# Introduction to Bermuda: Geology, Oceanography and Climate

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## Geographic Location and Setting

Bermuda is a subtropical island group in the western North Atlantic (Fig. 10.1a). A peripheral annular reef tract surrounds the islands forming a mostly submerged 26 by 52 km ellipse at the seaward rim of the eroded platform (the Bermuda Platform) of an extinct Meso-Cenozoic volcanic peak (Fig. 10.1b). The reef tract and the Bermuda islands enclose a relatively shallow central lagoon so that Bermuda is atoll-like. The islands lie to the southeast and are primarily derived from sand dune formations. The extinct volcano is drowned and covered by a thin (15–100 m), primarily carbonate, cap (Vogt and Jung 2007; Prognon et al. 2011). This cap is very complex, consisting of several sets of carbonate dunes (aeolianites) and paleosols laid down in the last million years (after Prognon et al. 2011, with reference to Vacher and Rowe 1997) (Fig. 10.2).

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Located at 32.4°N and 64.8°W, Bermuda lies in the northwest of the Sargasso Sea. It is isolated by distance, deep water and major ocean currents from North America, sitting 1,060 km ESE from Cape Hatteras, and 1,330 km NE from the Bahamas. Bermuda is one of nine ecoregions in the Tropical Northwestern Atlantic (TNA) province (Spalding et al. 2007).

Bermuda's national waters include pelagic environments and deep seamounts, in addition to the Bermuda Platform. The Bermuda Exclusive Economic Zone (EEZ) extends approx. 370 km (200 nautical miles) from the coastline of the islands. Within the EEZ, the Territorial Sea extends ~22 km (12 nautical miles) and the Contiguous Zone ~44.5 km (24 nautical miles) from the same baseline, both also extending well beyond the Bermuda Platform.

## Geography, Settlement and Early Economies

Of more than 150 islands and islets only six are of any size, and these are connected by causeways and bridges to form a narrow fish hook-shaped island chain 34 km in length and 1.6 km in average width (3 km at the widest). The main islands have a land area of 53.6 $km^2$ and a shoreline of about 290 km (State of the Environment Report 2005). Approximately 66% of this land area is built upon.

Bermuda consists of a series of low rolling hills, generally with heights only 40–50 m above sea-level and a maximum of 79 m (State of the Environment Report 2005). Natural flat areas are absent except at a few sea-level marshlands in the middle. There are no rivers, streams, or freshwater lakes due to the very permeable limestone cap. Rain, collected from roof tops and stored in tanks, is the principal source of drinking water.

Bermuda was not populated prior to its inhabitation by the British. In 1609 the *Sea Venture* on its way to Jamestown, Virginia from Plymouth, England wrecked on Bermuda's eastern coral reefs, unintentionally delivering Bermuda's first colonists. Only two of the castaways remained on the

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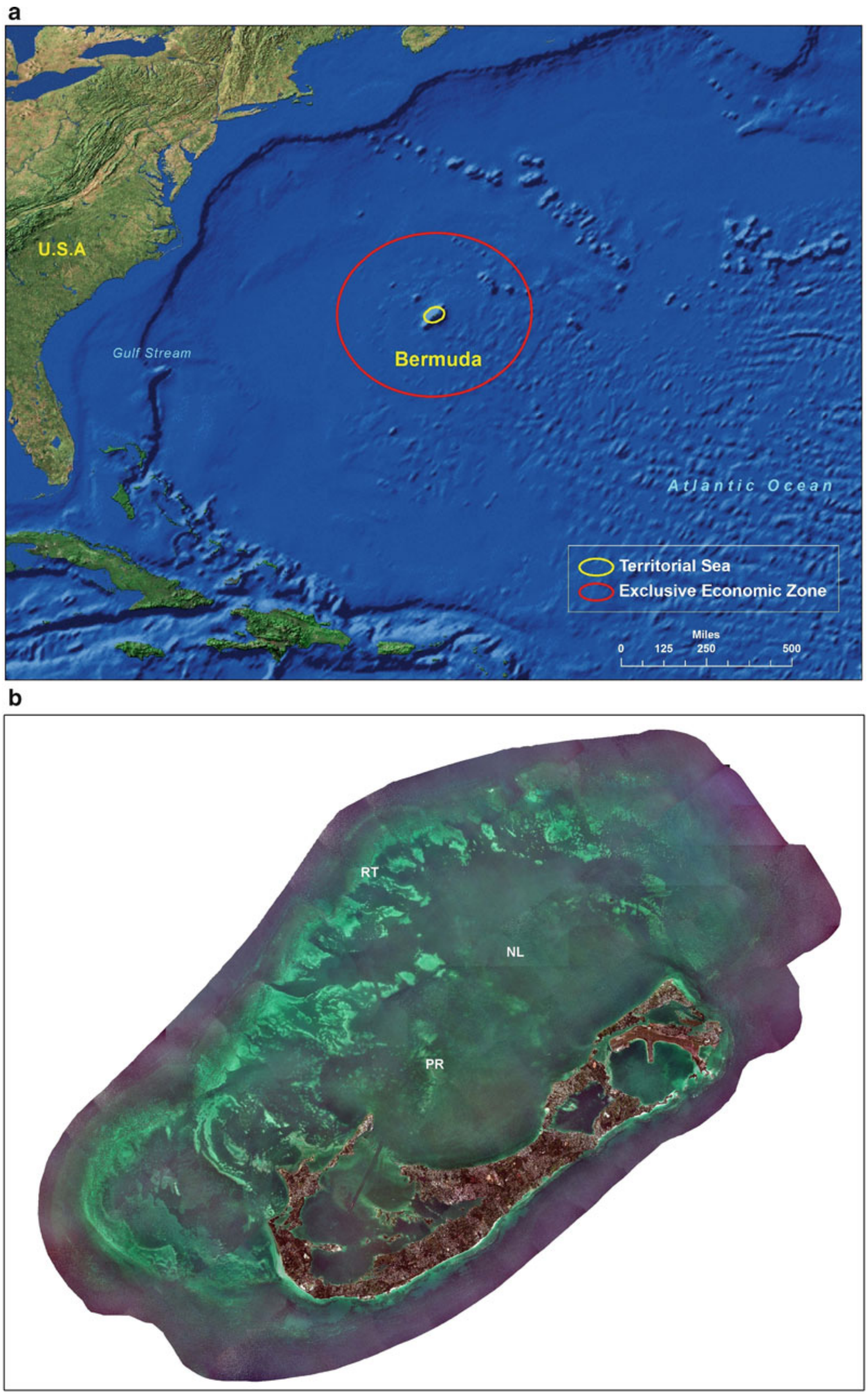


