Evolution of Equilibrium Slopes at Calvert Cliffs, Maryland
A Method of Estimating the Timescale of Slope Stabilization

By

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ASTRACT

The present study documents the evolution of coastal bluffs from steep, actively eroding, to low-angle stable slopes at Calvert Cliffs, Maryland, and provides historic age control for the rates of these changes. We measured slope angles at intervals along the bluff line northward from Cove Point and Flag Ponds Nature Park, and from the updrift harbor structure at the Flag Harbor Marina. In the Cove Point and Flag Ponds areas, coastal bluffs were protected from wave action for several centuries by prograding depositional landforms. Measured slope angles varied between 25°-37° with a mean of approximately 31°. There was no progressive decrease in slope with age on the centennial time-scale. This consistency of slope angles suggests that steep, eroding bluffs quickly change to stable slopes (at the angle of repose) once they are protected from toe erosion. In the Flag Harbor area, a least squares regression of slope angle vs. distance showed a decrease in angle from steep 60°-70° slopes north of the harbor to stable 30°-40° at the harbor. A relationship between time and distance along the shoreline allowed us to estimate a slope stabilization time for this area of 35-40 yrs.

Additional Keywords: Cove Point; Flag Harbor; cliff erosion; shore protection; jetties; groins, beach profile. *Article Received: 10/30/2003, Revised: 7/12/2004, Accepted: 7/12/2004*

INTRODUCTION

The increasing population of the District of Columbia metropolitan area promotes development in the surrounding coastal regions of Chesapeake Bay, such as the Calvert Cliffs area in Calvert County, Maryland (Figure 1). This section of the shoreline is comprised, almost entirely, of relatively high bluffs that are constantly eroding under natural conditions. Consequently, shoreline protection measures, such as groins, riprap and bulkheads have been installed in many areas along the bay shoreline to protect the toes of the bluffs. However, it is important to recognize that these protective measures do not eliminate slope failure in sediments exposed in cliff faces (Palmer 1973).

Several studies have been conducted in the Calvert Cliffs area to investigate the causes and processes involved in the bluff retreat, and to assess the functioning of the erosion control structures. Direct wave undercutting at the base of the bluff, groundwater seepage and freeze/thaw action are the most significant causes of cliff failure in the area. Wilcock et al. (1998) calculated a frequency distribution of wave strength and its effect on the bluff recession rates for 11 sites along the Chesapeake Bay shoreline in Calvert County. They showed that slopes directly undercut by waves recede at higher rates than non-undercut slopes, though the cohesive strength of the material at the toe of the slope also affects rate of retreat.

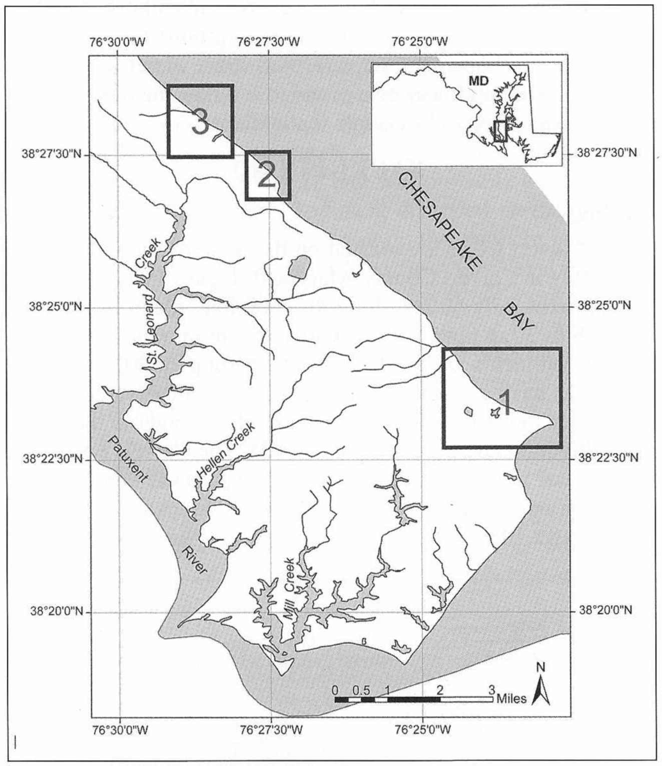

Figure 1. Calvert Cliffs study area, Calvert County, MD showing three study sites: 1 – Cove Point; 2 – Flag Ponds; 3 – Flag Harbor-Calvert Beach site.

