have some potential for liquefaction. Since seismic Category I electrical duct banks and pipes will be located at shallow depths, please discuss the liquefaction potential of soil where these components will be located."

"Section 2.4.12.5, please discuss the impact of using higher ground water level on site seismic response, SSI, settlement and lateral earth pressure analyses."

Currently with the Department of Geophysical Sciences, University of Chicago, Dr. Susan Kidwell's site research and paper (attached) discovered the Calvert Cliffs geological anomaly in 1997, but it was the keen eyes of a local geologist, Dr. Peter Vogt who brought up this concern to the Maryland Public Service Commission (PSC) by submitting his report during the CPCN 9127 proceedings.

However, since Dr. Vogt was not a party to that CPCN, the PSC customarily dismissed the submission and stated that this matter is under NRC jurisdiction, under safety. Recently, UniStar has applied for CPCN under Case 9218 and I am a Party /Intervenor to that PSC case as well as to these NRC proceedings for CC3, Docket 52-016.

Instead of litigating this issue as a Contention with the ASLB at this juncture, in good faith, I am presenting this plausible fault concern to the NRC through you, to consider the impacts as it affects CC3's FSAR.

Please copy me on your forwarding email to the other NRC staffs with responsibility on this issue and let me know who else I may follow through on this matter at NRC. I am also requesting to be informed on what actions you may take on this fault information as it affects your area of responsibility.

By way of background on new developments, Moran's Landing Fault at Calvert Cliffs was more recently reviewed by another local geologist, Dr. Curt Larsen, at the request of Calvert County Commissioner Susan Shaw. Dr. Larsen corroborated Dr. Vogt's analysis of Dr. Kidwell's mapping that the fault is plausible. I have also included Dr Larsen's analysis and communications between those three scientists and myself to show the "trail" of the source documents.

These fault documents were also submitted by myself to the PSC as a Party to CPCN 9218, under the parameters of the current proceeding with PSC. However, the SAFETY and SITING considerations that are under NRC purvey, impact to the parameters and assumptions used for soil and stability of the CC3 power block, piping connectivity to cooling towers, among other considerations, will be affected by the earthquake fault findings. Four documents relevant to this "Moran's Landing Fault" are attached herewith for your investigation and consideration. Public safety regarding building a nuclear power plant on a site with a plausible fault at Calvert Cliffs, just 1 1/4 miles of CCNPP and possibly closer, compels immediate investigation as part of the NRC's review of the FSAR. Dr. Vogt's recommendations on the conduct of the fault investigation are reasonable and can be easily investigated through USGS. Dr. Vogt's recommended expert on Coastal Plain faulting is Dr David Powars at USGS dspowars@usgs.gov (804-261-2619).

Thank you for your consideration and I look forward to hearing from you.
June Sevilla
(c) 301-351-3161
Attachments: Kidwell 1997 paper
Vogt 2009 appeal to PSC CPCN9127
Larsen review of Vogt findings and Kidwell paper (also submitted to PSC 9218)
email trail of earthquake fault documents (also submitted to PSC 9218)

>>>>>>>>>>>>>>>> below was the agenda for the March 17th teleconference:

Subject: DRAFT RAI No. 218 RGS1 4332
Sent Date: 2/19/2010 2:39:19 PM
Received Date: 2/19/2010 2:39:22 PM
From: Arora, Surinder

Created By: Surinder.Arora@nrc.gov

Recipients:
"CCNPP3COL Resource" <CCNPP3COL.Resource@nrc.gov>

Tracking Status: None
"Karas, Rebecca" <Rebecca.Karas@nrc.gov>
Tracking Status: None
"Wang, Weijun" <Weijun.Wang@nrc.gov>
Tracking Status: None
"Colaccino, Joseph" <Joseph.Colaccino@nrc.gov>
Tracking Status: None
"Steckel, James" <James.Steckel@nrc.gov>
Tracking Status: None
"Biggins, James" <James.Biggins@nrc.gov>
Tracking Status: None
"Vrahoretis, Susan" <Susan.Vrahoretis@nrc.gov>
Tracking Status: None
"Hair, Christopher" <Christopher.Hair@nrc.gov>
Tracking Status: None
"'Poche, Robert'" <Robert.Poche@constellation.com>
Tracking Status: None
"'cc3project@constellation.com'" <cc3project@constellation.com>
Tracking Status: None

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Files Size Date & Time
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Request for Additional Information No. 218 (eRAI 4332) DRAFT

2/19/2010

Calvert Cliffs Unit 3 UniStar

Docket No. 52-016
SRP Section: 02.05.04 - Stability of Subsurface Materials and Foundations
Application Section: 2.5.4

QUESTIONS for Geosciences and Geotechnical Engineering Branch 1 (RGS1)

02.05.04-3

Section 2.5.4.5.2 indicates that most Category I structures will be founded on the top of Stratum IIb cemented sand layer. In Section 2.5.4.2.1.3, the layer IIb is further divided into three sublayers: silty sand layer with SPT N value greater than 20; clayey sand layer with N value smaller than 20; and poorly-graded sand to silty sand layer with N value greater than 20. The shear wave velocity of the layer IIb shows great variation, ranging from 560 to 3,970 ft/s. In addition, the shear strength property of the IIb is only based on very limited laboratory test results (one triaxial test for sublayer IIb-1 and two tests for sublayer IIb-2). Because the properties of the load-bearing layer IIb directly affect the foundation stability, the applicant is requested to explain how specific soil parameters for this layer were incorporated into relevant calculations (such as bearing capacity, settlement, SSI and GMRS), and discuss how the soil shear strength property for this layer was characterized based on limited testing results. In addition, describe how the variability was accounted for in the soil parameters for layer IIb in the above analyses.

02.05.04-4

Section 2.5.4.5.2 presents information on the planned extent of excavation and fills to be placed in and around the Category 1 structures and indicates that the extent of excavation will be based on the observation of actual conditions at the time of the excavation. The applicant is requested to describe the procedures that will be used by field investigators to judge if in-situ soils are to be left in place.

02.05.04-5

Section 2.5.4.5.2 indicates that the excavations will be backfilled with compacted structural fill to the foundation level or, if necessary, lean concrete will be placed as a leveling mat. Since the lean concrete will be used directly underneath the Category 1 structures, please describe the properties of the concrete (such as strength and shear wave velocity), and the criteria that will be used to determine where the lean concrete leveling mat should be used. In addition, describe the controls to ensure that the concrete fill can provide adequate support of both static and dynamic loadings for the foundation.

02.05.04-6

Section 2.5.4.2.5.8 presents the low strain dynamic properties for the backfill soil and indicates that the shear wave velocity for the backfill below the EPGB is about 900 fps. This velocity is lower than the minimum shear velocity (1,000 fps) specified in the U.S. EPR standard design and thus was identified as a departure in this COL application. In addition, the minimum shear wave velocity definition was also revised in the latest U.S. EPR standard design, which no longer uses the “best estimate” concept. Please update the corresponding ITAAC to reflect the changes of the DCD and the departure. In addition, please refer the NRC’s August 7, 2009 letter to NEI regarding the NRC staff position and standard wording for backfill ITAAC under Category I structures.

02.05.04-7

Section 2.5.4.5.3 states that structural fill will be compacted to a minimum 95 percent of its maximum dry density, and within 3 percent of its optimum moisture content, based on the Modified Proctor Compaction test procedure. Section 2.5.4.5.3 further states that the in-place density and moisture content testing frequency will be a minimum of one test per 10,000 square feet fill placed. Please justify whether the backfill field density test parameter (one test for every 10,000 ft2) is adequate by itself without specifying other controls or procedures, such as no lift should be more than 8 inches in thickness and a routine acceptance control test should be conducted for at least every 200 cubic yards of compacted backfill material in critical areas

02.05.04-8

Section 2.5.4.2.2.2 states that dolomite or calcite was identified as the cementing agent for the sand soil layer and the absence of dolomite or calcite in certain parts of the layer might be due to low pH groundwater. Since most of the Category I structures will be founded on the cemented sand, please discuss the possible soil strength reduction caused by the low pH ground water entering the cemented sand layers, and subsequently breaking the soil particles bond.

02.05.04-9

Section 2.5.4.2.5.2 summarizes chemical test results and concludes that “all natural soils at the site will be considered aggressive to concrete, requiring protection if placed within these soils.” Since many Category I structures with concrete foundation will be built on Stratum IIb soil, please provide information on what measures will be taken to protect the concrete and if those measures will meet other design requirements, such as sliding coefficient parameter defined in the U.S. EPR standard design.

02.05.04-10

Table 2.5-58 referred in Section 2.5.4.2.5.7 provides the sliding coefficient for each stratum with values ranging from 0.35 to 0.45. Since the U.S. EPR FSAR Tier II Section 2.5.4.3 “Foundation Interfaces” requires that a COL applicant will confirm that the site soils have sliding coefficient of friction equal to at least 0.7, please explain why lower than the standard design values were used in this application and evaluate the effect of lower sliding coefficients on structure sliding stability.

02.05.04-11

Section 2.5.4.2.5.8, which provides low strain dynamic properties for the subsurface materials at the site, as well as for the backfill soil used, states that the groundwater level is at an approximate depth of 16 ft for the powerblock area. Once the construction is finalized, the expected depth of the groundwater is 30 ft due to new drainage patterns.

Also, Section 2.5.10.2.2 states that the post-construction groundwater elevation in the powerblock area was assumed at El. 55 ft for the settlement analysis, which is about 28 ft below grade surface (El. 83 ft). However, it is stated in Section 2.4.12.5 that the maximum pre-construction groundwater level is currently at or slightly above the proposed grade level in the nuclear island area, while post-construction groundwater level ranges from approximately 6 ft to 16 ft below ground surface. Since ground water level will affect the stability of site subsurface materials, foundations, structures and slopes, please explain the discrepancy of post-construction ground water levels provided in Section 2.4.12.5 and Section 2.5.4. If the post–construction groundwater level is as stated in Section 2.4.12.5, please discuss the impact of using higher ground water level on site seismic response, SSI, settlement and lateral earth pressure analyses.

02.05.04-12

Section 2.5.4.2.5.9 described states that “detailed description of the RCTS curve fitting process is provided in the report “Reconciliation of EPRI and RCTS Results, Calvert Cliffs Nuclear Power Plant Unit 3” (Bechtel, 2007), and is included as COLA Part 11J.” Although the Bechtel report describes how the strain dependent properties were developed for Strata 1, IIa, IIb, IIc and III soils, there is no discussion for the backfill. Please describe how the strain dependent properties for backfill soil, which are presented in Figure 2.5-172, were developed.

02.05.04-13

Sections 2.5.4.5.4 and 2.5.4.10.2.2 indicate that monitoring program specifications for foundation rebound (heave) and settlement will be developed during the detailed design stage of the project. Since foundation rebound and settlement are expected at the site, and estimated differential settlement of the reactor building will exceed the standard design criterion, please provide a detailed description of the monitoring program including all basic elements, such as the settlement monitoring bench marks, locations of instruments, monitoring and recording frequency, and evaluation of the magnitude of rebound and settlement during and after excavation and construction.

02.05.04-14

Section 2.5.4.8 presents liquefaction potential analysis results and concludes that liquefaction is not a concern for this site. However, the data also show that the upper soil layer (Terrace Sand) does have some potential for liquefaction. Since seismic Category I electrical duct banks and pipes will be located at shallow depths, please discuss the liquefaction potential of soil where these components will be located.

02.05.04-15

Section 2.5.4.10.1 states that three cases were considered during bearing capacity calculations. For the general case, the bearing capacity equation for homogeneous soil was used by applying weighted average values of soil parameters in the analysis, with the weight factors based on the relative thickness of each stratum within a specific depth. For the case of a footing supported on a dense sand stratum over a soft clay stratum, Meyerhof's model (Meyerhof, et al., 1978) was used to estimate ultimate static bearing capacity. Since the results of the bearing capacity analysis were controlled by the models, assumptions and parameters, the applicant is requested to:

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1. Provide details on how the weight factors were determined for all subsurface soil strata;

2. Clarify and justify if soil compressibility was considered during the analysis since a clayey sand layer (Layer IIb2) is presented;

3. Discuss whether the dimension of a structure will affect the analysis results for footing supported on a dense sand stratum overlying on a soft clay stratum, because the Meyerhof model is based on the assumption that one dimension of the rectangular foundation is much larger than the other. Also, please clarify why the equation of qult presented in page 2-1252 is different from Meyerhof's equation by a factor of 2.

02.05.04-16

1. Please verify that in the last paragraph of page 2-1247, "Only data points in the upper layers resulted in FOS >1.1" should be " … FOS <1.1."

2. Please verify that the term N' used in equation for qult, (page 2-1251), and Ng in the note should be Ng.

3. Please verify that in equation term notes (page 2-1252), qu should be qult.

Hearing Identifier: CalvertCliffs_Unit3Cola_Public_EX
Email Number: 1628

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Subject: CC3 FSAR- NRC/Steckel-request action on plausible earthquake fault 1.25 miles or closer, south of CCNPP-Docket 52-016
Sent Date: 3/28/2010 12:08:29 AM
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From: J Sevilla

Created By: qmakeda@chesapeake.net

Recipients:
"Allison Fisher" <afisher@citizen.org>
Tracking Status: None
"Michael Mariotte" <nirsnet@nirs.org>
Tracking Status: None
"Paul Gunter" <paul@beyondnuclear.com>
Tracking Status: None
"Peter Vogt" <ptr_vogt@yahoo.com>
Tracking Status: None
"Peter Saar" <peters@opc.state.md.us>
Tracking Status: None
"dspowars@usgs.gov" <dspowars@usgs.gov>
Tracking Status: None
"larsencurt@msn.com" <larsencurt@msn.com>
Tracking Status: None
"Arora, Surinder" <Surinder.Arora@nrc.gov>
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ANATOMY OF EXTREMELY THIN MARINE SEQUENCES LANDWARD OF A PASSIVE-MARGIN HINGE ZONE: NEOGENE CALVERT CLIFFS SUCCESSION, MARYLAND, U.S.A.

SUSAN M. KIDWELL

Department of Geophysical Sciences, University of Chicago, 5734 S. Ellis Ave., Chicago, Illinois 60637, U.S.A.

Abstract: **Detailed examination of Neogene strata in cliffs 25–35 m high along the western shore of Chesapeake Bay, Maryland, reveals the complexity of the surviving record of siliciclastic sequences ~ 150 km inland of the structural hinge zone of the Atlantic passive margin. Previous study of the lower to middle Miocene Calvert (Plum Point Member) and Choptank Formations documented a series of third-order sequences 7–10 m thick in which lowstand deposits are entirely lacking, transgressive tracts comprise a mosaic of condensed bioclastic facies, and regressive (highstand) tracts are present but partially truncated by the next sequence boundary; smaller-scale (fourth-order) cyclic units could not be resolved. Together, these sequences constitute the transgressive and early highstand tracts of a larger (second-order Miocene) composite sequence. The present paper documents stratigraphic relations higher in the Calvert Cliffs succession, including the upper Miocene St. Marys Formation, which represents late highstand marine deposits of the Miocene second-order sequence, and younger Neogene fluvial and tidal-inlet deposits representing incised-valley deposits of the succeeding second-order cycle. The St. Marys Formation consists of a series of tabular units 2–5 m thick, each with an exclusively transgressive array of facies and bounded by stranding surfaces of abrupt shallowing. These units, which are opposite to the flooding-surface-bounded regressive facies arrays of model parasequences, are best characterized as shaved sequences in which only the transgressive tract survives, and are stacked into larger transgressive, highstand, and forced-regression sets.**

Biostratigraphic analyses by others indicate that this onshore record contains the same number of third-order (~ 1 my duration) units as present offshore, and so thinning landward of the hinge zone was accomplished not by omission or erosion of entire cycles of deposition, but instead by omission of some subsidiary elements (e.g., lowstand tracts), by erosional shaving of sequence tops (removing the entire regressive tract in some sequences), by a reduced number of component high-order cycles surviving per larger set, and by qualitative changes in the anatomy or composition of elements (e.g., condensed transgressive tracts; shaved sequences rather than parasequences). All of these differences can be attributed to limited accommodation, but preservation of an onshore record of each baselevel cycle was probably also favored by the large amplitude and rapidity of eustatic fluctuations during the Miocene.

INTRODUCTION

The anatomy of marine siliciclastic depositional sequences—their three-dimensional form, disconformable boundaries, facies tracts, and stratal stacking patterns—has been documented for a variety of settings of moderate tectonic subsidence (i.e., foreland basins and passive margins seaward of tectonic hinge zones, with rock accumulation rates on the order of hundreds of meters per million years). These relatively expanded records and, to a lesser extent, studies of Holocene environments have shaped geologists' image of depositional sequences over the past 20 years, and have both influenced the search for reservoirs and served as the groundtruth for models exploring the generative effects of tectonism, eustasy, and sediment supply.

Much less information is available on the expression of such sequences landward of hinge zones, in settings of very low to zero tectonic subsidence. Such settings might present many obstacles to sequence analysis. These difficulties include the modest original thickness of sequences due to low accommodation, requiring high-resolution seismic reflection data or exceptional outcrops for study; the high potential for severe or complete erosion of these landward edges of sequences during subsequent lowstands; and the presumed or actual sparsity of marine fossils in such areas, limiting biostratigraphic resolution both along tectonic strike and downdip with expanded sections in the marine depocenter. Disconformity-based subdivision and correlation is also expected to be difficult because of the complex mosaic of erosional and nondepositional surfaces that can form in the coastal environments that typify basin margins, and the potential for these surfaces to crosscut and coalesce.

Many questions thus remain on the actual anatomy of very thin records in such settings, and the controls on their formation. What is the relative importance of erosion (complete removal of selected sequences in the succession), omission (nondeposition of selected sequences), and depositional attenuation (offshore sequences represented but very thin)? What is the physical expression of thin sequences where present: are these simply shrunken versions of offshore sequences, with each component systems tract present but accounted for by sets with fewer or individually thinner subsidiary parasequences? Or does sequence composition change qualitatively across the hinge zone, for example because of: (a) erosional shaving (i.e., partial truncation of the sequence, removing part or all of the highstand systems tract and possibly part of the transgressive systems tract), (b) omission (nondeposition) of one or more component systems tracts (e.g., extreme marine overstep such that the transgressive record consists only of a single flooding surface; bypassing rather than deposition of sediment during the "highstand" phase, leaving only an omission surface; baselevel drop sufficient to disallow deposition of lowstand deposits cratonward of the hinge zone); and/or (c) switchover from "normal" facies types to lithologically unusual facies indicative of low siliciclastic input and/or low net stratigraphic accumulation (e.g., condensed facies rich in biogenic and authigenic grains and fabrics; loss of discrete bedding planes or parasequence-type cyclicity due to amalgamation). Many different combinations of these alternatives are hypothetically possible.

Miocene strata exposed in Calvert Cliffs along the western shore of the Chesapeake Bay in Calvert County, Maryland provide an excellent vehicle to determine the anatomy of marine siliciclastic sequences landward of a passive-margin hinge zone (Fig. 1). The Cliffs contain a biostratigraphically complete record of ~ 10 million years of Miocene time in only ~ 70 m of record, approximately one-tenth the cumulative thickness of coeval strata in the offshore Baltimore Canyon Trough (Greenlee et al. 1992; de Verteuil and Norris 1992; Poag and Ward 1993). Moreover, the high quality of exposure in the Calvert Cliffs is unique in the Atlantic and Gulf Coastal Plains. A relatively continuous series of cliffs 25–35 m high are present along 40 km of shoreline in Calvert County; the largely unlithified strata dip very gently, providing good opportunities to document lateral facies changes (Figs. 1, 2). As the best-exposed onshore record of Neogene sequences in the Atlantic continental margin, the Calvert Cliffs have provided key reference outcrops for biostratigraphic zonations of shallow-water Miocene strata. They are additionally important to tests of eustatic models of sequence generation under "icehouse" conditions and the role of flexural deformation on such mature margins (Greenlee et al. 1992; Schroeder and Greenlee 1993; Sugarman et al. 1993; Poag and Ward 1987; Miller and Sugarman 1995; Pazzaglia and Gardner 1994).

Journal of Sedimentary Research, Vol. 67, No. 2, March, 1997, p. 322–340
1073-130X/97/067-322/$03.00

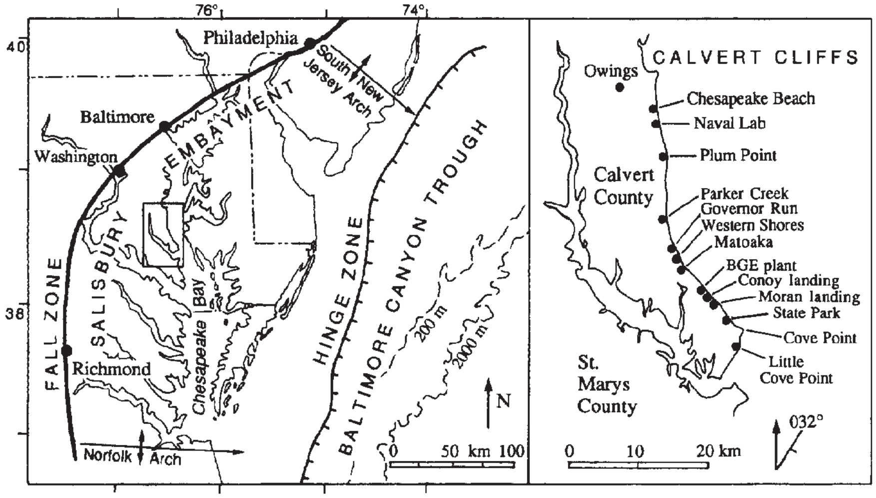


FIG. 1.—Location of Calvert Cliffs within the Salisbury Embayment, a broad structural basin inland of the continental-margin hinge zone. Miocene strata are exposed along the entire Chesapeake Bay shoreline of Calvert County, from Chesapeake Beach to south of Little Cove Point (cross section in Figure 2). The St. Marys Formation is well exposed in dip-aligned cliffs between the BGE nuclear power plant and Calvert Cliffs State Park, and in strike-aligned cliffs (032°) south of Little Cove Point. Adapted from Pazzaglia and Gardner (1994).

