Coastal Cave and Karst Resource Management

6

Michael J. Lace and John E. Mylroie

Abstract

Human impacts to coastal karst landscapes encompass a broad range of examples, including small and large scale construction, resource mining, and recreational and agricultural uses. The geographic definitions of coastal zones vary widely from one area to another. Coastal resource management, preservation and restoration efforts and their respective operational plans, are equally and understandably as diverse and in some instances overlapping or conflicting in their intended scope, legal frameworks and practical application. The very structure of coastal karst and associated carbonate aquifers introduces unique problems in terms of geologic stability, extraction of hydrocarbon reserves, environmental preservation, and water resource quantity and quality. These problems incorporate additional complexity to the definition of physical boundaries, resource documentation, and the design and implementation of management plans. Many of the case studies presented in Part II illustrate some of the regional karst resource management approaches applied to specific littoral settings. This chapter examines several examples of coastal karst resource utilization and outlines potential models for predicting geologic stabilities, identifying sustainable land uses and approaching preservation challenges associated with such landforms.

6.1 Coastal Karst Resource Management Approaches

The benefits and challenges of implementing a universal system for systematically classifying coastal areas have been discussed in other venues (Finkl 2004; Brommer and Bochev-van der Burgh 2009) and together with widespread coastal management and restoration approaches (Clark 1996; Green 2009; McConney et al.

M.J. Lace (✉)
Coastal Cave Survey, West Branch, IA 52358, USA
e-mail: michael-lace@uiowa.edu

J.E. Mylroie
Department of Geosciences, Mississippi State University,
Mississippi State, MS 39762, USA
e-mail: mylroie@geosci.msstate.edu

M.J. Lace and J.E. Mylroie (eds.), *Coastal Karst Landforms*, Coastal Research Library 5,
DOI 10.1007/978-94-007-5016-6_6, © Springer Science+Business Media Dordrecht 2013

Fig. 6.1 What is sustainable development in a coastal setting?

2003) will not be addressed in detail within this chapter. For a more comprehensive treatment of coastal hazard management, see the companion volume in this coastal research library series by Finkl (2013). Similarly, general approaches to cave and karst preservation, management and restoration are not addressed in detail but the reader is directed to seminal referenced works in these fields (Haslett 2009; Jones et al. 2003; Van Beynen 2011; Werker and Werker 2006). Yet, given the limited presence of proactive preservation in the face of increasing anthropogenic modification of many coastal zones, a discussion of the challenges faced in the design and implementation of effective models of coastal cave and karst resource management is warranted.

The following sections offer perspectives on sustainable resource management: (1) coastal karst resource documentation, (2) legal protections and (3) resource access, education and interpretation. The remainder of the chapter examines additional case studies and preventative modeling approaches specific to the potential pitfalls and consequences of land use patterns, small and large scale development and incumbent modification of coastal karst. As this chapter illustrates, the definition of sustainable land uses in coastal karst settings can prove problematic as they are often site-specific and may not readily conform to standardized criteria (Fig. 6.1).

Karst areas introduce a range of complexities to the management of coastal areas with considerations specific to these structures, including unique geologic stabilities and aquifer vulnerabilities (Bear et al. 1999) that directly influence resource preservation strategies (Fleury et al. 2007; Gillieson 1996). In spite of these complexities, coastal development in many areas continues and includes a wide range of land uses from minimal subsistence agriculture (Fig. 6.2a) to complex infrastructure and municipal scale expansion within the context of complex coastal geomorphologies (Fig. 6.2b). For additional examples of coastal modification and management issues, readers are also directed to the companion volume (no. 3) in this coastal research library series by Cooper et al. (2012) for a more expansive discussion of shorelines within this context. As discussed in Chap. 4, mechanisms of void development (e.g. cave formation) specific to coastal settings generate distinctive structures in abundance. Dissolutional voids in this setting comprise not only those that have been revealed by cliff retreat or platform erosion but also voids that are not visible

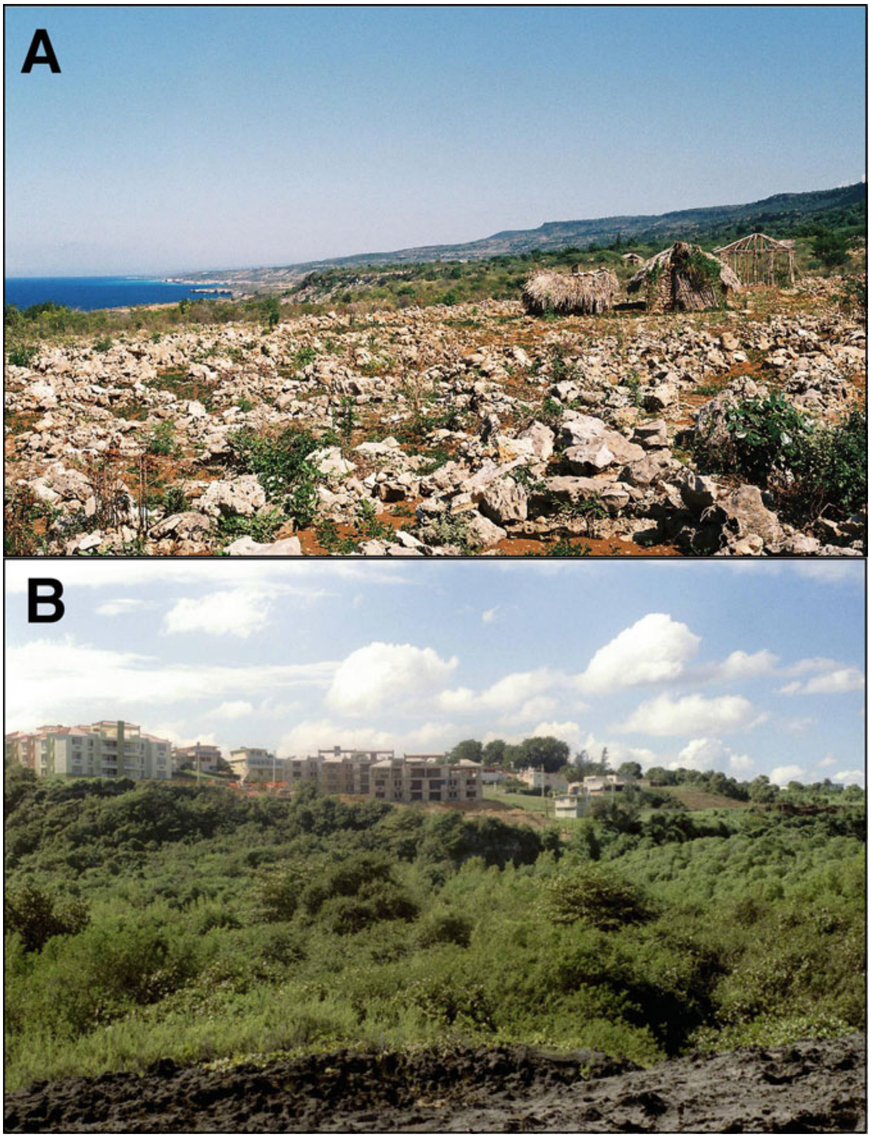


Fig. 6.2 (**a**) Basic construction and agricultural use on an uplifted karstic terrace on the Northwestern coast of Haiti. (**b**) Commercial construction overlying a karst limestone escarpment of the north-central coast of Puerto Rico

or quantifiable in the absence of remote sensing techniques, rendering the management of such unseen coastal resources problematic.