**Fig. 10.1** (**a**) Location of Bermuda in the western North Atlantic; the Bermuda EEZ extends over the Bermuda Rise, and includes the deeply submerged Crescent Seamount to the NNW and Muir Seamount to the NNE. (**b**) The Bermuda Platform. Aerial photograph from 1997 (Copyright Bermuda Zoological Society) showing details to approx. 10 m depth; the islands lie parallel to the south-eastern edge of the Platform and a reef tract bounds the whole Platform (RT). Numerous coral patch reefs (PR) occur in the North Lagoon (NL); these are separated by sandy bottom at depths up to 23 m. Images are oriented with North to the top

**Fig. 10.2** Aeolianite strata exposed along the South Shore of Bermuda

islands when the Bermuda built boats *Deliverance* and *Patience* set sail for Virginia in 1610. The first formal settlers, approximately 50, arrived from England in 1612. Today the population is about 64,000 (Bermuda Census 2010), with a population density of nearly 1,195 persons per km$^2$, one of the ten highest country-wide densities in the world, but still only a fraction of that of many similar-sized metropolitan areas. Early inhabitants mainly pursued maritime occupations but by the late 1800s agriculture had grown in importance (Hayward 1924) and later still tourism became the pillar of Bermuda's economy. The tourist industry peaked in 1980 (State of the Environment 2005) but now international business, including a wide variety of financial services, has become the mainstay of the economy. There are a few small manufacturing industries in Bermuda that cater primarily to locals.

There were 206 licensed commercial fishing vessels and 307 registered fisherman in 2011 (T. Trott, pers. com.). These fish primarily on the Bermuda Platform or along its edge although a very few venture further offshore. Baited lobster traps are deployed in-season but other nearshore fisheries primarily employ hook and line, with very limited long-lining. Nets are used primarily in shallow waters for the capture of bait fishes. Catches are discrete for the most part and there is little by-catch, although lobster traps seem to be effective for the capture of the invasive lion fishes. There is no fishery associated large-scale bottom destruction, such as would occur with bottom trawls. Anchor damage at highly frequented fishing sites has not been investigated.

Agriculture declined in importance during the first century of settlement, followed by a recovery based on different products and different markets in the mid 1800s, and there was an economically important production of exports into the early 1900s. However, since the 1940s, production has been primarily for local consumption, nonetheless about 90% of fresh produce is imported (State of the Environment Report 2005). Only a small portion of the island is under cultivation, with about 178 ha of arable fields or pastures designated, of which only 154 ha were being farmed commercially in 2001. Golf courses cover a greater area, 260 ha, and landscaped properties and playing fields total 669 ha. Fertilizers and pesticide use on all of these add to the nutrients and toxins that move into ground water and into the sea (State of the Environment Report 2005). Most foods are imported, as is all fuel and almost all other manufactured goods. Energy production is virtually all based on fossil fuels, but supplementation by solar and wind is beginning to be employed by a very few individuals and proposals are under development in 2012 for commercial-scale alternate energy supplies.

## Geology

Bermuda has a complex history of volcanism. The Bermuda Pedestal is the subaerially eroded stump of a shield volcano formed during middle Eocene (less than 45 mya) and early Oligocene (33–34 mya) volcanic episodes (Vogt and Jung 2007).