Groundwater movement, along with the wave undercutting, promotes bluff failure in Calvert Cliffs (Pomeroy 1987, McMullan 1976, Leatherman 1986). The water table here commonly lies between sandy units and the less permeable clay and silt layers. Groundwater seeps along this contact remove noncohesive sediment, which can lead to a slope failure. Vertical cracks that often form in the fine-grained sediments of the cliffs from wetting and drying cycles fill with water from overland flow or groundwater. During winter, water in the cracks freezes at night and thaws during the day resulting in ice wedging and spalling of thin slabs of sediment (Leatherman 1986, Wilcock et al. 1998). Processes involved in slope failure at Calvert Cliffs include: shear slips, spalls, translational slides, and debris flows (Pomeroy 1987, Leatherman 1986).

Shultz and Ashby (1967) analyzed the functioning of 45 groins constructed at Scientists Cliffs, about 5-6 km north of the study area. They suggested that factors such as the height of a groin above mean low tide, length of a groin, up- or downdrift position of a groin relative to the beach, and timing of the groin construction need to be considered when attempting to create a beach sufficient to protect adjacent bluffs from erosion. A study by Leatherman (1986) at the Chesapeake Naval Research Lab states that despite engineering stabilization of cliff toes at this site since 1945 the slopes are still failing "as evidenced by…recent debris flows."

Bluff retreat in Calvert Cliffs area is not driven solely by wave action. Many people in this area believe that failure of a bluff could be eliminated by protecting its base from wave undercutting or planting vegetation on the slope. Thus, many houses are built within 10-15 m from the bluff edge with the assumption that cliff erosion at the site could be prevented by construction of groins, bulkheads or rip-rap, or that this distance is great enough to safeguard from any damage to the property. Along with emphasizing a variety of processes involved in bluff retreat at our study site, we sought to understand centennial and decadal-scale development of stable slopes from eroding bluff faces. Our objective was to analyze the slope response once direct wave action (erosion) at the bluff toes ceases and to estimate the rates of slope change from steep to low-angle inclinations.

BACKGROUND

Geology

The Calvert Cliffs are located on the western shore of Chesapeake Bay in Calvert County, Maryland (Figure 1). Cliffs stretch for approximately 50 km along the shoreline, rising in places to as much as 30 m high. Calvert Cliffs are cut into unconsolidated marine sediments of the Chesapeake Group of Miocene age. The strata have a gentle dip to the south – southeast; sediments exposed in the cliff faces get progressively younger in the southward direction (Brace-Thompson 1993). The Calvert Formation is the basal unit of the Chesapeake Group and is comprised of dark diatomaceous sandy clay and marl (Jedlicka 1977, Pilkey and Zabawa 1989). Due to the dip, only the Plum Point member of the Calvert Formation is exposed in the northern section of the study area (Figure 2).

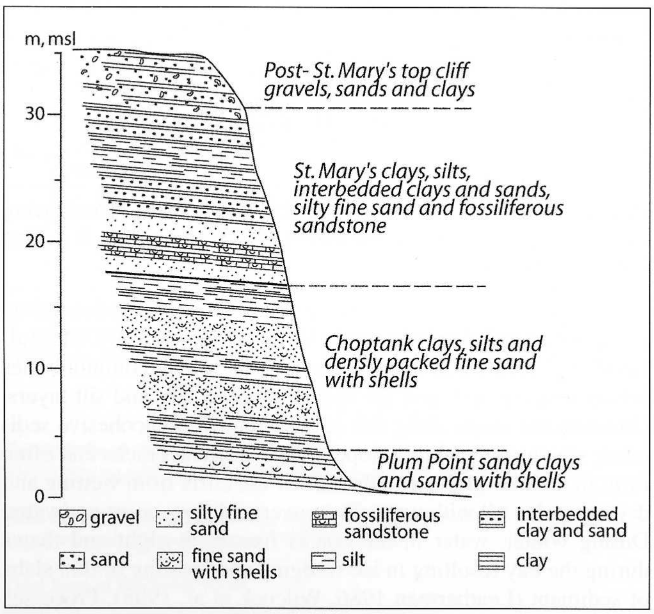

Figure 2. Generalized cross-section of strata exposed in the study area (Source: Vokes 1961; Newell and Rader 1982; Pilkey and Zabawa 1989).

The Choptank Formation, which overlies the Calvert Formation, is made up of yellowish sand and interbedded greenish clay and silt (Pilkey and Zabawa 1989, Pomeroy 1987). Along the Calvert Cliffs, the youngest formation of the Chesapeake Group is the St. Mary's. It includes bluish-gray sandy clay, silty sand and fossiliferous fine-grained sandstone (Vokes 1961, Newell and Rader 1982) discontinuously overlying sediments of Choptank Formation. Only the St. Mary's Formation is exposed around Cove Point, in the southern section of the study area.