6.1.1 Resource Documentation

As with any management plan, reconciling the physical and conceptual boundaries of a coastal resource is a critical first step, preceding detailed resource documentation and the design and implementation of successful initiatives. Defining the geographic boundaries of a coastal karst landform can be approached by three distinct, and often non-overlapping, perspectives: (1) geological/geomorphological; (2) geoarchaeological/cultural; and (3) coastal zone resource management. As discussed in Chap. 4, defining the relevant geomorphologic boundaries of coastal resources, for example, island structure, platform area and associated hydrogeology, has direct implications in modeling the sequence of geologic events that shaped its past and present form. Similarly, the previous chapter illustrated that the very definition of what constitutes a coastal landform influences our perceptions of past anthropogenic uses of coastal areas as well as associated geoarchaeological interpretations similarly can influence present coastal resource management and preservation approaches applied to such cultural sites. Thus, cultural landscapes in a coastal setting may not readily conform to either a geologic delineation of the landform structure or the coastal zone management boundaries of a given protected area and vice versa. Clearly, an integrated conceptual view of a coastal landform that incorporates multiple perspectives should prove useful but in practice is infrequently applied to coastal settings. Similarly, combining a range of systematic geophysical mapping techniques can prove effective in coastal karst modeling (ESRI 2007), such as LIDAR, microgravity assays, GPR and standard field mapping methods as shown in the following examples. Such methods can further support long term resource monitoring as another key component of karst resource management.

6.1.2 Legal Protections

In many coastal settings, government agencies are charged with the responsibility of managing both terrestrial and marine resources. A wide range of legal statutes are utilized as a framework to support specific cave resource management approaches. In some instances, practical necessity has prompted many government agencies to outsource management of protected resources to private foundations or land trusts – institutions which in some cases can offer greater continuity, broader management capabilities and at times have proven less susceptible to economic limitations or shifting political currents faced by publicly funded government initiatives. Examples of NGOs engaging in coastal karst management include the Bahamas National Trust, which oversees a wide range of natural resource areas (including karst). In parallel, the Antiquities, Monuments and Museums Corporation (AMMC) which oversees Bahamian cultural resources, often associated with caves. Such partitioned management is not uncommon with separate governmental ministries charged with environmental or cultural resources, respectively, even though both may employ similar protection strategies applied to the same coastal zone. The Republic of Haiti utilizes multiple ministries to manage aspects of environmental resources with several standing legal statutes. As in many countries however, continuity of legal enforcement of such statutes through political transition has proven challenging in the past.

Independent private agencies can also play an important role. The Carmabi Foundation (Caribbean Marine Biology Institute) is an NGO contracted to manage significant karst resources on the island of Curaçao as well as engaging in coral reef health monitoring in the broader region. The Puerto Rico Land Trust (as discussed in Chap. 9) has acquired and effectively manages a series of significant karst preserves in coastal areas and in the island interior. Thus, both developed and developing nations often share complex coastal zone management issues involving multiple agencies (private and governmental) charged with overseeing resources within the same karstic landforms, potentially leading to redundant or conflicting management approaches (Kueny and Day 2002).

6.1.3 Resource Access, Education/Interpretation and Preservation

The concept of caves as "underground wilderness" environments has gained traction in resource management in recent years, offering a more accurate definition of cave environments within a context that supports a range of preservation approaches. Cave management plans span a broad spectrum of preservation approaches, supporting a range of recreational cave uses (Figs. 6.3 and 6.4), scientific

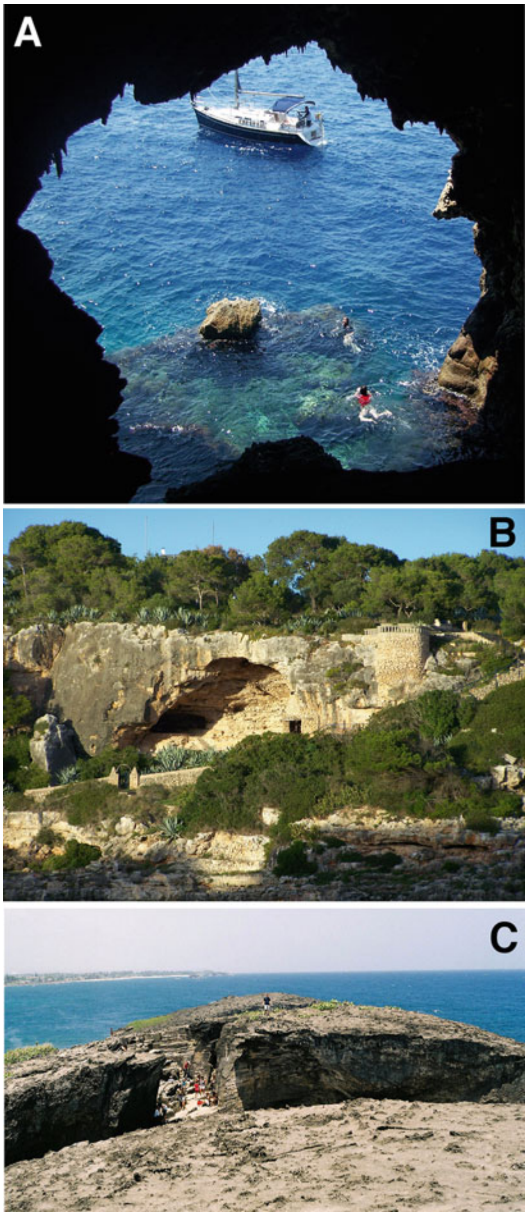


Fig. 6.3 Recreational use of undeveloped or altered coastal cave sites. (**a**) Pristine cave site, Dalmation coast, Croatia. (**b**) Anthropogenic modification of a coastal cave (Cala Figuera, Mallorca). (**c**) Modification (note large excavated trench for building material extraction) and modern tourism use of a pre-ceramic aged archaeological site within a karstic eolian calcarenite dune (Cueva del Indio) on the northern coast of Puerto Rico

research and associated land uses specific to each coastal karst resource as determined by the respective management entities. Recent qualitative approaches to modeling sustainable land uses in karst environments also show promise in shaping effective long-term management of such complex landforms but an established, universal assessment protocol remains elusive (Watson et al. 1997; Van Beynen et al. 2012).

In sharp contrast to a pristine underground wilderness model, cave commercialization has been invoked (although controversial) in some karst preservation approaches (Gurnee 1967; Huppert et al. 1994), ranging from small-scale community-based ecotourism strategies incorporating cave and karst features to full scale recreational development. Commercial cave development is not restricted to any specific coastal landform or cave type and can take many

