Estimating the Age of Near-Shore Carbonate Slides Using Coral Reefs and Erosional Markers: A Case Study from Curacao, Netherlands Antilles

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ABSTRACT

Carbonate mass failures are widespread, particularly along steep tropical shorelines, however, the age, frequency, and cause of these failures are often poorly constrained. As shorelines undergo intensive human development, understanding when carbonate slopes failure occur is becoming increasingly important. Using both land and marine-based observations, we present methods for making valuable first-order age estimates of near-shore slope failures. As a case study, we analyze the partially submerged lower carbonate terrace along the southern shoreline of Curacao, Netherlands Antilles. This terrace sits adjacent to a well-documented carbonate slope failure. Our combined land-sea study constrains the slide contact, the amount of post-slide coral reef growth, and the location of erosional shoreline notches. From these observations, we place limits on the timing of slope failure, and conclude that the Caracas Bay slide did not occur recently (within the last ~3000 years) but more likely at least ~116,000 years ago, near the end of the last interglacial sea level high stand. Slope failure likely occurred along the unconformable contact separating the base of the coastal limestone with underlying Cretaceous basalt, and may have been triggered by a large earthquake along the Caribbean-South American plate boundary.

Key Words: slide age; slope failure; Carbonate; Curacao

INTRODUCTION

Evidence for massive (>1 km^2) carbonate slope failures exists along many islands in the Pacific, Mediterranean, and Caribbean particularly in seismically active areas (e.g., Ota et al., 1997; ten Brink et al., 2006; Pedley et al., 1993). The age, frequency, and triggering mechanisms associated with these failure events remain poorly constrained, making it difficult to determine both the cause and the probability of future failure at these sites. Both recent and historic accounts of slope failures along steep coasts suggest they are generally triggered by earthquakes, although torrential rain and volcanism are also causes (e.g. Keefer, 1984; Densmore and Hovius, 2000; Ward and Day, 2003).

The combination of continued population growth and limited land area has led to more aggressive development and human occupation along elevated, potentially unstable shoreline carbonate marine terraces (e.g. Anderson et al., 2008). The foundations of these terraces often rest on steeply dipping heavily weathered former crystalline rocks that have degraded into clays and shales (e.g. Vitali et al., 1999). Most volcanic clays and shales are low-permeability, have low coefficients of sliding friction, and represent likely failure surfaces for overlying carbonate rocks (e.g. Frydman et al., 2007; Callot et al., 2008; Balance, 1991; Byerlee, 1978). Understanding when, why, and how shoreline carbonate slides occur constrains the overall stability of a site, their potential for generating tsunami, and ultimately whether they are suitable for human occupation (e.g. Anderson et al., 2009; Ward, 2001).

This paper represents a first approach at using geologic observations of late Quaternary shoreline features and newly acquired quasi-3D bathymetric chirp data near Caracas Bay, Curacao, to assess the age of a previously recognized mega-slide (De Buisonje and Zonnenfeld, 1976) (Fig. 1). Previous studies suggest the Caracas Bay slide may be only a few thousand years old with the implication that the adjacent carbonate terrace may be unstable and subject to future sliding (De Buisonje and Zonnenfeld, 1976). Integrating on-land data with the offshore bathymetry, we contend that the slide is a least 15 ka old, but likely much older (~116 ka). We also infer the location of the slide rupture surface and briefly discuss the possible mechanisms necessary to trigger failure. This analysis presents observation-based techniques for estimating the age of shoreline slides when no other age constraints are available.

GEOLOGICAL SETTING OF CARACAS BAY

Curacao is the largest of the three Leeward "ABC Islands" (Aruba, Bonaire, Curacao) of the Netherlands Antilles, and is situated along the crest of the Leeward Antilles Ridge in the Caribbean Sea about 70 km north of Venezuela (Fig. 1). The Leeward Antilles ridge forms a major crustal ridge along the currently active Caribbean-South America plate boundary; its crustal structure is consistent with a Cretaceous island arc and oceanic plateau origin (e.g. Magnani et al., 2009). Strike-slip and convergent plate motions modified the Leeward Antilles ridge during the Cenozoic creating northwest-striking faults separating the islands and forming steep coastlines (Gorney et al., 2006; Hippolyte and Mann, in press). The succession comprises a thick (5 km) section of Cretaceous basalts (Gorney et al., 2006) that is overlain by younger Neogene and capped by Pleistocene terraces. Pleistocene carbonate terraces unconformably overlie Neogene carbonates; these Pleistocene terraces make up the bulk of the carbonate terrace exposed at the surface, with progressively younger terraces found seaward.(e.g. Alexander, 1961; De Buisonje and Zonneveld, 1976; Fouke et al., 1996; Schellmann et al, 2004) (Fig 1).

