A Multiphase Model for the Formation of Enigmatic Coastal Geomorphic Features of NW Curaçao; A Case Study of Bokas from Shete Boka National Park

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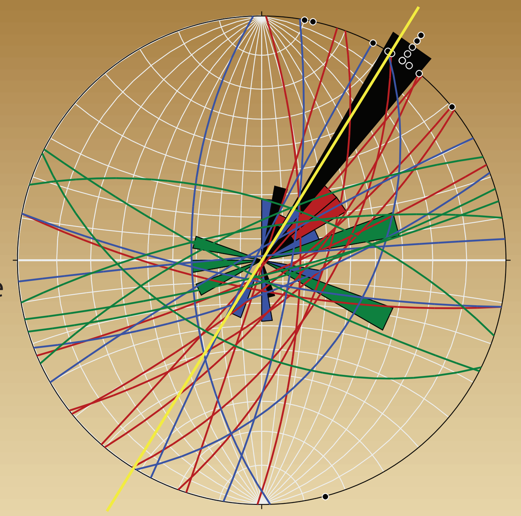
ABSTRACT:

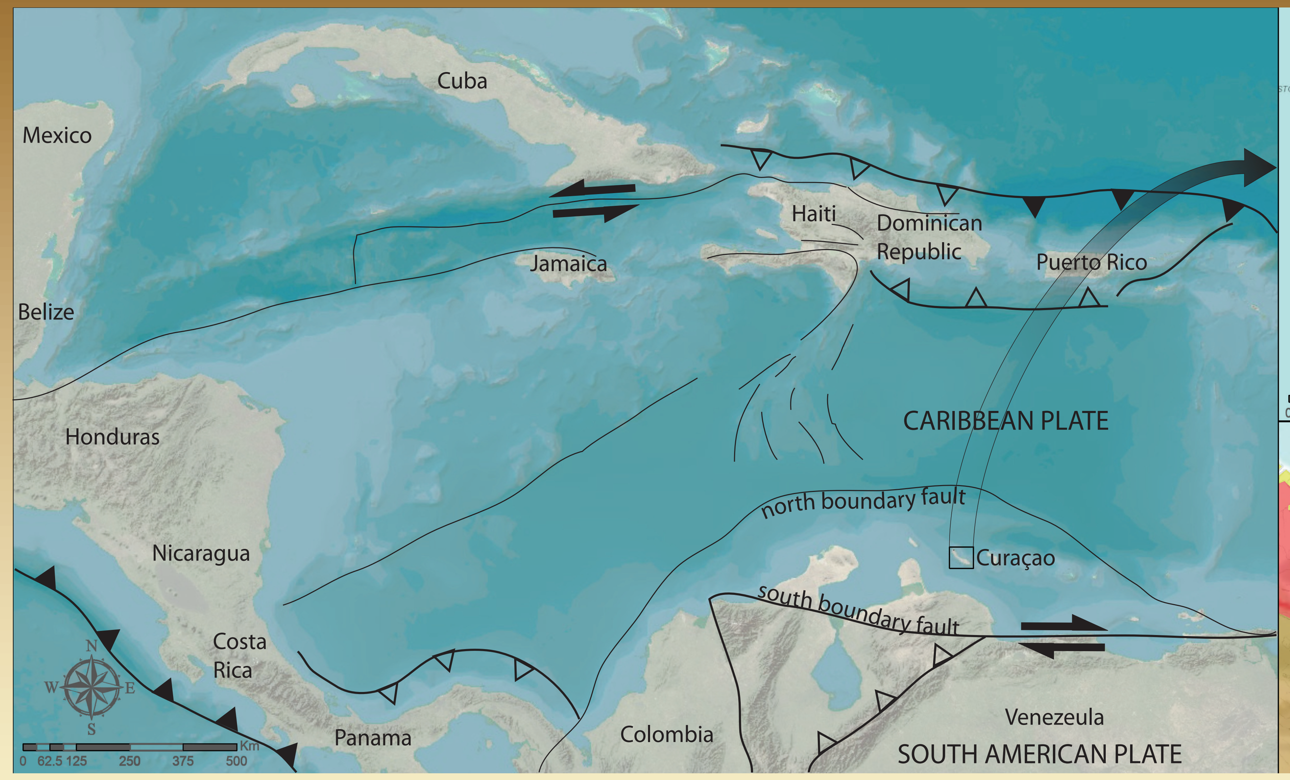
Shete Boka National Park, Curaçao is named after the presence of a series of at least seven narrow inlets cut into the limestone terraces of the rugged north coast. These bokas or "mouths" are connected to ephemeral streams (arroyos) that have eroded into the siliciclastic bedrock inland of the coastal limestone terraces. The arroyos rarely contain running water except on occasion during the rainy season – which lasts from October to December. The origin of these geomorphic features has not been well substantiated in the literature. The presence of the bokas is enigmatic because: 1) there are multiple sets along the North coast, 2) they demonstrate similar morphologies and structural trends, 3) there are multiple processes contributing to the development of the coastline, and 4) presently stream runoff and erosion rates through the arroyos is insufficient to form the bokas by vertical entrenchment in the limestone terraces. Similar features have been described in the Mediterranean region as bogaz, grikes, dolines, poljes, or strugas, and in the Caribbean and North America as zanjones or karst corridors. Such features are attributed to karst phenomena that enlarge fractures by solution processes. The colloquial nomenclature is dependent on size and dimension of the feature. Nevertheless, the formational histories are likely tied to regional changes in base level and tectonic uplift/subsidence processes. In the case of Curaçao, the occurrence of numerous bokas in various stages of development allows for the creation of a model to explain the development of such features. Consequently, the presence of larger pocket beaches and interior bird-foot bays located within close proximity to the narrower bokas suggests the possibility that the features might actually be related. This study establishes a new multiphase model to explain the origin of these subaerial features that is based upon structural lineaments, groundwater flow patterns, cave development, sea-level transgression and regression, and subsequent wave widening and collapse.