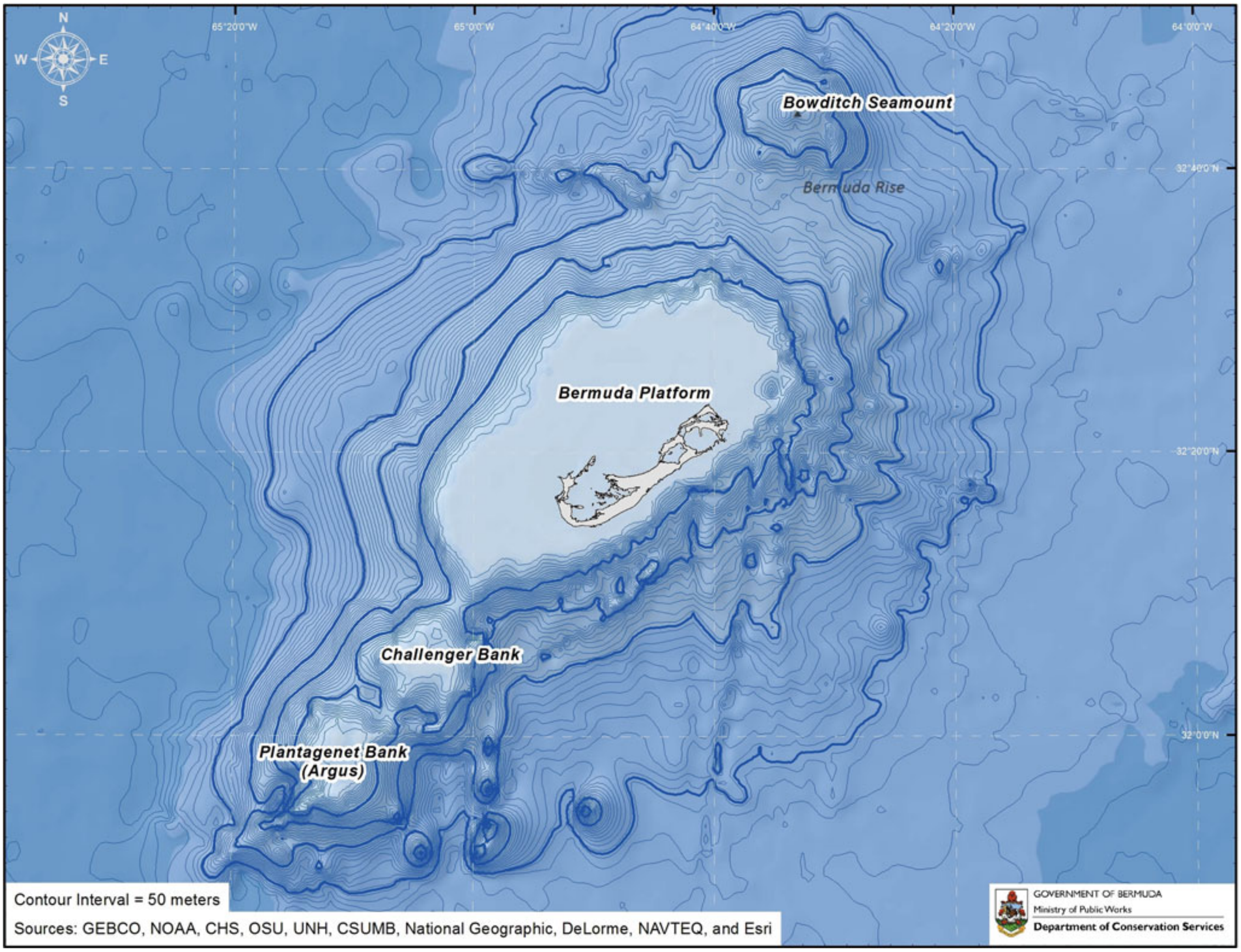


**Fig. 10.3** Bathymetry of the Bermuda Pedestal and nearby seamounts; Plantagenet and Challenger to the southwest have relatively shallow platforms, about 50 m deep, which support photosynthetic organisms; Bowditch to the northeast is a deeply submerged volcanic peak

On the top of the eroded stump, or Pedestal, is the Bermuda Platform.

Bermuda is one of a line of four associated volcanos that runs NE over approximately 100 km. This line is located near the summit of the Bermuda Rise, a NE-trending oval swell of the ocean bottom, about 1,500 km long and 500–1,000 km wide, which at its summit rises about 800 m above the surrounding deep sea bottom (see Vogt and Jung 2007 and references therein). Although the volcanos were extinct by the early Oligocene, uplift of the Bermuda Rise continued into the Miocene, thus the overall uplift of the volcanos also continued into this period.

Bermuda is the largest and highest of the four volcanoes (Vacher and Rowe 1997) (Fig. 10.3). To the southwest of Bermuda are Plantagenet (also called Argus; Plantagenet has also been used for Irving Seamount) and Challenger Banks (or tablemounts). These were also eroded subaerially and have relatively flat and shallow (but fully submerged) platforms. They are located about 41 km and 27 km respectively from Bermuda and rise to within about 47 m and 42 m respectively of the sea surface. The fourth volcano, Bowditch Seamount, lies about 39 km NNE of the Bermuda Platform and ascends only to about 600–800 m below the sea surface (Seamount Biogeosciences Network 2012).

The platforms of Plantagenet and Challenger, lie at depths of about 50 m and have areas of 65.6 km$^2$ and 74.1 km$^2$, respectively. There is a sharp change in slope at about 60–70 m depth to the steepening slopes of the underlying seamounts. The platforms and upper slopes are shallow enough to support photosynthetic communities including zooxanthellate cnidarians (Cairns 1979; Calder 2000) and algae, which have been found as deep as about 137 m (SRS, pers. obs.; http://oceanexplorer.noaa.gov/explorations/11bermuda/).

Bermuda has the shallowest platform, at about 20 m, with the greatest platform area, about 623 km$^2$. Water depths in the central lagoon are 14–16 m at many sites, with a maximum depth of 23.9 m in one of the sounds. Around the rim, the 20–22 m isobath (Iliffe et al. 2011) separates the broad

**Table 10.1** Classification of 90 tropical cyclones passing within 333.4 km (180 nautical miles) of Bermuda in the years 1899–1979. Intensity values are maximum sustained centre winds at the time of closest approach to Bermuda, here converted from knots to kilometers per hour (After Brand 2009)

| Maximum intensity | May to July | Aug | Sept | Oct–Nov | Totals |
|---|---|---|---|---|---|
| Hurricane (>118 kph) | 2 | 7 | 26 | 14 | 49 |
| Intense tropical storm (89–117 kph) | 0 | 1 | 5 | 8 | 14 |
| Weak tropical storm (63–88 kph) | 1 | 1 | 6 | 8 | 16 |
| Tropical depression (<63 kph) | 2 | 1 | 2 | 6 | 11 |
| Totals | 5 | 10 | 39 | 36 | 90 |

upper terrace of the Platform from a distinct seaward slope, rarely exceeding 10°. This shallow slope is followed by a markedly steeper slope commencing at about 55–65 m depth, which descends to almost vertical walls at about 100 m. A ridge, possibly a drowned reef, occurs at about 60 m (Stanley and Swift 1968; Iliffe et al. 2011).

## Bermuda Climate and Marine Environment

### Meteorology and Climate

The atmospheric pressure gradient over the western North Atlantic, the Gulf Stream that flows to the west of the island, and the prevailing conditions of the Sargasso Sea (Steinberg et al. 2001) strongly influence Bermuda's climate. Bermuda has a subtropical marine environment and climate despite its temperate latitude, experiencing relatively mild winters and moderately warm summers. Sea surface temperatures closely track air temperatures. Mean annual rainfall is about 1,410 mm, the driest months being April, May, and November and the wettest, on average, is October.

Tropical cyclones approach most years; indeed the initial colonizing of Bermuda relates to the survivors of one such storm in 1609 (Brand 2009). "Hurricane" season in Bermuda is officially June through November, with peak frequency being September and October (Neumann et al. 1985; Brand 2009). September storms are both the most numerous and the most intense (Brand 2009) (Table 10.1). Between 1871 and 1979, Neumann et al. (1985) report 127 storms passing within 333 km (180 nautical miles) of Bermuda, an average of more than one storm each year, of which, 49 were hurricane force, for an average of just more than one hurricane every second year.

Tropical cyclones typically approach Bermuda from the south or southwest (about 52% of storms for the period 1871–1979) and about 88% of all tropical storms approach from the west through the southeast (Brand 2009). Many of these have the strongest winds in their northwest quadrant, thus a passage to the east can have very different impacts than one to the west. Due to the common direction of approach and to the distribution pattern of reefs on the Bermuda platform, long period swells moving ahead of these storms have their highest impact on the southeastern coastline, where the breaking reefs are nearest shore (Smith Warner International 2004); these swells can exceed 10 m in height. To the west and north, breaking reefs lie far from shore, and lagoonal patch reefs further attenuate wave energy and reduce impacts on coastal areas. Maximum storm surge is usually less than 1.5–2 m, but wave energy and heights increase as waves move across shallow flats. Observations after recent storms suggest that the coral reefs, dominated by massive colonies of *Diploria* spp and *Montastraea* spp, do not show much direct wave damage (SRS, pers. obs.). Extreme weather events in summer can also bring heavy, prolonged, rainfall.