Figure 1. Geologic map of Caracas Bay and surrounding area showing the location of carbonate marine terraces. Note that Caracas Bay (as well as areas northeast) appear to have missing marine terraces compared to the southeast. Bathymetry is adapted from echosounder data originally collected by De Buisonje and Zonneveld (1976). These data show a clearly defined slide track. The extended slide run-out has a relatively constant width, suggesting a ~1 km² block translated as a single rigid mass along the slide track. The bottom inset shows the location of Curacao in relation to other islands and the Caribbean-South American plate boundary. The top inset shows the location of Caracas bay in relation to the island of Curacao.

Curacao originally evolved from part of a volcanic arc formed when the South American plate subducted beneath the Caribbean during the Cretaceous (e.g. Magnani et al., 2009). Radiometric dating of carbonate marine terraces indicate that younger late Pleistocene (~116 ka) terraces overly older Middle Neogene (~12 ma) terraces (e.g., Alexander, 1961; Fouke et al., 1996; Schellmann et al., 2004). The youngest terraces uplifted at a moderately slow rate, averaging ~0.05 mm/yr, with a maximum uplift of ~0.08 mm/yr (Alexander, 1961; Fouke et al., 1996; Schellmann et al., 2004). Today, the island represents an archetypal example of an eroded anticline, with the central region of the island exposing weathered basalt soil, and the island edges comprised of carbonate marine terraces overlying weathered basalt (Hippolyte and Mann, in press) (Fig. 1). The limestone cuestas ringing the island dip seaward and strike approximately parallel to shore.

We focus our slope stability study on Caracas Bay, Curacao, where a known carbonate terrace slope failure exists. Located at the southeast corner of the island, Caracas Bay formed when a wedge-shaped 50-350 m thick subaerially exposed seaward-dipping carbonate cuesta covering an area of ~1 km² broke free from its terrace and plunged into the ocean, plowing a 1 km wide and 50 m deep channel into the seafloor as it slid along the steeply dipping (~9°) submarine margin (De Buisonje, 1974; De Buisonje and Zonneveld, 1976) (Fig. 1). The slide, which likely occurred along the limestone-basalt contact, left house-size boulders strewn across the beach, displaced thousands of cubic meters of sediment from the seafloor and probably spawned a large tsunami. From the deeply-cut and well-defined slide track extending down slope, it appears as if this slide was a single catastrophic event (Fig. 1) (De Buisonje, 1974; De Buisonje and Zonneveld, 1976). A massive ~30 m high near-vertical headwall from the slide exists along the western half of Caracas Bay (Fig. 2). Although previous studies suggest the Caracas Bay slide occurred within the last few thousand years and that indigenous people might have witnessed the event (De Buisonje and Zonnneveld, 1976), the exact age of the slide remains unknown.

CARACAS BAY LAND-BASED FIELD SURVEY

In August, 2007, we conducted both land and marine-based field work in and around Caracas Bay. For the land-based field work, we examined carbonate terraces and slide headwalls. We also mapped geologic contacts, determined strikes and dips of limestone units, noted erosional markers, and compared our observations to previous regional geologic interpretations.

The cliff on the western flank of Caracas Bay was interpreted as a massive slide headwall (DeBuisonje and Zonnenfeld, 1976). This feature consists of moderately-to-poorly bedded limestone units of Quaternary age (De Buisonje, 1974, De Buisonje and Zonnenfled, 1976). The brittle nature of these units and the amount of talus at the base of the cliff indicate that mass wasting is an ongoing process along the cliff face. Strike and dip measurements of the marine terraces that make-up the cliff indicate the terrace surfaces, on average, dip ~10° seaward to the southwest.

Cretaceous basalts underlie the limestone cliff, however, because of erosion and mining operations that have covered the north edge of the terrace with tailings, no sharp basalt-limestone contact was observed. Nonetheless, a clear transition from eroded limestone to basalt talus occurs near sea level on the northern edge of the headwall. From our outcrop maps and estimated contact points, we infer that the basalt-limestone contact dips ~8-10° seaward, consistent with previous regional studies and with the offshore dip of the seafloor (De Buisonje and Zonnenfeld, 1976).

Figure 2. Photomosaic of the western headwall at Caracas Bay. The cliff face is approximately 0.75 km long and tens of meters high. Normal faults are located within the headwall.

Within the western headwall, several west-northwest striking normal faults exist with average apparent dips of ~30° (Fig. 2). Previous studies speculated that these faults played an important role in slope stability at this location (De Buisonje and Zonnenfeld, 1976). Fault offsets are on the order of meters or less, indicating relatively minor slip has occurred. An unfaulted Quaternary-age carbonate reef unconformably overlies these faults (De Buisonje, 1974; DeBuisonje and Zonnenfeld, 1976) and no evidence for the fault exists along the hard carbonate terrace surface above the faults, indicating that they have been inactive since emplacement of the unconformity and that faulting must have occurred before this carbonate unit formed.