The Calvert Cliffs succession includes strata from three Miocene formations—the Calvert, Choptank, and St. Marys of Shattuck (1904)—and an additional 20 m of poorly known coarse sediments of younger but uncertain age (pSM interval and cliff-top gravels; Figs. 2, 3). The anatomy of open-marine disconformity-bounded units in the Plum Point Member of the Calvert Formation and in the Choptank Formation has already been described in detail (Kidwell 1982, 1984, 1989). The present paper documents the facies composition and anatomy of the St. Marys and younger strata in comparable detail, elaborating upon a brief report by Kidwell (1988). St. Marys strata are less clearly cyclic than the Plum Point–Choptank interval, and are also muddier and less shelly, and contain more brackish-water fossils; post–St. Marys strata are coarse-grained, channel-form deposits of fluvial and tidal origin. This uppermost part of the Calvert Cliffs succession thus provides an opportunity to document sequence anatomy across a different subset of shallow marine and coastal environments and to establish a more detailed physical stratigraphic framework on which to base biostratigraphic and sequence stratigraphic correlations of onshore deposits with coeval sequences both offshore and along strike.

METHODS AND STRATIGRAPHIC OVERVIEW

Measured Sections

Because the Miocene record is very thin and laterally variable, extremely detailed methods of field description are required. Fifty-two sections of the St. Marys Formation were measured within the Calvert Cliffs, and beds were walked between sections whenever possible, with most areas revisited several times. (A complete listing of localities is available from the author.) These sections are in addition to 194 sections measured previously to document stratigraphic relations in the underlying Calvert and Choptank formations (46 of those sections are in the Calvert Cliffs; Kidwell 1982, 1984). As in that earlier study, bed thicknesses and elevations above mean sea level (amsl) were cross-checked within and between sections by handlevel. Field descriptions of sediment grain size were cross-checked and quantified for 8 key sections of St. Marys and younger strata by wet-sieving 100 g samples at 0.5 phi mesh intervals. Dominant macrobenthic genera and taphonomic features were recorded in the field as an additional basis for paleoenvironmental interpretation.

Sections were measured at ~ 100 m intervals wherever fresh cliff faces were available; additional sections were intercalated where the stratigraphy was especially complex (measured sections indicated by tick marks along the base of each cross section). Segments of the Calvert County shoreline where the stratigraphy is interpolated rather than documented are areas where tributary streams have destroyed shoreline topography or where wide beaches protect cliffs from wave sapping and rejuvenation. Examination of cliff faces from a distance of 50–100 m offshore is valuable to cross-check large-scale geometries of units. However, some features that from a distance appear to be important (e.g., resistant ledges) are in reality discordant with primary depositional and erosional contacts, and some key contacts are simply invisible from a distance (e.g., clay-on-clay contacts and very thin lags that are easily obscured by sheetwash).

Labeling of Disconformity-Bounded Units

Each throughgoing disconformity (i.e., laterally extensive discontinuity surface, cutting across rather than parallel to underlying facies boundaries) is numbered successively from the base of the enclosing lithostratigraphic unit, and intervening strata are named for their lower bounding surface, continuing the informal system used for the Plum Point–Choptank interval (PP- and CT-disconformities and sequences of Kidwell 1984; Fig. 3). Thus, the SM-0 surface is the disconformity that marks the base of the St. Marys Formation, and the SM-0 unit or interval refers to strata lying between this and the next higher disconformity. This is comparable to color coding of reflectors in seismic sections, although the convention generally used in subsurface records is for intervals to take the name of the upper rather than the lower bounding reflector.

Distribution

St. Marys and younger strata crop out in cliff faces from the southern tip of the Calvert County peninsula (Little Cove Point area) northward along the Chesapeake Bay shoreline to the northern edge of Baltimore Gas and Electric Company nuclear power plant property (= BGE; Figs. 1, 2). The largest gap in exposures is a 2.5 km segment at Cove Point beach. South of Cove Point beach, 5 km of cliffed shoreline extends south of Little Cove Point, providing exposures parallel to structural strike (032°). These cliffs are the most readily accessible and contain the best-preserved macrobenthic fossils, and thus have been the focus of most paleontologic and stratigraphic work on the St. Marys Formation in Calvert County.

North of Cove Point beach, cliffs extend for 7 km from Calvert Cliffs State Park to BGE in a shoreline oriented 130°, which is nearly perpendicular to structural strike. North of BGE, St. Marys and younger strata are present above 20 m elevation in cliffs between Matoaka and Western Shores and also at Governor Run, but exposures are discontinuous and very difficult to access. North of Governor Run, the Calvert Cliffs shoreline is

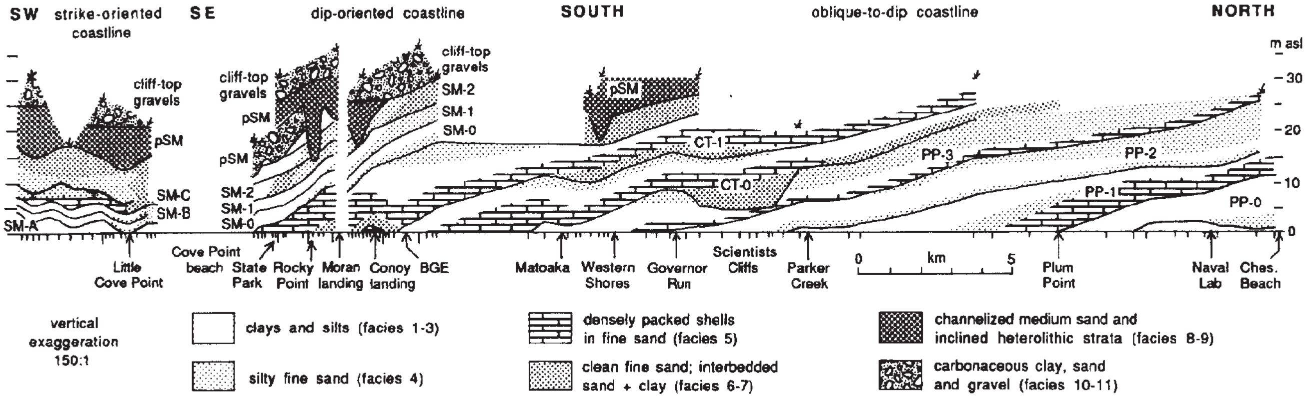


FIG. 2.—Cross section of the Calvert Cliffs showing disconformity-bounded units, labeled according to the lithostratigraphic position of the disconformity that defines their base. PP, Plum Point Member of Calvert Formation; CT, Choptank Formation; SM, St. Marys Formation (Miocene units all dip at 1.4–2: 1000); pSM, post–St. Marys Neogene strata (dip at 0.7: 1000); cliff-top gravels of probable Pleistocene age (dip at 0.5: 1000).

oriented 095°, oblique to structural strike, and exposes only Plum Point and Choptank strata.

Modifications of Original Dip

Original dip directions for Miocene strata in the Calvert Cliffs have generally been assumed to approximate present-day structural dip (i.e., ESE). The downdip decrease in grain sizes and increase in faunal diversity observed among subtidal facies within each disconformity-bounded unit in the Plum Point–Choptank interval (Kidwell 1984, 1988, 1989) and in St. Marys strata (present paper) indicate that this assumption is roughly justified (Fig. 2).

This overall pattern of an eastward or southeastward original dip is disrupted by a series of small monoclines and asymmetrical anticlines (Fig. 2 and other cross sections in this paper and in Kidwell 1984). Folds are especially pronounced in the area immediately south of BGE; fold axes are also present in the vicinity of Matoaka, Parker Creek, and south of the Naval Lab (erosional channels along the CT-0 and CT-1 disconformities should not be confused with folds). Plum Point–Choptank strata are affected most strongly, as evident by their truncation by the basal disconformity (SM-0) of the St. Marys Formation over the anticline at Conoy landing just south of BGE (Fig. 2). Gentle folding of St. Marys strata in the Little Cove Point area and subtle dip changes elsewhere, including over the anticline at Conoy landing, indicate continued but slight warping into St. Marys time. The up-section die-out and fold geometry suggest growth faults or other tensional structures at depth.

The entire succession, including cliff-top gravels of probable Pleistocene age, appears to be offset a few meters along a down-to-north fault at Moran landing (valley with unnamed stream 2 km south of BGE plant). Some fault-offset or related folding might also exist in the Cove Point beach area, inasmuch at St. Marys strata cannot be readily correlated across this gap in exposure (see later discussion).

Traditional Stratigraphic Units

Miocene strata in Maryland were subdivided into a series of 24 informal lithologic units or "Zones" by Shattuck (1904) on the basis of siliciclastic grain size, abundance of shell material, and, subordinately, the assemblage of molluscan species. Zones 3 through 23 are exposed in the Calvert Cliffs (Fig. 3). These zones are not biostratigraphic units in reality or intent, but are simply informal field labels for lithologic units that are finer than formal lithostratigraphic members.

The Zone 4 through Zone 19 interval comprises the Plum Point Member of the Calvert Formation and most of the Choptank Formation as originally defined by Shattuck (1904) (Fig. 3). Most individual zones in this series have proven to be readily identifiable by other workers throughout the Maryland coastal plain, and thus are widely used to describe stratigraphic relations. The Zone 4–19 interval is strongly cyclic, with alternations of bioclast-rich well-sorted sands (Zones 10, 12, 14, 17, and 19) and relatively bioclast-poor silty intervals of comparable or greater thickness (Figs. 2, 3).

Above Zone 19, Shattuck's scheme has proven more difficult to use. Lithologic differences are genuinely more subtle through the Zone 20–23 interval, but Shattuck's (1904) original descriptions of these zones at BGE (his Flag Pond section) are also atypically vague. Zones 20, 21, and 23 were each described as "drab clay and sandy bands", and Zone 22 was described as "another drab band of clay" with scattered bands of fossils. This ambiguity has led to confusion among subsequent workers in the labeling of strata at BGE, which is the only site where Shattuck described the St. Marys Formation in contact with the Choptank Formation. For example, because none of the zones at BGE were described as sands, Kidwell (1988, 1989) considered a lenticular sand body truncated by the SM-0 disconformity at BGE (Fig. 2; and see figures in Kidwell 1988, 1989) to be the upper part of Zone 20, leading her to describe the SM-0 disconformity as lying along the Zone 20–21 contact. However, this same sand body has consistently been referred to as Zone 21 by Gernant (1970) and subsequent workers (and to eliminate confusion, the present paper adopts this apparent consensus on the labeling of strata at BGE; Figs. 3, 4). Because stratigraphic relations in this upper part of the succession are proving to be complex throughout the Calvert Cliffs, the locations of outcrops need to be carefully specified when referring to strata above Zone 19, and Shattuck's Zone 21, 22, and 23 labels should probably be abandoned entirely.

LITHOFACIES AND PALEOENVIRONMENTS

General Features

Within the St. Marys Formation, 7 lithofacies can be differentiated on the basis of siliciclastic grain size (expressed as modal size of sand and percent admixed mud), physical sedimentary structures, extent of bioturbation (ichnofabric indices of Droser and Bottjer 1986, 1989), style of bioturbation (discrete burrows versus burrow-mottling and homogenization; ichnotaxa), and abundance of shell carbonate coarser than 2 mm (close-packing categories of Kidwell and Holland 1991) (Fig. 2, Table 1). An additional four lithofacies are recognized within younger post–St. Marys strata (pSM interval) and cliff-top gravels (Fig. 2, Table 1).

In general, strata in the Calvert Cliffs are quartzose, with accessory glauconite and phosphate and highly variable proportions of coarse carbonate bioclasts (up to 40% by weight; mollusk specimens to 18 cm). Previous paleoenvironmental studies have concurred that the Miocene succession records overall shallowing, although with multiple small deepening and shallowing cycles superimposed and with broad overlap in the facies composition of formations. Muddy inner to middle shelf deposits are most common in the Calvert Formation (planktonic foraminiferal diversity is highest in Zones 11–12, indicating maximum water depth), sandy shoreface deposits are volumetrically most important in the Choptank Formation, and muddy marginal marine and intertidal deposits are most common in the St. Marys Formation (Gernant et al. 1971; Blackwelder and Ward 1976; Kidwell 1984, 1989; McCartan et al. 1985; Ward and Strickland 1985; Ward 1992; Shideler 1994). Shattuck's (1904) "Pleistocene sands and gravels", lying above the St. Marys Formation, have been interpreted variously as shallow marine to nonmarine (Shattuck 1906; Stephenson and MacNeil 1954; Gernant et al. 1971; McCartan et al. 1985; Kidwell 1988, 1989).

St. Marys Formation

Lithofacies.—The St. Marys Formation (strata between the SM-0 and pSM disconformities as defined in this paper) is composed of clay, silt, and very fine to fine sand and various admixtures of these grain sizes. Shell material is dominantly molluscan and locally abundant, and burrows and burrow mottling are common in most facies. Facies include massive silty clay (facies 1), thick-bedded clay with silt and sand partings (facies 2), thin-bedded clay with silt and sand layers (facies 3), massive to thick-bedded silty fine sand (facies 4), densely packed shells with fine sand matrix and a variety of sedimentary structures (facies 5), laminated and cross-stratified fine sand (facies 6), and flat-bedded to wavy-bedded interlaminated clay and fine sand (facies 7).

Carbonate bioclasts are well preserved only in the Little Cove Point area, but molds indicate their former presence in most facies throughout the Calvert Cliffs. Assemblages are characterized by relatively thick-shelled venerid, crassatellid, and lucinid infaunal bivalves, thin-shelled tellinid, nuculanid, and mactrid infaunal bivalves (the latter dominate facies 5), high-spired turritellid gastropods (especially common in thin beds and lenses within facies 2 and 3), and diverse predatory neogastropods.

Paleoenvironmental Interpretation.—This suite of lithofacies closely resembles bathymetric arrays reported from modern open-marine siliciclastic coastlines (e.g., Reineck and Singh 1971; Howard and Reineck 1981): burrow-mottled or homogeneous muds from below normal storm wave base (facies 1); muds with widely to closely spaced sand layers from the storm-stratified transition zone between normal storm and fair-weather wave bases (facies 2 and 3); burrow-mottled to thick-bedded silty sands from an upper transition zone (facies 4); clean sands rich in shelly macrobenthos, burrowed or physically stratified with silty sand interbeds from upper transition zone and shoreface settings (facies 5); well sorted sands dominated by physical sedimentary structures, including in succession swaly, low-angle trough, wedge/tabular cross-stratification, and low-angle parallel lamination from shoreface and foreshore settings (facies 6); well-sorted to silty sands with abundant *Ophiomorpha* burrows in slightly more protected coastline and back-barrier positions (facies 4o); and parallel-bedded to wavy-bedded burrowed-disrupted heterolithic sands and clays from tidal flats and channels (facies 7).

Macrobenthic assemblages are dominated by euryhaline molluscan genera that typify sandy and muddy seafloors in modern shallow water habitats. Their presence, along with pervasive bioturbation and a dearth of lamination in fine-grained facies, indicates environments with well-aerated waters. The absence in the St. Marys Formation of stenohaline taxa such as echinoids and colonial corals, which accompany a similar molluscan fauna and the same suite of lithofacies in the Plum Point–Choptank interval, indicates fluctuating salinity levels such as found in embayed segments of humid marine coastlines or in the mouths of large bays. The relatively low diversity and abundance of epifauna such as scallops, barnacles, and bryozoans in the St. Marys Formation is consistent with the fine-grained bioturbated sediments, which suggest soft substrata, and with the scarcity of facies with coarse particles for attachment (e.g. facies 5 shell gravels). (Facies 5 is volumetrically much more important in the Plum Point–Choptank record, forming four 1–4 m-thick laterally extensive deposits with high epifaunal as well as infaunal diversity.) Greater brackish-water influence in the St. Marys Formation is also inferred from the declining diversity and abundance of stenohaline benthic and planktonic microfossils through the entire Plum Point–Choptank–St. Marys interval, and from the appearance of brackish-water indicator species among ostracods and dinoflagellates (Gernant et al. 1971; L. de Verteuil, personal communication, 1995).

pSM Channels and Cliff-Top Gravels

Lithofacies.—Channelized sedimentary bodies above the St. Marys Formation (post–St. Marys pSM series) are dominated by well-sorted medium to coarse sand with interbeds of laminated clay, clay intraclasts, and quartzose pebble conglomerates. Distinct burrows are more common than burrow mottling, but all trace fossils are less common than in the St. Marys Formation and body fossils are rare to absent. Facies include: parallel-stratified and cross-stratified medium to coarse sands in large-scale tabular, wedge, and trough sets, generally arranged in upward-fining successions (facies 8); large (0.5–4 m thick) sigmoidal sets of clay-draped sand (inclined heterolithic stratification; facies 9); a unique lenticular body of carbonaceous clay rich in plant fossils (facies 10); and unfossiliferous medium to coarse sand and gravel (facies 11). Facies 6 and 7 are also present locally. The stratigraphically highest part of the Cliffs (cliff-top gravel unit) is only locally accessible, and appears to consist solely of facies 11.

Paleoenvironmental Interpretation.—Facies in the pSM interval indicate a mosaic of tide-dominated coastal environments, including intertidal sand and mud flats (facies 7), tidal-inlet fills (channelized facies 8; cf. Kumar and Sanders 1974), and lateral-accretion deposits from tidally influenced rivers (channelized facies 9; cf. Thomas et al. 1987). The only exception is the carbonaceous clay body (facies 10) that interfingers laterally with unfossiliferous pebbly sands (facies 11) in one of the pSM channels; this is interpreted as an abandoned-channel fill from a fully nonmarine fluvial system. The gravelly nature of facies 11 sands and the absence of overbank deposits in both the pSM interval and in the cliff-top gravels suggest a braidplain rather than meander-belt system.

DETAILED ANATOMY OF THE ST. MARYS AND YOUNGER RECORD

Disconformable Base of the St. Marys Formation (SM-0 Surface)

Features of the SM-0 Surface.—In the BGE area, the SM-0 surface truncates a minimum of 8 m from the Choptank Formation, cutting downsection in a basinward direction to the top of Zone 19 (Figs. 2, 4). The surface bevels rather than irregularly incises gently deformed Choptank strata ("Zone 21" sand and then Zone 20 clay, as measured by Shattuck (1904) at BGE; loc. 222 in Figure 5), and erosion appears to have been checked by the lithified top of the Zone 19 shell bed (facies 5bc; Zones 19, 20 and "21" together constitute the CT-1 sequence of the Choptank Formation). In weathered outcrops, the thin sand that mantles the SM-0 surface usually produces either a notch or, where cemented, a vegetated ledge, but it does not always produce the most dramatic feature in a cliff face. In the cliffs just south of the BGE plant and north of Conoy landing, for example, the most prominent ledge is created by the remnant wedge of Zone 21 sand, which is lithified there because it (rather than the phosphate-rich sand mantling the SM-0 surface) rests immediately on the clays of Zone 20 and thus serves as the main conduit of water seeping from the cliff face (see figure 4 of Gernant 1970, which shows Zone 21 thinning to the south).