A major portion of the silt and sand of Calvert Cliffs has been redeposited from erosion of the older Coastal Plain and Piedmont province sediments (Jedlicka 1977) and deposited in shallow marine environment (Gernant et al. 1971, Molitor 1987). These deposits are associated with transgression-regression cycles of Lower to Middle Miocene age, and present a succession of shallow shelf facies to intertidal and deltaic facies assemblage (Shideler 1994, Kidwell 1997, McCartan et al. 1985). Overall, sediments exposed in Calvert Cliffs are characterized by zones of medium to fine sand with abundant shell fragments interbedded with shell-poor very fine silty sand, silt and clay. The contact between more permeable sand and underlying silt or clay is often damp due to shallow groundwater seepage.

Active wave erosion at the bluff toes results in rapid sloughing and facilitates complex slope processes in unconsolidated materials eroding from the cliffs. The constant erosion of Miocene outcrops maintains slope angles around 70° with relatively constant bluff-retreat rates. Once the undercutting of bluffs by wave action is halted, the bluffs continue to degrade until slopes achieve an angle of repose around 35°.

Site Description

The Calvert Cliffs area provides three examples of transition from eroding, steep faces to low-angle stable slopes. All three sections include actively eroding as well as stabilized bluffs. Yet, the period of time that the stable slopes were protected from direct wave action differs for each section. Naturally stabilized slopes are preserved as a fossil bluff line inland from a prograding cuspate foreland at Cove Point (Figure 3).

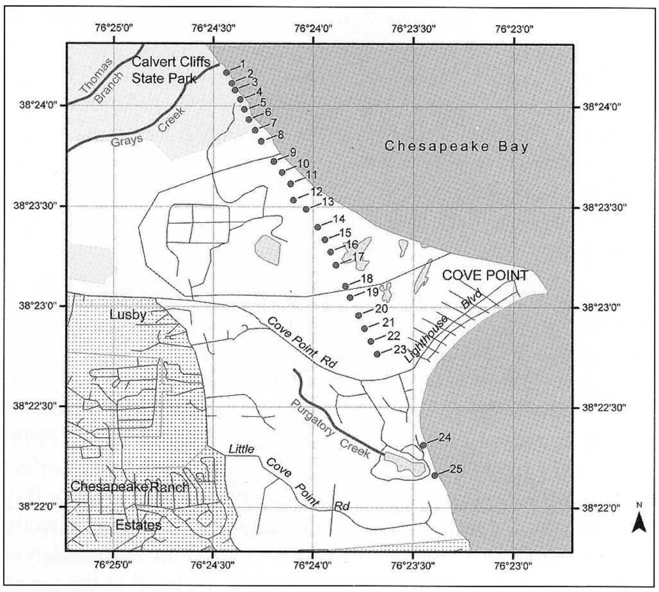

Figure 3. Cove Point study site with locations of slope angle profiles.

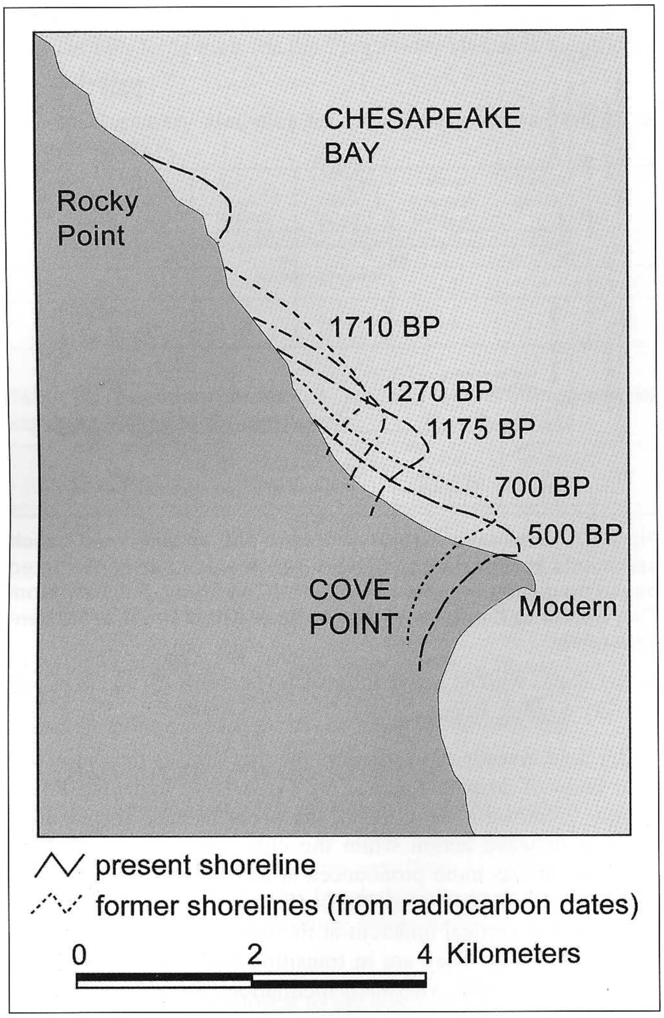

Figure 4. Inception and migration of Cove Point since ca 3,000 yr BP (Source: Beardslee 1997).