Incident solar radiation shows a large annual range. For the years 1983–2005 monthly means ranged from about 2.53 kW h $m^{-2}$ $day^{-1}$ in December to 7.03 kW h $m^{-2}$ $day^{-1}$ in July (NASA 2010). Day length is approximately 14.3 h at the summer solstice and only 10.0 h at the winter solstice and cloud cover is greatest from November to April, with overcast skies (7/8 obscured) on 35–45% of days, compared to only 15–20% of summer days (Morris et al. 1977).

### Tidal and Oceanographic Features

Bermuda experiences semi-diurnal tides, with mean range of ~0.76 m and a mean diurnal range of ~0.86 m (NOAA Tides and Currents 2012 http://www.tidesandcurrents.noaa.gov/geo.shtml?location=2695540). Mean daily differences are 0.02 m and 0.08 m, respectively. Tide heights are infrequently affected by the slow passage of mesoscale-eddies that can elevate or attenuate tidal heights by 25 cm (Seigel et al. 1999; McGillicuddy et al. 2007). Harrington Sound, an enclosed body of water with a single, restricted, surface entrance has incomplete tidal loading and unloading resulting in a reduced tidal range of about 0.20–0.25 m (Morris et al. 1977) and delays in maximum tide levels of about 30 min.

Morris et al. (1977) calculated current speeds for a number of entry points into largely enclosed waters; these were all about 5–103 cm $sec^{-1}$ (except at the entrance to Harrington Sound, with a maximum of 448 cm $sec^{-1}$ and an average of about 215 cm $sec^{-1}$). Measured coastal and North

Lagoon current speeds were mostly 3–9 cm $sec^{-1}$ and rarely greater than 15 cm $sec^{-1}$ (Simmons and Johnson 1993). Current speeds on outer rim reef sites of the North Shore are typically 8–10 cm $sec^{-1}$ but exceeded 25 cm $sec^{-1}$ under winter storm conditions (Badgley et al. 2006). At a South Shore reef site measured current speeds were typically less than 15 cm $sec^{-1}$. There was no clear indication of predominant tidal forcing of surface currents at all the sites investigated by Simmons and Johnson (1993) and flow at some offshore sites was largely unidirectional. At the South Shore site currents also were not predominantly tidally influenced (Marine Environmental Program 2007).

## Marine Physical Environment

The oceanography of the surrounding Sargasso Sea has been well characterized by a series of long term studies of physical, chemical and biological processes at National Science Foundation funded HydroStation S and the Bermuda Atlantic Time Series (BATS) site further offshore (Steinberg et al. 2001).

Since 2006 and the initiation of the Bermuda Benthic Mapping, Monitoring and Assessment Program (BMMAP), more than 17 sites on the Bermuda platform are monitored continuously for sea bottom temperature and other parameters, including oxygen concentration and saturation, *p*H, chlorophyll a, and various nutrients, were measured monthly until September 2012 (Boyer and Briceno 2010; KAC, JWF, WJK, SAM, unpub. obs.).

### Sea Surface Temperature

The open water around Bermuda has an average annual sea surface temperature about 23°C (Locarnini et al. 2006) and average monthly minima and maxima of 19.2°C in March and 27.4°C in August, respectively; maximum surface temperatures range as high as 29°C (Steinberg et al. 2001). Mean annual surface water temperature on the Platform is similar but the extreme temperature range is greater, from 14°C to 15°C during winter to 30–31°C in summer, although the surface water temperature over the rim reefs rarely exceeds 29°C (Marine Environmental Program 2007; Boyer and Briceno 2010).

Temperature range variation across the Platform is biologically significant. From the rim to the shore, temperature extremes at the sea bottom increase and the annual range increases from about 12.5°C to about 17.5°C. Thus, inshore habitats experience a cold winter environment compared to offshore and mid-platform habitats, with low seawater temperatures extending over many weeks. Shallow inshore sites can also be warmer in summer, but the differences compared to rim sites are not as pronounced as those during winter months. Extreme summer weather events (hurricanes and tropical storms) cause rapid drops in sea water temperature through the entire water column of the whole platform but these changes are more extreme and long-lived at sites near the rim.

### Salinity

Surface salinities in the offshore waters near Bermuda range annually from about 36.3 to 36.7 (Practical Salinity Scale), with an average annual value around 36.5 (http://ourocean.jpl.nasa.gov/AQUARIUS; Thacker and Sindlinger 2007). Gordon and Guilivi (2008) suggest that sea surface salinity in the Sargasso Sea near Bermuda has been slightly elevated since 1988 (at least up until 2005) and that a relatively salty period also occurred in 1963–1969. Steinberg et al. (2001) report anomalously high-salinity (36.8) water was present in the upper ocean from January to August of 1997 and attribute this to locally driven excess evaporation over precipitation.

On the Bermuda platform salinities range from about 36.4 to 36.8 (Boyer and Briceno 2010; KAC. JWF. WJK, SAM, unpub. obs.), with irregularly occurring highs and lows to above 37 or below 36. Despite the absence of streams and rivers, rain on the islands strongly influences salinity at specific locations due to surface runoff, and these may regularly have salinities of less than 36, with an extreme known minimum of 33.9 (Marine Environmental Program 2007). No clear seasonal pattern in salinity values has been recognized for platform sites nor is there a clear difference from rim to inshore sites, although the latter may be more variable through the year.

### Dissolved Oxygen

Dissolved oxygen (DO) in the water column around Bermuda is high throughout the year with a mean % saturation of 108.4% (81.8–221.4%) (oxygen concentrations from about 5.29 mg $l^{-1}$ to 14.65 mg $l^{-1}$) (KAC, JWF, JWK, SAM, unpub. obs., http://serc.fiu.edu/wqmnetwork/Bermuda/Data1.html) between March 2007 to April 2011. Saturation levels are generally lower in the summer than winter and lower offshore than inshore, although shallow inshore sites have greater ranges. (A number of monitored inshore sites are shallow seagrass beds.) Seasonal (June through August) anoxia at Shark Hole in Harrington Sound at depths greater than 15–20 m has been reported for the past 45 years (Morris et al. 1977), and more recently hypoxia was recognized in Little Sound (Marine Environmental Program 2007; KAC, SAM, unpub. obs.) at bottom depths greater than 20 m. Saturation levels well below the Platform average have also been observed at shallower locations in the Great Sound during summer months.