The structure along the northern and eastern shore of the bay sharply contrasts with the western headwall. Along the north edge of the bay, weathered basalt is anomalously exposed along the shoreline and large erratically dipping house-sized limestone boulders rest directly above weathered muddy basalt (Fig. 3A). Based on the measured dip at contacts between basalt and the scattered limestone blocks observed in the region, we estimate a seaward dip of the basalt of ~10 degrees, similar to the current dip of most exposed limestone terraces in the region. A cluster of small, isolated limestone blocks near Fort Beekenburg exhibit highly variable dip directions (Fig. 3B). We interpret this as a large semi-coherent limestone block that has partially slid and broken apart along the basalt contact (Fig. 3). At the far eastern edge of the bay another smaller marine terrace headwall exists, indicating the eastern limit of the Caracas Bay slide (Fig. 3). The eastern headwall comprises the same units as the western headwall with similar strike and dip, also consistent with previous studies (DeBuisonje and Zonnenfeld, 1976). The field analysis indicates the slide complex spans 1.2 km across the bay, with headwalls on the west and extreme southeastern edge of the bay and the slide rupture surface outcropping at the basalt contact along the northern shore (Figs. 1, 3).

CARACAS BAY MARINE SURVEY

In addition to our land-based field study, marine-based chirp sonar data were collected across Caracas Bay in order to constrain slide and seafloor geometry. In total, we collected more than 50 km of high-resolution seismic chirp sonar data in the bay using a portable Knudsen 320B echosounder. All data were processed and analyzed using Paradigm