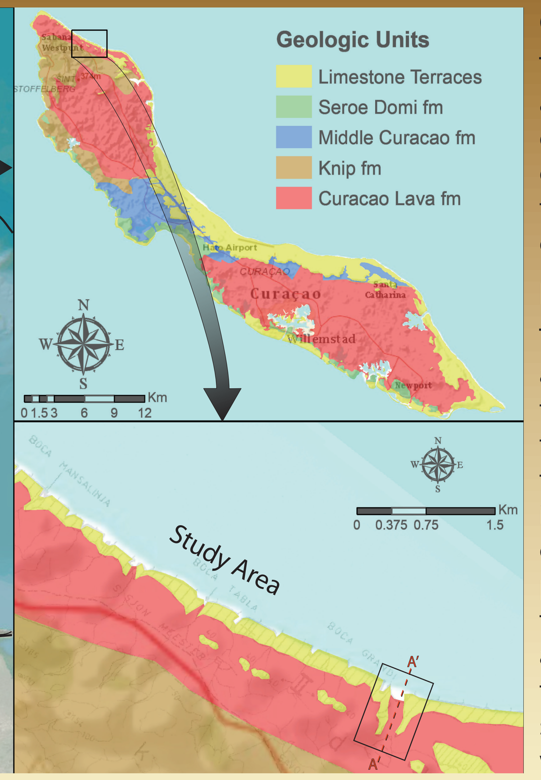
DATA & OBSERVATIONS:

Thirteen fracture traces and boka orientation measurements within Shete Boka National Park were taken during a day of data collection. The degree to which these features orient themselves correlates strongly with the lengthening strain axis associated with the recent dextral tectonic movement of the Caribbean plate. This brittle extension axis was identified by Beardsley and Avé Lallemant [2007] as F3, the youngest phase of deformation. The fracture orientations we measured have a mean angle of N 35.46° E. Beardsley and Avé Lallemant's 'Orientation A Fabric' Tertiary Limestone data for the Islands of Curaçao, Aruba and Bonaire have a mean angle of N 34.84° E. Rayleigh's Z and Watson's U^2 were calculated for both datasets. Rayleigh's Z determines weather or not a set of angular data is evenly (randomly) distributed or concentrated around a preferred vector. Watson's U^2 looks to see how related two sets of angular data are. For our data and Beardsley and Avé Lallemant's, the calculated Rayleigh's Z value allowed us to reject the null hypothesis of the fracture traces being uniformly distributed, thus suggesting a trend; in both datasets $p<0.001$. Watson's U^2 showed the azimuth direction from the two datasets was not significantly different, with $0.005>p>0.002$, allowing us to correlate our data to Beardsley and Avé Lallemant's. In addition to showing a statistical trend which matches their F3 deformation phase; we surmise that the presence of bokas on the island of Curaçao, and likely those found on Aruba and Bonaire, are the result of dextral motion of the Caribbean Plate fracturing the limestone terraces during the last and most recent deformation phase. Below is a time series model developed to explain how the bokas and related features were formed.