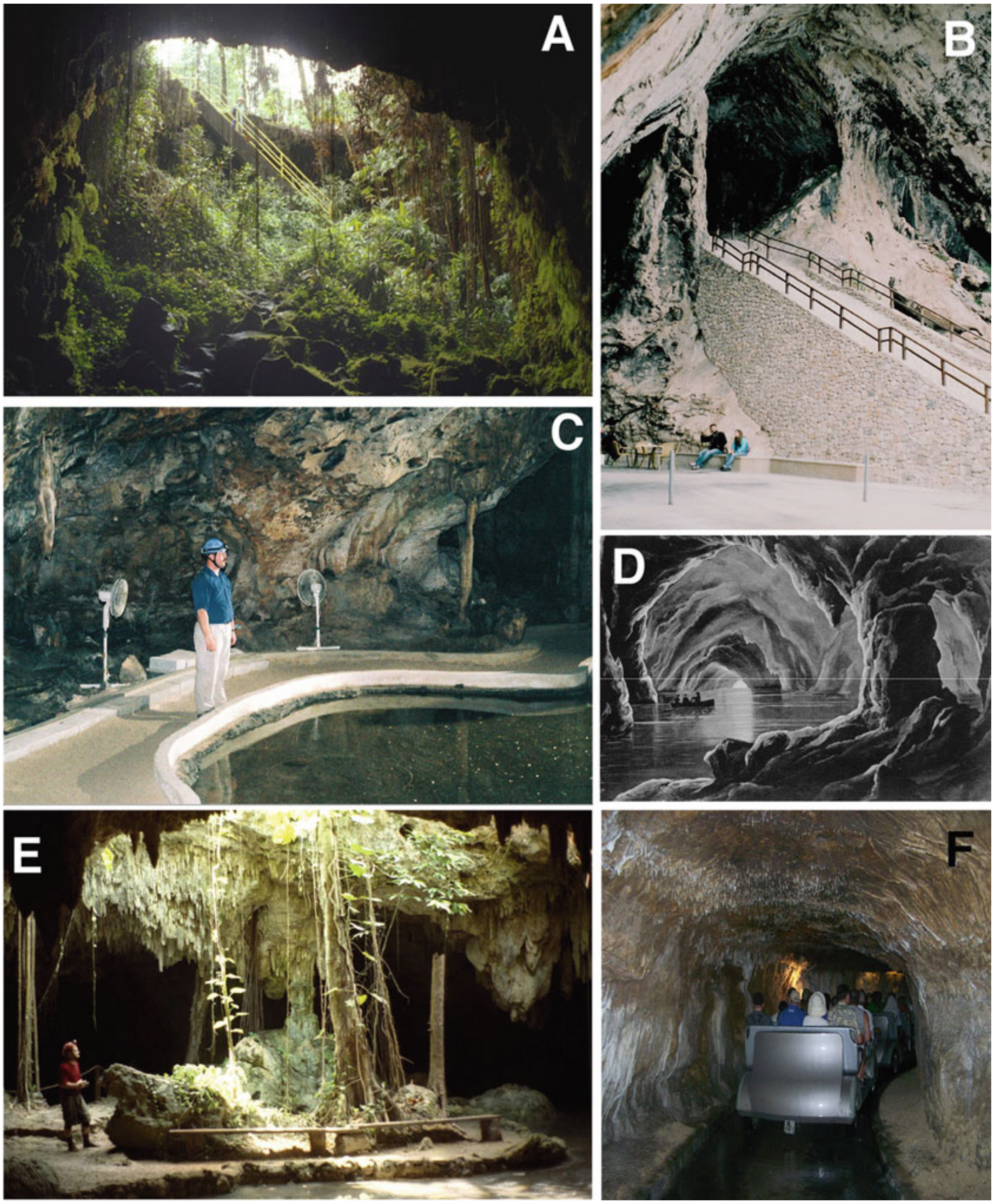


Fig. 6.4 Examples of commercial cave development. (**a**) Hawaiian Lava tube (Kaumana Caves), (**b**) Cueva Del Arte (Mallorca, Spain), (**c**) Hato Cave (Curaçao), (**d**) Grotte Azzurra (Capri) – ca 1900s postcard, (**e**) Yucatan cenote – Chaak Tun Caverns. (**f**) Harrisons Cave (Barbados) tram trail

forms (Fig. 6.4); examples include Grotte Marie-Jeanne (southern peninsula, Republic of Haiti), to moderate or large-scale commercial cave development, such as Green Grotto (Jamaica), Hato Cave (Curaçao), Rio Camuy Cave (Puerto Rico), Cueva Del Arte (Mallorca), Grotta Azzurra (Capri), Sea Lion Cave (USA – see Chap. 14) and Harrison's Cave (Barbados –

Chap. 10) as natural economic resources (in some cases comprising significant components of the national GDP) within broader sustainable management models (CRSTD 2008).

Cave commercialization has often proven effective in supporting resource education through interpretive programs stressing the complexities and importance of diverse cave ecosystems which in turn support future resource protection efforts. However, preservation caveats certainly apply as many sites with unrestricted or unmanaged visitor access have seen significant negative impacts that have proven devastating to archaeological and historical resources, cave biodiversity, hydrology and even significantly altering cave microclimate, resulting in a cascade of negative effects to cave environments and the species they support. Clearly, a universal resource management protocol may not be tenable as access to sensitive karst landscapes requires a balance between education, research and site preservation – specific to each setting and flexible enough to respond to an ever-changing status.

The following section explores ways of assessing potential pitfalls and remediation costs associated with coastal development on karst. It also illustrates the power and utility of expansive coastal cave inventories, derived from field exploration and refined by multidisciplinary analyses, as key resource management and karst modeling tools.

6.2 Modeling Geologic Instabilities in Coastal Karst

Coastal cliffs and terraces comprise a predominant portion of the world's coastlines (Emery and Kuhn 1982; Migon 2010). Coastline changes are the result of a dynamic interplay of natural and anthropogenic influences that are intimately linked to geological processes and climate change in coastal settings (Fitzpatrick et al. 2006; Harff et al. 2007). Consequently, many carbonate coastal zones can benefit from detailed karst resource and stability assessments in the face of expanding residential and commercial development on dynamic littoral landscapes.

As with karst in continental areas, land use issues in island karst are centered around three principal factors: (1) landform stability; (2) water quantity and quality; and (3) environmental preservation.

6.2.1 Landform Stability

As presented in Chaps. 3 and 4, there are major differences between island karst and continental karst. In terms of land stability, carbonates in tropical and subtropical locations are commonly eogenetic, with less diagenetic maturity, and therefore potentially less strength, than telogenetic carbonates in continental interiors. The development of dissolutional voids in the subsurface of islands, which can constitute a collapse or subsidence risk, follows different rules than for continents. In many cases, such as flank margin caves, the location of caves can be reasonably predicted, especially if the coastal sea-level history is known so that the site of past fresh-water lens margins can be identified. In the Bahamas, the development of banana holes in last interglacial strand plains creates a situation where the region of risk can be identified by geology (specifically, the strand plain facies location), but the site-specific risk within that region can be difficult to establish (where is the actual roofed banana hole that has not yet collapsed?). Large progradational collapse features such as blue holes in the Bahamas, indicate that very large collapse events can occur, and that their location is extremely difficult to predict in advance. Given that it is now believed the majority of blue holes (away from the bank margin) are collapses into conduit flow systems at depth in the Bahama Banks (Chap. 4), in this case the planning and prediction of karst collapse more closely resembles that for continental interior karst areas.

Geophysical techniques have been used in the Bahamas with varying degrees of success. Microgravity was demonstrated to be capable of locating small, shallow voids (Kunze and Mylroie 1991), however the technique is labor intensive in the field, especially as a reconnaissance tool as survey lines must be cleared and measured. Better success has occurred with ground-penetrating radar (GPR), as many caves are shallow, and the youth of the Bahamian limestones means there is minimal soil and clay to attenuate the signal (Wilson et al. 1995). Wilson et al. (1995) also developed a karst hazard report for San Salvador Island, in an attempt to quantify the geologic hazards presented by karst features. The report initially characterized the landforms of the island as plains, beaches, ridges, and inland water bodies. The location of known karst features was then catalogued as to landform specificity, and as to median size. From this work, the authors were able to generate a subsidence and collapse risk factor.

As noted in Chap. 4, sinkhole development, and therefore their collapse potential, is different in eogenetic carbonate islands from that found in continental interiors in telogenetic rocks. In the Bahamas, with thin to no soil, cover collapse sinkholes are almost non-existent. However, Barbados has a thick soil cover over its extensive limestone surface, and cover collapse sinkholes can occur there. In both localities, cave collapse sinkholes are common, especially true for the stand plain banana hole country of the Bahamas. True dissolutional sinkholes are also rare in the Bahamas, as the youth and eogenetic nature of the limestone has lead to pit cave development instead; pit caves could be considered an exaggerated mode of sinkhole development, where the dissolution is mostly downward and very little laterally. On Bermuda (Mylroie et al. 1995), vadose flow on the limestone/basalt contact created meandering cave streams that undermined the limestone, leading to numerous large progradational collapse features. The key point here is that based on the volume of meteoric recharge, a large conduit should not have developed. But because the vadose flow was perched, a relatively small stream, as it meandered, could create a broad void span that was mechanically prone to failure. Once collapse began, the vadose stream was able to dissolve and mechanically transport away the accumulated collapse debris, maintaining accommodation space so that the collapse could continue to prograde upward (collapsed rock takes up 40 % more space than the rock did when in place, so collapse generally ceases unless the surface has been reached or material is removed, see White (1988) for a full discussion of cave collapse). Large closed contour depressions, as discussed in Chap. 4, are mostly constructional in origin.