Primary features of the SM-0 surface also vary laterally. Where it cuts sandy facies 4 of the CT-1 sequence ("Zone 21"), the SM-0 surface is a burrowed firmground dominated by *Thalassinoides* and is mantled by a

TABLE 1.—*Facies types in the Calvert Cliffs succession. Modal phi and %-mud content of sediments refers to noncarbonate fraction only; size sorting and packing of shell carbonates are described separately. Trace-fossil abundance scored using ichnofabric index of Droser and Bottjer (1986).*

	Facies	Lithology and Paleontology	Paleoenvironment and Distribution
1	Homogeneous silty clay	Medium blue-gray slightly silty clay (88–94% mud); generally thinly laminated, locally structureless or burrow-mottled (ichnofabric 5); rare lenses of laminated silt, some with fine shell hash; rare molds of small articulated bivalves (*Nuculana, Yoldia, Caryocorbula*) and *Turritella*; whitish and smooth-surfaced in weathered outcrops, massive parting	Mud-dominated, below normal storm wave base; intergrades with facies 2
2	Clay with silt or sand partings	Medium to dark bluish slightly silty clay as in facies 1, but parted into 10–30 cm slabs by thin, ≤ 5 cm beds of burrow-disrupted laminated silt or silty very fine sand (ichnofabric 2–3), some with ripple lamination; clay beds locally laminated at top with silt, but generally structureless or burrow-mottled with pods of 1 mm fecal pellets (ichnofabric 5); rare molds of *Turritella* and *Nuculana* in clay; in Little Cove Point area, clay beds contain additional bivalves (*Thracia, Eucrassatella, Nucula, Caryocorbula*), silt beds contain well-sorted fine shell hash and small whole *Turritella* (≤ 1 cm length), and sand beds contain abundant large whole *Turritella*, often arranged in bimodal compass orientation indicating oscillatory currents; some *Turritella* sand beds are laterally amalgamated series of lenses; sandy shell beds have subsidiary *Nassarius, Mangelia, Lunatia,* and *Mercenaria*; distinctly bedded appearance in weathered outcrops, rare secondary gypsum	Mud-dominated, above storm wave base; intergrades with facies 1 and 3
3	Interbedded clay & sandy silt	Medium bluish gray slightly silty clay, parted into beds ≤ 10 cm thick by 1–5 cm beds of laminated sandy silt/clay (> 50% mud); clay is irregularly laminated, burrow-mottled, or structureless with pods of fecal pellets; locally abundant twigs and peaty carbonaceous matter; some small sand-filled burrows; molds of small bivalves sparse to abundant, generally disseminated uniformly, but in the Little Cove Point area shells are present in burrow pods and lenses (*Yoldia, Spisula, Ensis, Caryocorbula* and other bivalves, plus *Turritella*); depending on bedding, weathers as massive rough-surfaced unit or has vaguely thin-bedded aspect	Variably burrowed outer transition zone, above storm wave base; more offshore than sandier facies 4; intergrades with facies 2 and 4
4	Silty fine sand	Dark gray slightly silty to silty very fine to fine sand (15–60% mud); mottled with spreiten, sand-filled ≤ 1 cm-diameter burrows, and clay blebs; local clay laminae suggest original bedding (ichnofabric 4); dispersed to loosely packed molds of small bivalves (*Yoldia?, Solen, Ensis, Caryocorbula*) and *Turritella*, plus less common relatively large species (*Cerastoderma, Dosinia, Panopea, Chesapecten*) preserved in disarticulated convex-up orientation, plus nacreous fragments of *Isognomon*; pods of carbonaceous debris including carbonized wood chips; massive with brown, rough-weathering surface, usually damp	Intensely burrowed inner transition zone, above storm wave base; intergrades with facies 3 and 2; common lithology mantling burrowed discontinuity surfaces
	4o = *Ophiomorpha*	As facies 4, but usually 30% mud maximum, only dispersed shells, and lumpy weathering from abundant *Ophiomorpha* and clay-lined burrows of ~ 2 cm diameter (ichnofabric 5); large sand-filled articulated bivalves, especially *Cerastoderma* & *Dosinia*; Gernant et al. (1971) also report *Lunatia, Mercenaria,* and *Anadara*; includes at least one pavement of fossil leaves and stems (loc. 261); weathers to buff color with limonitic blebs ± liesegang banding	Low-energy shoreface; intergrades with facies 4 and with foreshore facies 6p & 6c and intertidal facies 7 at Little Cove Point
5	Molluscan coquina	Dense-packed (shell-supported) shells with greenish-gray clean fine sand matrix (≤ 15% mud), weathering white to deep rust; sedimentary structures vary, as do proportions of aragonitic and calcitic shells and of whole, coarsely fragmental, and finely fragmental carbonate; sparse non-molluscan macrobenthos; generally ledge-forming, even if not indurated [thin coquinas also present in facies 2, which see]	Above-storm-wave-base accumulations of primarily locally produced benthic hardparts; common lithology mantling burrowed discontinuity surfaces
	5w = wedge cross-sets of coquina	Large 10–20 cm wedge to tabular sets with north-directed low-angle foresets of shell-supported sand; composed predominantly of well-sorted small shells (≤ 1 cm *Spisula* valves and *Turritella*, plus subsidiary small gastropods), but relatively large disarticulated bivalves (*Dosinia, Mercenaria, Cerastoderma, Polynices*) are dispersed through sets and aligned convex-up on foresets; although disarticulated, many shells are whole and in good condition; includes minor wedge-shaped intercalations of less shelly silty sand; ledge former, commonly indurated	Flood-directed skeletal sandwaves in tidal channel or shoreface; Little Cove Point area only; intergrades with facies 4
	5t = trough cross-sets of coquina	Faunal composition and arrangement very much like 5w, but in 20–50 cm trough cross-sets, variously amalgamated; north-dipping foresets; interfingering silty sand contains only ripple cross-lamination, by contrast; ledge former, commonly indurated	Flood-directed skeletal sandwaves in tidal channel or shoreface; Little Cove Point area only; intergrades with facies 4o and 6p
	5 + 4 = interbedded coquina & silty sand	Large convex-up disarticulated bivalves (*Dosinia, Mercenaria, Macrocallista*) support or nearly support the coquina, which has a matrix of densely packed small shells and shell fragments (*Spisula* and *Turritella* dominant); these 10–40 cm thick beds are clearly amalgamations of subsidiary shell lenses with clean fine sand matrix (such as found embedded in facies 2 at Little Cove Point); coquina is interbedded with less fossiliferous ripple-laminated to burrow-mottled silty sand (facies 4); corrugated weathered surface, coquina commonly indurated	Upper transition zone; Little Cove Point area only; intergrades with facies 4o and 5w
	5bc = Boston Cliffs Mbr of Choptank Fm (Zone 19)	Amalgamation of many subsidiary densely to loosely packed shelly sand bodies. These subunits include fragmental shell hash resting on basal CT-1 disconformity, with varied admixtures of large bivalves; sand with discrete pavements of mostly articulated bivalves; densely packed large disarticulated aragonitic bivalves and shell fragments; densely packed flat-bedded convex-up scallop shells (commonly indurated and, at, or near the top of the Member); massive intervals with mixed calcitic-aragonitic assemblage. High diversity assemblage of mollusks, barnacles, bryozoans (see Shattuck 1904 and Kidwell 1989 for species lists)	Transition zone to lower shoreface; subsurface only in Little Cove Point area; intergrades with facies 4, lenticular bodies of facies 6 along base; transgressively overlain by facies 2
	5dc = Drumcliff Mbr of Choptank Fm (Zone 17)	As facies 5bc but with different set of diverse molluscan species, plus echinoids, corals, barnacles, bryozoans (see Shattuck 1904 and Kidwell 1989 for species lists)	Transition zone to lower shoreface in open marine conditions; subsurface in all cliffs south of immediate BGE area
6	Clean fine sand	White clean fine to very fine sand (modes 2.5 to 4 phi), ≤ 15% mud; varied structures; no body fossils; loose weathering slope former, locally indurated layers	Beach and subtidal sands above fair-weather wave base
	6p = parallel laminated	< 5% mud; faint horizontal to low-angle very thin (< 1 cm) and uniform parallel bedding, with rare 2 mm clay blebs; south dips predominate	Foreshore and backshore; present updip of facies 1 through 5
	6c = clay blebs	Bedding absent or irregularly stirred, with abundant clay blebs (up to 5 cm) and 4 cm-diameter limonite-lined burrows (ichnofabric 4–5); similar to facies 4o, but less admixed silt; rust-stained in weathered outcrops	Burrowed, lower-energy variant of 6p foreshore; intergrades with facies 4o
	6t = trough cross-sets	Large scale (> 10 cm) low-angle trough cross-bedding	Upper shoreface
	6s = swaly cross-sets	Large scale (> 10 cm) swaly cross-bedding	Lower shoreface; intergrades laterally with facies 6t and 6p
7	Flat to wavy bedded clay and fine sand	Light gray sticky clay, locally with 1 mm laminae of fine sand, interbedded with light gray to orange-weathering laminated very fine sand; thin to medium (1–15 cm) interbeds, flat to wavy to lenticular bedding; varies from clay- to sand-dominated on a m-scale; 30–80 cm deep channel incised locally, filled with laminated very fine sand; traces include *Skolithos* and *Arenicolites* (ichnofabric 2, locally 3); no body fossils found, but limonitic casts of ophiuroids found as float at Little Cove Point are probably from this interval	Clay- and sand-dominated intertidal flats with small-scale channels; intergrades with facies 4o and 6 in Little Cove Point area; largely cut out by pSM channels farther updip; see Figure 2d–e in Kidwell et al. (1985) for photo
8	Medium to coarse sand	Light gray to white clean medium to coarse sand (0.5–2 phi mode; < 6 % mud), moderately sorted, with iron-stained cemented layers and subsidiary rounded vein quartz and metamorphic rock pebbles; locally abundant clay pebbles to cobbles, but no *in situ* clay beds; varied sedimentary structures; body fossils absent; present only in channel-form bodies; white to orange weathering	Facies-sequence and sand-body geometry suggest tidal-inlet fill: 8w or 8t with clay clast lags, grading up into 8p and then 8b; restricted to pSM channels

TABLE 1.—*Continued.*

Facies		Lithology and Paleontology	Paleoenvironment and Distribution
	8p = parallel laminated	Horizontal to low-angle thin to very thin beds (< 10 cm)	
	8b = burrowed	As 8p but with spreiten burrows including *Arenicolites* (ichnofabric 2); climbing ripples	See Figure 2c in Kidwell et al. (1985) for photo
	8w = wedge cross-sets	Large-scale low-angle wedge to tabular cross-sets	See Figure 2a in Kidwell et al. (1985) for photo
	8t = trough cross-sets	Large-scale high-angle (30° foresets) and low-angle trough cross-sets (20–30 cm)	
9	Large-scale inclined heterolithic stratification (IHS)	Alternating light-colored sand and gray clay in 2–4 m sets of inclined thin to medium beds, foreset toes are concave-up; sands coarsen upward through each set, from poorly sorted fine sand (broad 2–3.5 phi mode) to medium or coarse sand, locally with subsidiary pebbles (1.5–2 phi mode); thickness of clay interbeds decreases upward from thin beds to very thin clay partings and bedding flattens; some sets capped by 50 cm-thick channels with clay-draped trough cross-stratified medium sand and clay chips; no body or trace fossils; present only in channel-form bodies	Lateral accretion deposits in tidally influenced river or tidal inlet; locally rests on facies 8w or 8t; restricted to pSM channels; best illustrated in Rocky Point (loc. 213a)
10	Carbonaceous clay	Medium to very dark gray silty clay with abundant macerated organic matter and compression plant fossils; local intercalations of medium sand in thin to very thin beds; root traces, especially toward top of facies; lenticular overall form	Nonmarine, abandoned channel fill; single example in pSM lower State Park channel (loc. 240)
11	Bedded sand and gravel	Light-colored medium to coarse and pebbly sand interbedded with clast-supported pebble to gravel conglomerates with sand matrix; medium bedding, flat to slightly inclined with local high-angle trough cross-sets; rare intercalated layers of clay chips; clay cobbles present in basal gravel of some bodies, largest grains otherwise are vein quartz and lithic clasts; no trace or body fossils; buff to orange-weathering with local induration	Nonmarine, probably fluvial

thin (≤ 10 cm) clayey very fine glauconitic sand (e.g., loc. 222 immediately north of BGE power plant; Fig. 5). This contains loosely packed flat-lying articulated *Isognomon* (semi-infaunal to epifaunal bivalve) and broken and worn bivalves, including nacreous debris (nacreous *Isognomon* and *Atrina* are both present in the underlying sand). Abundant fish otoliths and shell-gravel-dwelling benthos (epifaunal gastropod *Amalthea*, small ramose coral colonies, encrusting bryozoans, barnacles, and small scallops infested with boring sponges) are also present. These features persist updip to Western Shores, although there the SM-0 surface has completely removed the "Zone 21" sand and lies within a few meters of Zone 19.

Where the SM-0 surface closely approaches or intersects clayey facies 2 and 3 of the CT-1 sequence (Zone 20), the trace assemblage includes the corkscrew burrow *Gyrolithes* (e.g., loc. 245 south of BGE plant in Figure 7). The mantling silty fine sand is 30–100 cm thick, with sparse to loosely packed molds of infaunal and epifaunal mollusks and one or more 10 cm layers rich in phosphatic pebbles, phosphatized internal molds of bivalves (steinkerns), otoliths, sharks teeth, polished bone fragments, and sparse pebbles of quartz and gneiss. Where the SM-0 surface reaches the top of shelly Zone 19 in the Rocky Point area, a single surface can be difficult to discern within a 1-m-thick sandy interval that contains a series of alternating scoured and *Thalassinoides*-burrowed limonite-stained surfaces (e.g., loc. 230 in Figure 5), but in many sites the top of Zone 19 is scoured and mantled directly by a pebbly phosphatic lag. Farther downdip in the State Park area, the SM-0 disconformity becomes a single, laterally continuous scoured surface in direct contact with the Zone 19 shellbed (loc. 240 in Figure 5). In such sections, the top of the shellbed is stained dark rust or black by iron oxides and may have a highly irregular and corroded-appearing topography, and mollusk shells are poorly preserved (aragonite and calcite in chalky condition, or molds only).

Paleoenvironmental Interpretation of the Disconformity.—The SM-0 disconformity is clearly erosional, but unambiguous evidence for subaerial exposure is lacking. Root traces were not observed, and cementation and corrosion of the Zone 19 shellbed may reflect much younger diagenesis and weathering. Coarse material mantling the SM-0 disconformity was derived mostly from eroded beds; the preservational state of vertebrate fossils and phosphatic steinkerns indicates exhumation of specimens that had already been buried and prefossilized by early diagenesis; exhumed specimens were then abraded and polished by physical reworking on the seafloor during subsequent transgression. Less durable marine bioclasts such as aragonitic fish otoliths and bivalve shells would have been added to the lag assemblage during this final hiatal period. The pebbly bone sand thus records both erosional and nondepositional phases in the formation of the SM-0 disconformity.

Alternative Stratigraphic Interpretations.—Previous workers have suggested that the Choptank–St. Marys transition includes one or more unconformities, but reached no consensus on their relative importance or precise stratigraphic positions (Fig. 3). Gernant (1970) identified an unconformity at the base of Zone 21 on the basis of northward thickening of this sand body in the BGE area, which he attributed to its filling a small basin created by structural warping of the underlying Choptank Formation. Elsewhere, Zone 22 lies directly on Zone 20. Ward (1984, 1992) also placed an unconformity at the base of Zone 21 at BGE, but believed that a more significant unconformity in that section lay at the Zone 19–20 contact, which was recommended as the formational boundary (Ward and Strickland 1985, following Blackwelder and Ward 1976; other reports cited in Figure 3).

The present study found that several scoured and burrowed surfaces are present in the Zone 19–21 interval in the cliffs immediately north and south of the BGE plant (Fig. 4). The basal contact of Zone 21 is characterized by *Thalassinoides* burrows and sparse shell hash in a few sites (Fig. 4; loc. 222 and loc. 245 in Figure 5), suggesting a hiatus, but the contact is usually gradational.

The Zone 19–20 contact is similarly variable. Along the southern flank and crest of the anticline immediately south of Conoy landing and in the cliffs immediately north of the BGE plant, the upper contact of the Zone 19 shellbed is sharp and undulatory (~ 10 cm scale), suggesting local erosion (Fig. 4; loc. 222 in Figure 5). Where scoured, the Zone 19 shellbed is mantled by a thin (50–80 cm) silty fine sand with loosely packed, largely disarticulated and worn bivalve shells and steinkerns. The shallow-water assemblage resembles but is less diverse than that of Zone 19 (infaunal venerid and crassatellid bivalves, *Turritella,* wood debris, large mussels, balanid barnacles, and the scallop *Chesapecten*), and is overlain sharply by Zone 20 clay. However, in intervening areas at BGE as well as elsewhere in the outcrop belt (Kidwell 1984), the Zone 19 shellbed grades into or is clearly interbedded with Zone 20 clays (Fig. 4; loc. 245 in Figure 5, facies 2 + 5). Clay interbeds, commonly with burrowed tops, pinch out landward as they intertongue with and overstep the underlying shellbed, indicating a transgressive relationship. A similar mosaic of scoured and interbedded contacts is present along the Zone 19–20 contact within the cliffs immediately south of Western Shores, about 6 km north of BGE (Fig. 2). The top of Zone 19 is consistently scoured only in areas where the SM-0 disconformity has cut down to it, and in those sections is mantled with the distinctive SM-0 phosphatic pebble lag (e.g., loc. 213a in Figure 5).

Erosion was thus localized rather than pervasive along both the Zone 19–20 and the Zone 20–21 contacts, and appears to have been a syndepositional response to warping of the seafloor, which was especially pro-

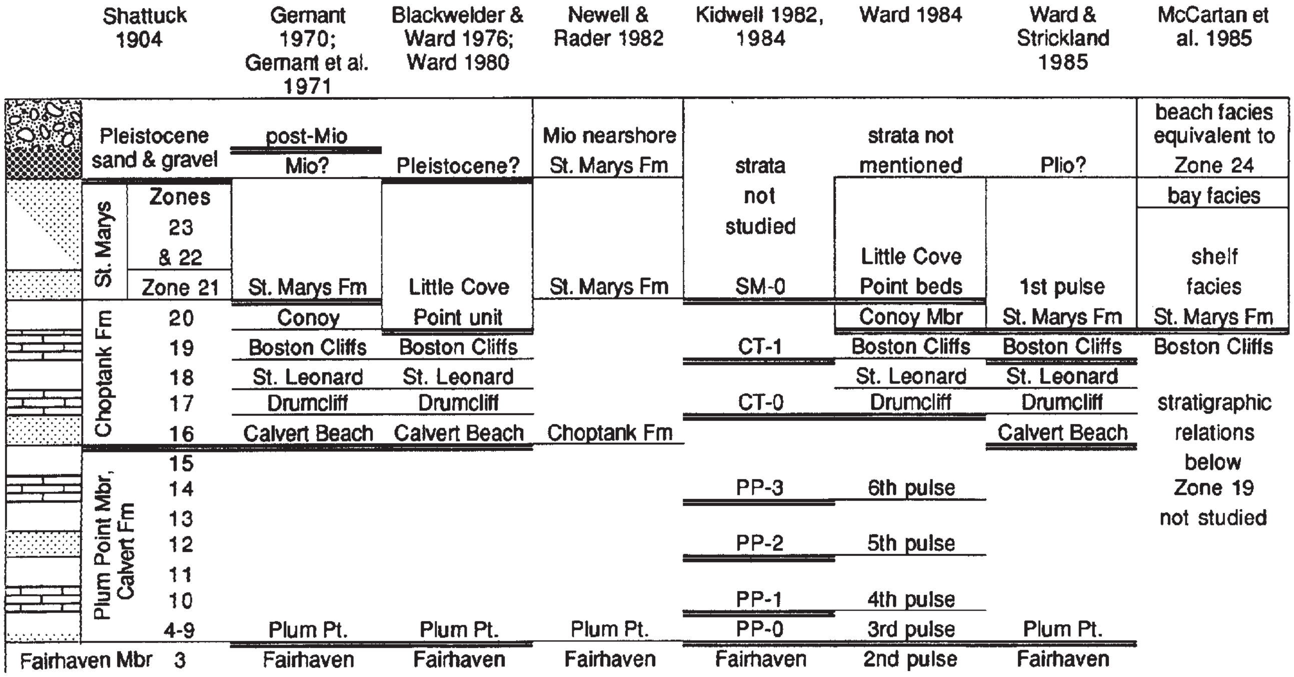


FIG. 3.—Summary of physical stratigraphic interpretations within the Calvert Cliffs succession, synonymized using the numbered lithologic "Zones" of Shattuck (1904). Double horizontal lines indicate unconformity; all other unit boundaries conformable; lithostratigraphic terms of unspecified rank are formal members (e.g., Calvert Beach, Drumcliff). Stratigraphic limits of the St. Marys Formation are indicated by vertical lines. Lithologic column simplified and not to scale (key to patterns is shown in Figure 2). * reflects corrected labeling of lenticular sand body at BGE as Zone 21 of Shattuck (1904); see text. ** = subsidiary erosion surfaces also identified within and between each of Shattuck's Zones 21–23.

nounced in the BGE area. Neither of these contacts exhibits the same lateral continuity in scouring as the SM-0 surface or cuts through as much section, and both are clearly part of the record that underwent folding before truncation by the SM-0 surface. For these reasons, the entire Zone 19–20–21 interval is considered part of the Choptank Formation (CT-1 sequence), and the SM-0 surface is recommended as the base of the St. Marys Formation (following Kidwell 1988).

Biostratigraphic Corroboration.—Independent biostratigraphic analyses corroborate the physical stratigraphic relationships in the cross sections (Table 2). At BGE, where the Choptank–St. Marys transition is well exposed and most thoroughly sampled, biozone boundaries coincide only with the CT-1 surface (base of Zone 19) and the SM-0 surface (top of Zone 21 sand at BGE), indicating that these disconformities signify the largest lacunae. The CT-1 surface marks the first appearance of diagnostic species for East Coast Diatom Zone 7 of Andrews (1988), dinoflagellate biozone DN7 of de Verteuil and Norris (1994), and mollusk biozone M11 of Ward (1992). The SM-0 surface marks the first *certain* appearance of diagnostic species for dinoflagellate biozone DN8 (Zone 21 at BGE unsampled; L. de Verteuil, personal communication, 1995) and mollusk biozone M10 (according to Ward 1992, Zone 21 contains morphologically transitional specimens with affinities to guide taxa of the older mollusk zone M11). No biozone boundaries coincide with either the Zone 19–20 or the Zone 20–21 contacts, notwithstanding their locally erosional natures.