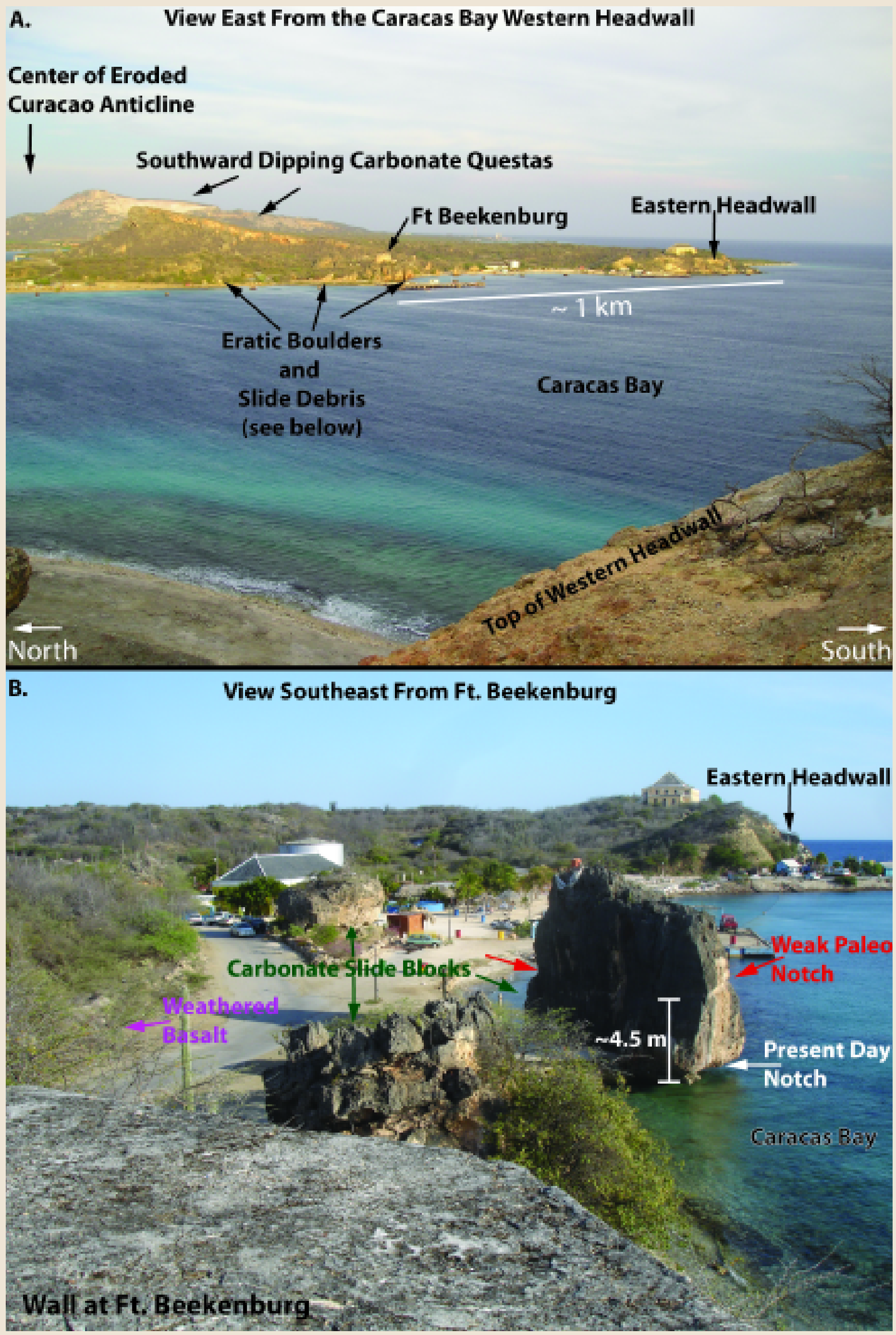

Figure 3. (A) is a photograph taken in the east-northeast direction atop of the western headwall. (B) is a photograph taken in a south-southeast direction from Ft. Beekenburg. A weak but clear erosional notch exists ~4.5 m above sea level in the slide block right-center of the photograph.

Geophysical software Geodepth. We merged the data to create high-resolution quasi-3D images of the site that reveal valuable information regarding the shape, depth, and structure of the slide (Fig. 4).

Generating shaded 3D images that note dip angle changes, we identified several sharp angular seafloor features along the southwest portion of the bay (Fig. 4B). We interpret these jagged seafloor features as remnant slide blocks, since they appear similar in size and shape to the slide debris observed along the north shore (Fig. 4D). The largest and best defined slide blocks appear as anomalous sharp-edged seafloor bulges located just east of the western headwall. We estimate the largest "blocks" have heights of ~10-20 m and widths up to ~40 m, comparable to the largest slide debris found along the north shore of Caracas Bay.

Jagged slopes, steeply dipping contours and contacts, and slide debris exist along the extreme western and southeastern portion of land surrounding Caracas Bay. Nonetheless, the seafloor along the eastern half of the bay appears generally flat, and shows no significant evidence of slide debris in the region (Figs. 4, 5). This is particularly true in water depth of ~40 meters and is surprising since this flat region is adjacent to a coastal zone covered with house-sized boulders and slide debris with erratic dips (Fig. 4). Given (1) the uniformity and flatness of the eastern half of the Caracas Bay seafloor (Fig. 4), (2) the strong seafloor reflectivity in this region (Fig. 5); and (3) the lack of slide debris in the offshore area - despite being adjacent to significant subaerial carbonate slide debris - we interpret this region as a carbonate platform that formed post-failure. Two clearly identifiable carbonate platforms exist offshore: a pronounced platform at ~40 m below sea level extends more than 200 m from the shoreline, particularly along the eastern half of the bay; a less developed platform ~10 m below sea level extends ~50 m from shore, ringing the bay (Figs. 4, 5). A ~40 m deep subsurface knob also exists just southeast of the lighthouse, south of the western headwall (Fig. 4). From the shape and high-amplitude reflectivity of this knob, we interpret this as a pinnacle reef that likely formed since sliding occurred (Fig. 4).

Analysis of seafloor images also suggests a paleochannel once cut north-south through the deepest section of the Bay (Fig. 4). Because of human development around the north end of the bay, it remains difficult to link this channel to an obvious on-land drainage. Nonetheless, a gully currently empties into the northwest corner of Caracas Bay, and according to local residents, part of the narrow isthmus