Hydrologically, the epikarst inflow in eogenetic carbonates is dispersed across the entire carbonate outcrop, and not specifically directed to joints as in continental telogenetic limestones. If a significant soil cover exists, predicting the meter scale bedrock topography can be quite difficult. Loading such a landscape with a building structure, in the absence of proper site investigation, can result in differential compaction and building failure (Fig. 6.5).

As noted by the CIKM, karst development is very island specific. Knowledge of the island's geologic history is critical to risk assessment. The age and strength of the rock, the amount of soil, the development of vadose flow along the limestone/non-limestone contact, the tectonic rate, are all important factors to determine where the voids are, and what risks they represent.

6.2.2 Water Resource Quantity and Quality

Water quantity. As described in Chap. 3, flow within a fresh-water lens is quite different from the aquifer setting in continental interiors. The presence of underlying and adjacent marine water makes the fresh-water lens vulnerable to salt water contamination. This problem is true for all marine coasts and islands in any type of rock or sediment material. In carbonates, the development of dissolutional flow paths can accentuate the difficulties in utilizing the resources of the fresh-water lens (Farrell and Boyce 2007).

Two simple examples can provide perspectives on the pitfalls of water extraction in islands. In most continental aquifers, if one had a water-producing interval of 20 m, one would drill and set the extraction pipe close to the bottom of the aquifer, so as to be able to extract the greatest amount of water. If this approach is taken with

Fig. 6.5 Road cut, northern Puerto Rico, as seen in 1992 when newly made. The overlying grass-covered surface is a uniform slope, but the road cut reveals that the bedrock beneath has a jagged form produced by karstification, with a terra rossa soil overlying it. That soil will compact on the right side, while the bedrock to the left will not, leading to differential compaction if the site was loaded by a building or other construction. Note that test boring could strike pinnacles and not troughs (or vice versa), creating a false impression of depth to bedrock

a fresh-water lens, marine water from below is almost immediately taken up the well, and the aquifer is salt contaminated. Less obvious is what happens if one drills only a few meters into the fresh-water lens, so as to avoid the previous problem. As the well is pumped, a depression in the water table, called a *cone of depression*, is formed. This cone of depression creates the slope that delivers water from the farther reaches of the aquifer to the well. The problem is that the fresh-water lens is floating as a buoyant body on the underlying marine water. Because the difference in density of fresh water compared to marine water is one part in 40, for each meter downward a cone of depression forms, the underlying marine water rises up 40 m, a process called *upconing* (see Chap. 3 for details). Successful extraction of water from the fresh-water lens requires skimming the top of the lens at multiple locations and multiple times to prevent upconing. On Guam, where the northern part of the island acts as a carbonate cover island, wells are sunk into the part of the fresh-water lens that has ramped up onto the volcanic basement, a region called *parabasal water*, which can be strongly pumped as there can be no upconing from the volcanic rocks below (Jocson et al. 2002).

In carbonate rocks, dissolution through time results in the aquifer undergoing self-modification, permeability increases even as net porosity decreases, as the remaining porosity is organized into flow paths called touching vug permeability (Vacher and Mylroie 2002). The longer a carbonate rock has held a fresh-water lens, the more permeable the lens becomes. Initially this increase might seem like a good thing, the better aquifers tend to be the more permeable ones. In carbonate islands, however, this is a bad thing. As explained in Chap. 3, a fresh-water lens forms because for meteoric recharge to reach the sea, a gradient must be established from the island interior to the sea. If the aquifer has low permeability, this slope will be steep so as to drive the water coastward. If the aquifer is highly permeable, the slope will be very gentle. Because of the buoyant nature of the fresh-water lens, the more the water piles up to make a steep gradient, the more the lens extends below sea level in the 40–1 ratio. Therefore, as the carbonates hosting the fresh-water lens become more permeable, the lens thins over time. Storage is lost, and less water is available for extraction. In the Bahamas, the thickest fresh-water lens is commonly in Holocene sand bodies near the coast (Wallis et al. 1991), because although the porosity is high, commonly over 30 %, it is not organized as in the adjacent older Pleistocene rock, and

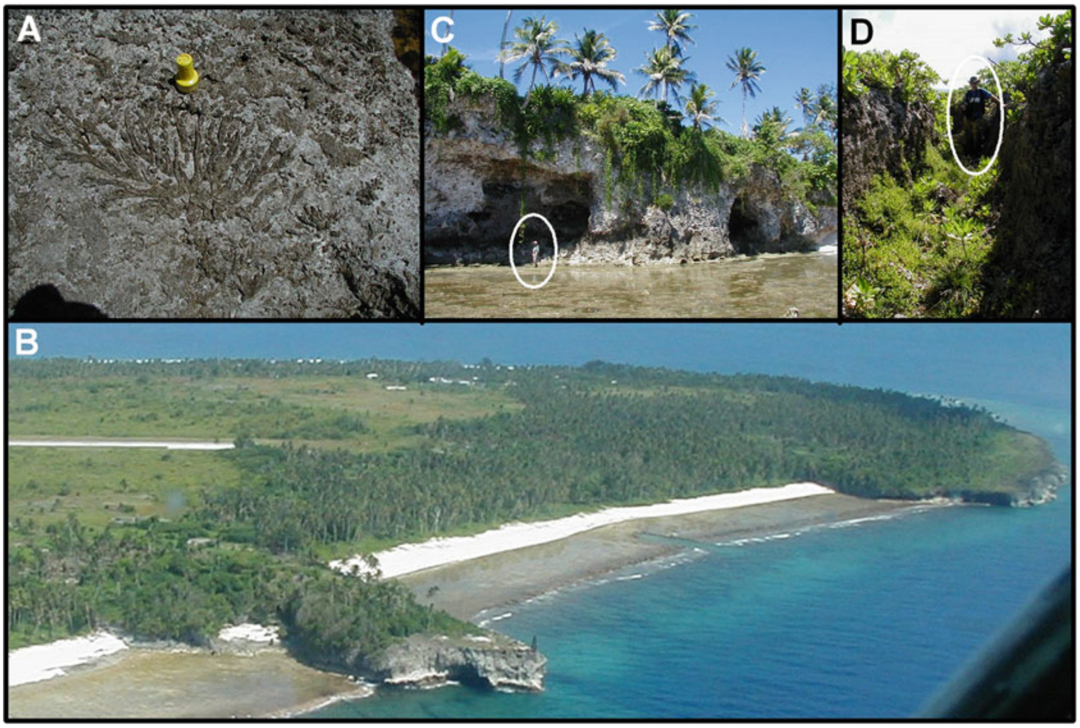


Fig. 6.6 (**a**–**d**) Fais Island. (**a**) Outcrop of Late Cenozoic reef facies, flashlight 12 cm high for scale. (**b**) Aerial view of a portion of Fais Island, looking southwest; the impermeable reef flat, and the rock peninsulas that cross the reef flat visible to left and right. (**c**) The west – facing cliff of the peninsula to the *left* in image **b**, showing uplifted flank margin caves. Person in *white oval* for scale (**d**) Fossil spur and groove topography that mimics karst. Note person in *white oval* for scale

the lens is consequently thicker, despite its near-coast position. On a siliciclastic island, such as Nantucket, dissolutional modification does not occur over time, but in the Bahamas and Bermuda (Vacher 1988), the older the carbonate rock, the thinner the fresh-water lens.

Fais Island is part of the Kingdom of Yap, within the Federated States of Micronesia in the western Pacific. The island is an uplifted atoll 220 km east of Yap, the only uplifted island in a large archipelago of atolls. The ∼320 inhabitants use rainwater collection as their source of drinking and cooking water. Typhoons blow off the building roofs, and ENSO conditions lead to drought, both of which create a water crisis on the island. The work described here is presented in detail in MacCracken et al. (2007) and Mylroie et al. (2008).