Disconformity-Bounded Units within the St. Marys Formation

Basic Patterns.—Between the SM-0 surface, which cuts across deformed Choptank strata, and the highly irregular pSM surface, which marks the base of coarse-grained channelized bodies, lie ~ 15 m of thinly bedded dark gray clays and silty fine sands. This interval contains a series of co-parallel burrowed firmgrounds of low relief; each is mantled by a thin mollusk-bearing sand and defines the base of a tabular unit 2–5 m thick. Each firmground is a stranding surface, marking an abrupt basinward (regressive) offset in facies, so that shallower-water deposits rest on deeper deposits. Intervals between firmgrounds comprise transgressive facies tracts, in which downdip, basinward facies step up over updip, landward facies. Regressive facies tracts are not present, but each transgressive interval is shifted sufficiently basinward from the preceding interval that an overall regressive trend is produced through the St. Marys Formation (Fig. 2; Kidwell 1988). The extent of stratigraphic overlap between exposures north and south of Cove Point Beach is unclear, and so the two outcrop areas are described here separately.

Dip-Oriented Shoreline between BGE and Calvert Cliffs State Park.—Three firmgrounds can be traced continuously with confidence, and all mark significant regressive facies offsets; these surfaces are numbered SM-0, SM-1, and SM-2 (Fig. 4). Intervening burrowed surfaces with minor facies offset and only local or questionable lateral extent are labeled relative to the primary surfaces; these are the SM-0′, SM-2′, and SM-2″ surfaces (Figs. 4, 5).

Scour structures are preserved only along the SM-0 surface, and these are limited to areas where the SM-0 surface is in contact with the Zone 19 shellbed, as described above. The other SM surfaces are so thoroughly perforated by burrows that any small-scale scour features that might have existed originally have been obliterated. The most common burrow types are *Thalassinoides*, *Gyrolithes* (especially where the SM-1 and SM-2 surfaces cut across facies 1 clays), and small (1 cm diameter) nonbranching vertical burrows (SM-2 and its subsidiary surfaces). The SM-2 disconformity exhibits evidence of erosion at a broader scale, in that facies 1 of the underlying SM-1 interval terminates against it both landward and basinward (Fig. 4). Some degree of erosion is also necessary to exhume strata that are sufficiently stiff to permit colonization by a firmground assemblage of burrowers.

	Vogt & Eschelman 1987	Kidwell 1988	Ward & Powars 1989	Ward 1992	Poag & Ward 1993	Shideler 1994	deVerteuil & Norris 1996	this paper
Pleist. sand & gravel	littoral Upland Deposits (=Zone 24)	SM-3 fluvio-marine channels	not mentioned Plio?	Pleist? Mio? XIV?	Hudson Cyn Alloformation not studied	Pleistocene not studied	Plio?	cliff-top gravel (Quat.) pSM (Neog.)
Zones		SM-2			(no info on		SE10	SM-2
23		SM-1			possible			SM-1
& 22		SM-0*			allomembers)	Upper	SE9	SM-0
21	Little Cove		1st pulse	XII **	Mey	Sequence		
20	Point Mbr		St. Marys Fm	XI	Alloformation	HST		
19	Boston Cliffs	CT-1	2nd pulse	X		TST	SE8	CT-1
18	St. Leonard		1st pulse			Lower		
17	Drumcliff	CT-O	Choptank Fm	IX		Sequence	SE7	CT-0
16	Calvert Beach		4th pulse			HST		
15			(= Calvert		(composed of			
14		PP-3	Beach Mbr)	VIII	3 unspecified	stratigraphic	SE6	PP-3
13					allomembers)	relations		
12		PP-2	undefined	VII		below	SE5	PP-2
11			pulses 1 to		Phoenix	Zone 16		
10		PP-1	3 (= Plum	VI	Canyon	not studied	SE4	PP-1
4-9	Plum Pt.	PP-0	Point Mbr)	V	Alloformation		SE3	PP-0
3	Fairhaven	Fairhaven	2 pulses	IV	Berkeley Allo.		SE2	Fairhaven

FIG. 3.—Continued.

The shell-bearing silty sands (facies 4) that mantle each firmground thin basinward (downdip), so that some firmgrounds are clay-on-clay contacts in their most basinward outcrops (e.g., SM-1 surface at locs. 213a and 240 in Figure 5). The SM-0 basal sand was described above; it and the subsidiary SM-0′ firmground, which is restricted to the crest of the Conoy anticline, are the only SM surfaces marked by significant authigenic minerals, vertebrate fossils, or lithic pebbles. The SM-1 surface is mantled by a thin (10–90 cm) silty or clayey sand with sparse molds of small-bodied, soft-bottom-dwelling bivalves (*Cardium, Solen, Corbula, Caryocorbula, Yoldia, Lucinoma, Spisula*) and gastropods (*Turritella*), plus comminuted shell hash (see well-preserved fossils at loc. 222 in Figure 5). The SM-2 surface is mantled by a similar burrow-mottled silty sand 15–30 cm thick; molds indicate that mollusk shells were originally loosely packed and more diverse than along the SM-1 surface. Mantling silty sands on the subsidiary SM-2′ and SM-2″ surfaces are only 10–20 cm thick.

Across each SM firmground, facies shift abruptly to shallower-water deposits, indicating that these are stranding surfaces; within each interval, deeper-water (more basinward) facies step up and over shallower-water (more landward) facies, forming transgressive facies tracts (Fig. 4). In the SM-0 interval, which has a maximum thickness of 5 m, facies 1 clay dominates the most basinward (downdip) outcrops and steps up landward over silty clays of facies 2, which in turn step over facies 3, which in turn steps over silty sands of facies 4, which continues to thicken landward (updip). Upward fining can be observed within individual sections of the SM-0 interval (e.g., locs. 245, 213a, and 240 in Figure 5). The SM-1 surface marks a minor regressive offset, with facies 3 juxtaposed on facies 1 in basinward outcrops and with facies 6 on facies 3 in landward outcrops. The SM-1 interval is 4 m thick and consists of facies 1, 3, 4, and 6 in transgressive array.

The basal SM-2 surface shows a major regressive offset, juxtaposing facies 4 on facies 1 in basinward sections and facies 6 and 7 on facies 3 in landward sections. Subsidiary SM-2′ and SM-2″ surfaces appear to have minor regressive offsets, however, and so the total family of transgressive SM-2 intervals yields a net transgressive trend up to the pSM surface. Thicknesses of the SM-2, SM-2′, and SM-2″ intervals are 4 m, 4 m, and 3 m, respectively. Stratigraphic relations within the SM-2 interval (between the SM-2 and SM-2′ surfaces) suggest lateral shingling of at least two discrete transgressive tracts; each tract is floored on the low-relief SM-2 surface, and each tract has an updip "leading edge" of facies 6 sand representing transgressive beach or upper shoreface environments (these sands appear to have convex bases, as sketched in Figure 4). Presumably the more updip tract, whose leading edge cuts into intertidal facies 7 at the BGE plant (loc. 241 in Figure 4), is older than the downdip tract (leading edge at loc. 214 in Figure 4). This basinward (regressive) stepping is geometrically analogous to stranded parasequences within forced regressive records and precedes the transgressive stepping of the SM-2′ and SM-2″ intervals. The overall SM-2 interval (up to the pSM) thus appears to be genetically much more complex than the other SM intervals.

Strike-Oriented Shoreline at Little Cove Point.—The St. Marys Formation in the Little Cove Point area contains a series of burrowed and locally scoured discontinuity surfaces (Fig. 6). Each is a stranding surface mantled by a thin fossiliferous silty sand (too thin to indicate in Figure 6); abrupt shallowing is most marked across the SM-B and SM-C surfaces (e.g., facies 4 or 5 on facies 2), and less so across the subsidiary SM-B′ and SM-C′ surfaces (strata at the base of the cliffs are assigned to a SM-A interval, but no SM-A basal disconformity is exposed). The intervals bounded by these surfaces are more variable in thickness and facies patterns than those exposed in the cliffs between BGE and Calvert Cliffs State Park, probably because of the strike orientation of the outcrops, and fossils are much better preserved. The overall trend is upward shallowing (subtidal clays in SM-A interval to intertidal-flat sediments at the top of the SM-C′ interval; loc. 255 in Figure 5).

The SM-B surface is mantled by a thin (10–30 cm) silty sand with sparse worn fragments of thick-shelled, shallow-burrowing bivalves (*Mercenaria, Eucrassatella*) and heavily bored valves of the scallop *Chesapecten* and is paleoecologically and taphonomically distinct from the fauna of thin-shelled, deep-burrowing bivalves present in the underlying facies 2 clay (loc. 255 in Figure 5). This burrow-mottled shelly sand is piped into *Thalassinoides* burrows that penetrate 1 m into underlying clays all along the SM-B contact. Within the SM-B interval, finer-grained lower-energy facies step up over coarser, higher-energy facies (e.g., at Little Cove Point proper, locs. 206 through 209), suggesting transgressive migration.

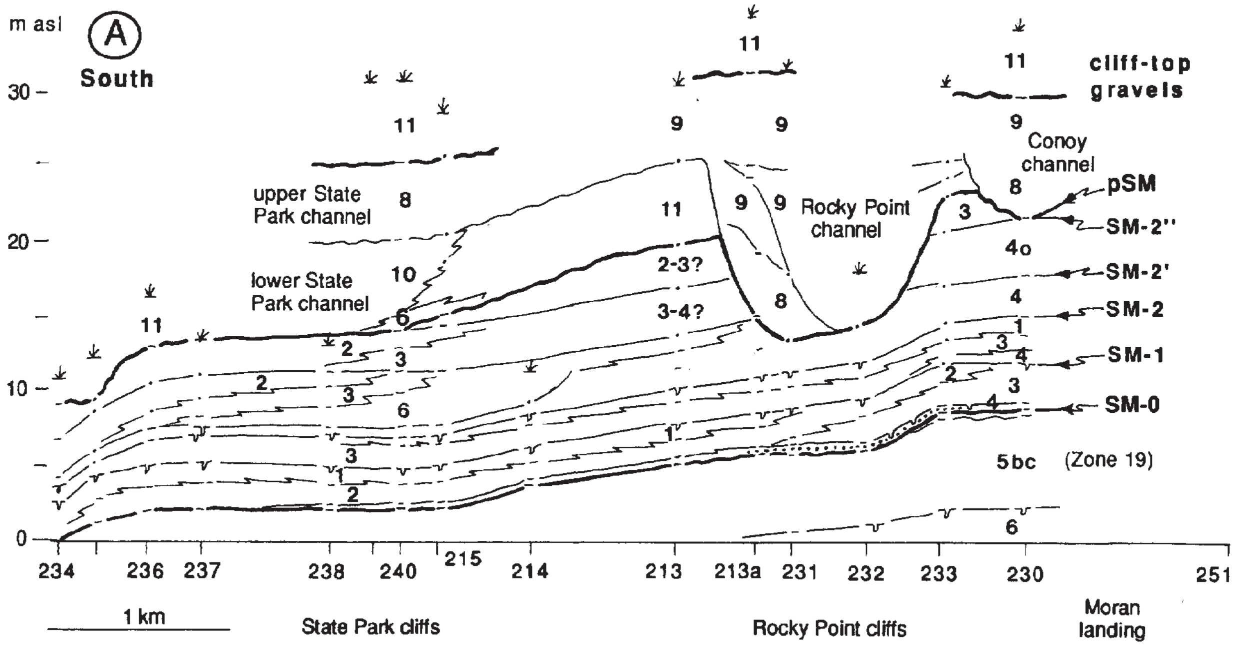


FIG. 4.—Dip-oriented (NW-SE) cross section of the Calvert Cliffs from the BGE area south to Calvert Cliffs State Park, showing throughgoing disconformities and lateral facies relations within the upper part of the Choptank Formation (CT; Zones 17–21), St. Marys Formation (SM units), post–St. Marys interval (pSM channels), and cliff-top gravels. Cross section is broken into southern (A) and northern (B) segment at Moran landing, where there is a gap in outcrops; the offset in bed elevations on either side of Moran landing is real and not due to a change in vertical scale (see Figure 2). Datum is mean sealevel. Three-digit numbers at base are locality numbers; other numbers within cross section indicate facies type (Table 1). Lithologic symbols as in Figure 5.

This upward fining continues through the SM-B′ interval, although clayey facies are much more fossiliferous. In facies 2, lenses of bimodally oriented *Turritella* (figure 5 in McCartan et al. 1985), a high-spired gastropod, are probably storm-generated (sufficient energy to exhume infaunal gastropods and establish oscillatory currents with strength to orient shells; rapid post-event burial to preserve these orientations); in facies 3, pavements of mostly broken *Turritella* are consistent with shallower water permitting greater post-storm reworking of shells. The SM-B′ surface itself is characterized by erosional gutters 15 cm deep and a few burrows, chiefly *Thalassinoides*. The mantling sand is 10–30 cm thick and densely packed with both fresh and worn whole and broken shells, including abundant *Turritella* and disarticulated cardiid, venerid, and *Spisula* bivalves. This coquina has a pinch-and-swell geometry created by the shingling of primarily northward-dipping lenses of shell gravel (10–25 cm thick, 0.3–1.0 m long) with rare clay drapes, and is truncated locally by swaly cross-sets of silty sand. This highly distinctive and broadly undulatory coquina persists throughout the Little Cove Point area, and makes this the visually most impressive of all SM stranding surfaces.

The SM-C surface is a locally scoured *Thalassinoides*-dominated firmground. It is overlain by a relatively thick (3 m) basal "sand", which varies laterally from interbedded silty sand and coquina (facies 5 + 4), to wedge and trough cross-bedded coquina (facies 5w and 5t), and parallel-laminated clean sand (facies 6p) (Fig. 6). Facies 5 contains abundant *Turritella* along its base, perhaps reworked from the underlying SM-B′ interval, but the bulk of the coquina is a fine groundmass of ≤ 1 cm disarticulated *Spisula* bivalves. These are arranged in large cross-sets with only scattered whole disarticulated specimens of larger bivalves (Table 1; figure 2B in Kidwell and Holland 1991). This coquina grades laterally into *Ophiomorpha*-burrowed silty sand (facies 4o).

The SM-C′ surface is marked by a relative concentration of bone, wood, and molluscan debris, especially where it scours the top of the SM-C coquina (e.g., loc. 255 in Figure 5). The SM-C′ interval is an overall regressive 7-m-thick section of complexly interfingered *Ophiomorpha*-burrowed silty sand (facies 4o) and wavy-bedded sand and clay (facies 7). Throughgoing surfaces could not be detected within this stratigraphic interval, perhaps because of deep weathering and slumping of facies 4o sands.

Paleoenvironmental Interpretation of the Surfaces.—None of the SM surfaces show root traces or other evidence of subaerial exposure, although each marks an abrupt shallowing in the record. With the exception of the SM-0 and SM-0′ surfaces described above, shell material in basal sands shows little evidence of having been exhumed from significantly older deposits. Both thin and robust shells are in generally good condition aside from being disarticulated or sharply broken (fragmentation is consistent with bioturbated sand matrix), truncated facies generally lack the appropriate taxa to have served as the source of bioclasts, and the paleoecology of taxa hosted by these basal sands is consistent with that matrix (facies 4 or 5). Shell material thus appears to have been derived entirely from benthic communities that migrated across the area during transgression; modification and concentration of shells reflect ordinary processes of matrix deposition and winnowing within either an upper transition or shoreface environment.

Firmground-mantling shellbeds in the St. Marys Formation are much thinner than their transgressive analogues in the Plum Point–Choptank interval (Zones 10, 14, 17, and 19; Kidwell 1989), and also have less complex accretionary histories that do not involve widespread environmental condensation. Even the comparatively thick and internally complex shell deposit in the SM-C interval is limited to a small area (facies 5 in Figure 6) and is genetically fairly simple. It consists of a straightforward stack of wedge and trough cross-sets of disarticulated bivalves interspersed with swaly cross-bedded silty sand, indicating migrating dunes of mobile hardparts driven by strong currents, perhaps in a subtidal channel. The assemblage is overwhelmingly dominated by the infaunal bivalve *Spisula* and other small-bodied (≤ 1 cm) mollusks that would not have been indigenous to shell-gravel substrata of the channel, but that instead must have been

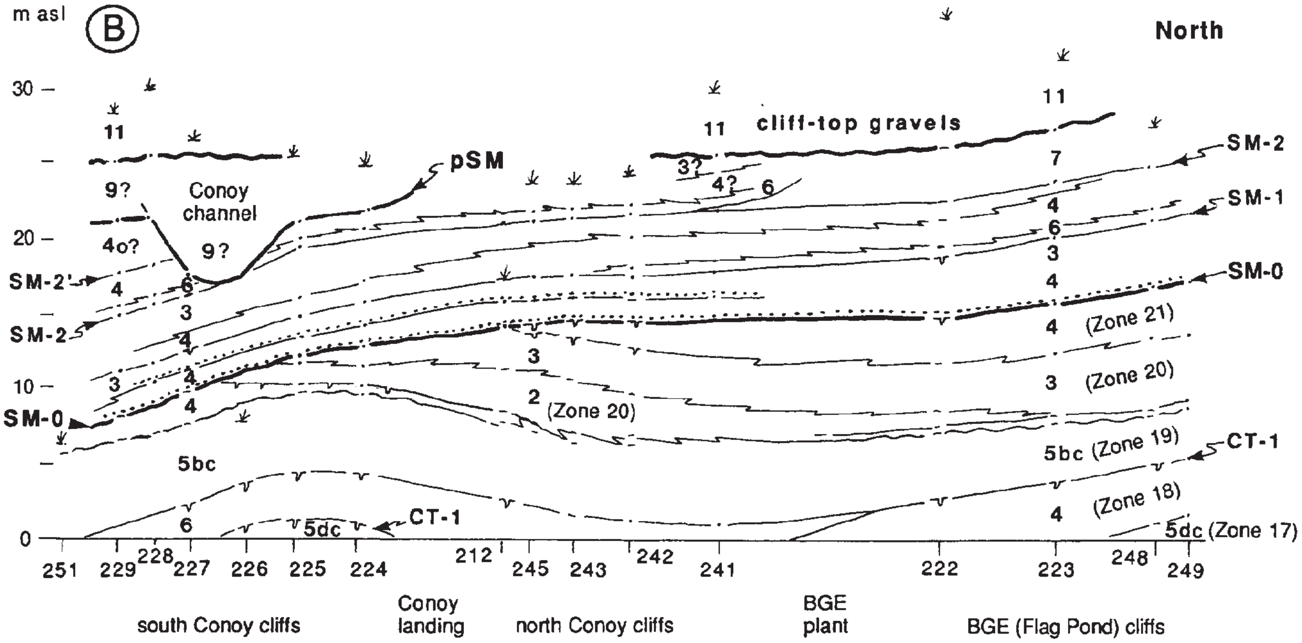


FIG. 4.—Continued.

reworked and transported from adjacent muddy substrata. The SM-C shellbed thus reflects multiple short-term events of shell import, concentration, and reworking, but little evidence of the environmental condensation and prolonged time-averaging that produced the high-diversity, complexly amalgamated, and laterally extensive transgressive shell deposits in the Plum Point–Choptank interval.

Correlation of Outcrop Areas.—Provisional correlations of SM intervals between the BGE–State Park area and Little Cove Point can be made on the basis of physical stratigraphy alone. Comparing facies in the nearest outcrops north and south of Cove Point beach, the clayey SM-A interval (facies 2) might represent the basinward continuation of facies tracts in either the SM-1 or SM-2 intervals (facies 3 and 2, respectively, at downdip limit of outcrops at State Park; the SM-A interval is not a continuation of Zone 20 as that Zone is defined at BGE, contrary to correlations by previous workers). In contrast, the SM-B through SM-C′ intervals at the northern edge of Little Cove Point outcrops are all composed of much sandier facies than SM intervals at State Park, and may be entirely younger than any of the SM intervals exposed to the north. The provisional correlation preferred here is that the SM-B interval is the downdip continuation of the SM-2 forced regression, and that the combined SM-C/C′ interval is younger than the SM-2′ and SM-2″ intervals and is stranded downdip of them (Fig. 2, and see later discussion).

Independent analysis of the physical stratigraphy described in this paper by a new, high-resolution biozonation based on dinoflagellates indicates that the SM-A interval at Little Cove Point contains the same diagnostic taxa as the SM-0 and SM-1 intervals (very early DN8 time, below the lowest occurrence of *Achomosphaera andalousiensis*; de Verteuil and Norris 1996; Table 2). De Verteuil and Norris (1996) thus conclude that the SM-A interval correlates with the SM-1 interval. Strata from the SM-B surface up to the pSM surface at Little Cove Point contain the same diagnostic taxa as the SM-2 interval (later DN8 time, above LO of *A. andalousiensis*). The range of *A. andalousiensis* within DN8 is so prolonged (~ 2 my; de Verteuil and Norris 1996), however, that strata of this biozone at Little Cove Point may still be chronologically and genetically distinct from "same age" strata in updip outcrops, thus permitting the provisional correlations of the present paper.

Incised Channels Capping the St. Marys Formation (pSM Interval)

The tabular, fine-grained SM intervals are truncated by a series of crosscutting channels, designated the pSM interval for post–St. Marys. Individual channels show as much as 12 m of erosional relief and are named informally for geographic features (Figs. 4, 6); the master erosion surface that defines the lower boundary of the entire array is called the pSM surface (equivalent to SM-3 surface in Kidwell 1988). The change in sedimentary geometry across the pSM surface is accompanied by coarser sand modes, less mud overall, greater segregation of sand and mud into distinct beds, and far less burrowing and bioturbation.