A cuspate foreland is one of the coastal formations produced by littoral drift of sediments and by wave interaction. Around Cove Point, the dominant wave energy is supplied by northerly winds. Sediment is eroded from the northern flank of the foreland and is transported alongshore to its southern end. The result is a cuspate foreland migrating southward at a rate of ca. 1.3 m/yr (Beardslee 1997). Not much of the drifting offshore sediment is carried around Cove Point into Patuxent River (Schubel et al. 1972). The foreland is prograded by a succession of beach ridges that rise in elevation to the south indicating its response to rising sea level. Beardslee (1997) considered the beach ridges at Cove Point to be constructed by swash or as emergent bars. As the landform migrates south, the older beach ridges on the north are truncated while new beach ridges are created at the southern tip of the foreland. Radiocarbon dating of swales between beach ridges shows the complex to span 1,700 yrs of progressive migration history (Beardslee 1997; Figure 4). As the foreland moves south, it progressively protects bluffs from wave action as new beaches are deposited at their toes.

With time, previously steep and actively eroding slopes achieve low-angle inclinations and become stable. In effect, cuspate foreland preserves a progressive record of the protection of actively eroding bluffs over a 1,700-yr period. Wave undercutting at the bluffs' base is re-initiated at the northern end of the cuspate complex as the landform passes.

Our second study site was at Flag Ponds Nature Park (Figure

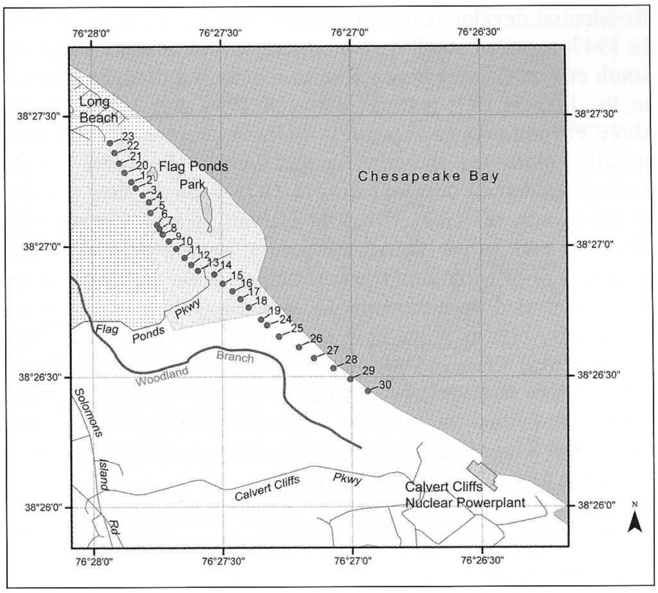

Figure 5. Flag Ponds study site with locations of slope angle profiles.

5), approximately 5 km northwest from Cove Point. Similar to Cove Point, southward longshore sediment transport produced and maintains a prograding spit complex at this location with a rate of migration of approximately 4.5 m/yr (Schubel et al. 1972). Flag Ponds is a smaller feature that will probably evolve into a cuspate foreland with time. Sediment is eroded on the northern flank of the landform and is accreted on the southern end. From recent vibracores taken by Peter Vogt from the Naval Research Laboratory, we know that the spit complex is not more than 400 yrs old (Larsen and Clark 2003). Like at Cove Point, a fossil bluff line is preserved inland from the Flag Ponds cape. Slopes to the south of the landform are progressively protected from the wave erosion as the spit migrates. Stabilized bluffs at Cove Point and Flag Ponds, form a single bluff line with the actively eroding bluffs extending past the landform's boundaries.

To the north of Flag Ponds, at Flag Harbor marina and at Calvert Beach (Figure 6), coastal bluffs were protected from wave erosion through the construction of engineering structures.