### *p*H

Andersson and Mackenzie (2011) point out the importance of recognizing the variability of carbonate chemistry on shallow platforms. Surface seawater $CO_2$ chemistry in shallow water coastal areas is not predictable from air-equilibrium models and differs significantly from open ocean systems (Andersson and Mackenzie 2011). Many shallow water environments undergo large diurnal fluctuations in seawater chemistry associated with daily changes in benthic biological processes that produce and consume $CO_2$, such as photosynthesis/respiration and calcification/dissolution, as well as with water exchange owing to tidal cycles and changes in winds.

In 1976–1977, *p*H of the Sargasso Sea varied between 8.11 and 8.2 (Morris et al. 1977) and for the same period it was 7.94–8.23 at sites on the Platform, with a decrease in the summer related to increased water temperatures. Bates et al. (2010) indicate average *p*H is lower over coral reefs at the Platform rim (Hog Reef) than at nearby open water sites (BATS site; Bates et al. 2010). Some inshore sites have consistently lower *p*H than others, for example Harrington Sound compared to Great Sound; summer stratification in Harrington Sound may account for this difference (Morris et al. 1977; Andersson and Mackenzie 2011).

During daylight, the average *p*H of Platform waters is 8.06 (std. dev. 0.23; median 8.11), with a measured range from 6.67 to 8.74 (KAC, SAM unpub. obs., http://serc.fiu.edu/wqmnetwork/Bermuda/Data1.html). Surface *p*H at rim and lagoonal sites is generally less variable. There is no clear seasonal pattern, but 2010 was very different to either 2009 or 2011 at rim sites with *p*H below 8 measured on a number of dates.

### Light in the Water Column

The light environment varies with daily, seasonal and probably other temporal cycles (Siegel et al. 1995). Deep water around Bermuda generally has high water clarity; diffuse attenuation coefficient, $K_d$, values of 0.045, 0.070 and 0.080 $m^{-1}$ were reported by Morris et al. (1977). Siegel et al. (1995) report $K_d$ for 488 nm wavelength light, generally the most penetrating wavelength, of between 0.02 $m^{-1}$ and 0.05 $m^{-1}$ over the upper 200 m of the water column. For wavelengths about 400–600 nm, those higher than 500 had increasingly higher $K_d$ values (Siegel et al. 1995) and for shallower depths, up to 20 m, $K_d$ was higher from fall to spring than in summer months.

Earlier studies of Platform waters reported $K_d$ values ranging from 0.13 $m^{-1}$ to 0.56 $m^{-1}$ (Morris et al. 1977; McGlathery 1995). Recent studies (KAC, JWF, JWK, SAM, unpub. obs.) found summertime $K_d$PAR values from 0.025 $m^{-1}$ to 0.55 $m^{-1}$, with a median of 0.12 $m^{-1}$ ($n = 270$). The pattern from the rim to inshore waters is not a simple trend, and large areas of the North Lagoon, extending well into the lagoon, have on average lower $K_d$PAR than found over large areas of the north and east rim reefs.

### Nutrients

Concern about anthropogenic effects in the protected inshore water stimulated study of several parameters including nutrient levels and dynamics (Morris et al. 1977; Barnes and von Bodungen 1978; von Bodungen et al. 1982). These showed nitrogen loading in the restricted inshore basins (Jickells et al. 1986; Lapointe and O'Connell 1989; Simmons and Lyons 1994; Boyer and Briceno 2010) and some of these studies implicated contaminated groundwater (Jones et al. 2010).

## Geological History and Coral Reef Development

The maximum elevation of the Bermuda volcano, since its formation, was estimated as 2–4 km above sea-level (Pirsson 1914a, b; Vogt 1979), and it was the highest and the biggest volcano on the Bermuda Rise. Subaerial erosion to sea-level is estimated to have taken between 3 to 10 my (Vogt and Jung 2007); some of this may have occurred as early as the Middle Oligocene, about 30 mya, not long after the final periods of volcanic activity, for which period there is evidence of sea surface levels 50–75 m below present. Reef limestone began to accumulate on the eroded Platform somewhat more recently, probably in the Early Miocene (<25 mya). During the Miocene the global climate was moderately cool but by the Pliocene the earth was cooling and most of the accumulation of coral limestone on Bermuda is thought to have occurred during the Quaternary (Prognon et al. 2011) – a globally cold period. Coral limestone in Bermuda has been found as deep as 200 m below present day sea-level (Gees and Medioli 1970).

## Pleistocene History, Sea-level and Coral Reef Development

"For more than a decade it has been recognized that the sedimentary and fossil record of Quaternary coral reefs has the potential to help decipher the role of history in the study of living reefs …" (Precht and Miller 2007). Most recently, it has been hoped that history will provide insights into what appear to be pressing issues for reef management arising from global changes and threats to modern reefs, for example, understanding the recent precipitious decline of acroporids throughout the Caribbean.

Because of its history, the Bermuda Pedestal can serve as a stable benchmark to determine Pleistocene sea-level changes (Hearty 2002; Hearty et al. 2007; Vogt and Jung 2007) both through submerged and emergent features (Hearty and Olson 2011). Sea-level fluctuations during the Pleistocene must have driven the location and rate of coral reef development and of species diversity on the Bermuda Platform and Pedestal. In the early Pleistocene, sea-level repeatedly rose to about present day sea-levels and then fell to levels up to 200 m below present.

The Bermuda islands are formed from several sets of carbonate dunes (aeolianites) and paleosols, which record the main glacial/interglacial cycles from about 430 kya to the present (Prognon et al. 2011). Bermuda is on the fringe of the marine "carbonate belt", with many coral species having slower growth rates than their more tropical conspecifics, so that limestone sediments accumulate relatively slowly. Several thousand years of submergence of the Platform may be required for development of the store of sediments sufficient to build dunes of the size of the Pleistocene record. Such a deposition has not happened yet during the Holocene submergence, and Bermuda remains in an erosional period, losing land mass during each major storm (Smith Warner International 2004).