Lower State Park Channel.—Crosscutting relations indicate that the oldest pSM deposits are in the lower of two channel-form bodies whose maximum exposed thickness is at Calvert Cliffs State Park (Fig. 4). The base of this lower channel, marked by a lag of limonite-stained coarse to pebbly sand (facies 11), cuts down ~ 3 m from the top of the SM-2″ interval in the Rocky point area (Fig. 7) to the SM-2′ interval in the main stretch of cliffs on Park property (loc. 240 in Figure 5), where it is overlain by fine sand and highly carbonaceous clay with variable sand partings, root casts, and layers of well-preserved leaf-compression fossils and seeds (facies 10). The carbonaceous clay is ~ 5 m thick and broadly lenticular, and interfingers laterally with coarse flanking sands (Fig. 4). Limonitic crusts mark several sand/clay contacts in the upper part of the SM-2′ interval and just above the pSM surface, making this important contact quite subtle in individual sections, despite the broad erosional geometry of the pSM unit.

These deposits are interpreted as an abandoned-channel fill from a fully nonmarine fluvial system. The coarseness of the sands and the absence of overbank deposits suggests a braidplain rather than meander-belt system. This unit represents the oldest unambiguous evidence for subaerial exposure in the Calvert Cliffs succession.

Other pSM Channels.—All other individual channels within the pSM interval contain a quite different suite of tide-dominated facies (facies 7, 8, and 9), marking the return of marine influence on sedimentation.

The upper channel at State Park is scoured into the carbonaceous clay of the lower channel and filled with ~ 5 m of upward-coarsening medium to coarse pebbly sand (loc. 240 in Figure 5). Tabular or wedge cross-sets

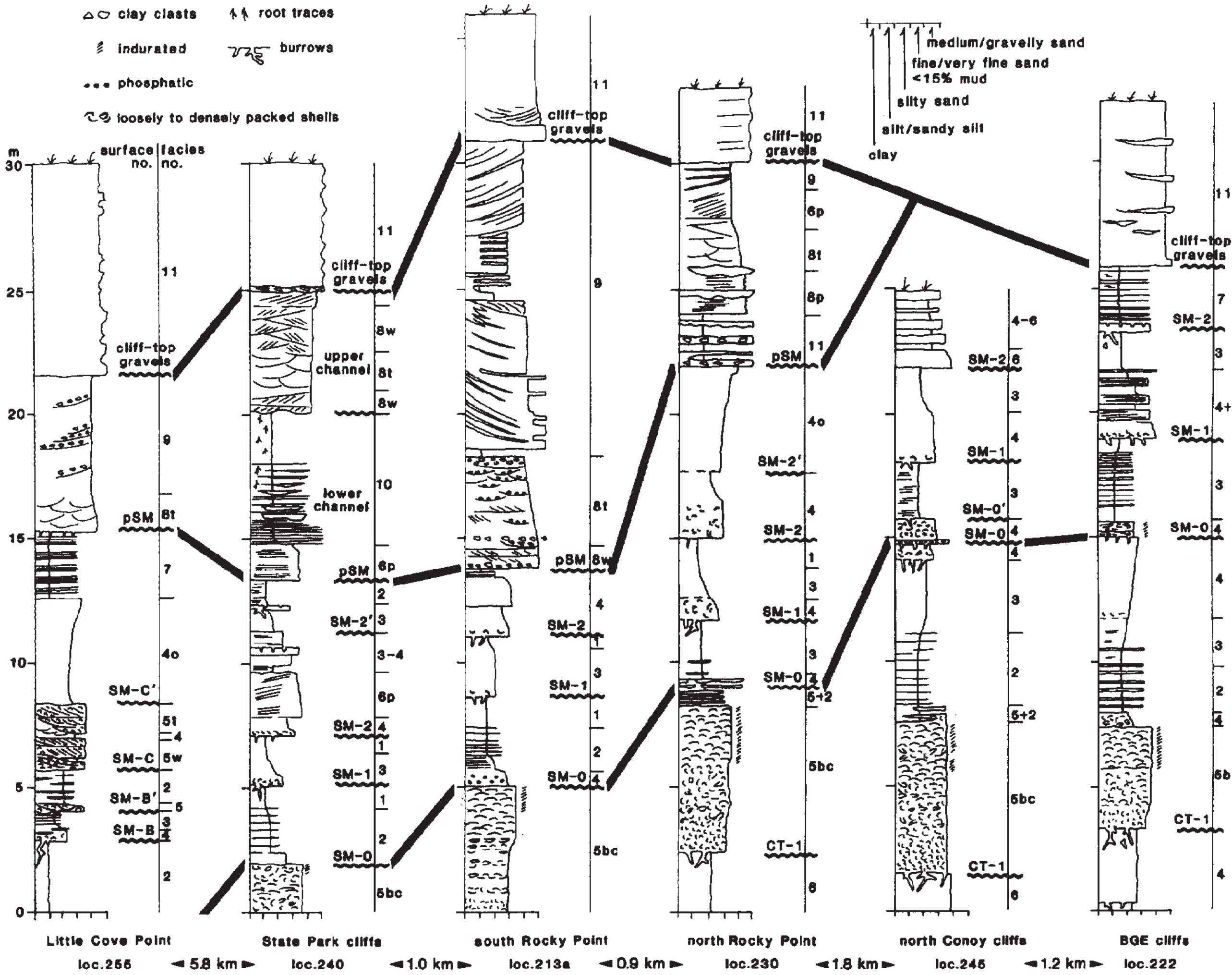


FIG. 5.—Key measured sections from the Calvert Cliffs, arrayed from north (right) to south (left), with column width scaled to grain size of siliciclastic sediment. Sediments of SM and pSM units are thoroughly burrowed and mottled unless physical sedimentary structures are indicated. Locality names and numbers as in Figures 4 and 6. Datum is mean sealevel. Heavy lines mark unconformities at the base of the St. Marys Formation (SM-0), post–St. Marys Neogene deposits (pSM), and Pleistocene cliff-top gravels.

at the base are succeeded by large-scale low-angle trough sets, wedge sets with strongly graded laminae, and gently inclined parallel lamination (south-dipping).

The Rocky Point channel cuts through at least 12 m of clayey SM-2 strata, and has a basal contact marked by abundant rounded clay clasts in large low-angle cross-sets of coarse sand (Figs. 4, 7; loc. 213a in Figure 5). The fill is divisible into at least three stories, each dipping down toward the axis of the channel from the south flank. The lowest story consists of ~ 5 m of fining-up trough cross-bedded coarse and medium sands with clay clasts, and the upper two stories are each ~ 6-m-thick sets of laterally accreted inclined heterolithic strata (facies 9) with clay drapes and thin beds of clay chips. The channel is capped by an additional ~ 6-m-thick multistoried interval of facies 9, which laps beyond the edges of the preserved channel (northern edge of this body of facies 9 appears in Figure 8).

The Conoy channel was impossible to reach except at one peripheral locality at the north edge of Rocky Point (loc. 230 in Figures 4 and 5). It is not clear whether it cuts across or is cut by the Rocky Point channel, but it incises at least 4 m down into clays and sands of the SM-2 interval in the cliffs north of Rocky Point and is filled with an upward-fining succession of interbedded clay and pebbly sand, flat-bedded coarse sand, and wedge and trough cross-sets of coarse to medium sand with clay drapes (facies 11 and 8). It is capped by an additional 2.5 m of low-angle laminated fine sand and inclined heterolithic strata (facies 6 and facies 9). The rest of the Conoy channel, which is well exposed but inaccessible in the cliffs south of Conoy landing, appears from a distance to be filled and capped entirely with facies 9 (Fig. 8; see also figure 29 of Hack 1955).

A series of low-relief channels is present in the Little Cove Point area (Fig. 6; illustrated as a single channel in Kidwell 1988, 1989). Postdepositional warping has accentuated the convexity of the channel bases, but their erosional origin is still evident from the truncation of underlying beds. The main channel has a basal interval of trough cross-bedded medium to pebbly sand with clay clasts, but the dominant fill is heterolithic lateral-accretion deposits (facies 9; loc. 255 in Figure 5). The southern set of channels are smaller and have more complex internal stratigraphy. At locality 261 (Fig. 6), the basal 4–5 m consists of high- to low-angle trough cross-sets of medium sand with clay clasts and some clay laminae; *Arenicolites, Skolithos,* and ghost crab burrows are present along some bed

TABLE 2.—*Coincidence of biostratigraphic zone boundaries with disconformities (double lines).*

Lithologic Zones of Shattuck (1904)	Surface-bounded units of Kidwell (1984, this paper)	Diatoms	Diatoms	Radiolaria	Foraminifera	Foraminifera	Mollusks	Dinoflagellates
		Abbott 1978*	Andrews 1988	Palmer 1986	Gibson 1983	Olsson et al. 1987	Ward 1992	de Verteuil & Norris 1996
"Pleist. sand"	top gravel	●	●	●	●	●	●	●
	pSM	●	●	●	●	●	●	●
22 and 23	SM-C & C′	●	●	●	●	●		
	SM-2′ & 2″	●	●	●	●	●		(post *A. a.*)
	SM-2/B	●	●	●	●	●		DN8 = L
	SM-1/A	●	●	●	●	●		(pre-*A.a.*)
	SM-0	●	●	●	●	●	M10 = L	DN8 = L
21		●	●	●	●	●	M11? = M	●
20			●	●	●			
19	CT-1		ECDZ7 = M	*D. petterssoni*	●		M11 = M	DN7 = M
18				●	●			
17	CT-0	VI = M	ECDZ6 = M	●	?N12 = M	N16 = L		DN6 = M
16			●		●			●
15			●		●			●
14	PP-3	V = M	ECDZ5 = M		●		M12 = M	
13					●			
12	PP-2				N9 = M	N8 = M		DN5 = M
11		IV = M			N9 = M			
10	PP-1	III? = M	ECDZ3-4 = M		N8/9 = M	N7 = E		DN4 = E/M
4–9	PP-0			*D. alata*	●	N6 = E		
3	Fairhaven	II = M	ECDZ2 = L/M	*C. costata*	●	●	M13 = E/M	DN3 = E

CT-0 sequence includes incised channel deposits at Governor Run. * Detailed data on distribution relative to disconformities is in Kidwell (1984).
● Indicates no data (bed not sampled or barren). E = Early Miocene, M = Middle Miocene, L = Late Miocene.

contacts in this interval (variants of facies 8). This is succeeded by an ~ 8-m-thick upward-fining interval of flat-laminated coarse sand, gently dipping laminated coarse to medium sand with spreiten (variants of facies 8), and undulatory beds and climbing ripples of medium to fine sand with clay laminae and clay-lined burrows (facies 6 and 7).

The sandy, upward-fining successions (facies 8) in these channels match almost perfectly the tidal-inlet sequences described by Kumar and Sanders (1974). From a basal lag of quartz gravel and clay rip-ups, pSM channel fills fine upward into relatively large trough, wedge, or tabular cross-sets of coarse to pebbly sand, medium-grained bidirectional cross-sets, and foreshore-laminated medium or fine sand, sometimes with *Ophiomorpha* burrows. Restriction of these successions to incised channels further supports this interpretation. Some of the pSM channels were capped by tidal-creek point bars, owing to the intertidal flat sediments (facies 7) that cap facies 8 locally (cf. Barwis 1978). Well-sorted sands of facies 8 commonly include thin beds of clay rip-ups, further suggesting the proximity of contemporaneous mud flats. The large-scale inclined heterolithic stratification (facies 9) that dominates and/or caps these channels is interpreted as lateral-accretion deposits from tidally influenced rivers (cf. Thomas et al. 1987).

With the exception of the fluvial lower State Park channel, the overall pSM paleogeography was thus a tide-dominated shoreline complex of tidal inlets, intertidal flats, and tidally influenced rivers (small true estuaries). The 5–6 m sets of facies 8 and 9 indicate a minimum paleotopographic relief of that scale in the channels at any given time, and the crosscutting nature of the pSM channels and inclusion of clay cobbles that could have been ripped from their walls suggest that the channels were modified by erosion during infilling, even if their basic topographic form was inherited from the preceding period of subaerial exposure.

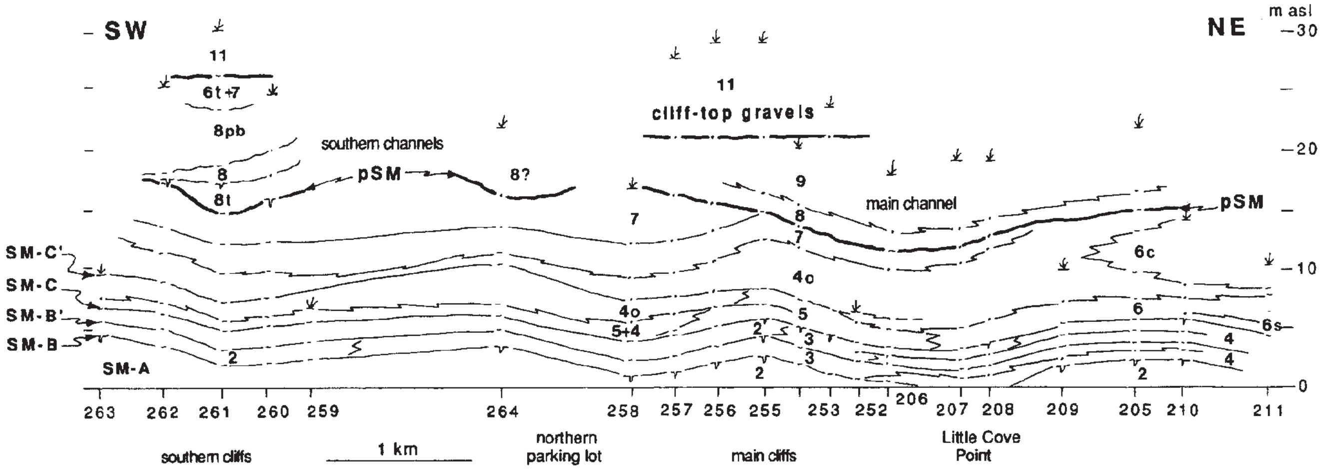


FIG. 6.—Strike-oriented (NE–SW) cross section of the Calvert Cliffs in the Little Cove Point area. Conventions as in Figure 4.

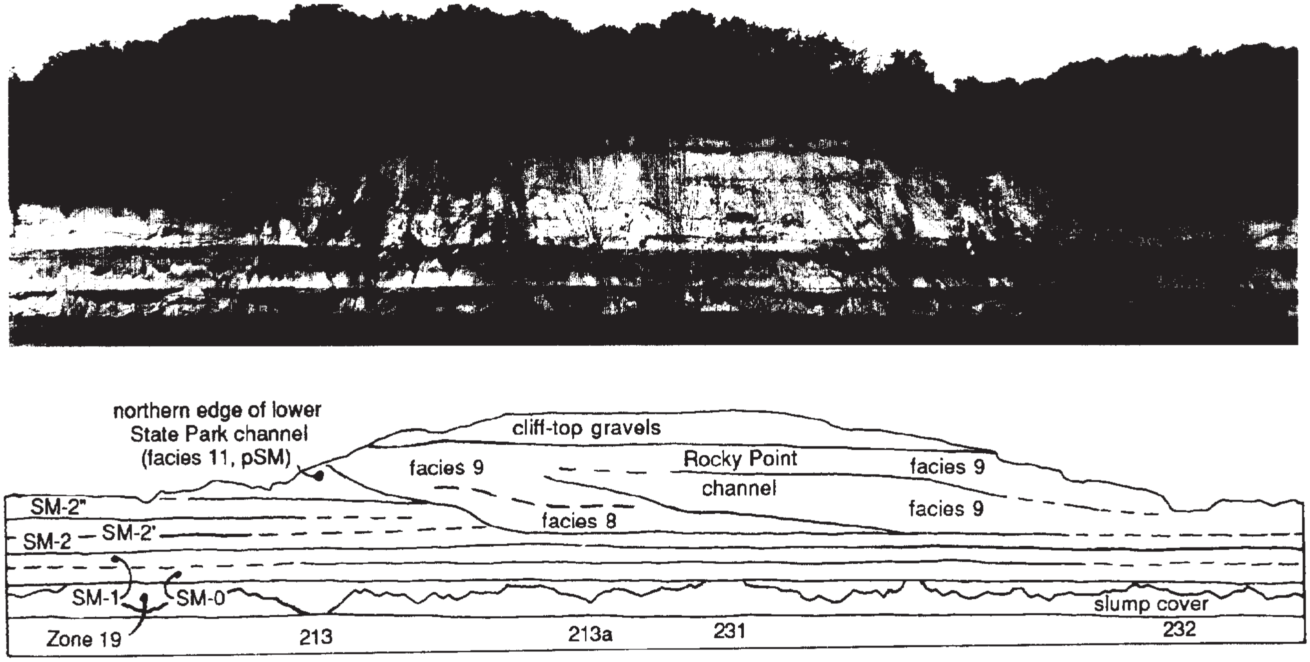


FIG. 7.—View of cliffs at Rocky Point (~ 35 m high), where the SM-0 disconformity lies along the indurated top of Zone 19, having completely removed Zone 20. The upper indurated part of Zone 19 forms the major shadow-casting ledge near the cliff base and is overlain directly by smooth-weathering, light-colored clays of the SM-0 interval. The sandier SM-1 interval is darker (damper), and cut by a thin dark ledge, which is the SM-2 disconformity (12 m amsl, about one-third of the way up the cliff). St. Marys strata above the SM-2 disconformity are sandier and lighter colored here. The flat-bottomed Rocky Point channel incises to a level between the SM-2 and SM-2′ disconformities, and is dominated by tidal-inlet (facies 8) and heterolithic estuarine deposits (facies 9). The ledge near the top of the cliffs marks the base of the cliff-top gravel unit.

Cliff-Top Gravels

A broadly tabular unit of unfossiliferous bedded sands and gravels truncates pSM and St. Marys strata at a low angle 20–30 m above mean sea level (facies 11; Figs. 2, 4, 6). The base of these capping gravels could be reached at several points, but the entire interval could be examined at only one locality (BGE, loc. 222 in Figure 5). This limited access, combined with very limited preservation of strata at this elevation, makes it impossible to characterize these strata in any detail. They do include, however, some high-angle trough cross-sets (< 1 m scale) and minor pure clay interbeds, in some instances inclined in such a way as to suggest small channels. These channels appear to be much smaller, or at least less steep-sided, than those of the pSM interval.

This interval marks the return of nonmarine fluvial, possibly braidplain, conditions in the Calvert Cliffs succession. This terrace-like unit is considered a distinct disconformity-bounded interval because of the erosional nature of its lower contact and its discordance with older strata, which by contrast have detectable dips (Fig. 2).

Other Interpretations of Uppermost Strata in the Calvert Cliffs

The distinct cycle of subaerial exposure and incision, fluvial aggradation, and estuarine transgression inferred for the pSM interval in the present paper contrasts with the interpretation of McCartan et al. (1985), the only previous study of the pSM interval in the Calvert Cliffs. They considered the coarse sands at Little Cove Point to be a conformable set of beach deposits recording the final phase of Miocene marine regression (correlative with shallow marine facies of Zone 24 of the St. Marys Formation exposed 20 km south in St. Marys County, Maryland; and see Newell and Rader 1982, Vogt and Eschelman 1987; Fig. 3). In contrast, Hack (1955), Schlee (1957), and Glaser (1968) considered all coarse-grained, high-elevation deposits in southern Maryland to be part of a single unconformable and exclusively fluvial Plio-Pleistocene unit. Shattuck (1906) also grouped all coarse deposits as a single, unconformable Pleistocene unit, but argued for a complex fluvial–estuarine–marine origin on the basis of mapping patterns. The interpretation in the present paper is most consistent with that of Stephenson and MacNeil (1954), who, in a largely overlooked paper that briefly described the Calvert Cliffs, recognized the pSM interval as an unconformable nearshore sand body (transgressive facies of Pliocene Yorktown Formation) distinct from the St. Marys Formation below and from unconformable nonmarine terrace gravels above.

The present enlarged set of observations indicates that the complexity of this interval has been underestimated by recent workers. Given the quality of exposures and the association with well-dated marine units, the fluvio-estuarine pSM interval and fluvial cliff-top gravels in the Calvert Cliffs should be reexamined carefully for integration into the detailed chronostratigraphy of late Cenozoic nonmarine deposits that is evolving for the coastal plain (e.g., Pazzaglia 1993). Judging by its downcutting of the Choptank and St. Marys formations, the pSM interval is probably a distal, marine-influenced toe of Pazzaglia's (1993) fluvial Bryn Mawr phase 3, which he correlated with the upper Miocene Eastover Formation of Virginia (synonymous with the lower Yorktown Formation of Stephenson and MacNeil 1954). The cliff-top gravel appears to be a distinct terrace deposit; its attitude is so different from underlying strata that a Pleistocene age is probable.