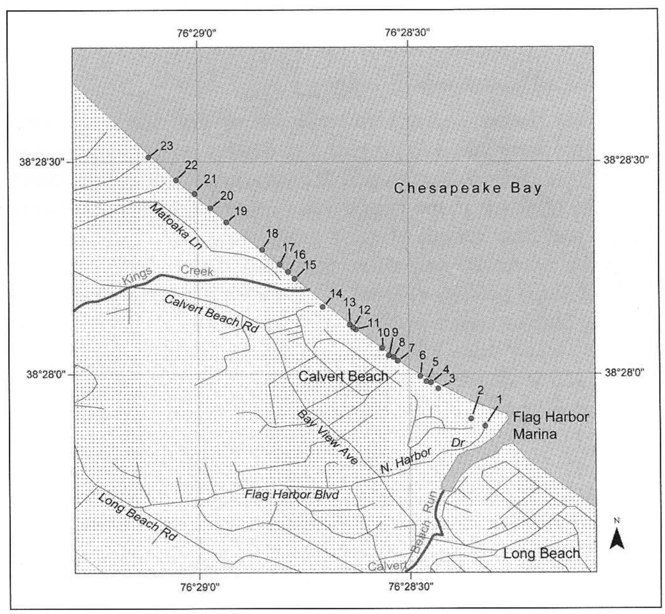

Figure 6. Flag Harbor – Calvert Beach study site with locations of slope angle profiles.

Residential development in this area started around the 1930's. In 1947, a pair of small harbor structures was constructed at the south end of Calvert Beach Run to maintain a dredged channel to the Flag Harbor marina. Between 1950 and 1980, various shore erosion-control measures, including several groins, were installed along the shoreline in this area to slow cliff erosion around residential development. In 1975 a single jetty was put at the mouth of Kings Creek at Calvert Beach. Construction of jetties and groins altered the natural pattern of erosion and sediment re-distribution. These structures serve as a barrier for material eroded from the cliffs to the north. When structures are sufficiently big, as is the case with the Flag Harbor and Kings Creek jetties, it leads to build-up of sediment on the north side of the structure and sediment starvation on its south side. Updrift deposition behind the northern jetty at Flag Harbor marina and the jetty at Kings Creek progressively created protective beaches along the toes of the updrift bluffs.

METHODS

In order to document the rate of retreat from the steep eroding faces to the low-angle vegetated slopes, we measured slope angles at 50-110 m intervals along the bluff line. A total of 25 stations were surveyed at Cove Point study site for a distance of 2,500 m; 30 stations were surveyed in Flag Ponds Nature Park area for a distance of 2,200 m; and 23 stations northward from the northern jetty at the Flag Harbor marina for a distance of 1,500 m. Slope angles were measured using an Abney Level. In cases where a break in the slope was apparent, slope angles were measured for each segment of the slope. Distance from the bluff toe to the top was also measured. Based on these data and distances between each station, we constructed slope profiles for each section of the study area.

As was mentioned above, southward migration of the cuspate foreland at Cove Point by the successive progradation of beach ridges progressively protects bluff toes. Thus, the ages of the relict beach ridges give us an estimate of how long the certain section of bluff line at this location was protected from wave undercutting. Beardslee (1997) reconstructed the migration of Cove Point for the last 1,700 yrs based on a series of vibracores and historic maps. He was able to date beach ridges at several locations along the seaward face of the landform. These radiocarbon ages were used in our study to estimate the ages of the stabilized bluffs at the Cove Point study site.

Ages of adjacent beach ridges.

At Flag Harbor and at Calvert Beach several additional measurements were taken to provide age control on the evolution of bluffs from steep to low angles. We measured width of the beach from the bluff toe to the beach/water interface, distance between groins and total length of each groin. Based on these data we created a schematic map of accumulated sand bodies with positions of slope profiles (Figure 7). The relative time required for eroding bluffs to reach stability was estimated at the Flag Harbor/Calvert Beach study site by interpolating the distance and time for the stable slopes to prograde northward since construction of jetties at Flag Harbor and at Kings Creek.

RESULTS

Cove Point and Flag Ponds Area

Bluffs in Cove Point and Flag Ponds areas ranged widely in slope and vegetation density. They could be generally divided into three groups: vegetated slopes with active toe erosion; vegetated slopes with no active toe erosion (stabilized); and exposed, actively eroding slopes.

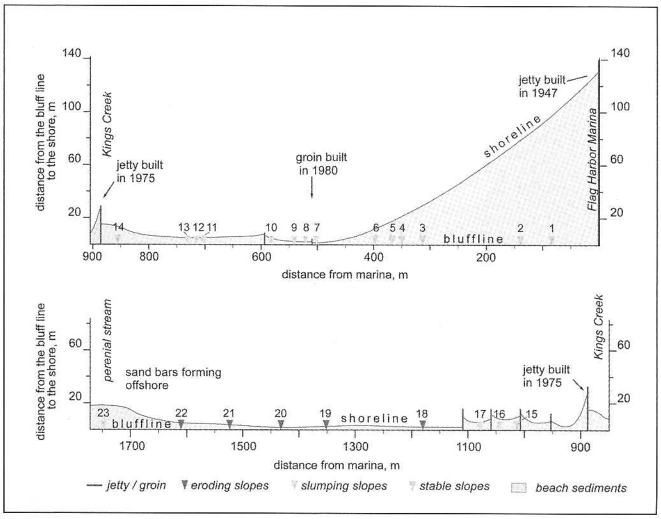

Figure 7. Schematic map of shoreline and accumulated beach sediments at Flag Harbor-Calvert Beach study site constructed based on measurements taken during the study. Sections from Flag Harbor to Kings Creek and north of Kings Creek are shown separately.