Equal Angle Sterionet showing *Beardsley and Avé Lallemant's* 'Orientation A Fabric' planar Tertiary Limestone data for the Islands of Curaçao (blue), Aruba (green) and Bonaire (red) with our linear data (black). Mean angle for all data = N 31.73°E (yellow)





GEOLOGY of the STUDY AREA:

The limestone formations of Curaçao originated from barrier and backreef limestones consisting of coral debris and siliciclastics. Prior to five million years ago, as part of a horst and graben complex, the islands of Aruba, Bonaire and Curaçao elevated from the ocean floor allowing carbonate to accumulate on the igneous and siliciclastic-cored horst blocks. Since the end of the Miocene, the shallow water around these islands allowed for the formation of coral reefs. The limestone terraces developed through time as the reefs tracked the variable sea-levels associated with glacial and interglacial cycles and any local tectonic uplift or subsidence - especially during the Pleistocene.

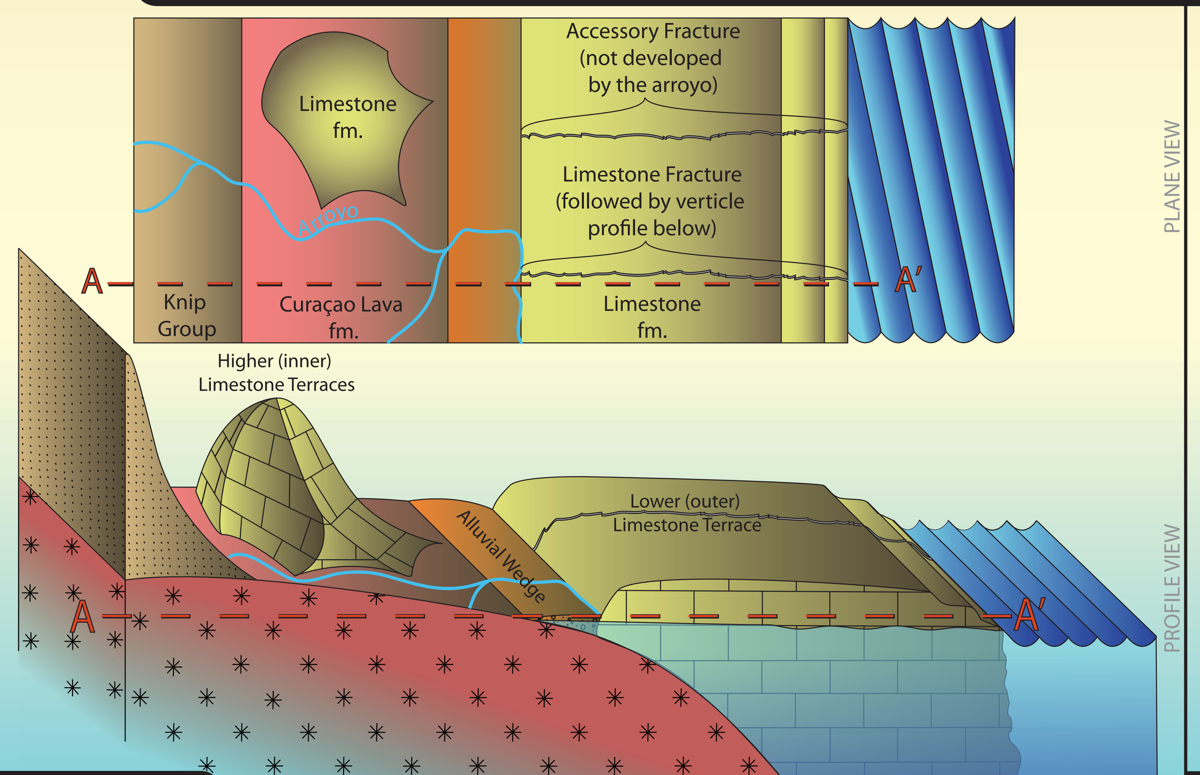
DISCUSSION & CONCLUSION:

Together with sea-level oscillation, tectonic stresses along the Caribbean-South American Plate clearly play a role in the formation and development of the Bokas of the ABC islands including Curacao. Following the deposition and growth of the limestone terraces that surround the island, strain fields resulted in the formation of NE-SW oriented joint sets within the limestones. Subsequent to the fracture episode(s), relative sea-level drop (through terrace uplift or global sea-level fall) initiated solution expansion along the fractured joint sets as groundwater flow resulted in cave development. Once cave systems became too large, cave collapse resulted in the formation of narrow-elongate gorges (aka bokas) that connected inland surface drainage networks with the open sea. With continued runoff, wave action, and bioerosion along the intertidal-supratidal interface, bokas continue to expand laterally until pocket beaches form at the back of the limestone terrace where surface runoff enters the ocean. Pocket beaches thus formed, allow for stronger and more persistent wave erosion that can accentuate the beach morphology. For the final stage, plate tectonic activity may have come into play again as tilting of the island to the southeast may have resulted in subsidence of the limestone terrace as suggested by *Schellmann et al.* [1994]. Subsidence, coupled with global sea-level rise is thought to have inundated several pocket beach – arroyo complexes (on the southern side of Curacao) thus flooding these ephemeral drainages with marine waters. These transgressive events resulted in the formation of the bird-foot bays that made Curacao so famous as a deep water port. This correlation can also be extended to the neighboring islands of Aruba and Bonaire; where the larger and more prominent saltwater interior island features are found on the same side.