SEQUENCE ANALYSIS

Comparison with Sequence and Parasequence Models

St. Marys Formation: Shaved Sequences.—The St. Marys Formation consists of thin (2–7 m), tabular units bounded by stranding surfaces of abrupt shallowing. Strata between successive surfaces consist of a transgressive tract, normally deepening upward, in which downdip facies step

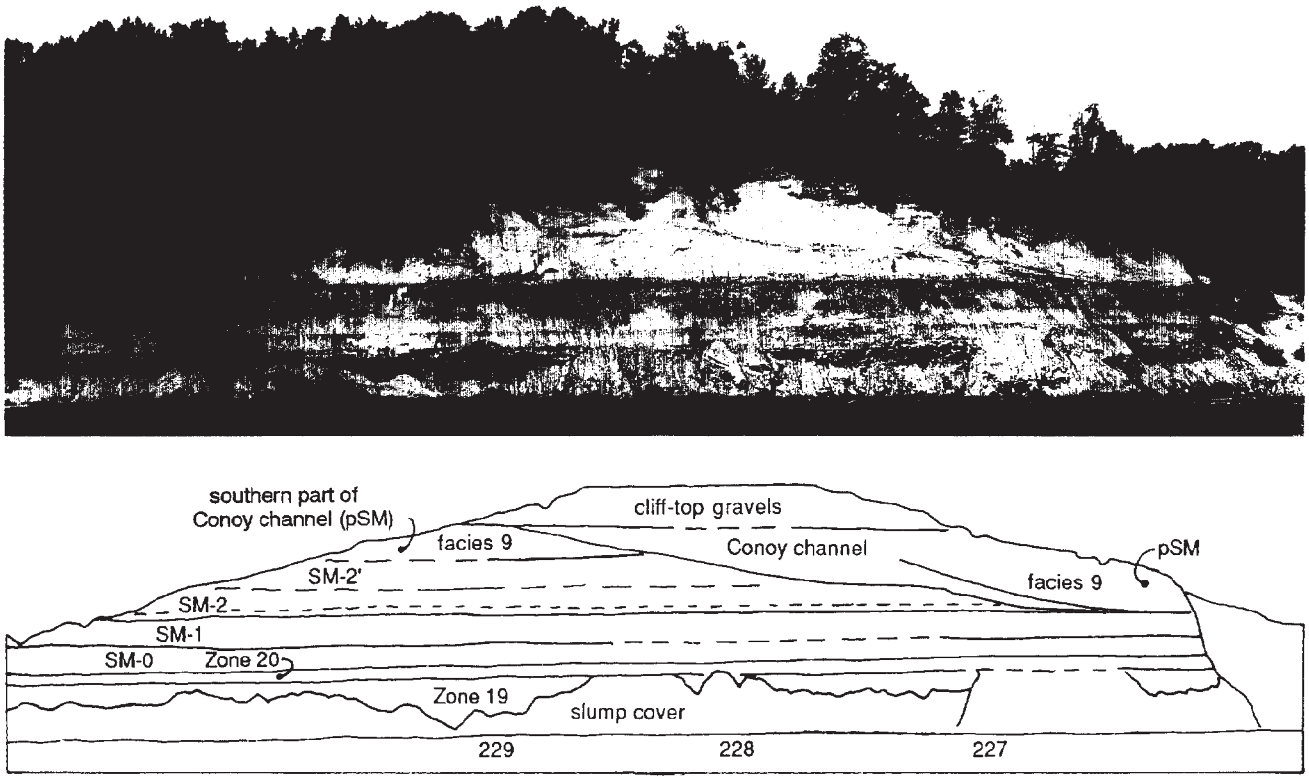


FIG. 8.—View of cliffs south of Conoy landing (~ 35 m high), showing tabular disconformity-bounded units of the shallow-marine Choptank Formation (Zones 19–20) and St. Marys Formation (SM units), and large estuarine channels of the post–St. Marys (pSM) interval. Zone 19 is the rough, shadow-casting ledge at the base of the exposure (partially obscured by slumps); the three bands of relatively smooth-weathering clay above Zone 19, each slightly thicker and darker colored than the one below, are Zone 20, the SM-0 interval, and the SM-1 interval (top of SM-1 interval is 15 m amsl, almost half-way up the cliff; the base of the pSM Conoy channel is coterminous with the top of the SM-1 interval in the north (right) edge of the cliff). Zone 20 thins measurably (from 2.5 m to 1.6 m) from north to south across this outcrop because of truncation by the SM-0 disconformity. The distinctive phosphatic pebble lag mantling this disconformity is evident on close examination but does not form an impressive notch or ledge.

up over updip facies; regressive facies tracts are lacking, either because regression was nondepositional or because regressive deposits were eroded during the final phase of regression and/or during the next transgression (Fig. 9A). The anatomy of SM units is thus opposite to parasequences, which by convention are sets of genetically related beds bounded by marine-flooding surfaces of abrupt deepening (Fig. 9A; Van Wagoner et al. 1988; Van Wagoner et al. 1990). In siliciclastic systems, each parasequence consists of a regressive facies tract that shallows upward; transgressive deposits are negligible or entirely absent. Flooding surfaces are commonly accompanied by minor submarine erosion and nondeposition, but not by subaerial erosion or by a basinward shift in facies.

Stranding surfaces are so fundamentally different from flooding surfaces that it seems counterproductive to equate the SM units with parasequences or to modify the parasequence definition to accommodate them. Instead, SM units are most readily classified as shaved sequences, in which any regressive "highstand" deposits (HST) have been removed entirely by erosion, leaving only transgressive deposits (TST) to represent the baselevel cycle.

Notwithstanding anatomical differences from parasequences, the isolated transgressive tracts of the SM sequences can be stacked into analogous larger-scale transgressive (backstepping) and regressive (progradational) sets (Fig. 9B; cf. Van Wagoner et al. 1988). The magnitude of facies offset across individual stranding surfaces is greater within regressive stacks than within transgressive stacks, for the same geometric reasons that facies offsets across individual flooding surfaces are greater within transgressive stacks than within regressive stacks (Fig. 9B). SM intervals can also be shingled into basinward-stepping sets in a pattern analogous to the stranded parasequences of forced regression (Figs. 9C, 10; cf. Posamentier et al. 1992).

Shideler (1994) interpreted the SM-0, SM-1, and SM-2 units of Kidwell (1988) as parasequences, on the basis of grain-size analysis of the BGE section. However, the only way to transform the transgressive arrangement of facies within SM units into the regressive arrangement that typifies parasequences would be to reverse regional dip (to the northwest), and this is contrary to regional isopach and paleogeographic patterns for the Salisbury Embayment (e.g., Poag and Ward 1993; de Verteuil and Norris 1996).

pSM Interval: Incised-Valley Deposits.—This interval is not divisible into hemicyclic units of either parasequence or "anti-parasequence" anatomy, but instead consists of a set of incised channels with single- and multiple-story fills 7–15 m thick. The aggradational nature of fluvial fill within the lower State Park channel suggests a remnant incised-valley fill (a second deposit of this type was reported by Shattuck 1906 ~ 40 km north, near Owings, Maryland). Aggradational tidal inlet and estuarine channels in the pSM interval are the leading depositional edge of marine transgression, and are readily classified as incised-valley fills (IVF). Other transgressive deposits are lacking, as are any regressive deposits, and so this interval too is the remnant of a severely shaved sequence, albeit dominated by a different part of the transgressive system tract (IVF). Given that the upper bounding unconformity is overlain by

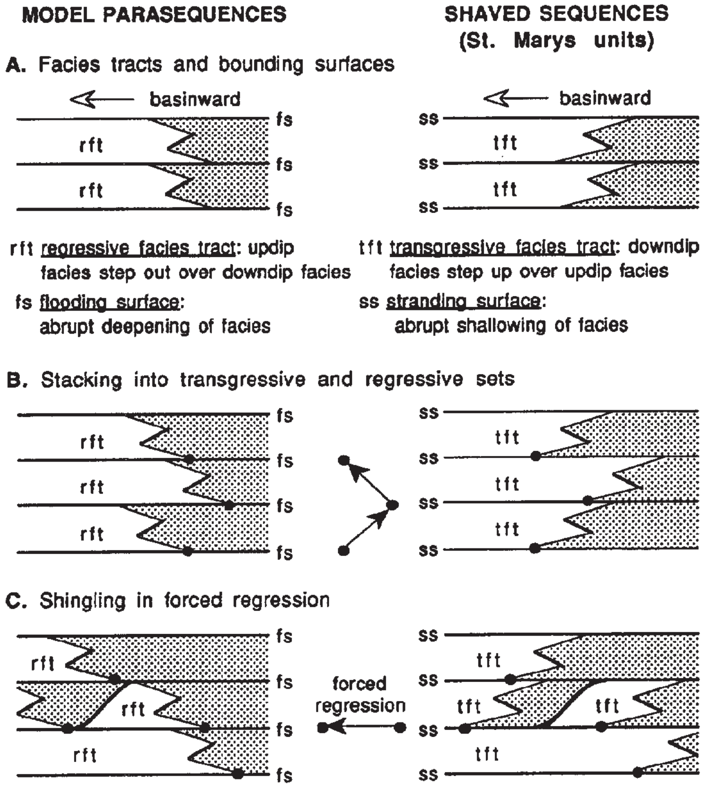


FIG. 9.—Schematic illustration of the contrasting anatomy of model parasequences (Van Wagoner et al. 1990) and isolated transgressive tracts (shaved sequences) in the St. Marys Formation. Stippled pattern indicates foreshore and shoreface sands, which interfinger basinward with deeper-water muds. **A**) Facies within SM shaved sequences are arranged in dominantly transgressive rather than dominantly regressive relation to each other, and are bounded by stranding surfaces of abrupt shallowing rather than by flooding surfaces of abrupt deepening. **B**) SM shaved sequences can be stacked into transgressive (backstepping) and regressive (progradational) sets, analogous to stacking patterns for parasequences. **C**) SM shaved sequences can be shingled basinward into forced-regression sets analogous to those composed of parasequences (cf. Posamentier et al. 1992).

fluvial deposits (cliff-top gravels), truncation of the pSM interval records a subsequent lowstand.

Plum Point–Choptank Interval: Thin but Complete Sequences with Condensed Transgressive Tracts.—Disconformity-bounded units in this oldest part of the Calvert Cliffs succession are roughly tabular units, 6–10 m thick, that thicken slightly downdip (Fig. 2; intervals are labeled successively through the Plum Point Member (PP) and the Choptank Formation (CT); all description and interpretations below are from Kidwell 1984, 1989). In individual sections, disconformities are heavily burrowed firmgrounds dominated by *Thalassinoides*; on a larger scale, the disconformities are demonstrably laterally continuous surfaces that locally incise and broadly bevel underlying strata. Incised channels are filled with intertidal and/or very shallow subtidal facies (e.g., in the Scientists Cliffs area along the CT-0 basal disconformity, and in the Scientists Cliffs to Matoaka area and in the Conoy area along the CT-1 basal disconformity). Broad erosional beveling preferentially thinned the updip reaches of each unit (Fig. 2) and also thinned sequences over folds, which apparently were syndepositional (e.g., thinning of PP-0 interval south of Naval Lab; thinning of PP-2 interval in Parker Creek area; thinning of PP-3 interval south of Governor Run; thinning of CT-0 interval south of Matoaka; thinning of CT-1 interval south of BGE).

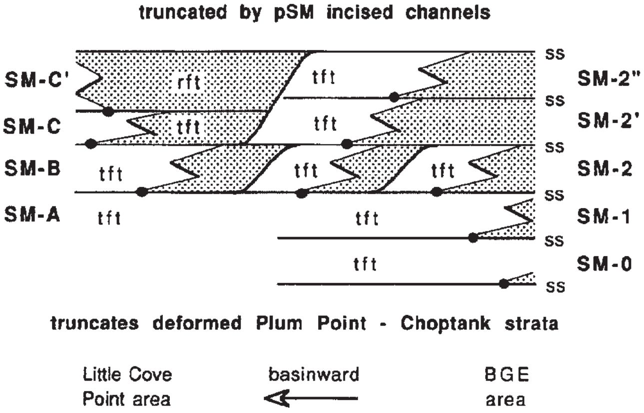


FIG. 10.—Schematic illustration of stacking patterns within the upper Miocene St. Marys Formation. The basinward shingling of SM sequences into at least two forced-regression sets (SM-B relative to SM-2, and SM-C/C′ relative to SM-2′ and SM′2″) complicates the correlation of St. Marys strata within the Calvert Cliffs, and may also explain difficulties of correlation with St. Marys strata in St. Marys County. Abbreviations as in Figure 9.

Plum Point and Choptank sequences are composed of the same range of lithofacies as the St. Marys Formation but have a qualitatively different anatomy, comprising a condensed record of transgression and more normal record of regression. Transgressive tracts are dominated by environmentally condensed bioclastic facies that are rich in both macrobenthic and marine vertebrate material. These bioclastic facies have a laterally and vertically complex stratigraphy that onlaps the basal disconformity, and consist of condensed and entirely shell-supported clean sands in updip and paleohigh areas (facies 5; dynamic bypassing and starvation), and thicker intervals of interbedded shell-rich sand and shell-poor silty sand or clay in downdip and other paleolow areas, including incised valleys (facies 5 and 4). In contrast, regressive tracts are lateral arrays of rather normal-looking siliciclastic facies (facies 1, 2, 3, 4), and are as thick as or thicker than the transgressive tract they cap. Neither tract can be subdivided readily into subsidiary parasequences or other cyclic or hemicylic units, although the contact of the regressive tract on the transgressive tract may be a slight flooding surface in some instances (locally burrowed or scoured; typically facies 2 or 3 superposed on facies 5).

Lowstand deposits and nonmarine facies are entirely lacking, and the disconformities show no direct evidence of subaerial exposure, although in some instances intertidal or extremely shallow subtidal deposits immediately underlie or overlie the erosion surface, suggesting that subaerial exposure was highly likely. Each nonetheless marks a significant basinward offset in facies (Fig. 2), and biostratigraphic zone boundaries coincide with these disconformities (Table 2), providing independent corroboration for hiatuses. The PP and CT disconformities thus meet most criteria for sequence-bounding unconformities (Van Wagoner et al. 1988; Mitchum and Van Wagoner 1991), namely that they indicate a significant hiatus (i.e., more erosion than from point-bar or runnel migration), are onlapped by overlying strata, are traceable over a significant region and into deep-water environments (see Kidwell 1984), and show either a basinward shift in facies (Type 1 unconformity) or a vertical change in stacking patterns (Type 2 unconformity).

These units are thus anatomically fairly complete, albeit very thin, sequences. This miniaturization, which is accompanied by condensation within the transgressive facies tract, contrasts with SM sequences that are thin because of severe erosional truncation at the end of the baselevel cycle. The major anatomical differences between PP-CT sequences and model sequences from settings of moderate subsidence are (1) the absence of lowstand deposits, so that sequence boundaries are also transgressive surfaces, and (2) the absence of well-developed subsidiary parasequences within transgressive and regressive tracts (but see Van Wagoner et al. 1990 and Shideler 1994, who interpreted PP and CT units themselves as parasequences).

The only exceptions to this pattern concern the PP-2 and PP-0 intervals. The PP-2 firmground contains only sparse *Thalassinoides* and lacks clear evidence for erosion, although the underlying PP-1 interval thins dramatically updip within the Calvert Cliffs (Fig. 2). Moreover, the 0.6-m-thick bone-rich but shell-poor sand that immediately overlies the PP-2 disconformity is uniquely rich among all units in the Calvert Cliffs succession in glauconite, well-preserved marine mammals, and planktonic microfossil species, and splays into a series of thinner discrete sand beds in an updip rather than downdip direction. In downdip areas and throughout the rest of its outcrop area in Maryland and Virginia, this bone sand is remarkable among all mantling skeletal sands for its uniformity in thickness and composition. For these reasons, the PP-2 surface and bone bed have been interpreted as recording maximum transgression, marked by conditions of siliciclastic starvation on the relatively distal shelf, and the PP-2 interval has been grouped with the underlying PP-1 interval into a single depositional sequence (Kidwell 1984, 1988, 1989). The presence of sand and a limited degree of erosion along the PP-2 surface would not be inconsistent with this interpretation, given the potential for small-scale storm winnowing of fines even on relatively deep seafloors given enough time (e.g., description of palimpsest sands by Galloway 1989). The coincidence of biozone boundaries with the PP-2 surface (Table 2) is as consistent with a nondepositional hiatus as with an erosional hiatus.

The PP-0 interval, which is preserved only locally within the Calvert Cliffs and onlaps the demonstrably erosional PP-0 disconformity, may be best regarded as an incised-valley fill. The thin sand that mantles the PP-0 disconformity contains abundant worn vertebrate material and phosphatic pebbles consistent with erosional reworking of older marine deposits, and in taphonomy resembles the SM-0 lag more than any other disconformity in the Calvert Cliffs succession.

Sequence Ranks and Stacking Patterns

Biostratigraphic analyses of diverse taxonomic groups concur that the PP and CT sequences record evolutionally distinct time increments (Table 2). Absolute calibration of the dinoflagellate zonation by de Verteuil and Norris (1996) indicates that the PP and CT disconformities have frequencies of 0.5–1.5 my (avg. 1.05 my; Fig. 11). These sequences would thus be classed as third order in the ranking scheme of Mitchum and Van Wagoner (1991; if PP-1 and PP-2 intervals are combined into a single sequence, its duration would be 2.0 my, still third order). In contrast, calibrated dinoflagellate evidence (de Verteuil and Norris 1996) indicates that SM disconformities have frequencies of ~ 300–450 ky at most (2 units within the 0.7-my-duration very early part of DN8; 5 to 7 units within the remaining 2.3 my of DN8 time, depending on how units within the SM-2 forced regression set are counted). Individual SM sequences would thus be classed as fourth-order units (Fig. 11).

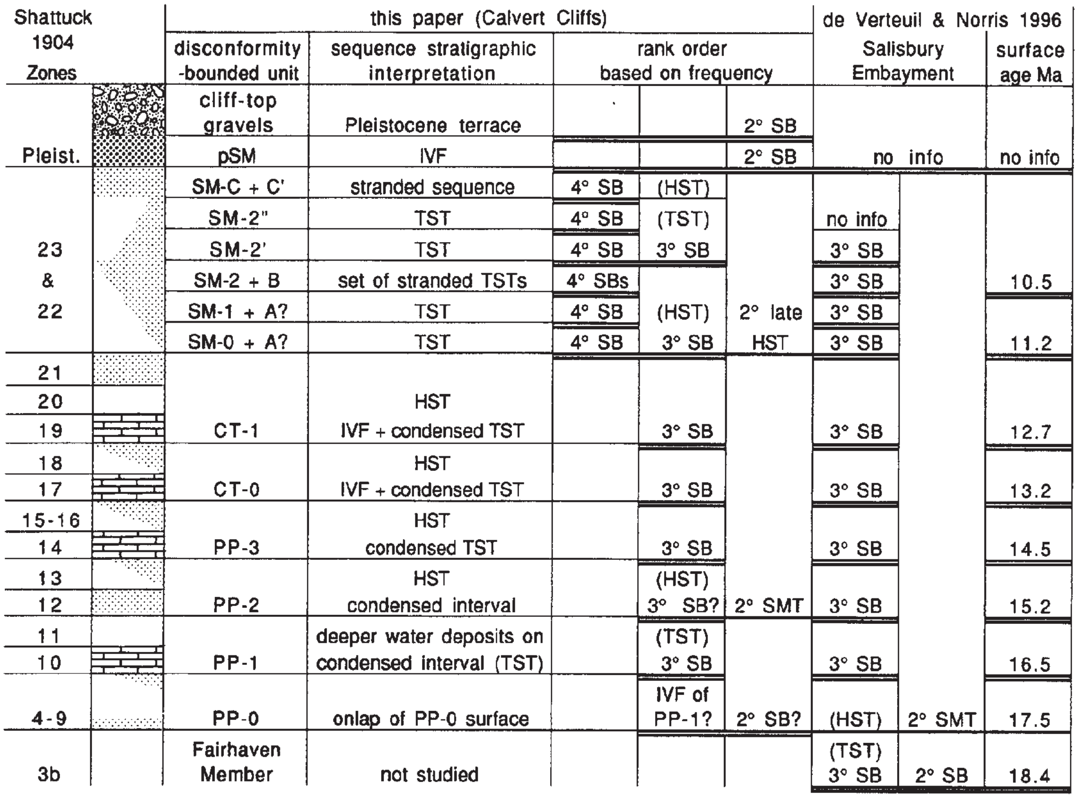
Unit geometries and stacking patterns in cross section (Fig. 2) suggest that the third-order PP and CT sequences constitute the transgressive and early highstand tracts of a second-order composite sequence (Fig. 11). The PP-2 disconformity is the surface of maximum transgression within this second-order cycle, and successive PP and CT sequences exhibit progressively greater low-angle erosional beveling of regressive facies tracts, more channel-form incision along disconformities, and an increasingly shallow-water part of the bathymetric spectrum. In the absence of detailed physical stratigraphic information for older (Fairhaven) strata, the PP-0 disconformity is provisionally interpreted as the basal second-order sequence boundary. The PP-1 disconformity merges with this surface in updip areas away from the Calvert Cliffs (Kidwell 1984), and so the intervening PP-0 interval may be either incised-valley-fill deposits related to the PP-1 sequence or, alternatively, the remnant of a genetically distinct but largely truncated third-order sequence. These interpretations do not differ substantively from those of Kidwell (1984, 1989), although they are updated to current sequence stratigraphic terminology (but see de Verteuil and Norris 1996, who interpret the PP-0 disconformity to be the master downlap surface of the Miocene second-order cycle; Fig. 11).