Our field investigation supports the fact that, as the protective sand body of cuspate foreland by Cove Point and Flag Ponds migrats southward, the cliffs in the north become increasingly exposed to wave action while the cliffs in the south become protected. It was more pronounced at the Cove Point study site, where three northern-most bluffs (Stations 1-3, Figure 3) had 1.5 m to 3 m vertical undercut at the base. These slopes fit into the first category. They are in transition from low angle slopes to high-angle bluffs. Measured inclinations for these bluffs are between 45° and 49°.

The slopes behind the protective cuspate foreland spit complexes of Cove Point and Flag Ponds (second group) were generally in the 26° to 36° range (42 slopes out of 47) with a mean of approximately 31° (Table 1). Individual slope angles varied from 3° to 4° around the mean. Our hypothesis was that we should see a progression in slope angle with distance from the modern tip of the cuspate foreland at Cove Point and at Flag Ponds. Cliffs closer to the tip of the landforms were protected from wave action for a shorter period of time than the slopes further north. Thus, if the time required for actively eroding slopes to reach stable inclinations is on a centennial scale, there should be a trend in slope angle. A simple linear regression of the slope angle vs. distance from the southern tip of one or the other spit complex, gave us a slight negative trend of 0.002 degrees/m. The R^2 values are very small.

To the south of Cove Point and Flag Ponds spit complexes, cliffs are directly adjacent to the Chesapeake Bay with very little beach deposits (Stations 24, 25, Figure 3; Stations 28-30, Figure 5). These bluffs (considered to fit into the third category) had slope angles ca 10° higher than the stabilized slopes protected by the spit complexes. All bluffs had faceted slopes, with the bottom section of a slope being steeper than the upper section. For the purpose of calculating summary statistics (Table 2) we have combined slope angle data for these, actively eroding, bluffs with the data for the three undercut slopes from the Cove Point study site. We also calculated generalized slope angles for faceted slopes (which probably explains the resulting 36° slope for one of the actively eroding bluffs at Flag Ponds). The regression coefficient (R^2) in this case is negligible for the Cove Point site. Though R^2 is high for the Flag Ponds site, it is based only on 3 values.

Table 1. Summary statistics for stabilized/protected slopes in the study area.

Location	Max slope angle (degrees)	Min slope angle (degrees)	Mean slope angle (degrees)	Standard deviation +/-	R^2
Cove Point	37	22	30	3.5	0.2
Flag Ponds	39	26	31.5	4	0.07
Flag Harbor–Calvert Beach	36	29	34.3	2.4	0.02

Table 2. Summary statistics for actively eroding/recently exposed slopes in the study area.

Location	Max slope angle (degrees)	Min slope angle (degrees)	Mean slope angle (degrees)	Standard deviation +/-	R^2
Cove Point	49	40	45.8	3.7	0.002
Flag Ponds	53	36	43.7	8.7	0.97
Flag Harbor–Calvert Beach	65	42.5	54	10.6	0.8

Farther south from the Cove Point and Flag Ponds spit complexes were actively eroding bluffs with slope angles that appear higher that those measured in our study at this locations.

Flag Harbor-Calvert Beach Area

In the Flag Harbor–Calvert Beach area, the gradual change from actively eroding bluffs to stable slopes was more apparent. Three groups of slopes were seen here: 1) stable, vegetated slopes; 2) slopes protected by beach deposits or groins that are in transition from undercut, eroding slopes to stable slopes; and 3) actively eroding bluffs.

Stable slopes were closest to the northern jetty at Flag Harbor and to the jetty at Kings Creek (Stations 1-6 and 14, 15, Figure 6). The bluffs were vegetated, often with a wide band of shrubs growing at the base of the bluff. These slopes were protected from the wave erosion only by beach deposits. Except for mentioned jetties and a groin downdrift from Station 15, no rip-rap or bulkheads were installed in these locations. Mean angle for these bluffs was around 34° (Table 1). Linear regression of slope angle vs. distance from the Flag Harbor jetty gives a slope of 0.001 degrees/m and an R^2 value of 0.02.