Proposed Multiphased Transitions

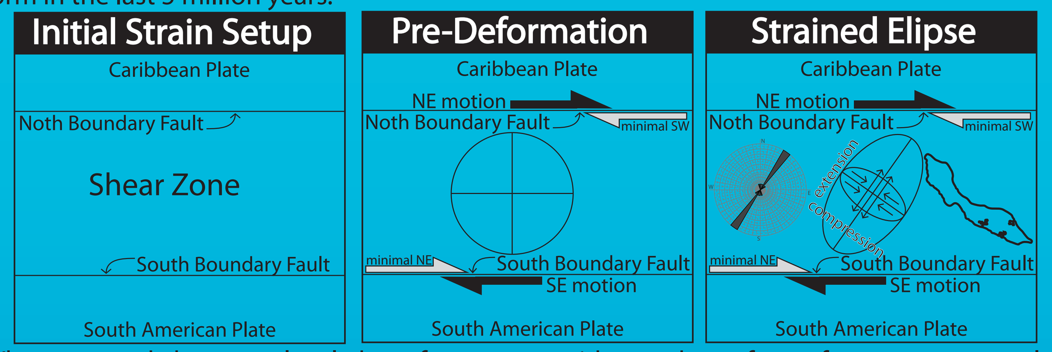
NOT TO SCALE

Phase 1



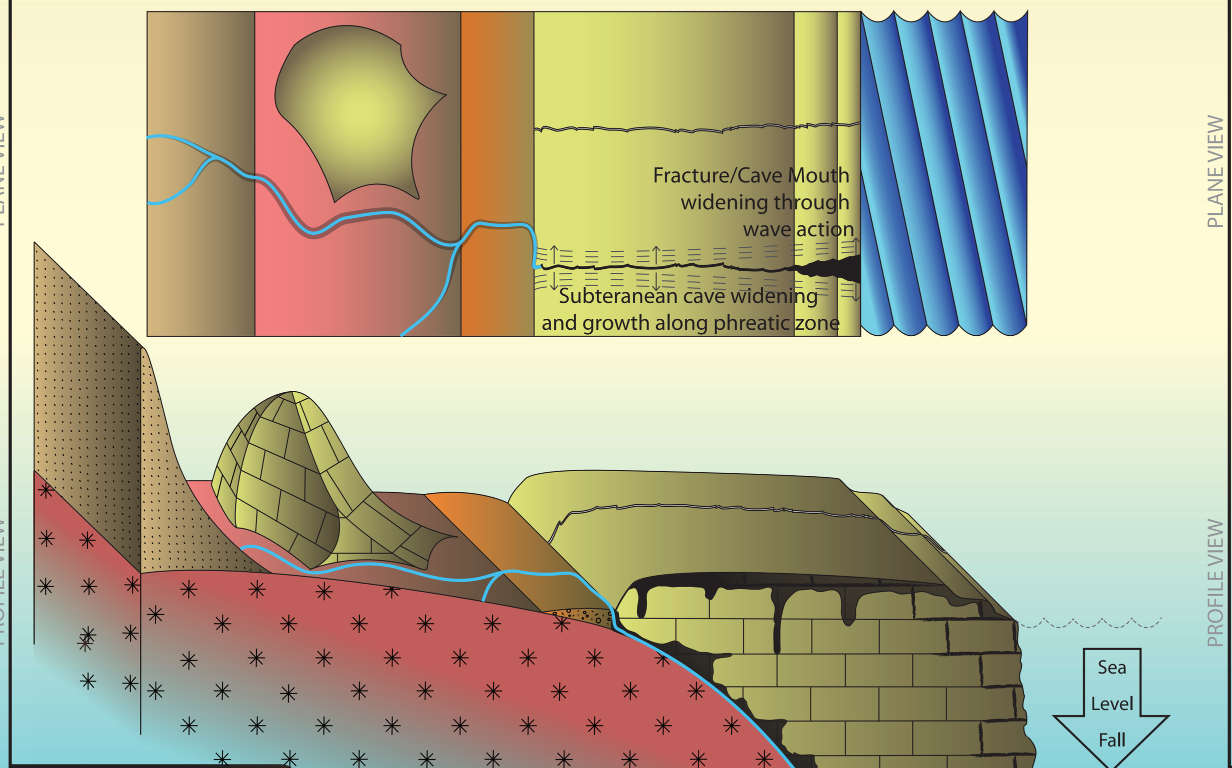
Tectonic Stress:

- The Caribbean Plate has been moving eastward between North and South America.
- Curaçao and the other ABC islands are located on the southern boundary of the Caribbean Plate and are involved tectonically in a shear zone system with the South American Plate.
- Major shear zone fracturing is observed in the limestone fm. of Curaçao, tangential to the shear zone and parallel to the lengthening strain axis. These are correlated to our field data (see rose diagram). The dextrial motion of the Caribbean Plate has caused these fractures to form in the last 5 million years.



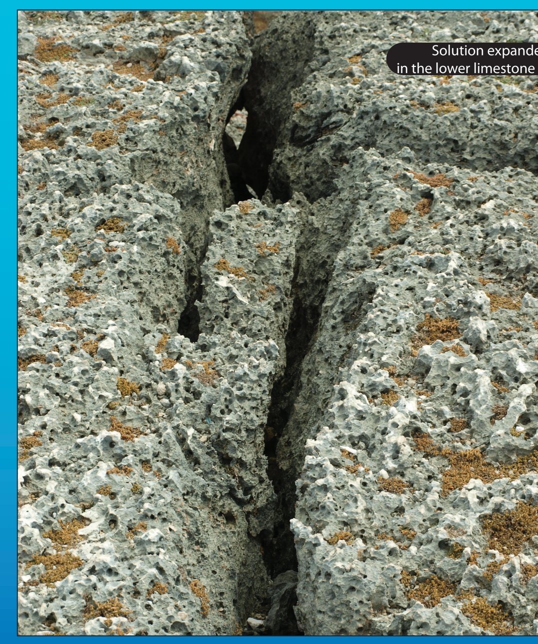
- When exposed above sea-level, these fractures provide a pathway for surface water to travel from the island down slope to the sea.
- Runoff across the island surface is controlled by bedrock type
  - Siliciclastic & igneous rocks have low permeability so runoff doesn't infiltrate readily & is shed across the surface to the neighboring limestone bedrock areas
  - Once on the high permeability limestone, the low pH rain water (coming off the siliciclastic & volcanic bedrock areas) interacts with calcite/aragonite minerals and begins to develop soulution channels along the fracture sets produced during tectonics.
  - When sea level is high & limestone is mostly submerged; ground water flow networks are close to or at the surface and rarely extend across the limestone terrace.
  - When relative sea level is low; Phase 2 ensues.