The part of the St. Marys Formation preserved within the Calvert Cliffs is a complex set of fourth-order shaved sequences that rests erosionally and with slight structural discordance upon older strata. The overall aggradational to weakly progradational appearance of SM units includes one and possibly two forced regressions, which are indicated by downdip shingling of fourth-order sequences (within the SM-2/B interval, and possibly the SM-C/C′ sequence relative to the SM-2′/2″ interval; Fig. 10). These forced regressive sets can be used as a basis for grouping fourth-order sequences into two third-order units (Fig. 11). The simplest and preferred interpretation is that the entire set of SM units constitutes the late highstand record of the preceding PP-CT second-order composite sequence, continuing the up-section trend of progradation and increasingly severe erosional beveling of highstand deposits in each subsidiary third-order sequence; the appearance of forced regression sets within the St. Marys Formation is consistent with this overall up-section trend (Fig. 11). An alternative interpretation that places greater significance on qualitative changes at the SM-0 disconformity—e.g., the structural discordance, the paleogeographic change implicit in the shift from condensed to noncondensed transgressive deposits (Kidwell 1988), and the coincidence with the middle/upper Miocene boundary—is that the St. Marys Formation constitutes the initial shelf margin systems tract of a second-order (upper Miocene) cycle distinct from the (lower and middle Miocene) cycle that includes Plum Point and Choptank strata.

The pSM interval is fairly readily interpreted as transgressive incised-valley deposits from a second-order cycle of deposition distinct from the St. Marys Formation. The cliff-top gravels represent lowstand deposits of an even younger second-order cycle (Fig. 11).

Comparison with Offshore Records

Third-order PP, CT, and SM units (as defined in this paper; Fig. 11) have been correlated throughout the outcrop and subsurface record of the Salisbury Embayment (Fig. 1; Kidwell 1984; Ward and Powars 1989; Ward 1992; Miller and Sugarman 1995; de Verteuil and Norris 1996). (Some authors have erected allostratigraphic labeling schemes for PP, CT, and SM units in order to avoid sequence stratigraphic interpretations; Figure 3.)



Shattuck 1904 Zones	this paper (Calvert Cliffs)					de Verteuil & Norris 1996		
	disconformity -bounded unit	sequence stratigraphic interpretation	rank order based on frequency			Salisbury Embayment		surface age Ma
	cliff-top gravels	Pleistocene terrace			2° SB			
Pleist.	pSM	IVF			2° SB	no info		no info
23 & 22	SM-C + C'	stranded sequence	4° SB	(HST)				
	SM-2"	TST	4° SB	(TST)		no info		
	SM-2'	TST	4° SB	3° SB		3° SB		
	SM-2 + B	set of stranded TSTs	4° SBs			3° SB		10.5
	SM-1 + A?	TST	4° SB	(HST)	2° late	3° SB		
	SM-0 + A?	TST	4° SB	3° SB	HST	3° SB		11.2
21 20 19	CT-1	HST IVF + condensed TST		3° SB		3° SB		12.7
18 17	CT-0	HST IVF + condensed TST		3° SB		3° SB		13.2
15-16 14	PP-3	HST condensed TST		3° SB		3° SB		14.5
13 12	PP-2	HST condensed interval		(HST) 3° SB?	2° SMT	3° SB		15.2
11 10	PP-1	deeper water deposits on condensed interval (TST)		(TST) 3° SB		3° SB		16.5
4-9	PP-0	onlap of PP-0 surface		IVF of PP-1?	2° SB?	(HST)	2° SMT	17.5
3b	Fairhaven Member	not studied				(TST) 3° SB	2° SB	18.4

FIG. 11.—Summary of sequence stratigraphic interpretations for the entire Calvert Cliffs succession, showing nesting of simple sequences (PP, CT) and shaved sequences (SM) within larger composite sequences. Designation of sequences as fourth-, third-, or second-order in the present paper applies the general definitions of Mitchum and Van Wagoner (1991). Ages of disconformities are based on independent biostratigraphic data of de Verteuil and Norris (1996; calibrated to Berggren et al. 1995), whose sequence stratigraphic interpretation diverges slightly. Double lines are disconformities.

More tentatively, these cyclic units have been correlated into the adjacent Baltimore Canyon Trough seaward of the structural hinge zone (Poag and Ward 1987; de Verteuil and Norris 1992; Poag and Commeau 1995; and see Poag and Ward 1993, who group all PP and CT units into one alloformation, and all SM units into a second alloformation). All of these broader regional studies indicate that third-order sequences thicken seaward across the Embayment and particularly into the Trough, where each is ~ 150–300 m thick (Greenlee et al. 1992), and are part of the HST of a second-order Miocene depositional cycle in the Atlantic continental margin.

Seismic reflection data indicate that the internal anatomy of third-order sequences also changes substantively across the hinge zone. Greenlee et al. (1992) found that, although a one-to-one correlation of third-order sequences between the Calvert Cliffs and the Trough is not possible because of limits to biostratigraphic resolution, there are six roughly coeval middle Miocene sequences of ~ 1 my duration in the Trough and two younger sequences of less certain age. Each of these is a strongly progradational clinoform body that contains both lowstand and highstand systems tracts but negligible or no transgressive tracts; the sequence boundaries indicate extensive erosion of the shelf (i.e., all are Type 1 unconformities; Greenlee et al. 1992).

The erosional nature of Miocene sequence boundaries in these offshore records strengthens the erosional interpretation of PP, CT, and SM disconformities within the Calvert Cliffs (Kidwell 1984, 1988). In addition, the anatomical asymmetry of the offshore Miocene sequences complements that of the PP, CT, and SM sequences onshore of the hinge zone, where (1) transgressive records are present, albeit highly condensed in some instances, (2) highstand tracts are not condensed but are as thin as transgressive tracts or, in the case of the St. Marys Formation, are completely missing, and (3) lowstand deposits are absent (Fig. 11). Poag and Commeau (1995) reported a dominance of transgressive and highstand deposits and a lack of lowstand deposits throughout the Paleocene to middle Miocene subsurface record of the Salisbury Embayment, and so this appears to be a general pattern landward of the hinge zone.

All of these differences can be attributed to the limited accommodation available landward of a passive-margin hinge zone. Preservation of an onshore record of each baselevel cycle was, however, no doubt favored by the large amplitude and rapidity of eustatic fluctuations in sealevel during the Miocene, ensuring repeated lapping well up onto the continental margin and relatively little time during lowstand for erosion of the preceding depositional sequence. The low relief of the PP, CT, and SM disconformities suggests transgressive planing as the dominant timing and process of erosion, rather than fluvial incision during lowstand. The relative thinness of each highstand tract may additionally reflect considerable omission by dynamic bypassing during regressive phases, both passive and forced. The deeply crosscutting incised-valley deposits of the pSM interval are also consistent with an accommodation-limited setting, resulting in removal or cannibalization during transgression of any lowstand deposits that might have accumulated.

CONCLUSIONS

The anatomy of Neogene strata in the Calvert Cliffs, Maryland, reveals the complexity of the surviving record of siliciclastic sequences at the landward edge of a major depositional basin, and in particular the relative importance and diverse styles of erosion and omission in low-accommodation settings. Landward thinning was not accomplished by omission or erosional removal of entire cycles of deposition: the onshore record contains the same number of third-order units as present offshore (Poag and Commeau 1995; de Verteuil and Norris 1992, 1996). Instead, thinning was achieved by elimination of some elements and attenuation of surviving elements within individual sequences. For example, each third-order unit consists of only a few rather than many resolvable fourth-order units, lowstand tracts are missing entirely, and highstand deposits are not significantly thicker than transgressive tracts, in contrast to their highly disproportionate thickness offshore, and are entirely missing in some fourth-order units. Transgressive surfaces thus coincide with sequence boundaries despite probable subaerial exposure, producing the relatively subtle marine-on-marine contacts observed at sequence boundaries in this study and heightening the likelihood of stratigraphic disordering of microfossils and diagenetic blurring of chemical signals between successive sequences (cf. Miller and Sugarman 1995; Poag and Commeau 1995).

Thinning of the record also involved qualitative shifts in anatomy and composition among surviving elements. For example, fourth-order cyclic units in the St. Marys Formation do not have the anatomy of model parasequences, but instead are shaved sequences bounded by stranding rather than flooding surfaces and consist entirely of transgressively arranged facies. Another example of qualitative change is the highly condensed and richly bioclastic nature of transgressive deposits in PP and CT sequences, in which densely packed macroinvertebrate assemblages record an upward-deepening series of shoreface and transition-zone environments over only a few meters of total stratigraphic thickness. The lack of such condensation within transgressive tracts of the St. Marys Formation has been attributed to their accumulation in an area more proximal to siliciclastic input, so that it was a sink for sediment rather than being sediment-starved during base-level rise (not an estuary in the sense of a flooded river valley, but a freshwater-influenced embayment of the open shelf; Kidwell 1988, 1989). This up-section change in the paleogeography of the Calvert Cliffs area may be coincidental, but it is also consistent with progressive progradation through the local Miocene record.

The Calvert Cliffs succession demonstrates that, despite the thinness of surviving deposits, biostratigraphically complete records can be preserved in settings of very low accommodation by miniaturization and shaving of subsidiary sedimentary cycles, leaving a record that is rich in marine deposits and transgressive facies tracts even in the latest phase of stratigraphic offlap. Such records can contain a coherent set of throughgoing disconformities useful in genetic subdivision and correlation, and are interpretable in terms of standard depositional sequence models, although not all elements of sequences are present and surviving elements may be one or two orders of magnitude thinner than their offshore counterparts.

ACKNOWLEDGMENTS

This research would not have been possible without the generous cooperation of many private landowners, particularly Connie and Larry Smith, Mrs. Margaret Moran, and the Chesapeake Ranch Club Estates, and parkland administrators from the State of Maryland. I am also grateful to Jon A. Moore for field assistance; Laurent de Verteuil for sharing his biostratigraphic results before publication and coaxing this manuscript into existence; Gordon Bowie for photographic work; N. Christie-Blick, D. Jablonski, R.R. Rogers, C.L. Summa, and L. de Verteuil for helpful reviews; and the Donors of The Petroleum Research Fund, administered by the American Chemical Society, for support of the field research (14340-G2-1983).

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Received 23 January 1995; accepted 25 August 1996.

Dr Larsen's Confirmatory Analysis of Calvert Cliff's Moran's Landing Fault -Dr. Vogt's CCNPP Appeal

(Sent 2/23/10 as Requested by Susan Shaw, Vice President, Calvert County Board of County Commissioners)

Dear Susan:

Thank you for the opportunity to comment on the appeal for licensing the third reactor at the Calvert Cliffs Nuclear Power Plant (CCNPP). I've noted that the appeal was initiated by Peter Vogt of our county. I should also note that Peter Vogt is a colleague of mine. He is a geophysicist and I am familiar with some of his work offshore in the Bay. Neither of us is a seismologist specializing in earthquakes. Nonetheless, Peter Vogt has raised some cogent questions in the text of the appeal. He has clearly written to a technical audience and I think it would be very hard for a lay person to appreciate what he has tried to say. I've tried to review the main parts of his presentation and will attempt here to simplify it (at least to my understanding).

Vogt has raised concerns regarding the possible existence of a geological fault line located in the vicinity of the CCNPP. An indication of the fault along the cliffs south of the power plant is apparently suggested in a scientific paper by the paleontologist Susan Kidwell of the University of Chicago published in 1997. It would be extremely difficult for anyone other than a professional in her field to ascertain that she might be discussing a geological fault exposed in the cliffs. Dr Kidwell calls our attention to an area of the cliffs where offsets in the stratigraphic sequence of beds are indicated. While she does not specifcally state it, such offsets commonly indicate breaks in sedimentary beds, possibly due to faults or perhaps significant folds in the original orientation of the beds. Vogt has helped to define this work by noting that the exposure is approximately 1 ¼ miles south of the power plant at a site called Moran's Landing. I am not familiar with this site, but it appears to be located near the mouth of a stream called Thomas Branch in the Calvert Cliffs State Park. It will help you to visualize the probable fault location by using Google Earth and focusing on the state park. Click on some of the blue squares along the parks shoreline until you find one labeled Thomas Branch. At this point you will see two streams that intersect near the beach. One has a NE/SW trend while the other trends NW/SE. If you back out enough to change the scale of the photo image to see St. Leonard Creek to the west, you will also see a cove at Vera's marina at White Sands. It has the same NW/SE trend and apparently connects with the ravine with the same trend at Thomas Branch. Such erosion patterns often reflect underlying zones of weakness in the underlying sediments. In some cases this erosion occurs along fault planes (these are really common in California, for example). In other cases it might occur in anomalies in the underlying sediments. A good example would be erosion of a buried stream channel. Linear erosion patterns are more suggestive of underlying fractures.

Peter does not identify this connection between the cliffs and St. Leonard Creek in his discussion. I point it out because it helps to understand his argument. He then cites work by the Zobacks (noted seismologists with the USGS—Mary Lou Zoback is a member of the National Academy of Sciences). They have noted that ongoing compression forces are indicated in the eastern U.S. and that compression is directed to the Northeast. Directional compression forces like these tend to cause fractures in earth materials. The fractures commonly occur parallel with and at right angles to the direction of the compression. In terms of earthquakes, a major zone of seismic activity along the NW/SE trend is associated with Charleston, SC and the famous 1886 earthquake there. Small quakes along this trend are common. If you check out the Maryland Geological Survey earthquake page or the USGS site and query the earthquake hazards section you will find a map of hazard intensities. It illustrates the NW/SE Charleston, SC trend and is at right angles to the compression force.

To simplify this as much as possible, NW/SE and NE/SW trends are common across the entire eastern U.S. north of Charleston. Fractures are commonly associated with these trends. While seismic (earthquake) activity is not necessarily associated with such fractures, stream erosion quite frequently follows the oriented fractures. Slow amounts of movement over centuries and thousands of years have been noted along faults that follow the same trends however. To put this in perspective for you, back out on the Google Earth image to see the entire Chesapeake Bay region. You can quickly see that the major river systems along the western shore follow this NW/SE trend and suggest erosion along fractures. An extreme example of the intersection of the two trends is shown by the Potomac River. The lower Potomac follows the NW/SE trend and then makes a sharp turn to the NE/SW trend. The turn to the Northeast is along a documented geologic fault that is labeled the Stafford Fault Zone. Slow movement has been verified along this fault zone, but seismic events have not been recorded. A geologist still active with the USGS, Wayne Newell (wnewell@usgs.gov) could provide more detailed information on this one. Wayne is currently investigating a possible fault along the NW/SE trend near the Blackwater Wildlife Refuge. The same kinds of stream erosion patterns are common on the Eastern Shore. The Choptank River makes the same types of right angle turns in its channel. Other rivers show the same orientations.

To get back to Peter Vogt's discussion, I think he is relating a possible offset in sedimentary beds along the cliffs to a fracture or fault that follows one of these zones weaknesses. I personally think he is on to something although I have never considered it until reading his document. My own sense is that a fracture or fault may be indicated by the sedimentary beds exposed in the cliffs—especially when you view the stream erosion patterns between the mouth of the Thomas Branch and St. Leonard Creek. The patterns are more than coincidental. Whether or not a fracture at this location could impact the CCNPP is another question. I think that the main thing is that it has never been investigated since Calvert seems to be in a low seismic risk zone. It is perhaps significant that an extension of the eroded trend at Thomas Branch projects into St. Leonard Creek at White Sands near Vera's should be investigated as the pipelines from the gas plant pass through this community.

Vogt has recommended a couple of means to investigate movement along this probable fracture. He recommends a "chirp" profile offshore the cliffs to see if there is a projection of a fracture in the sediments offshore the cliffs. This is a common geophysical method for recording the sediments and structures beneath the seafloor. The Maryland Geological Survey has the necessary equipment and vessel to accomplish this type of investigation. If this appeal was to be granted, the offshore work would certainly be easy to accomplish. If it verified faulting of any scale, the type of core recovery he suggests might be undertaken as a next step.

To wrap up, I think the subject of the appeal is plausible, especially since the whole topic of the intersecting fracture patterns has apparently never been investigated thoroughly—at least to my knowledge. If the Board were to take a position on this appeal calling for further study, it might be accomplished through the Maryland Survey and USGS. I know that USGS has a geologic mapping project that encompasses our area. It might be possible to do something in cooperation with the State and the Feds that way.

These are my ideas at the moment without a lot of additional research into the topic. I hope it helps and doesn't confuse the situation more.

Best wishes,

Curtis E Larsen, Phd.

Lusby, MD

EMAILS ON CCNPP APPEAL- EARTHQUAKE FAULT

----- Original Message -----
From: Peter Vogt
To: June Sevilla
Sent: Monday, March 01, 2010 5:49 PM
Subject: fault email

June, I found out from Susan Kidwell (who copied me her reply to Curt) that he had been asked for his opinion about my appeal.
Then I asked Curt, who said it was Susan Shaw. That's how it went. When I find Curt's comment to Susan, I'll forward that, given that he sent it to a government official so it's public record. BTW I know Curt well (do you know him? He lives in Drum Point I think).

P

----- Forwarded Message ----
From: "vogtpr@comcast.net" <vogtpr@comcast.net>
To: ptr_vogt@yahoo.com
Sent: Mon, March 1, 2010 5:35:41 PM
Subject: Fwd: [Fwd: Calvert Cliffs work]

----- Mensaje reenviado -----
De: "Susan Kidwell" <skidwell@uchicago.edu>
Para: larsencurt@msn.com
CC: "Peter Vogt" <vogtpr@comcast.net>
Enviados: Lunes, 22 de Febrero 2010 14:03:47 GMT -05:00 Región oriental EE. UU./Canadá
Asunto: Re: [Fwd: Calvert Cliffs work]

Hi Curt,

Thanks for your note, and for the reprint of the really interesting work on shoreline retreat along Calvert County -- that will be a useful addition to the packet of readings for any future fieldtip there.

I'm happy to attach a pdf of the 1997 paper. If there are others involved in the review who would like access to it or any of my other papers on the MD Mio, they are all freely available on my departmental website.

RE JSR paper: In addition to the cross-section, which speaks for itself, there's a section on p.324 labeled "Modification of original dip" that will be of interest. The section on the SM-O disconformity will also be of interest, including the subsection "alternative stratigraphic interpretations" and "biostratigraphic corroboration". These spell out the reasoning as well as highlight the data supporting the SM-0 surface as the key discontinuity in this part of the record.

Best wishes,

Susan Kidwell

On Feb 22, 2010, at 8:50 AM, Steve Koppes wrote:

> Hi Susan,
> Is this intended for you?
>
> Steve
>
> From: Curtis Larsen <larsencurt@msn.com>
> Date: February 20, 2010 6:58:34 AM CST
> To: <s-koppes@uchicago.edu>
> Subject: Calvert Cliffs work
>
>
> Hi Susan: Peter Vogt has cited your 1997 JSP paper in an appeal re
> the Calvert Cliffs nucluear power plant. One of the county
> commissioners has asked me to comment on Peter's appeal. His case
> for possible post Miocene faulting at Moran's Landing seems
> plausible, but I would like to be able to see your paper. Could
> you please send me a pdf file? I'm a Chicago Phd (1980)
> (Anthropology) and am retired from USGS. I've included a paper by
> my former interns on bluff stability in exchange.
>
> Curt Larsen
> <Evolution of Equlibrium Slopes.pdf>

Susan Kidwell
Department of Geophysical Sciences
University of Chicago
5734 South Ellis Avenue
Chicago IL 60637
773-702-3008
fax 773-702-9505

>>

EMAILS ON CCNPP APPEAL- EARTHQUAKE FAULT

----- Original Message -----
From: Peter Vogt
To: June Sevilla
Sent: Monday, March 01, 2010 5:51 PM
Subject: Fw: Kidwell cliff profile

----- Forwarded Message ----
From: Curtis Larsen <larsencurt@msn.com>
To: ptr_vogt@yahoo.com
Sent: Tue, February 23, 2010 7:34:22 PM
Subject: RE: Kidwell cliff profile

You must have heard that I was asked to comment on your appeal. I've attached my comments to Susan Shaw for your info.

Curt
Attachment: Review of CCNPP appeal.docx (14.9 KB)

Date: Tue, 23 Feb 2010 13:29:15 -0800
From: ptr_vogt@yahoo.com
Subject: Kidwell cliff profile
To: larsencurt@msn.com

Curt, Apropos that possible post-middle Miocene fault, attached is the Kidwell profile I marked up in color to suggest the structural interpretation; the intent was to include this fig with the appeal, not sure if that happened. Peter

>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>

A) **SUMMARY OF APPEAL**: The appellant notes that PSC CCNPP report and all previous reports/studies, dealing with possible risks to CCNPP, especially the proposed third reactor, have failed to note the probable presence of a potentially active earthquake fault which intersects the Calvert Cliffs 1 ¼ mile south of CCNPP, and is likely to pass closer to CCNPP. This is the only such structure known along the entire Calvert Cliffs. Appellant strongly recommends delaying any permit until geological mapping by experts demonstrates said fault is real (not mapping errors), and if so demonstrated, that boreholes with sediment cores be taken on land, and seismic chirp profiling conducted offshore, to determine the strike (map trend) and dip (incline) of the fault, and its history of activity.