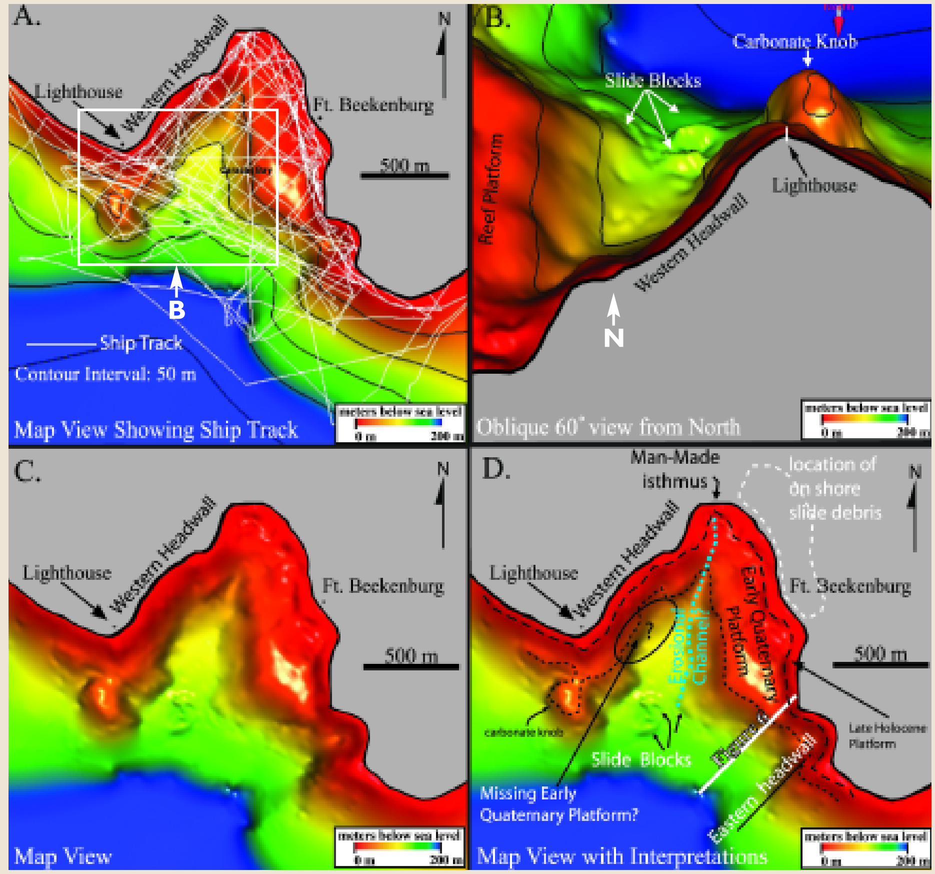

Figure 4. (A) map-view of ship tracks of the collected chirp data. (B) oblique view of the seafloor along the western half of the bay illustrating the location of slide debris on the seafloor. (C) uninterpreted interpolated quasi-3D bathymetric image of the seafloor in and around Caracas Bay. (D) interpretation of (C), including the location of carbonate reef terraces, a possible channel, a zone of possibly missing carbonate terrace, and the location of profiles shown in Fig. 5.

connecting the western and eastern portion of Caracas Bay is man-made (Figs. 1, 4). Therefore, we propose that the channel that runs north-south along the western half of the bay is the down-dip extension of a now-filled channel that once cut through Caracas Bay into Spanish Water (Figs. 1, 4). Silt and other particulates were likely transported into the western half of the bay along this channel and may have muddied the waters in this region, offering one explanation for why less reef growth occurred along the northwestern portion of the bay.

OBSERVATIONAL CONSTRAINTS ON SLIDE TIMING

Constraining slide timing without robust radiometric data represents a challenging task filled with dangerous assumptions and potential pitfalls. Nonetheless, first-order observations shed some light on when this slide likely occurred. Our observations offer insight into the initial shape of the slide rupture surface. We use insights from our observations in conjunction with coral growth rates and sea level curves to place constraints on sliding timing.

The age and location of coastal reef terraces and the existence of associated erosional sea level highstand markers offer useful constraints on slide age. Previous studies indicate that the last globally significant sea level highstand occurred at 116 - 125 ka (Thompson and Goldstein, 2005; 2006) (Fig. 5C). Exact estimates for mean sea level during this highstand are equivocal, however, most studies suggest sea level was 2.5 - 8 m higher than today (e.g. Stirling et al., 1998; Hearty and Vacher, 1994; Vezina et al., 1999; Blanchon and Eisenhauer, 2001; Zazo, 1999). Evidence for this sea-level highstand exists across Curacao in the form of an exposed near-horizontal lower terrace reef formation that fringes most of the island's shoreline (Focke 1978; Schellmann et al., 2004) (Fig. 1). Electron spin resonance dates indicate the lower terrace is the youngest terrace on Curacao, with an age of ~122 ka, consistent with the timing of the last sea-level highstand (Schellmann et al., 2004).

Although the lower terrace exists around most of the island, the lower terrace is conspicuously absent in the immediate vicinity surrounding Caracas Bay (De Buisonje and Zonneveld, 1974) (Fig. 1). The lack of a lower terrace surrounding Caracas Bay indicates either (1) coral failed to grow in the bay during the highstand, or (2) the lower terrace formed but has since been removed. Given that corals currently flourish in and around the clear waters of Caracas Bay as in most parts of Curacao's coast, it is unlikely that coral growth would have been impeded during the last highstand only around Caracas Bay. We therefore infer that removal of the lower reef terrace during sliding offers the most plausible explanation for the missing lower terrace around Caracas Bay. This suggests the Caracas Bay Slide has a *maximum* age of ~122 ka.

Erosional highstand markers, often called "erosional notches" since they generally appear as horizon-parallel indentations cross-cutting sea-cliffs, may form during prolonged stillstands of relative sea level preceded and followed by relatively rapid sea level change (Newmann, 1966; Focke, 1978; Vezina et al., 1999; Hearty and Vacher, 1994). These notches are caused primarily by bioerosion, but also chemical, and mechanical weathering in the intertidal zone (e.g. Trudgill, 1987). Lower reef terraces and erosional notches are ubiquitous along coastlines in tropical oceans and have been used in the past to constrain uplift rates and geologic age (e.g., Taylor and Bloom, 1977).