Phase 2

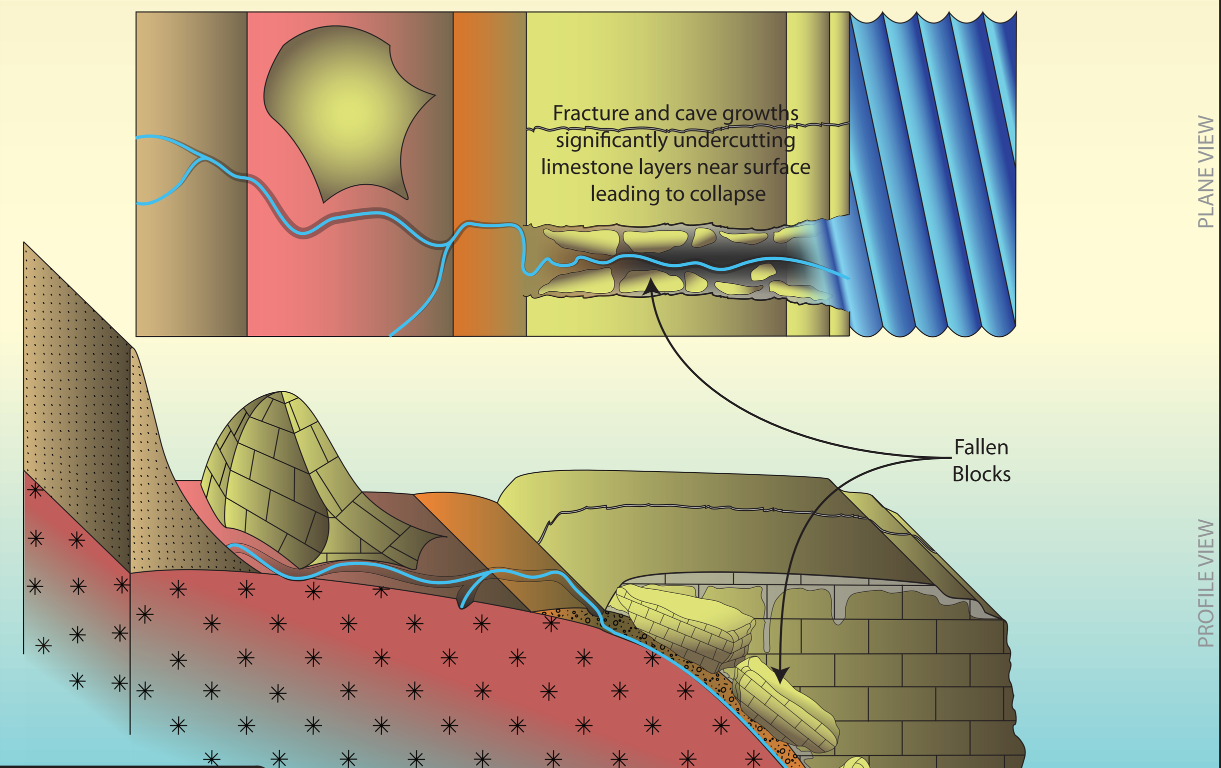


Hydraulic Interaction & Geochemistry:

- As sea-level falls, the limestone terraces are exposed & the groundwater table drops to the new sea-level position.
- At this point, wave action & bioerosion begins to form a wave cut notch on exposed terrace fronts.
- Surface water more readily penetrates into porous sub-surface networks where low pH water dissolves existing fault fractured limestone and widens phreatic tubes along the top of the groundwater table. This results in widening of cave passages that empty into the ocean at the level of the wave cut notch.