Fais Island is 1.2 km wide and 2.9 km long, with a maximum elevation of 40 m, composed entirely of Late Cenozoic limestones (Fig. 6.6a). Because of the water resources issues for the island population, a study was done to determine if a karst analysis of the island would allow a better water recovery strategy than just a simple assumption of a uniform fresh-water lens. The work was done in late spring, when the maximum negative tides of the year are experienced, so that selective water discharge from the lens, if it occurred, would be identifiable. The island is surrounded by a well-cemented reef flat, except in a few areas where rocky peninsulas cross the reef flat and extend to deeper water (Fig. 6.6b). Field work demonstrated that uplifted flank margin caves were found only in the rocky peninsulas, and not in the back-beach cliff areas inland of the reef flat (Fig. 6.6c). Fresh-water discharge was also only found in these rocky peninsulas, directly beneath the areas where uplifted flank caves were found. The reef flat displayed almost no fresh-water discharge, indicating it was acting as an aquitard or aquiclude. The only exception was an embayment on the northeastern side of the island, filled with Holocene sand. As has been reported earlier, these Holocene sand bodies have a high porosity but an undeveloped permeability, and so hold water in a thick lens. This sand-filled embayment has a dug well lined with a stone wall, and the water present is fresh. It is located some distance from the island village, and the water was not considered as clean as rainwater, so this resource was not utilized. Long linear troughs on the island surface, considered anecdotally to be collapsed caves, were recognized as uplifted fossil spur and groove structures inherited from a lagoonal origin (Fig. 6.6d).

The model that was developed from these observations is that the fresh-water lens does not discharge uniformly to the coast, because of the inhibiting nature of the well-cemented reef flat. Where rocky peninsulas cross the reef flat, the rock provides a flow matrix that allows preferential fresh-water discharge. The uplifted flank margin caves are excellent proxies for modern lens flow, as they themselves had formed at an earlier time when they were at sea level and the lens discharged through them. These karst interpretations allowed for a better strategy to provide fresh water to the island population.

Water quality. Carbonate islands can have a myriad of flow systems, from simple diffuse flow through a porous matrix, as in the Holocene sands described above, or high permeability flow in touching vug conditions, as in older Pleistocene carbonates, or conduit flow within the carbonate mass, as in large banks, or a perched flow on underlying non-carbonates. In addition, if the rock has been fractured, those fractures can also provide efficient flow paths. These many possible flow paths create a major water quality issue in carbonate islands. The porous media flow will be slow, with maximum storage. The touching vug flow system will be moderate in flow velocity, with some storage. The conduit and fracture flow pathways move rapidly, but with low storage. If a contaminant is introduced into the fresh-water lens, where and when that contaminant reappears depends on which flow paths are taken (they are not mutually exclusive), and how the aquifer is being managed (will water wells draw flow to them?). Moran and Jenson (2004) were able to demonstrate on Guam how water flow from injection wells and sinkholes through the carbonate aquifer took different simultaneous pathways with very different arrival times and destinations. Davis and Johnson (1989) on San Salvador Island, Bahamas, found that the fresh-water lens was partitioned by interior hypersaline water bodies, and that favored flow paths had distorted the lens. These examples demonstrate that water quality issues on carbonate islands require a full understanding of the CIKM and the local geology (White et al. 2006). Contaminant issues are heightened by the fact that on islands, there are not many groundwater resource alternatives. One cannot run a pipeline to an adjacent aquifer. Watershed contamination, however is not limited solely to island settings as continental coastal settings face the same difficulties and require the same in-depth understanding of the karst hydrogeology specific to coastal aquifers (Bonacci and Roje-Bonacci 1997; Harmon and Wicks 2006; Metcalfe et al. 2010).

6.2.3 Environmental Preservation and Biodiversity

Islands can be near to continents, part of archipelagoes, or distant in the far ocean. They contain ecologies that have evolved in isolation, and the impact of human colonization has been devastating. First, humans place a stress on the existing fauna and flora; second, they import competing or exotic species that undermine the existing ecology, particularly in geophysically constrained island settings (see Chap. 12 for a good example). Caves can act as refugia for some species (as discussed in Chap. 5), and thereby assume significant ecological importance on islands and in submerged continental karst (Bakran-Petricioli and Petricioli 2008), requiring site-specific resource protections.

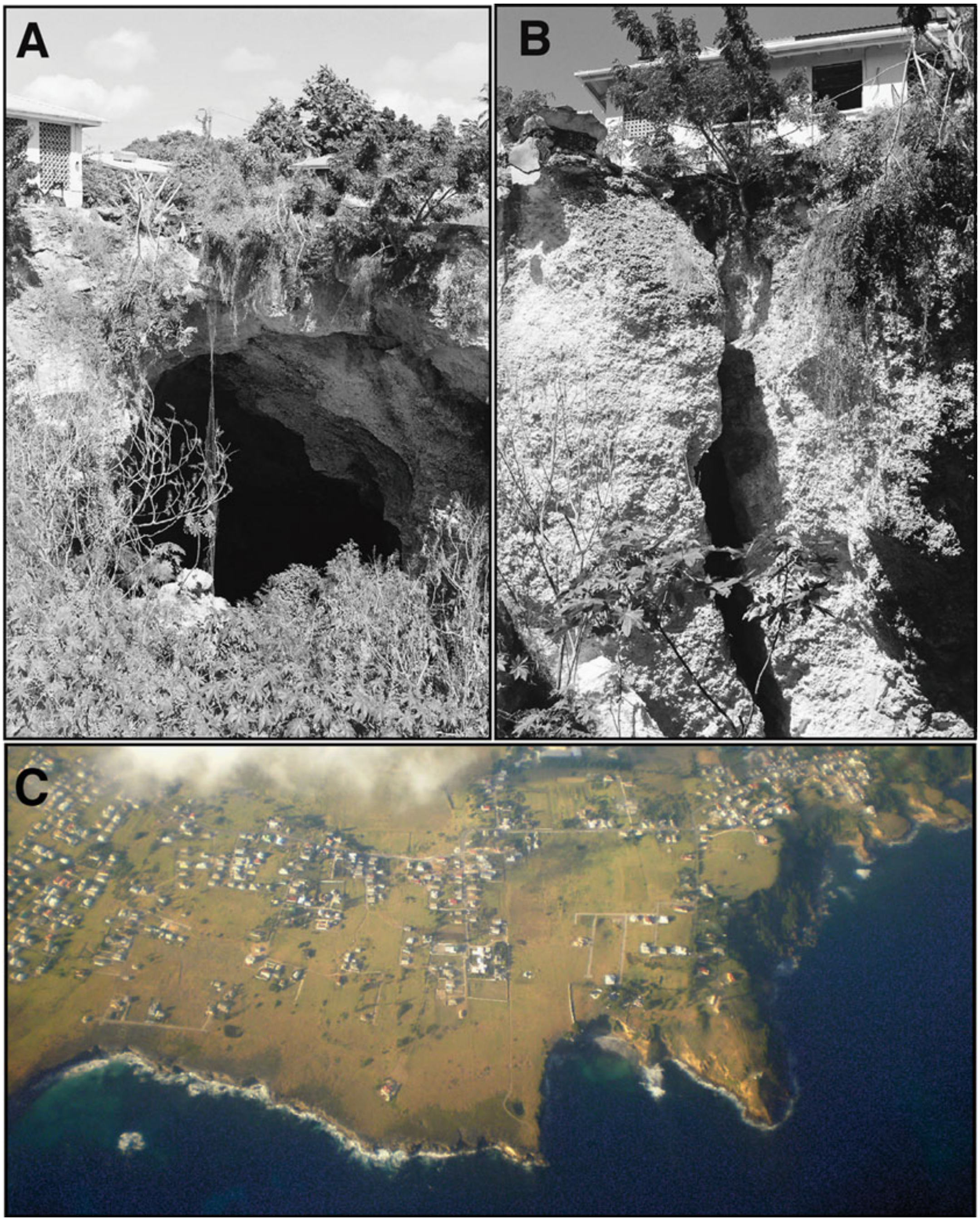


Fig. 6.7 (**a**, **b**) Impacts of coastal karst instability on Barbados. (**c**) Development on a karstic coastal terrace Barbados

6.3 Additional Examples of Karst Management and Resource Utilization in Coastal Settings

6.3.1 Barbados: The Arch Cot Collapse

Similar to other carbonate-overlain islands in the Caribbean region, Barbados is composed of series of well-defined uplifted reef terraces. Each of these carbonate escarpments has been found to be intensely karstic with dense dissolutional cave development expressed as a variety of cave structures. As similarly illustrated in the coastal limestone escarpments of Puerto Rico (Chap. 9), construction on such terraces on Barbados is widespread with the concomitant risk of geologic instability (Chap. 10). In August of 2007, a catastrophic collapse of a large cave segment directly beneath a residential area (Fig. 6.7) resulted in complete structural failure of a residence built above the main chamber and the tragic loss of a family of five. The immediate area has since been evacuated in the wake of continuing karst landscape instability.