B) BACKGROUND FOR APPEAL: Among the risks that have to be evaluated at proposed and present sites of nuclear power plants are the risks from shaking from earthquakes. Most earthquakes are caused by failure (rupture) of the earth's crust or upper mantle along faults; occasionally they are associated with volcanic eruptions and very rarely, including the very greatest, by comet or asteroid impacts. Even though the reactor containment structure may be engineered to withstand a major earthquake, coolant pipes with small defects (e.g. bad welds) may break, or alarm systems triggered, and in areas such as Calvert Cliffs where earthquakes are rare, power plant employees fooled into an inappropriate response.

These risks are generally estimated statistically, e.g. 'the probability this structure will be exposed to ground motion accelerations at least Y, of type X is estimated to be less than Z per year". Such statistics are obtained from 1) earthquake seismicity data during about the last half century of instrumentally recorded shocks, 2) historical accounts of earthquake-induced observations, including damage, which along the Eastern US coastal areas extend back 300-400 years; and 3) geological mapping of 'geologically recent' structures (faults or folds) in the earth's surface and shallow subsurface geology. However, many if not most major earthquakes are caused by failure along deeply buried faults, and have no surface or near-surface expression. The absence of earthquake seismicity during the instrumentally recorded and even the 'historical' reporting periods does not necessarily mean that no major earthquake could occur with small but significant probability over the expected lifetimes of a nuclear power plant (25-50+ years?). **A case in point is the 31 Aug 1886 Charleston, SC event (estimated at Richter magnitude between 6.6 and 7.3). There had been few or no earthquakes reported in this area prior to the shock. Had this earthquake not yet occurred, a low seismic risk would now still be assigned to the Charleston area.**

The CCNPP site, including proposed third reactor, is located on the US eastern seaboard (Coastal Plain), since the advent of plate tectonics placed more or less in the middle of the North America plate (Simkin et al.,2006), far from the seismically very active plate boundaries. However, the region (except for Florida) is not aseismic; earthquakes do occur, but less frequently. Much of the North America plate between the western North Atlantic and the Rockies appears to be under horizontal NE/ENE compression (e.g., Zoback et al.,1986). Most earthquakes in the region are caused by rupture along deeply buried, ancient faults, which this current stress pattern is 'reactivating' because the old faults remain zones of persistent weakness. Faults which rupture and displace young, near surface sediments of the Coastal Plain are uncommon but exist. The Stafford Fault (Virginia) is a good example.

Major earthquakes, capable of massive damage, have occasionally occurred within the interior of the North American Plate. For example, a series of four major earthquakes with estimated "Richter" magnitudes from 7.0 to 8.1, struck the area of New Madrid, Missouri from 16 Dec, 1811 (largest) to 7 Feb 1812. Fortunately this area was then only sparsely populated, but New Madrid was destroyed and many houses damaged in St. Louis. The seismic waves were felt on the US East Coast, and were reported to have cracked ice on the Chesapeake Bay. The recurrence times for similar shocks in the same area are now estimated at ca. 300-500 years, several times longer than for large plate boundary earthquakes e.g. along the San Andreas fault in California.

On 31 Aug 1886, a ca. 6.6-7.3 magnitude event caused severe damage in Charleston, SC, and some damage as far north as southern Virginia. It was strong enough in Calvert County to be noted by the Drum Point lighthouse keeper and to scare guests in the old Evans Hotel to flee the building, as reported by the Calvert Gazette. Significant to this appeal is the fact that little or no prior earthquake activity had been reported in the Charleston area. Lesser earthquakes, felt but not damaging, have occurred (that is, their epicenters) historically in Maryland and surrounding states.

Geological mapping of the sedimentary strata (layers) exposed in the Calvert Cliffs (most recently conducted and summarized by Kidwell, 1997) shows the layers are more or less continuous (no faults) and only very gently folded, except at one place, hereafter called Moran's Landing (ML), located near (ca. 1 ¼ mile) south of CCNPP. At this point (See Figure) there appears to be a break in the strata, either due to mapping errors (considered possible but unlikely) or a neotectonic structure, hereafter called the "Moran's Landing Fault ?" or "MLF?" (The question mark needs to be retained pending certain verification or falsification). Because at present only the intersection of the MLF? with the Calvert Cliffs is known, its trend (and trace, or intersection with the ground surface, in a map view) remains unknown. **Therefore the closest approach of the fault to the CCNPP and to the site of the proposed third reactor is unknown, but cannot geometrically be any more than 1 ¼ mile, and could be much closer.** The south side of the MLF? appears offset "up" relative to the north side (see Figure), so the **structure is probably a thrust fault with the crust to the south shoved over the top of the crust to the north**. Thrust faulting is consistent with the regional NE to ENE compression of this region (e.g., Zoback et al., 1986). Because the shallow marine Miocene-aged strata (ca. 12 to 10 million years old at this site) are offset, the faulting must postdate this time. The offset appears to continue into the overlying 'Upland Gravel' formation, meaning the faulting was still going on until after about 2 or 3 million years ago. Based on this interpretation of long term and geologically "neo-tectonic" (post-Miocene) activity, the structure is unlikely to be extinct. For the purposes of risks (*sensu lato*) to nuclear power plants, it is not enough to say that CCNPP is located in a region where destructive earthquakes occur rarely, if at all. Surface topography might help shed light on possible fault trends—because faulting generally loosens and weakens earth materials, facilitating erosion by water. GOOGLE-EARTH imagery suggests linear ravine/stream valley trends of about WNW and NW-NNW in the area from the Calvert Cliffs State Park north to the CCNPP area, so these are possible, but unproven fault strikes. If the MLF? strikes NW-NNW, it would pass through the CCNPP property not far from the present two and proposed third reactor.

Establishing an annual probability at less than 1:1,000,000 that an event with magnitude at least 7 or 7.5 occurs within 100 miles of CCNPP in a given year is very different from saying this probability is less than 1:500 or 1:1000. The point of this appeal is to emphasize that these probabilities (large shocks with low recurrence times) are not well established, due to the short historical and instrumental records and lack of detailed subsurface mapping. This makes it essential to evaluate and factor in any significant evidence for neotectonic structures such as the MLF?, which has been ignored, notwithstanding e.g. Kidwell's 1997 publication 12 years ago.

RECOMMENDATION: Given the possibility, or even probability, that a significant neotectonic structure ,"Moran's Landing Fault?"—a post-Miocene and potentially active earthquake-generating fault that offsets the strata exposed in the Calvert Cliffs such that the land on the south side has moved up relative to the north side- passes within 1 ¼ mile or less of the Calvert Cliffs Nuclear Power Plant, and that past CCNPP risk assessments—including the 2009 preliminary PSC report-- have failed to take this potentially seismically active (with high-frequency accelerations due to fault proximity) structure into account, this appeal recommends the following:

1) **No permit should be issued by PSC until detailed geological mapping, by experts, of the cliff exposures for at least several hundred meters on either side of the Moran's Landing area can discriminate with certainty between the "neotectonic fault" interpretation (considered more likely) and the "mapping errors" interpretation (considered less likely).** If (but only if) mapping errors are demonstrated, this appeal is groundless.

2) **In the event the Moran's Landing Fault (MLF?) is demonstrated to be real, no permit should be issued before a A) series of shallow (several hundred meters depth) boreholes have been placed, with core recovery and analysis, to determine the strike (trend) and dip (incline) of the fault, and of its offset history (when it was active, with an estimate of how often on average a fault offset occurred); and B) as a minimum a seismic 'chirp' profiler grid survey (similar to those conducted further north; see Vogt et al., 2000ab) be conducted in the Chesapeake Bay in the area where the putative MLF? would extend in the subbottom**. The chirp profiler could reveal evidence (or lack thereof) for offset of young sediment strata. The nearshore (with a mile or so of the cliffs) unconsolidated sediments range in age from a few thousand years (at most, a mile out) to zero (at the beach and in the shallow subbottom), so any offset of such strata along a fault would increase the odds of a new rupture in the future. It would

also be helpful to **deploy a small array of seismometers for several months to detect any local, low-magnitude activity, below the threshold felt by humans or detected by regional networks**.

APPPENDIX : CREDENTIALS OF APPELLANT AND DISCLAIMERS, and GEOLOGICAL REFERENCES: The following is an abbreviated Curriculum Vitae, with selected publications. Disclaimer: The appellant is speaking as a geoscientist and long-time (40 year) Calvert County resident for himself only, and in no way on behalf of any institution or employer with whom he is or has been associated. While a geophysicist by profession, the appellant does not claim specialized expertise in the fields of earthquake seismology nor in engineering applications of such knowledge. While the appellant is familiar with the geology of the Calvert Cliffs, he defers to Prof. Susan Kidwell, University of Chicago, as the geologist most knowledgeable in this field, having herself mapped the geology exposed in the Calvert Cliffs. The primary basis for this appeal is the apparent break in continuity (suggesting an earthquake fault) mapped by Prof. Kidwell (Kidwell, 1997) at just one locality along the entire cliffs: the site she labels as Moran's Landing, about 1 ¼ miles south of the BG&E/Constellation CEG nuclear power plant and proposed site of third reactor. Publications cited in this appeal are prefaced by an asterisk (*).

1) **Curriculum Vitae and selected publications by appellant**

Home Address:
3555 Alder Rd.
Port Republic, MD 20676

Phone: 410-586-0067
EMAIL: ptr_vogt@yahoo.com

Education:

PhD (Oceanography) Univ. of Wisconsin, Madison	1968
MA (Oceanography) Univ. of Wisconsin, Madison	1965
BS (Science; Geophysics; "With Honor"), Caltech	1961

Von Karman Scholarship 1957-61
US Fulbright Scholarship, Univ. Innsbruck, Austria (Glaciology) 1962-63

Professional Positions:

Currently (2009): Research Associate, Smithsonian Institution; Adjunct Professor, Horn Point Environmental Laboratory ; Professional Researcher, Marine Science Inst., Univ. California at Santa Barbara

Marine Geophysicist, US Naval Oceanographic Office- 1967-1975
Marine Geophysicist, Naval Research Laboratory - 1976-2004
Sabbatical, Univ. Oslo, Norway - 1978-1979

Professional Awards:
Within Navy:
Henry Kaminski Award, Research Society of America, 1971
(US Naval Oceanographic Office)
Alan Berman Research Publication Award, 1980, 1986, 1995
(Naval Research Laboratory)

Academia:
Fellow, Geological Society of America, 1973
Honorary Doctorate, Univ. Bergen, Norway, 2000
Foreign Member, Norwegian Academy of Science and Letters, 2000
Distinguished Alumni Award, Univ. of Wisconsin, 2003

Publications: over 150 authored or coauthored, and peer-reviewed professional publications, starting 1965. Those excerpted below demonstrate appellant's geoscience research publication history in the Chesapeake Bay, the western North Atlantic Ocean, global synthesis including seismicity, and geology of Calvert County, including the Calvert Cliffs.

Estuarine Processes & Gassy sediments: Chesapeake Bay

Hagen, R.A. and **Vogt, P.R.,** 1999, Seasonal variability of shallow biogenic gas in Chesapeake Bay, Mar. Geol., 158, 75-88.

***Vogt, P.R.**, Halka, J.P., Hagen, R.A. and Cronin, T., 2000, Geophysical environment in Chesapeake Bay: *Marion-Dufresne* Sites MD99-2205, 2206 and 2208, in Cronin, T., ed., Initial Report on IMAGES V Cruise of the *Marion-Dufresne* to the Chesapeake Bay June 20-22, 1999, USGS Open File Report 00-306, p.18-31.

***Vogt, P.R.,** Czarnecki, M. and Halka, J.P., 2000, *Marion-Dufresne* Coring in Chesapeake Bay: Geophysical Environments at Sites MD99-2204 and 2207, in: Cronin, T., ed., Initial Report on IMAGES V Cruise of the *Marion-Dufresne* to the Chesapeake Bay June 20-22, 1999, USGS Open File Report 00-306, p. 32-39.

Halka, J.P.,**Vogt, P.R.,** Colman, S.M. and Cronin, T.M., 2000, Geophysical Environment: Site MD99-2209, in: Cronin, T., ed., Initial Report on IMAGES V Cruise of the *Marion-Dufresne* to the Chesapeake Bay, June 20-22, 1999, USGS Open File Report 00-306, p. 40-48.

Colman, S.M., Baucom, P.C., Bratton, J.F., Cronin, T.M., McGeehin, J.P., Willard, D., Zimmerman, A.R. and **Vogt, P.R.,** 2002, Radiocarbon dating, chronologic framework, and changes in accumulation rates of Holocene estuarine sediments from Chesapeake Bay, Quat. Res., 57, 58-70.

Shah, A.J., Brozena, J., **Vogt, P.**, Daniels, D., and Plescia, J., 2005, New surveys of the Chesapeake Bay impact structure suggest melt pockets and target-structure effect, Geology, 33, 417-420, doi:10.1130/G21213.1

Cronin, T.M., **Vogt, P.R**., Willard, D.A., Thunell, R., Halka, J., Berke, M., and Pohlman, J., 2007, Rapid sea level rise and ice sheet response to 8,200-year climate event, Geophys. Res. Lett., L20603, doi:10.1029/2007GL031318

Synthesis and Review

Vogt, P.R. and Tucholke, B.E., eds., 1986, The Western North Atlantic Region, v. M of The Geology of North America, Geol. Soc. Amer., Boulder.

Vogt, P.R. and Tucholke, B.E., 1989, North Atlantic Ocean Basin; Aspects of geologic structure and evolution: An overview, in Palmer, A. et al., eds., v. A. of The Geology of North America, p.53-80.

Regional and Global Charts:

Simkin, T., Unger, J.,Tilling, R.I., **Vogt, P.R.** and Spall, H., 1994, This Dynamic Planet—World map and interpretations of volcanoes, earthquakes, plate tectonics and bolide impact craters, Second Edition, US Geological Survey (Chart).

*Simkin, T., Tilling, R.I., **Vogt, P.R.,** Kirby, S., Kimberly, P. and Stewart, D., 2006, This Dynamic Planet, Third Edition (chart and website), US Geological Survey Geologic Investigations Series, Map I-2800

Local (Southern Maryland) geology:

***Vogt, P.R.** and Eshelman, R., 1987, Maryland's Cliffs of Calvert: A fossiliferous record of Mid-Miocene inner shelf and coastal environments, in: Roy, D.C., ed., Geological Society of America Centennial Field Guide-Northeastern Section, v.5, Geol. Soc. Amer., p.9-14.

***Vogt, P.R.,** 1991, Estuarine stream piracy: Calvert County, US Atlantic Coastal Plain, Geology, 19, 41-44.

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2) OTHER PUBLICATIONS RELATED TO THIS APPEAL:

*Kidwell, S.M., 1997, Anatomy of extremely thin marine sequences landward of a passive-margin hinge zone; Neogene Calvert Cliffs succession, Maryland, USA, Jour. Sedimentary Research, 67(2), 322-340.

*Zoback, M.L., Nishenko, S.P., Richardson, R.M., Hasegawa, H.S., and Zoback, M.D., 1986, Mid-plate stress, deformation, and seismicity, in **Vogt, P.R**. and Tucholke, B.E., The Western North Atlantic Region, v. M in The Geology of North America, Geol. Soc. Amer., Boulder, p.297-312.

Dr Larsen's Confirmatory Analysis of Calvert Cliff's Moran's Landing Fault -Dr. Vogt's CCNPP Appeal

(Sent 2/23/10 as Requested by Susan Shaw, Vice President, Calvert County Board of County Commissioners)

Dear Susan:

Thank you for the opportunity to comment on the appeal for licensing the third reactor at the Calvert Cliffs Nuclear Power Plant (CCNPP). I've noted that the appeal was initiated by Peter Vogt of our county. I should also note that Peter Vogt is a colleague of mine. He is a geophysicist and I am familiar with some of his work offshore in the Bay. Neither of us is a seismologist specializing in earthquakes. Nonetheless, Peter Vogt has raised some cogent questions in the text of the appeal. He has clearly written to a technical audience and I think it would be very hard for a lay person to appreciate what he has tried to say. I've tried to review the main parts of his presentation and will attempt here to simplify it (at least to my understanding).

Vogt has raised concerns regarding the possible existence of a geological fault line located in the vicinity of the CCNPP. An indication of the fault along the cliffs south of the power plant is apparently suggested in a scientific paper by the paleontologist Susan Kidwell of the University of Chicago published in 1997. It would be extremely difficult for anyone other than a professional in her field to ascertain that she might be discussing a geological fault exposed in the cliffs. Dr Kidwell calls our attention to an area of the cliffs where offsets in the stratigraphic sequence of beds are indicated. While she does not specifcally state it, such offsets commonly indicate breaks in sedimentary beds, possibly due to faults or perhaps significant folds in the original orientation of the beds. Vogt has helped to define this work by noting that the exposure is approximately 1 ¼ miles south of the power plant at a site called Moran's Landing. I am not familiar with this site, but it appears to be located near the mouth of a stream called Thomas Branch in the Calvert Cliffs State Park. It will help you to visualize the probable fault location by using Google Earth and focusing on the state park. Click on some of the blue squares along the parks shoreline until you find one labeled Thomas Branch. At this point you will see two streams that intersect near the beach. One has a NE/SW trend while the other trends NW/SE. If you back out enough to change the scale of the photo image to see St. Leonard Creek to the west, you will also see a cove at Vera's marina at White Sands. It has the same NW/SE trend and apparently connects with the ravine with the same trend at Thomas Branch. Such erosion patterns often reflect underlying zones of weakness in the underlying sediments. In some cases this erosion occurs along fault planes (these are really common in California, for example). In other cases it might occur in anomalies in the underlying sediments. A good example would be erosion of a buried stream channel. Linear erosion patterns are more suggestive of underlying fractures.

Peter does not identify this connection between the cliffs and St. Leonard Creek in his discussion. I point it out because it helps to understand his argument. He then cites work by the Zobacks (noted seismologists with the USGS—Mary Lou Zoback is a member of the National Academy of Sciences). They have noted that ongoing compression forces are indicated in the eastern U.S. and that compression is directed to the Northeast. Directional compression forces like these tend to cause fractures in earth materials. The fractures commonly occur parallel with and at right angles to the direction of the compression. In terms of earthquakes, a major zone of seismic activity along the NW/SE trend is associated with Charleston, SC and the famous 1886 earthquake there. Small quakes along this trend are common. If you check out the Maryland Geological Survey earthquake page or the USGS site and query the earthquake hazards section you will find a map of hazard intensities. It illustrates the NW/SE Charleston, SC trend and is at right angles to the compression force.

To simplify this as much as possible, NW/SE and NE/SW trends are common across the entire eastern U.S. north of Charleston. Fractures are commonly associated with these trends. While seismic (earthquake) activity is not necessarily associated with such fractures, stream erosion quite frequently follows the oriented fractures. Slow amounts of movement over centuries and thousands of years have been noted along faults that follow the same trends however. To put this in perspective for you, back out on the Google Earth image to see the entire Chesapeake Bay region. You can quickly see that the major river systems along the western shore follow this NW/SE trend and suggest erosion along fractures. An extreme example of the intersection of the two trends is shown by the Potomac River. The lower Potomac follows the NW/SE trend and then makes a sharp turn to the NE/SW trend. The turn to the Northeast is along a documented geologic fault that is labeled the Stafford Fault Zone. Slow movement has been verified along this fault zone, but seismic events have not been recorded. A geologist still active with the USGS, Wayne Newell (wnewell@usgs.gov) could provide more detailed information on this one. Wayne is currently investigating a possible fault along the NW/SE trend near the Blackwater Wildlife Refuge. The same kinds of stream erosion patterns are common on the Eastern Shore. The Choptank River makes the same types of right angle turns in its channel. Other rivers show the same orientations.

To get back to Peter Vogt's discussion, I think he is relating a possible offset in sedimentary beds along the cliffs to a fracture or fault that follows one of these zones weaknesses. I personally think he is on to something although I have never considered it until reading his document. My own sense is that a fracture or fault may be indicated by the sedimentary beds exposed in the cliffs—especially when you view the stream erosion patterns between the mouth of the Thomas Branch and St. Leonard Creek. The patterns are more than coincidental. Whether or not a fracture at this location could impact the CCNPP is another question. I think that the main thing is that it has never been investigated since Calvert seems to be in a low seismic risk zone. It is perhaps significant that an extension of the eroded trend at Thomas Branch projects into St. Leonard Creek at White Sands near Vera's should be investigated as the pipelines from the gas plant pass through this community.

Vogt has recommended a couple of means to investigate movement along this probable fracture. He recommends a "chirp" profile offshore the cliffs to see if there is a projection of a fracture in the sediments offshore the cliffs. This is a common geophysical method for recording the sediments and structures beneath the seafloor. The Maryland Geological Survey has the necessary equipment and vessel to accomplish this type of investigation. If this appeal was to be granted, the offshore work would certainly be easy to accomplish. If it verified faulting of any scale, the type of core recovery he suggests might be undertaken as a next step.

To wrap up, I think the subject of the appeal is plausible, especially since the whole topic of the intersecting fracture patterns has apparently never been investigated thoroughly—at least to my knowledge. If the Board were to take a position on this appeal calling for further study, it might be accomplished through the Maryland Survey and USGS. I know that USGS has a geologic mapping project that encompasses our area. It might be possible to do something in cooperation with the State and the Feds that way.

These are my ideas at the moment without a lot of additional research into the topic. I hope it helps and doesn't confuse the situation more.

Best wishes,

Curtis E Larsen, Phd.

Lusby, MD