Across much of the north coast of Curacao an erosional notch exists approximately 10 m above sea-level where the top of the lower terrace intersects the steep slope to an older higher middle terrace (Schellmann et al., 2004; Fock, 1978; Fouke et al., 1996; De Buisonje 1974). The 10 m notch likely formed during the last interglacial, and its anomalously high elevation (most notches from the last interglacial exist between 2.5 – 8 m) is likely due to a few meters of uplift along the northwest shore of the island during the past ~122 ka (Schellmann et al., 2004; De Buisonje and Zonneveld, 1976).

Although the lower terrace and erosional notch exist 8-10 m above sea-level along much of the north shore, along the south shore the lower terrace and notch are located at lower elevations. For example, in the Caracas Bay area and along the southeast shore of Curacao the lower reef terrace is no more than 4 to 5 m above sea level (Schellmann et al., 2004). This observation suggests a much slower (or negligible) uplift rate along the southeast half of the island compared to the northwest half since the last interglacial period (Schellmann et al, 2004). The analysis also indicates that if an erosional notch exists in Caracas Bay from the last interglacial, it should occur closer to 4 - 5 m above sea level around Caracas Bay, and not ~10 m above sea level, as suggested by previous studies (De Buisonje and Zonneveld, 1976).

Although no clear notch exists above the shoreline in the western headwall where mass wasting is ongoing, a weak but clearly identifiable notch exists at ~4 m above sea level in several slide debris blocks along the north shore of Caracas Bay (Fig. 3B). However, the erosional notches within the slide debris appear poorly developed and not as severely eroded as most erosional notches found around the island. Although we were unable to reach the notch and measure directly its exact dimensions, from remote observation, we estimate the amount of inward erosion at the 4 m notch found in slide debris is a few centimeters with a vertical width of ~30 cm (Fig. 3B).

In general, other erosional notches found around Curacao appear more deeply cut and more pronounced than the notch observed in the slide debris at Caracas Bay. Many notches on Curacao are incised several meters and can be several meters in height from top to bottom. For example, the present day notch found at the water line in the slide debris at Caracas Bay indicates perhaps as much as ~1 m of inward erosion (Fig. 3B).

Why the erosional notch found ~ 4 m above sea level in slide blocks is so shallowly eroded compared to both current and older sea-level high-stand notches remains unclear. Adding to this uncertainty is the existence of other well defined erosional notches found across Curacao at ~ 4 m above sea level, although many of these notches appear associated with geological unconformities (Schellmann et al., 2004). Notch erosion rates can be highly variable and site specific. Nonetheless, along many shorelines where carbonates exist, it often takes only a 1000 years to generate notches 0.5 m deep if sea level remains relatively constant (e.g. Spencer, 1985).

Although it is impossible to confirm without more detailed study why only a shallow notch four meters above sea level exists along Caracas Bay slide blocks, one hypothesis is that the slide (and block emplacement) occurred near the end of the Late-Pliestocene sea-level high stand, approximately 116 ka. This hypothesis offers an explanation for why (1) no trace of the lower reef terrace exists within Caracas Bay and also (2) why there is only a weak erosional notch from the last interglacial sea-level high stand.

Comparison of carbonate terrace formation with sea level curves offers further support for this theory. Our marine survey along the eastern half of Caracas Bay suggests significant coral growth has occurred since sliding. As noted previously, no discernable slide debris exists along the eastern half of the bay where two carbonate platforms are interpreted (Figs. 4 and 5). Nonetheless, given that slide debris exists both along the shoreline and in deeper water adjacent to the platforms, it is unlikely that such debris was not originally deposited in the region where the 40 m-deep reef platform now resides. We therefore postulate that post-slide reef growth ultimately covered and removed all traces of slide debris in the eastern half of Caracas Bay.

Using basic field observations to reconstruct the rough original shape of the Caracas Bay slide, we can estimate how terrace formation occurred. At the north shore of the bay, slide debris rests directly on top of basalt clay, the likely slide rupture surface (Figs. 1, 3B). As a minimum estimate for the base of the slide, we postulate that the slide debris observed in the 3D seafloor image rests on the original slide rupture surface (Figs. 4, 5). Therefore, we assume the depth of the slide rupture surface is approximately 130-150 m below present day sea-level in the southwestern portion of the bay where the largest underwater slide debris exists (Fig. 4). Using the location and depth of slide debris both on and off shore and assuming a strike direction near 100 ± 15 degrees, we calculate a minimum apparent dip of ~8-10° for the slide rupture surface (Fig. 5). This is consistent with the dip of the basalt/limestone contact and the regional seafloor slope, further supporting the hypothesis that failure occurred along this contact.