Other emergent deposits include isolated sublittoral and beach deposits that record sea-level high stands and shorelines; however there are no emergent reef formations or individual in situ coral fossils. The beach deposits do provide evidence of species that occurred around Bermuda at particular times, but not the exact locations or elevations at which the species were living. Emergent fossil coastline formations in Bermuda have been correlated by aminostratigraphy and radiometric dating to at least three marine oxygen isotope stages (MIS), MIS 11, 9 and 5e (Olson et al. 2006). Odd numbered MIS all relate to interglacial periods when sea-level highstands occurred and which were possibly globally warmer. MIS 11, 9 and 5e are all recognized in Bermuda as warmer-than-present periods when sea-levels were higher than present (Hearty and Kaufman 2000; Muhs et al. 2002). Maximum sea level heights during two of these stages, have been estimated for Bermuda at 18–22 m above present for MIS 11 (about 427 kya) and 10 m above present for MIS 5e (130–133 kya). The islands of Bermuda are supposed not to have been fully submerged for close to 1 my and MIS 11 is the most recent highest known sea level highstand.

The total range from a highstand to a subsequent lowstand (corresponding to evenly numbered MIS) would be significant to growth and survival of any reefs that became established during sufficiently long and stable sea-level periods. The extreme low stand of MIS 12 (period start about 474 kya) of about 120–130 m below present sea level to the extreme high stand at MIS 11 (period start about 424 kya), of > +20 m represents an extreme range for the Pleistocene and perhaps a period of rapid sea level rise. MIS 11 has long been recognized as one of the longer and warmer Quaternary periods (Olson and Hearty 2009).

The modern sea-level curve for Bermuda reflects a postglacial rise of sea-level that slowed in the last 5 ky and reached "present" sea-level in the past 0.5–2 ky, with no intervening highstands. The rise was about 3.7 m $ky^{-1}$ up to about 4,000 y BP, after which it rose at about 1 m $ky^{-1}$ to its present position. Sea-level rise has likely been at 1.43–2.8 m $ky^{-1}$ in the past 100 years (Ellison 1993; Pirazzoli 1987), greater than the rate of the past 4,000 years but less than in the early Modern Era.

Temperature has been considered the main control on reef distribution (Precht and Miller 2007) and temperatures during the last full interglacial period (MIS 5e) have been simulated using atmospheric general circulation models. Sea surface temperatures (Montoya et al. 1998) were inferred to have increased only ~1°C relative to present. Muhs et al. (2002) studies of molluscan and coral faunas dated to recent interglacials, MIS 3 and MIS 5, also suggest that temperatures were slightly warmer than in present-day Bermuda, based on the presence at those times of three extra-limital species, including the coral *Colpophyllia natans*.

During the last glacial maximum (LGM), which occurred about 18 kya, temperatures may have been between 1°C and 2.5°C (Crowley 2000; Trend-Staid and Prell 2002) or as much as 4°C or 5°C (Guilderson et al. 1994; Beck et al. 1997) lower than present. Nonetheless, Precht and Miller (2007; pp.263–264) indicate that temperatures … [in the subtropics were] … not low enough to terminate reef development during the [LGM].

## The Under-Pinnings of Modern Reefs

The relatively stable period in the first half of highest most recent interglacial sea-level highstand, MIS 5e, could have corresponded to the establishment of the fringing reefs and coastline terraces (Hearty et al. 2007) that underlie present day reef tracts. Apparently, Holocene reef growth covers any surviving remnants of these older reefs in shallow water. Shallow patch reefs (2–10 m depth) of the North Lagoon and deeper soft sediment basins (~15–18 m) correspond to Pleistocene topographic features (Kuhn et al. 1981; Logan 1988).

Data from 240 km UNIBOOM seismic tracts (12 tracts) indicated Pleistocene foundations underneath reefs along the northwestern through southwestern margins of the Platform, and under patch reefs in Castle Harbour, but not under those in Harrington Sound (D. Meischner pers. comm. to AL; 17/04/2012). Cores from a few of the patch reefs in Castle Harbour, down to the Pleistocene substrates, showed the same hermatypic growth forms as seen in Holocene reefs of Bermuda. The seismic sections showed Pleistocene reefs of similar dimensions and extension to the overlying Holocene breakers and it seems reasonable that a reef line similar to the Holocene one extends under the whole of the recent rim-reef. A few Th/U dates from cores taken of the Pleistocene rim reefs rendered values about 125 kya.

Reefs of glacial periods would be deep, submerged, reefs. Submersible studies along the north slope (near North

Rock) revealed little of fossil reefs with the exception of a few vertically incised channels that offer profiles of stacked Pleistocene formations down to 160 m, but "Submersible observations around the platform edge by Meischner (pers. comm. to AL) indicate the presence of a supposed Wisconsin-age reef beginning at about 110 m and resting on even older reefs which can be seen in gully walls through the rhodolith cover down to 200 m depth" (Logan 1988; p. 5). The last glacial period, and other transitional periods, may be evidenced by sea bottom profiles between 60 m and 120 m depth that are now being explored (Iliffe et al. 2011).

## Modern Reefs

Present broad reef zones are shown in Fig. 10.4. Bermuda has a fairly consistent diversity of coral species, representing a subset of those found in the greater Caribbean. However, species of *Colpophyllia* (Muhs et al. 2002) and *Cladocora* (Moore and Moore 1946), found as fossils, no longer occur in Bermuda. The predominant *Diploria-Montastraea-Porites* coral assemblage of the Caribbean also dominates Bermudian reefs. The genus *Acropora,* an important reef-builder in the Caribbean, is notably absent throughout the history of Bermuda.

The shallow system of rim reefs that borders the lagoon is formed primarily by either stony corals or by vermetid molluscs and coralline algae. The rim reef system is about 2–10 m deep and 1–1.5 km wide, and descends to the main terrace at about 20 m depth; below this terrace is the fore-reef slope with hermatypic corals extending to about 70 m. Scattered coral reef patches and coral communities occur within the North Lagoon and other inshore waters, intermixed with unconsolidated carbonate sediments. The coral patch reefs rise to within a few meters of the water surface. Coral communities that are spread across the Platform include meadows of seagrasses and extensive beds of calcareous green algae (KAC, JWF, WJK, SAM, unpub. obs.).

In surveys of the benthic habitats of the entire Bermuda platform, up to about 15–20 m outside the rim, soft corals and hard corals were found at 27.8% and 33.7% out of about 530 survey sites, respectively (Fig. 10.5a, b). Thus, roughly one third of the Platform is a coral community zone.