At this study site, we observed many bluffs that were in transition from actively eroding to stable slopes. Toes of the bluffs were protected by either engineering structures (rip-rap) or by a narrow strip of beach. Some vegetation was still present on these slopes. Masses of slumping sediment or scarps left from recent events were noticeable on each of the slopes in this group. Inclinations were in general ca 5° higher than for the stable slopes (mean of 41.6° and standard deviation of 4.3°). Linear regression shows that these slopes have also more noticeable trend in slope vs. distance from the Flag Harbor jetty (trend is 0.007 degrees/m, R^2=0.36)

Five northern-most bluffs at the Flag Harbor-Calvert Beach study site are actively eroding slopes undercut by waves. These are non-vegetated, exposed slopes, often with big blocks of collapsed sediment at their bases (up to 3 m^3 in volume). At some of the stations we noticed fallen or sliding trees as well. Mean angle for these slopes was 54° (Table 2). The steepest slope we observed was 65°; slopes farther north from the study area had even higher inclinations around 35° (Figure 6).

A relationship between slope angle and distance along the

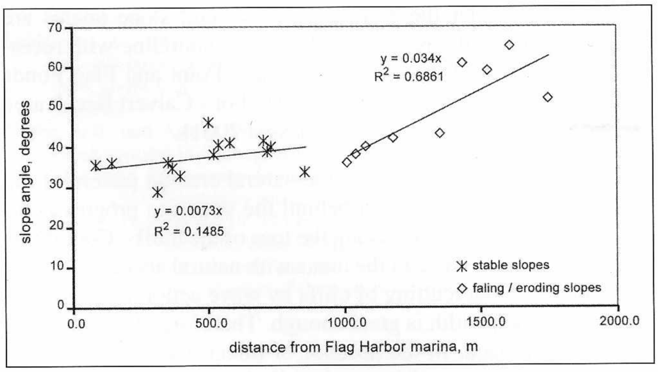

Figure 8. Linear regression analysis for slopes at Flag Harbor-Calvert Beach study site.

shoreline allowed us to estimate the rate of slope change for this area. We have divided data into two groups: slopes between the Flag Harbor jetty and Kings Creek (protected more or less since 1947), and slopes north of the Kings Creek jetty (protected since 1975). Slope angles for the bluffs closest to both jetties are similar (between 30° and 40°). Yet, the angle change for the slopes between the Flag Harbor and Kings Creek is 0.7 degrees per 100 m (Figure 8) while the angle change for slopes north of Kings Creek jetty is 3 degrees per 100 m.

DISCUSSION

The dominant erosion mechanism for bluffs not protected by beach deposits is wave undercutting at the toe of a bluff (Wilcock et al. 1998). Failure of the slope face and top retreat take place in the form of translational slides, spalls, slumps and free degradation. Degradation material at the toe is removed by waves

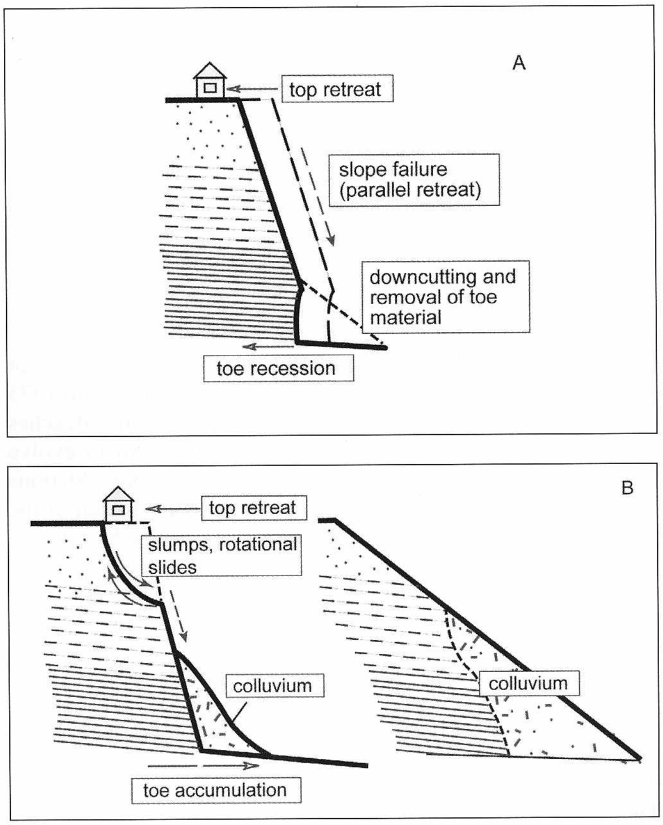

Figure 9. Bluff failure processes in the study area: A) section of shoreline with actively eroding cliffs; B) section of shoreline protected by beach deposits.