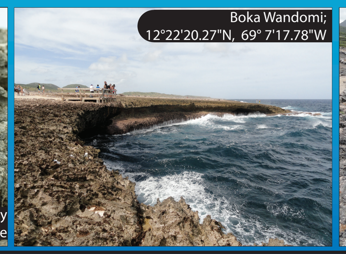
Phase 3



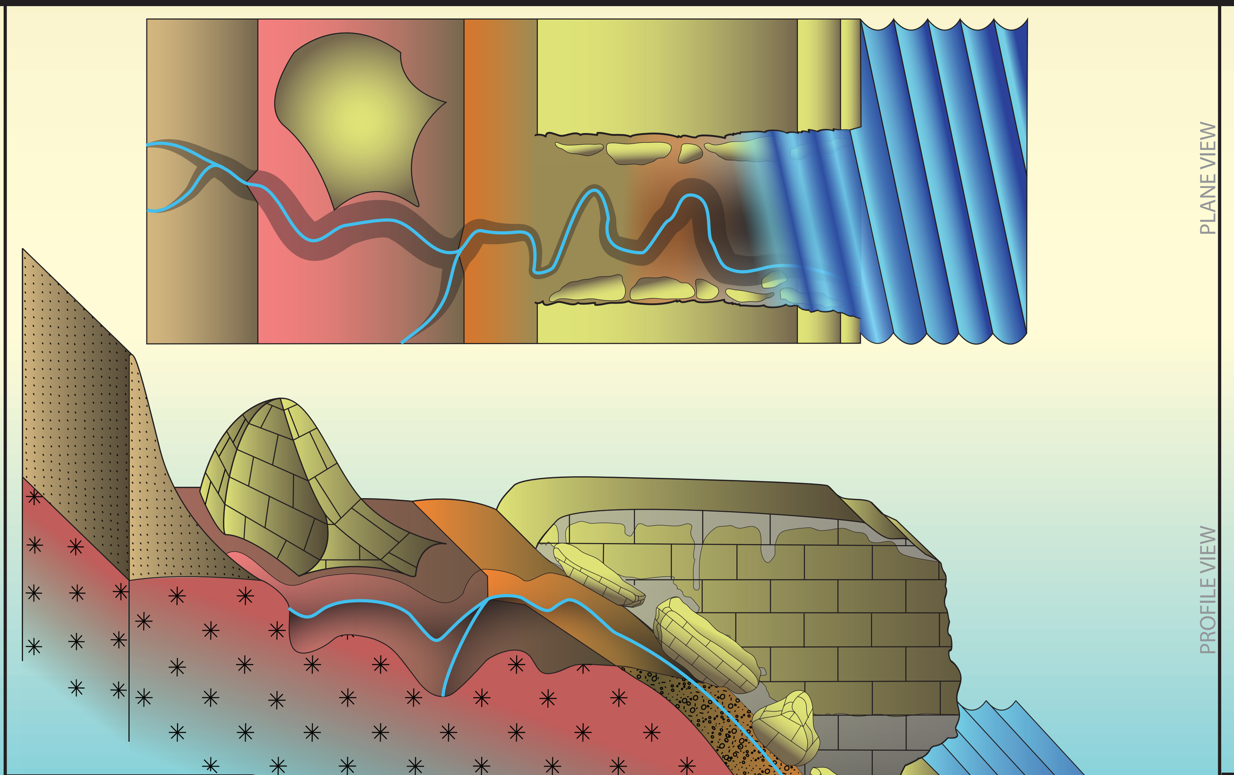
Gravity & Instability - Roof Collapse:

- As the cave grows horizontally (following bedding), the cave ceiling becomes unstable and collapses into itself, exposing the cave to the surface.
- The blocks that fall become exposed to the geochemical reactions in the pheratic zone and the physical weathering of wave action and abrasion from the alluvium carried by the arroyos further erode and dissolve the fallen block.
- Overtime & depending on wave action & groundwater flow rates, the boka will continue to elongate and widen. Boka growth may cease as sea-level rises once again.
- This elongated vertical depression through the limestone terrace is what is classified as a Boka.