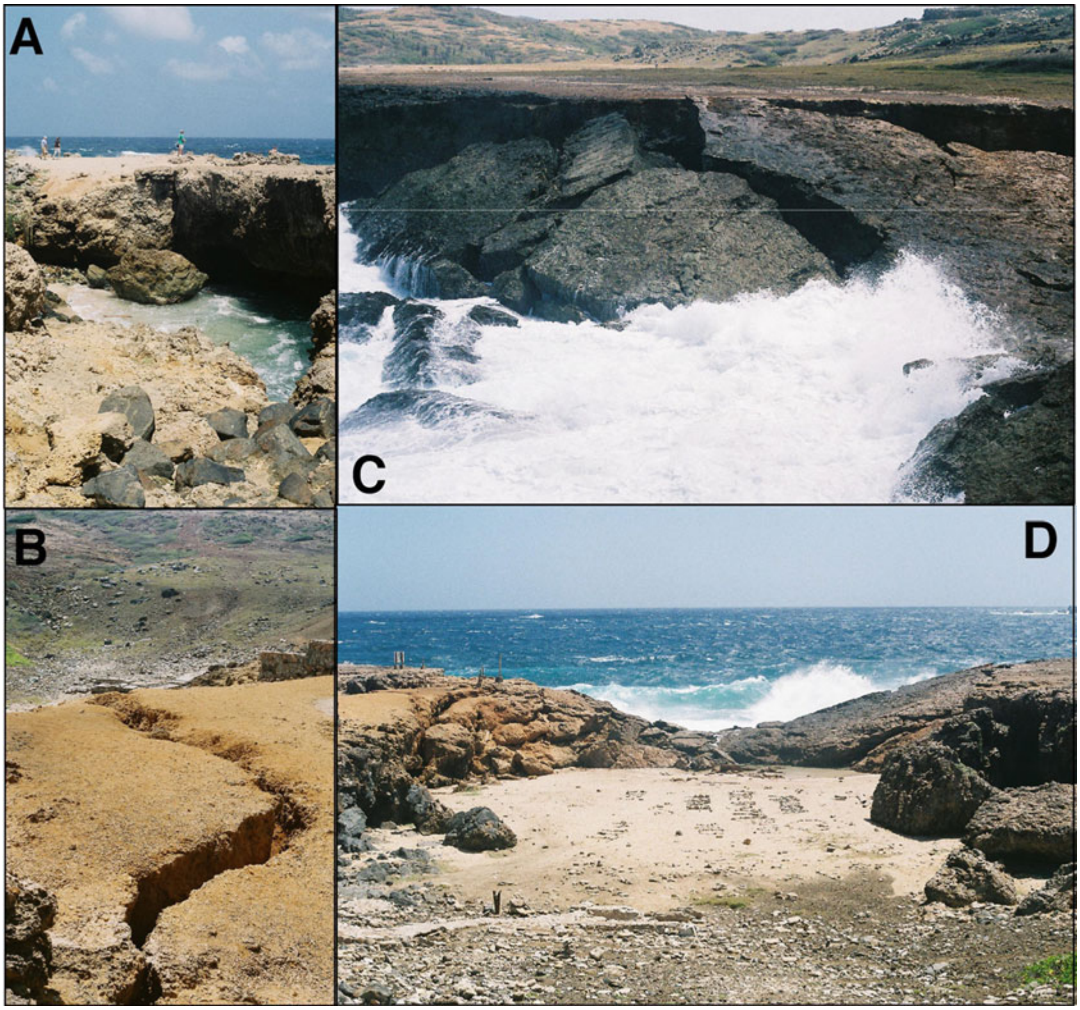


Fig. 6.8 Natural Bridge of Aruba. (**a**) A residual cave and natural bridge structure. (**b**) Fissure development adjacent to collapse area. (**c**, **d**) Seaward and landward views of collapsed natural bridge

6.3.2 Aruba Natural Bridge: Structural Failure of a Coastal Landmark

Coastal karst landforms frequently function as important economic resources in terms of tourism development which is not surprising as coastlines the world over harbor some of the most stunning vistas. The Natural Bridge on the northern coast of Aruba (Andicuri Bay) was touted as one of the largest such structures in the Caribbean, spanning more than 40 m and standing 7 m above the energetic Atlantic surf; it continues to serve as a popular tourist destination. Formed within Pleistocene-aged coral limestone overlying loosely consolidated, weathered basalt, the structure collapsed on September 2nd, 2005 (Fig. 6.8). A similar collapse was also recently recorded at Waverly Beach Cave (New Zealand) in June of 2012. Fortunately, no injuries were associated with either event. A second Aruban bridge remnant (known as "The Baby Natural Bridge") adjacent to the former Natural Bridge remains intact however contemporary fissures (prominently visible in satellite imagery) have recently formed (Fig. 6.8b) within the segment of cliffline that once separated the two bridges, raising the potential of future instability and collapse events. This recurrent coastal structure (the "sea arch") has also been recorded on Curaçao (e.g. Sheta Boka), Barbados (Chap. 10) and other islands in the Caribbean region and elsewhere (Chap. 1). Evolution of this landform is consistent with emerging theories of coastal gully genesis (called "*bokas*" in the Netherlands Antilles and "*calas*" on Mallorca) which in many cases involve the complex interplay of fluvial incision intersecting preexisting dissolutional voids (or conversely, the creation of the incision allows mixing dissolution in the incision walls) formed by the freshwater lens within coastal limestone terraces (Fig. 6.9).