(Figure 9A). Under these conditions constant slope angles are maintained and cliffs retreat parallel to the shoreline with recession rates of 0.3 – 0.6 m/yr for the Cove Point and Flag Ponds areas and 0.7 – 1.3 m/yr for the Flag Harbor - Calvert Beach area (personal communication, L. Hennessee 2001).

Construction of groins alters the natural erosion pattern of the shoreline. Updrift deposition behind the structure progressively creates protective beaches along the toes of the bluffs. Conditions become similar to those in the areas with natural accumulation of sand bodies. Undercutting of cliffs by wave action is eliminated where the beach width is great enough. Therefore, the position of a cliff is stabilized. In the absence of direct wave undercutting, other slope processes, driven primarily by groundwater seepage and freeze and thaw action, still force bluff failure. Rotational slides or slumps propagate from the top of the bluff. Colluvial material is accumulated at the base of a bluff and forms an "accumulation zone" (Figure 9B). Ultimately the slope profile reaches the stable angle equal to the effective angle of shearing resistance of the soil. In the Calvert Cliffs area, stability is attained when the slope angle reaches 30°-35° (angle of repose).

Comparison between bluffs protected by the cuspate foreland complexes at Cove Point and at Flag Ponds and bluffs protected by engineering structures in Flag Harbor-Calvert Beach area gives us an estimate for the rates of slope evolution in these and similar settings. Coastal bluffs inland from Cove Point did not show progressive decrease in slope. Though the spit complex of Cove Point protected some of the bluffs for a longer period of time than others, all of the slopes were within the range of the angle of repose. Out of the few slopes that were classified as eroding, three had re-initiated toe erosion for at least a century and the other two were to the south of the spit complex, therefore were never protected by it.

A similar situation was observed at the Flag Ponds study site. Almost all slopes were in the stable range of 30°-35°. Bluffs failed after protection from waves and subsequent toe stabilization and established low angle vegetated slopes within a 400 yr period. Three actively eroding bluffs at the southern limit of this study site were, once more, never protected by the sand body of the Flag Ponds foreland. The similarity between slopes at Cove Point and Flag Ponds, therefore, shows that the stabilization of a slope through a series of processes, once its toe is stabilized, happens on a decadal rather than centennial scale.

The progression in slope angle that we observed at Flag Harbor – Calvert Beach site supports this finding. Construction of jetties at Flag Harbor marina in 1947 and at Kings Creek in 1975 created conditions for deposition of beach sediments. Beaches protected toes of the adjacent bluffs allowing them to evolve to stable slopes. Bluffs next to the Kings Creek jetty (Stations 14 and 15) were probably stable prior to the construction of the jetty, since a small beach created by the creek outwash protected their toes. Stabilized bluffs were observed for a distance of close to 400 m north of Flag Harbor and about 100 m north of Kings Creek. That suggests that the stabilization time for the Calvert Cliffs is between 25 and 50 yrs, probably closer to the second estimate.

All stable bluffs at Cove Point, Flag Ponds, and Flag Harbor-Calvert Beach study sites were vegetated. Many residents in this area believe that planting vegetation will stabilize the slope. Though the presence of vegetation is a good indicator of bluff stability (Mickelson et al. 1977), it does not prevent slope failure in Calvert Cliffs sediments. Debris flows, spalls and slides are driven primarily by groundwater seeping through the cliff face. Planting vegetation will not resolve the problem and in some cases could even exaggerate it (Leatherman 1986).

CONCLUSIONS

Cliff stability is a great concern for homeowners and developers that have built or are planning to build houses and structures in the Calvert Cliffs area. Similar to the results obtained previously (Shultz and Ashby 1967, Leatherman 1986, Palmer 1973), our study shows that simple toe stabilization through construction of jetties and riprap at the bases of the bluffs is not an answer for preventing bluff recession. The various erosion processes involved do not cease by the protection of bluff toes from undercutting by wave action. Bluffs composed of unconsolidated sediments, such as those exposed in the Calvert Cliffs, attain stability in the span of 30 to 40 yrs once they are protected at the base. They evolve from steep, eroding 60-70+ degree slopes to stable 30°-40° slopes by failure of the slope face and retreat at the top.

Thus, simple shoreline protection methods at the bluff toes may not preserve property at the bluff edge. This study presents a simple method for coastal planning and management to estimate time required for an actively eroding bluff in similar geologic settings to fail and be transformed into a stable slope once it has been protected by an engineering structure. Further, these finding may help planners to determine setback lines for building construction.

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