### Modern Reef Types and Their Communities

There are two major reef-building communities in Bermuda: a coral-algal consortium responsible for most of the reefs on and around the Platform (Fig. 10.6a) and an algal-vermetid consortium, found mainly around the edge of the Platform and particularly along the South Shore. Sea rods and sea fans (soft corals or octocorals) are very prominent members of most reef habitat around Bermuda, which can cover up to 50% of the bottom on coral reefs. Cover values for soft corals are lower along more exposed southeast facing reefs than on reefs to the north, east or west.

Logan (1988) provided a detailed account of coral reef zones of Bermuda, which is summarized below.

#### Fore-Reef Slope

Fore-reef slope coral-algal reefs occur outside the margin of the platform from 20 m to 50 m depth (Logan and Murdoch 2011). Constructional coral growth along the southwest side extends only to about 30 m (Meischner and Meischner 1977). Total coral coverage ranges from about 50% (20 m) to 25% (30 m) in the shallow part of this reef zone (Logan 1992); coral cover and species diversity are reduced below 40–50 m (Focke and Gebelein 1978; Fricke and Meischner 1985). The presence of mobile rhodolith fields below 50–60 m may prevent the establishment of coral reefs (Fricke and Meischner 1985). The deep fore-reef has not been studied extensively, but submersible dives and recent mixed-gas diving studies have described a distinctive, depauperate, hermatypic coral fauna to 60 m (Fricke and Meischner 1985). Isolated remnants of Pleistocene reefs and patches of lithified rhodoliths (rhodolites) support an association of *Montastraea cavernosa*, *Agaricia fragilis*, *Scolymia cubensis*, antipatharians, sponges and deep water octocorals. The deepest hermatypic coral observed was a specimen of *M. cavernosa* found at 78 m (SRS and T. Iliffe, unpub. obs.). The dominant corals from 20 to 30 m are large overlapping shingle-like or platy colonies of *Montastraea franksi* (Fig. 10.6b) and domal heads of *Diploria strigosa* and *M. cavernosa*. These species account for over 85% of the total coral coverage. The bottom is highly irregular, with holes of 1–2 m relief between coral colonies. Understorey species include *Porites astreoides* and *Diploria labyrinthiformis,* but overall coral diversity compared to inshore reefs is low (Logan 1992). Octocorals are common, as is the encrusting growth form of the hydrozoan *Millepora alcicornis*. There is high, but seasonal, coverage by species of the fleshy phaeophytes *Lobophora, Dictyota* and *Stypopodium* (Logan 1998).

#### Main Terrace

The main terrace of reefs extends from 10 m to 20 m depth, seaward from the rim reefs. A series of reef ridges, separated by sand channels and forming an anastomosing pattern, similar to spur-and-groove structure (Upchurch 1970), extends from a narrow sediment apron at about 5 m depth to a relatively flat terrace at 15–20 m, which then merges into the fore-reef slope (Fig. 10.6a). These ridges are particularly well-developed along the western edge of the platform. Total coral cover is the highest in Bermuda, frequently reaching 50%, but coral diversity is low (Logan 1992; MEP 2007). The bottom has less relief than the fore-reef slope,

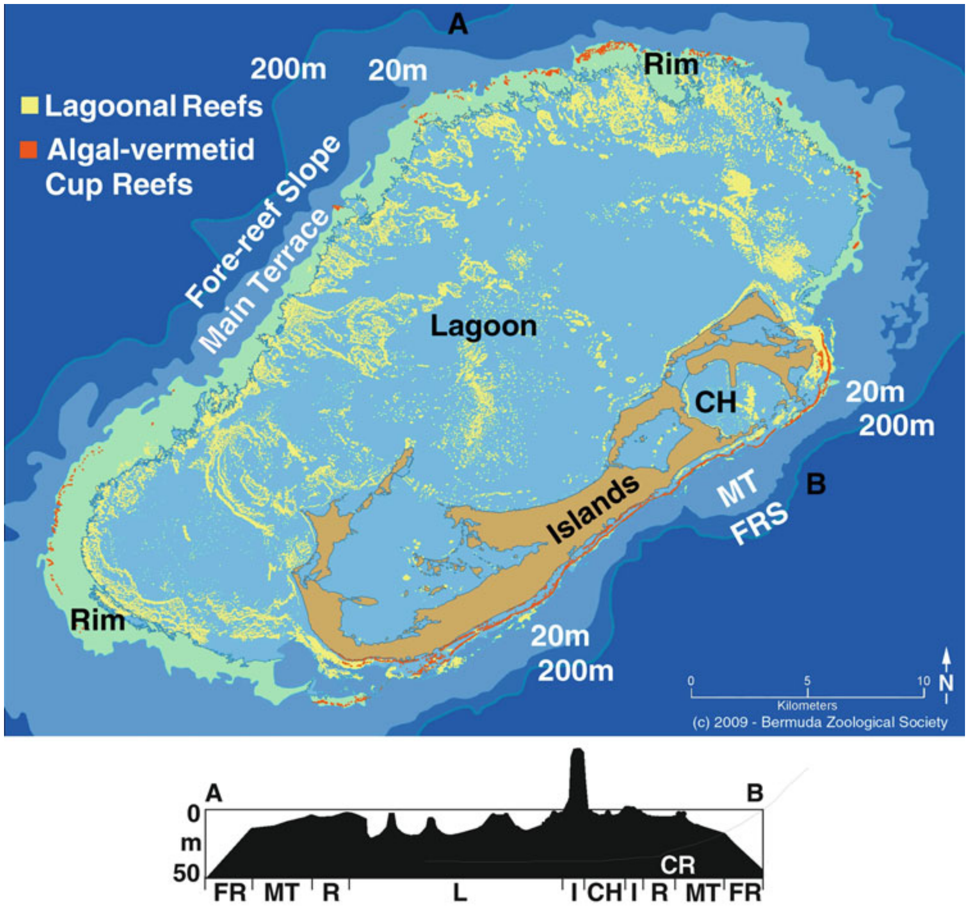


**Fig. 10.4** Reef zones on the Bermuda Platform, interpreted from a geo-referenced aerial photomosaic (Copyright Bermuda Zoological Society), showing 20 m and 200 m isobaths. *Below*: NW to SE profile across the Bermuda Platform between points A-B indicated in the upper image; vertical exaggeration approx. 600 times. CH, Castle Harbour; CR, South Shore algal cup reef tract; FR and FRS, fore-reef slope; I, Bermuda Islands; L, lagoon; MT, main terrace; and R, rim. Figure after Logan and Murdoch (2011)

and is dominated by domal colonies of *Diploria* spp (64%), sheet-like or encrusting colonies of *Montastraea* spp (32%) and small hemispherical colonies of *Porites astreoides* (3%). Octocorals cover less than 6% of the bottom (MEP 2007).