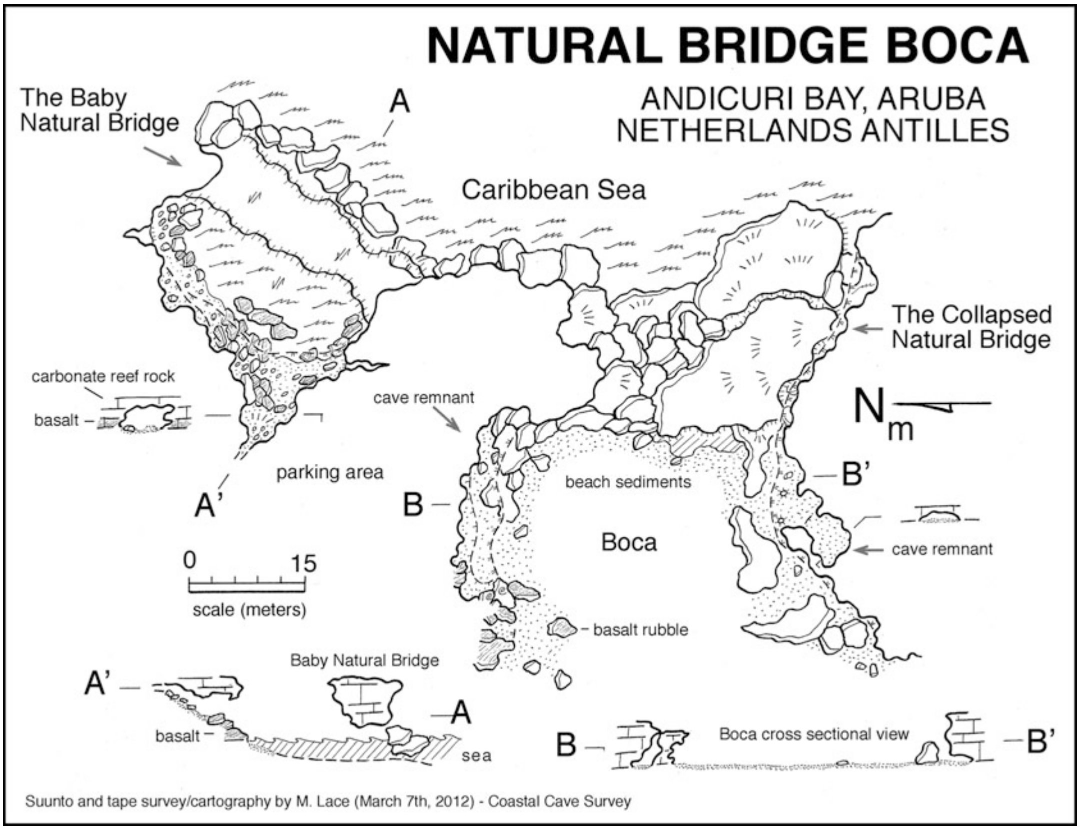
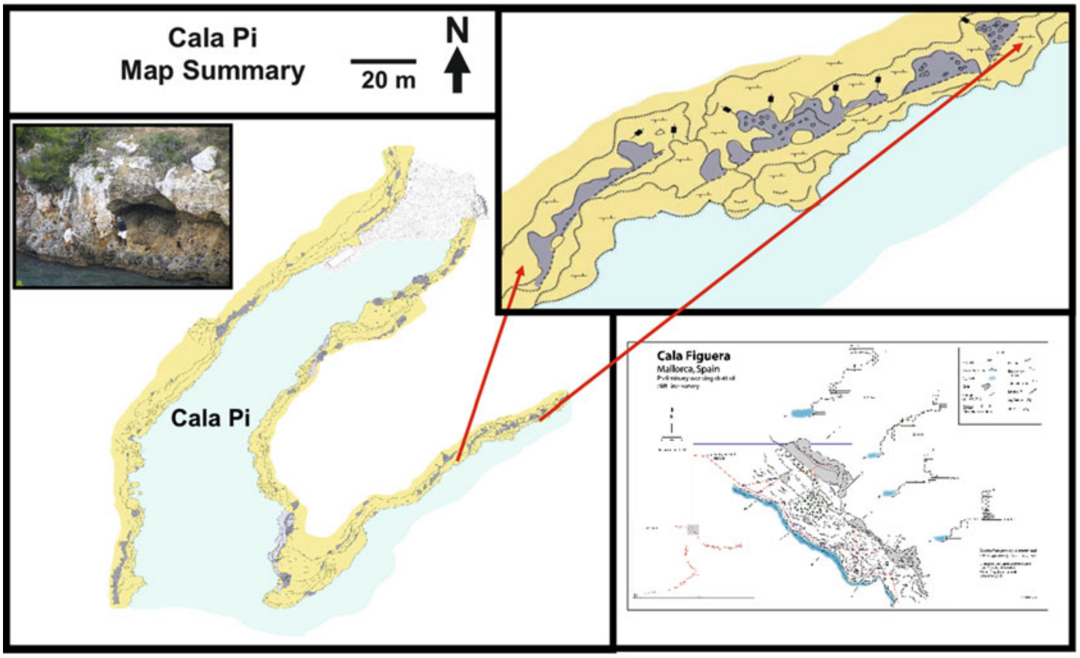


Fig. 6.9 Map of Natural Bridge (Aruba) and associated coastal landform



TOTAL CAVES: 63
EXPOSED: 12 Caves Area: 360 m² Volume: 716 m³
INTERIOR: 51 Caves Area: 1125 m² Volume: 3146 m³

Fig. 6.10 Coastal landform mapping and quantitative density analysis of void development (Mallorca, Spain)

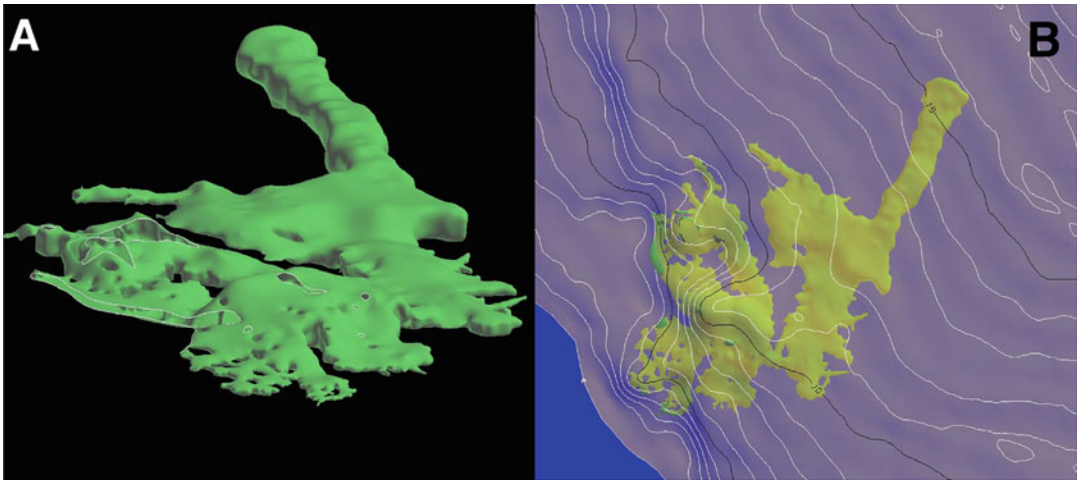


Fig. 6.11 (**a**) Computer generated 3D map of Salt Pond Cave, Long Island, Bahamas, with (**b**) a topographic contour overlay of associated coastal landform (Lascu 2005)

6.3.3 Mallorcan Coastal Karst: Applied Modeling of Void Development in Coastal Karst

The eogenetic coastal karst of the Balearic Islands is associated with complex patterns of speleogenesis, coastal aquifer structure and associated land uses (Chap. 13). In addition to geologic stability assessments, coastal karst landform mapping and quantitative analysis of associated void development can be applied to the study of speleogenetic processes (as discussed in Chap. 4) and to modeling petroleum reservoir structure and porosity preserved within deeply buried carbonates, as illustrated in the following example from the Mallorcan coast.

Analysis of cave development associated with protected coastal inlets (i.e. "calas") composed of Messinian-Tortonian carbonate cliffs was used to define speleogenetic controls within a differential coastal cliff retreat model (Mylroie et al. 2012). Several geophysical criteria were incorporated into a quantitative assessment of void development on varying scales (Fig. 6.10). The approach further supported 3D modeling of macroporosity and microporosity of preserved structures within deeply buried carbonate reefs associated with petroleum reservoirs, similar to mathematical modeling of flank margin cave development reported by Labourdette et al. (2007) and Lascu (2005) (Fig. 6.11). Thus, eogenetic coastal karst can serve as a quantitative model for diagenetically mature paleo-coastal structures with implications for petroleum resource utilization.

In summary, coastal karst landforms present significant and complex challenges to effective management, resource utilization and preservation. Inherent to any sustainable approach is the need for a detailed conceptual and practical understanding of coastal karst processes borne of detailed exploration and documentation of these evolving landscapes.