Special Thanks To: Dr. Sean Cornell, Dr. Claire Jantz & Dr. Scott Drzyzga for organizing and leading the class trip to Curacao



Phase 4



Continued Growth - Pocket Beach:

- Phase 3 repeats indefinitely through undercutting of the limestone face and overburden collapse as the newly collapsed boka continues to widen.
- The boka continues to grow laterally following the near horizontal bedding of the limestone.
- This process is driven by wave action extending wave cut notches inland and by the arroyo carrying away the sediment and undermining the upper bounding layers.
- Eventually the undercutting of the boka walls will intersect accessory fractures much like the ones described in Phase 1, however these were never fully developed. The intersection of this vertical cut with the undercutting from the expanding boka not only widens the boka into a pocket beach, but maintains its northeast orientation.

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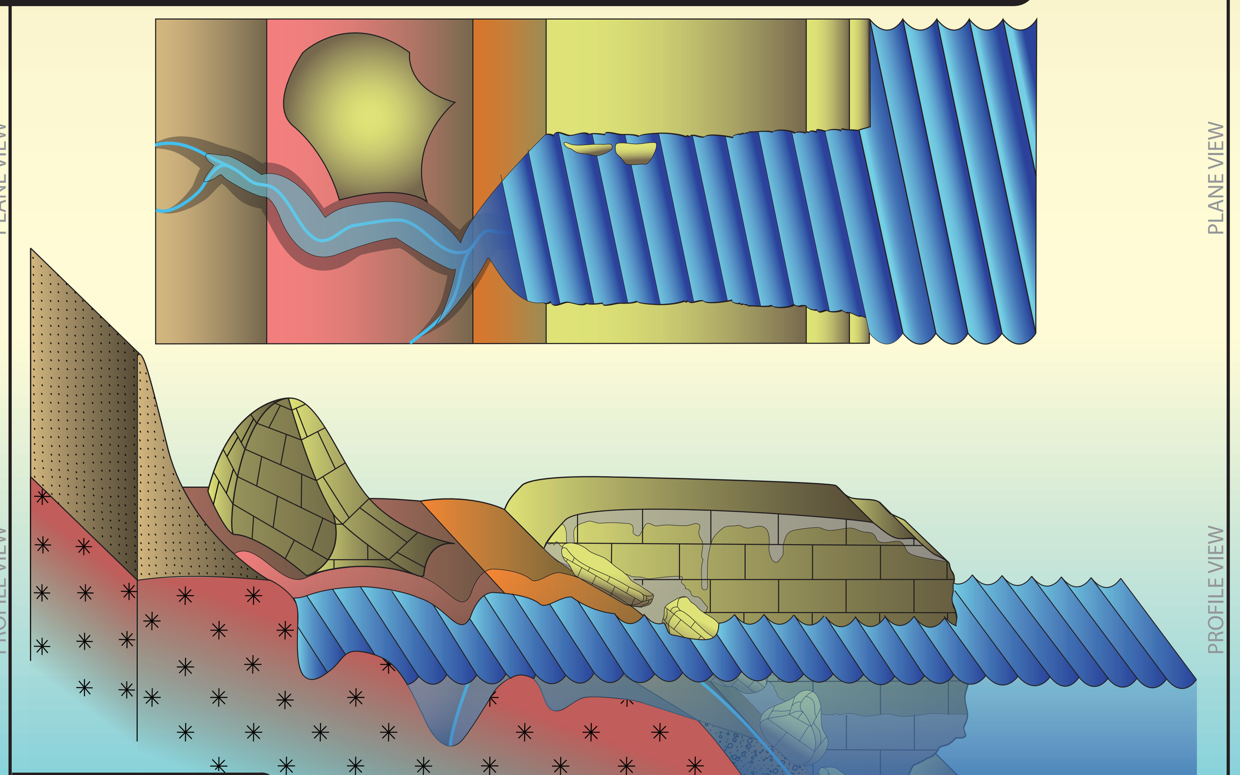
Phase 5



Continued Growth - Bird-Foot Bay:

- As relative sea level increases (i.e. tectonic subsidence or global sealevel rise) the boka or pocket beach and the inland forming arroyo channels will become inundated with seawater.
- The best expressed bird-foot bays are located in Curaçao's southeast are likely the result of a southeast tilting of the island as suggested by *Schellmann Et a.l* [1994].