From the estimated dip of the slide rupture surface, we calculate a cross-section shape of the bay along one of our chirp profiles in 2D (Fig. 5B). Comparison between our estimated shape of the seafloor in Caracas Bay with the bay's current shape suggests the eastern carbonate platform located at ~40 m depth has grown ~60 m vertically since the slide occurred (Figs. 5A, B).

We can use coral reef growth rates alone as one way of constraining slide age. In shallow, clear-water environments where seafloor rubble exists, the accumulation rates for coral reefs vary from 1 to as much as 21 mm/yr, depending on wave action, surf-level, water clarity, and coral species present (Montaggioni, 2005). Direct measurements of coral reef growth rates on southern Curacao indicate that coral reefs in this region grew at a rate between 1 - 4 mm/yr during the past ~10,000 years (Focke, 1978). Using these growth rates and a maximum vertical thickness for coral reef growth of 60 m, we infer the slide is at least 15 ka, but perhaps older than 60 ka.

Nonetheless, our terrace formation analysis completely ignores possible sea-level fluctuations

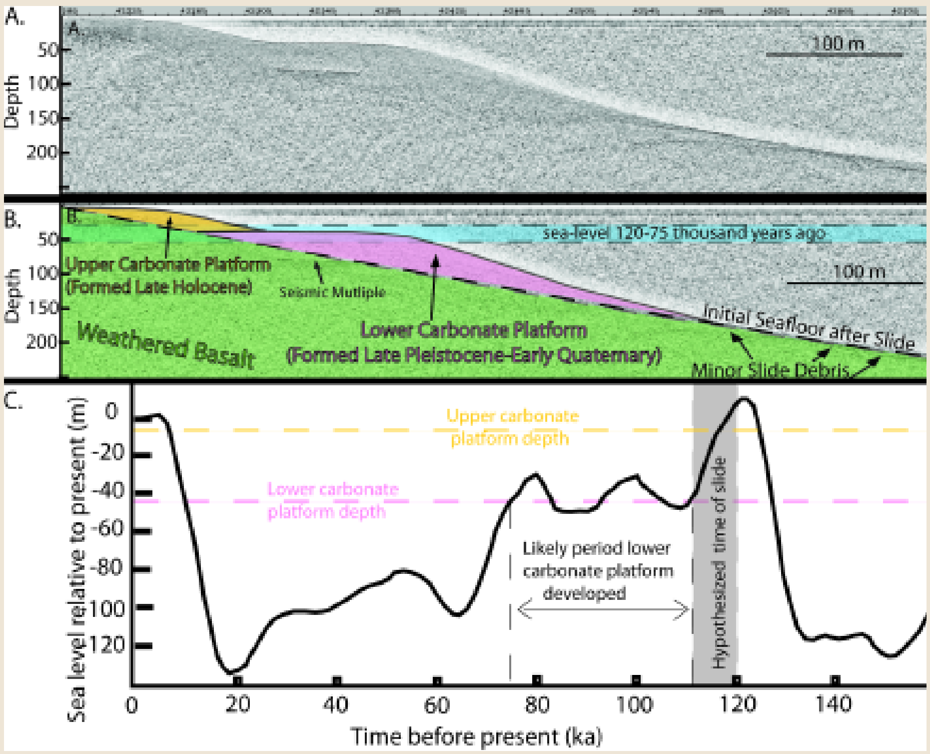

Figure 5. (A) uninterpreted 2D chirp profile across the bay. (B) interpreted version of (A). Note the anomalously flat seafloor at ~40 mbsl (meters below sea level), interpreted as a reef terrace that formed since sliding occurred. Another smaller terrace exists at <10 mbsl. (C) sea level curve for the last 160 ka (adapted from Martinson et al., 1987, and Fleming et al., 1998).

which can impede coral growth. Furthermore, it also ignores the key question of why lower terrace formation abruptly stopped at 40 m below sea-level. To address these issues we look closely at sea level curves since the end of the Pleistocene (~122ka), the inferred maximum possible age of the slide (Fig. 5 C).