References

Bakran-Petricioli T, Petricioli D (2008) Habitats in submerged karst of the eastern Adriatic coast – Croatian national heritage. Croat Med J 49:455–458

Bear J, Cheng A, Sorek S, Oazar D, Herrera I (eds) (1999) Seawater intrusion in coastal aquifers: concepts, methods and practices, vol #14, Theory and applications of transport in porous media series. Springer-Verlag, New York

Bonacci O, Roje-Bonacci T (1997) Sea water intrusion in coastal springs: example of the Blaz spring, Croatia. Hydrolog Sci J 42(1):89–100

Brommer MB, Bochev-van der Burgh LM (2009) Sustainable coastal zone management: a concept for long-term and large-scale coastal evolution. J Coastal Res 25(1):181–188

Clark JR (1996) Coastal zone management handbook. CRC Press, Boca Raton, 694 p

Cooper J, Pilkey AG, Orrin H (2012) Pifalls of shoreline stabilization. Coastal research library series, vol 3. Springer Publishing, Dordecht, 131 p

CRSTD (2008) Development of a strategic business management model for the sustainable development of heritage tourism products in the Caribbean. Caribbean regional sustainable tourism development programme report, Barbados, 102 p

Davis RL, Johnson CR (1989) Karst hydrology of San Salvador. In: Mylroie JE (ed) Proceedings of the fourth symposium on the geology of the Bahamas. Bahamian Field Station, Port Charlotte, pp 73–81

Emery K, Kuhn G (1982) Sea cliffs: their processes, profiles and classification. Geol Soc Am Bull 93(7): 644–654

ESRI (2007) GIS for caves and karst. GIS best practices. www.esri.com/library/bestpractices/caves-karst, 51 p

Farrell D, Boyce S (2007) Water resources management in coastal aquifers in the Caribbean. Eos. Trans. AGU proceedings 88(23), Jt. Assembly Supplement (abstract HS1F-03)

Finkl CW (2004) Coastal classification: systematic approaches to considering the development of a comprehensive scheme. J Coastal Res 20(1):166–213

Finkl CW (2013) Coastal hazards, Coastal research library series. Springer, Dordrecht, 800 p, (in press). ISBN 978-94-007-5233-7

Fitzpatrick SM, Kappers M, Kate Q (2006) Coastal erosion and site destruction on Carriacou, West Indies. J Field Archaeol 31(3):251–262

Fleury P, Bakalowicz M, de Marsily G (2007) Submarine springs and coastal aquifers: a review. J Hydrol 339:79–92

Gillieson D (1996) Caves: processes, development and management. Blackwell Publishing, Malden, 324 p

Green DR (2009) Coastal zone management. Telford Publishing, London, 392 p

Gurnee RH (1967) Conservation through commercialization: Rio Camuy development project. B Natl Speleol Soc 29(2):27–71

Harff J, Hay WW, Tetzlaff DM (2007) Coastline changes: interrelation of climate and geological processes. Geol Soc Am Spec Pap 426, 214 p

Harmon RS, Wicks CM (eds) (2006) Perspectives on karst geomorphology, hydrology and geochemistry: a tribute volume to Derek C Ford and William B White. Geological Society of America, Boulder, 306 p

Haslett SK (2009) Coastal systems. Taylor and Francis Publishing, Routledge, 216 p

Huppert GH, Burri E, Forti P, Cigna A (1994) Effects of tourist development on caves and karst. Cave Conservationist 13(3):13–22

Jocson JMU, Jenson JW, Contractor DN (2002) Recharge and aquifer responses: Northern Guam lens aquifer Guam, Mariana Islands. J Hydrol 260:231–254

Jones WK, Hobbs HH, Wicks CW, Currie RR, Hose LD, Kerbo RC, Goodbar JR, Trout J (2003) Recommendations and guidelines for managing caves on protected lands, Special publication no. 8. Prepared for the National Cave and Karst Research Institute, National Park Service. Karst Waters Institute, 81 p

Kueny J, Day MJ (2002) Designation of protected karstlands in Central America: a regional assessment. J Cave Karst Stud 64(3):164–174

Kunze AWG, Mylroie JE (1991) Use of gravity techniques to detect shallow caves on San Salvador Island, Bahamas. In: Bain RJ (ed) Proceedings of the 5th symposium on the geology of the Bahamas. Bahamian Field Station, Port Charlotte, pp 139–149

Labourdette R, Lascu I, Mylroie JE, Roth M (2007) Process-like modeling of flank margin caves: from genesis to burial evolution. J Sediment Res 77: 965–979

Lascu I (2005) Speleogenesis of large flank margin caves of the Bahamas. M.Sc. thesis. Department of Geosciences, Mississippi State University, Mississippi State, 218 p. http://library.msstate.edu/etd/show.asp?etd=etd-05102005-132949

MacCracken RS, Jenson JW, Heitz LF, Rubenstein DH, Mylroie JE (2007) Water resources analysis of Fais Island, Federated States of Micronesia. Technical report no. 111, Water and Environmental Research Institute of the Western Pacific, University of Guam, p 41

McConney P, Pomeroy R, Mahon R (2003) Guidelines for coastal resource co-management in the Caribbean: communicating the concepts and conditions that favour success. Caribbean Conservation Association (CCA), 55p

Metcalfe CD, Beadows PA, Gold Bouchot G, Metcalfe TL, Li H, van Lavieren H (2010) Contaminants in the coastal karst aquifer system along the Caribbean coast of the Yucatan Peninsula, Mexico. Environ Pollut 159:991–997

Migon P (ed) (2010) Geomorphological landscapes of the world. Springer publishing, Dordrecht, 375 p

Moran DC, Jenson JW (2004) Dry trace of groundwater from Guam International Airport and Harmon Sink to Agana Bay and Tumon Bay. Water & Environmental Research Institute of the Western Pacific, University of Guam technical report 9

Mylroie JE, Carew JL, Vacher HL (1995) Karst development in the Bahamas and Bermuda. In: Curran HA, White B (eds) Terrestrial and shallow marine geology of the Bahamas and Bermuda, Geological Society of America, Boulder, special paper no. 300. Geological Society of America, Boulder, pp 251–267

Mylroie JE, Mylroie JR, Jenson JW, MacCracken RS (2008) Fresh-water lens anisotropy and flank margin cave development Fais Island, FSM. In: Freile D, Park L (eds) Proceedings of the 13th symposium on the geology of the Bahamas and other carbonate regions, pp 135–139. Reprinted in speleogenesis and evolution of karst aquifers, 2011, Issue 11. http://www.speleogenesis.info/content/

Mylroie JE, Mylroie JR, Kambesis PN, Lace MJ, Larson EB, Owen AM, Sumrall JB (2012) Quantitative description and coastal mapping of flank margin caves on Mallorca island, Spain. Geologia, special issue. In: Onac BP, Fornos JJ (eds.) Proceedings of the National Science Foundation workshop. Sea level changes in MIS 5E, from observations to predictions. Palma de Mallorca, Spain, pp 42–44

Vacher HL (1988) Dupuit-Ghyben-Herzberg analysis of strip-island lenses. Geol Soc Am Bull 100:223–232

Vacher HL, Mylroie JE (2002) Eogenetic karst from a perspective of an equivalent porous medium. Carbonate Evaporite 17:182–196

Van Beynen PE (ed) (2011) Karst management. Springer Publishing, Dordrecht, 489 p

Van Beynen PE, Brinkman R, Van Beynen K (2012) A sustainability index for karst environments. J Cave Karst Stud 74(2):221–234

Wallis TN, Vacher HL, Stewart MT (1991) Hydrogeology of the freshwater lens beneath a Holocene strandplain Great Exuma, Bahamas:. J Hydrol 125: 93–100

Watson J, Hamilton-Smith E, Gillieson D, Kiernan K (1997) Guidelines for cave and karst protection. WCPA Working Group. IUCN – the World Conservation Union. Gland, Switzerland and Cambridge, UK, 63 p

Werker V, Werker J (2006) Cave conservation and restoration. National Speleological Society, Huntsville, 600 p

White WB (1988) Geomorphology and hydrology of karst terrains. Oxford University Press, New York

White S, White N, Middleton G (2006) Report of findings on the proposed Iralalaro hydro-electric power scheme, Timore-Leste. Report submitted by the Haburas Foundation and the Australian Conservation Foundation, 65 p

Wilson WL, Mylroie JE, Carew JL (1995) Quantitative analysis of caves as a geologic hazard, San Salvador Island, Bahamas. In: Proceedings of the 7th symposium on the geology of the Bahamas and other carbonate regions. San Salvador, Bahamas, pp 103–121