As noted previously, there has been minimal vertical uplift along the southeastern coast of Curacao during the Quaternary; we can therefore use global sea level curves as direct proxies for sea-level at Caracas Bay. Analysis of Late Pleistocene-Quaternary sea level curves offers valuable insight into how terrace formation likely occurred in Caracas Bay following the slide. Immediately following the Pleistocene (~116 ka), sea level drops to approximately 40-50 m below current sea level (Fig 5.C), where it more or less remains for the next 35 ka. Sea level then precipitously drops for the next ~60 ka, before rebounding rapidly during the Holocene. We propose that the lower (40 mbsl-meters below sea level) carbonate terrace formed between 116-75 ka, when sea level maintained a relatively constant depth of ~45 m below current sea level. This assumes the coral grew ~60 m vertically during this period (approximately 50 ka) (Fig. 5B, C), or approximately 1.2 mm per year which is well within estimate limits of coral growth rates at Curacao (Focke 1978). The sustained sixty thousand years of sea-level drop beginning 75 ka explains why the lower carbonate terrace abruptly terminates at 40 m below sea level, but does not explain why the terrace failed to redevelop as sea level rose during the Holocene. Our best guess as to why the lower terrace failed to redevelop during Holocene sea level rise is that coral growth simply could not keep up with the rapid ~120 m rise in sea level that occurred in just 7 thousand years (from 15-7 ka). This rise in sea level corresponds to a rate of ~17 mm/yr, well above the maximum observed coral growth rates of 4 mm/yr at Curacao. Coral growth rates drop sharply with depth below sea level, and it is therefore unlikely any significant coral growth now occurs at the 40 m platform. We suspect that the smaller, shallower platform ringing Caracas Bay at <10 m depth recently grew outward from the shoreline. Sea level has been relatively constant for the past 8 ka, and assuming a maximum coral growth rate of ~4 mm/yr, we would expect this platform to extend ~ 30 m offshore, similar to what we observe in our marine data (Fig. 5A, B). Nonetheless, the entire story of how Caracas Bay formed cannot be explained completely with carbonate platform growth rates and sea level curves. For example, why does no 40 mbsl carbonate platform exist on the far western edge of Caracas Bay? Without a doubt, intermittent, smaller-scale failures also shaped Caracas Bay; and we propose the lack of a lower submarine carbonate platform at 40 mbsl on the extreme western edge of Caracas Bay is the result of either intermittent erosion and mass wasting along the western cliff face or reduced water clarity due to run off (Fig. 4). Ultimately, we will use detailed 2D and 3D coral growth models to constrain further how terraces formed and when sliding occurred.

SUMMARY AND CONCLUSIONS

Our preliminary analysis suggests that sliding occurred near the end of the Pleistocene during the last significant sea level high-stand (~116 ka). Starting approximately 122 ka, sea level rose rapidly over a few thousand years from -120 m below present sea level to perhaps 10 m above present levels, where it remained relatively constant until the end of the Pleistocene (e.g. Thompson and Goldstein, 2005). Although it is difficult to determine exactly when the slide occurred without more detailed dating of coral terraces and erosional notches, we propose that failure occurred near the end of the last major sea-level highstand about 116 ka, when the contact between the basaltic basement of the island and the Quaternary coral terrace was partially, if not fully submerged. Many studies suggest saturated clays exposed to long periods of low strain will maintain only a fraction of the cohesive strength of normal sediments, and therefore, are prone to failure (e.g. Carlisle, 1965; Byerlee, 1978). It is therefore possible that failure occurred at the site in part because the top of the Cretaceous basaltic layer became progressively more saturated and weaker as water permeated along the clay contact during sea level rise at the end of the Pleistocene.

What ultimately triggered the Caracas Bay Slide remains unclear, however, it's well known that subduction zone earthquakes often generate carbonate slope failures (e.g. Reid and Tabor, 1919; Tappin et al, 1999). Curacao experiences little seismic activity and has a relatively low probability of experiencing significant earthquake-induced ground accelerations compared to most of the Caribbean (e.g. Tanner and Shedlock, 2004; Perez, 1997). Nonetheless, the island is situated within 150 km of a major subduction zone, the South Caribbean deformed belt (Gorney et al., 2007; Magnani et al., 2009) where the potential for large, if infrequent, earthquakes exists (Perez et al., 1997; 2001), and sea level is once again at Late Pleistocene levels where much of the clay surface is submerged. Although other slide triggers, such as flood-induced elevated fluid pressures, cannot be ruled out, we suggest that infrequent, large earthquakes along the Caribbean-South American plate boundary represent a logical slide-trigger for the region. Using marine and land-based geological observations, we place new constraints on the age of the Caracas Bay slide. Our combined analysis of Quaternary shoreline notches, submarine seafloor images of Caracas Bay, and inferred submarine carbonate terrace formations suggests the slide is no older than 122 ka; probably no younger than 15 ka, with our best estimate for slide occurrence at ~116 ka.

Traditional methods for determining slide age incorporate sediment coring techniques that require a depositional environment above the slide contact and the hope that datable material exists above. Our methods demonstrate a means of constraining slide age in shallow erosional submarine environments where traditional sediment coring techniques fail. Although this study focuses on the Caracas Bay slide, the general techniques described here can be applied to many other locations, since coral reef growth rates and the chronology of late Quaternary terraces and notches exists along many other shoreline where active tectonics, volcanism, and near-shore sliding occurs (e.g. Cox et al, 2008; Webster et al., 2004; Clouard et al., 2001; Taylor and Bloom, 1977; Fairbridge, 1950). Thus, this technique may be applied broadly to make first-order assessments of slide age at similar shoreline marine terrace sites.

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