### Rim

The rim reefs, known locally as ledge flats, are developed on the elevated shallow shoals that encircle North Lagoon. The rim reefs project lagoonwards by lobate extensions (Fig. 10.6a). The reef tops lie between 2 m and 6 m depth and are dissected by ramifying sand channels of about 10–15 m depth. Reef tops show relief of about 1 m between coral heads. Coral coverage is about 20% (Dodge et al. 1982). Large octocorals are attached to the reef tops and channel sides, experiencing almost continuous surge from the open ocean. The *Diploria-Montastraea-Porites* assemblage is again predominant (Fig. 10.7), accounting for over 90% of the coral coverage, with *Diploria* spp alone accounting for over 65%. A wide variety of coral growth forms occur, from domal to encrusting to platy. Sponges, zoanthids, hydrozoans, anemones and corallimorphs are common, with smaller colonies of less common coral species (*Madracis* spp., *Stephanocoenia intersepta, Siderastraea radians, Agaricia fragilis*) present as understorey species. Diverse coelobite communities colonize shaded areas beneath coral heads or in caves and tunnels near the base of the reef (Logan et al. 1984).

### Lagoonal Reefs

Reefs of the North Lagoon comprise patch reefs of many sizes and shapes (Logan 1988, 1992). Typical lagoonal patch reefs reach close to the sea surface, with steep flanks running down to 20–23 m. Coral coverage on the tops of these reefs is generally less than 20% (Dodge et al. 1982), although the flanks may have higher values (T. Murdoch, pers. comm.). Species of *Diploria* and *Porites* dominate the outer patch reefs, *Montastraea franksi* the central areas and *Madracis* spp the nearshore reefs (Murdoch 2007). The lagoonal reefs have more coral species than the outer platform reefs, and in

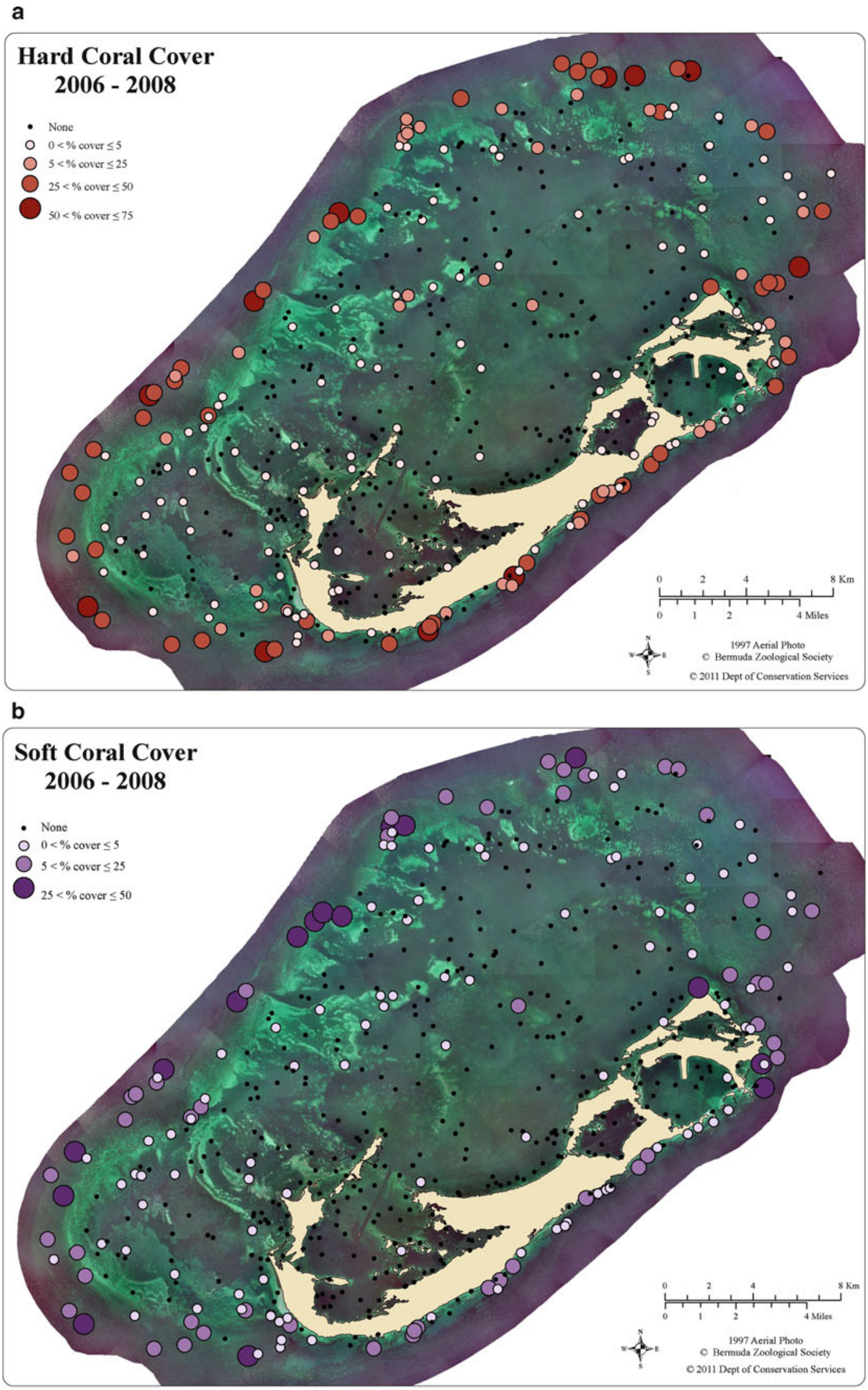


**Fig. 10.5** Average percent bottom cover estimates based on 530 benthic transect sites of 50 m by 0.5 m for (**a**) Hard corals, including *Millepora* and (**b**) Soft corals. Based on KAC, JWF, WJK, SAM unpub. data

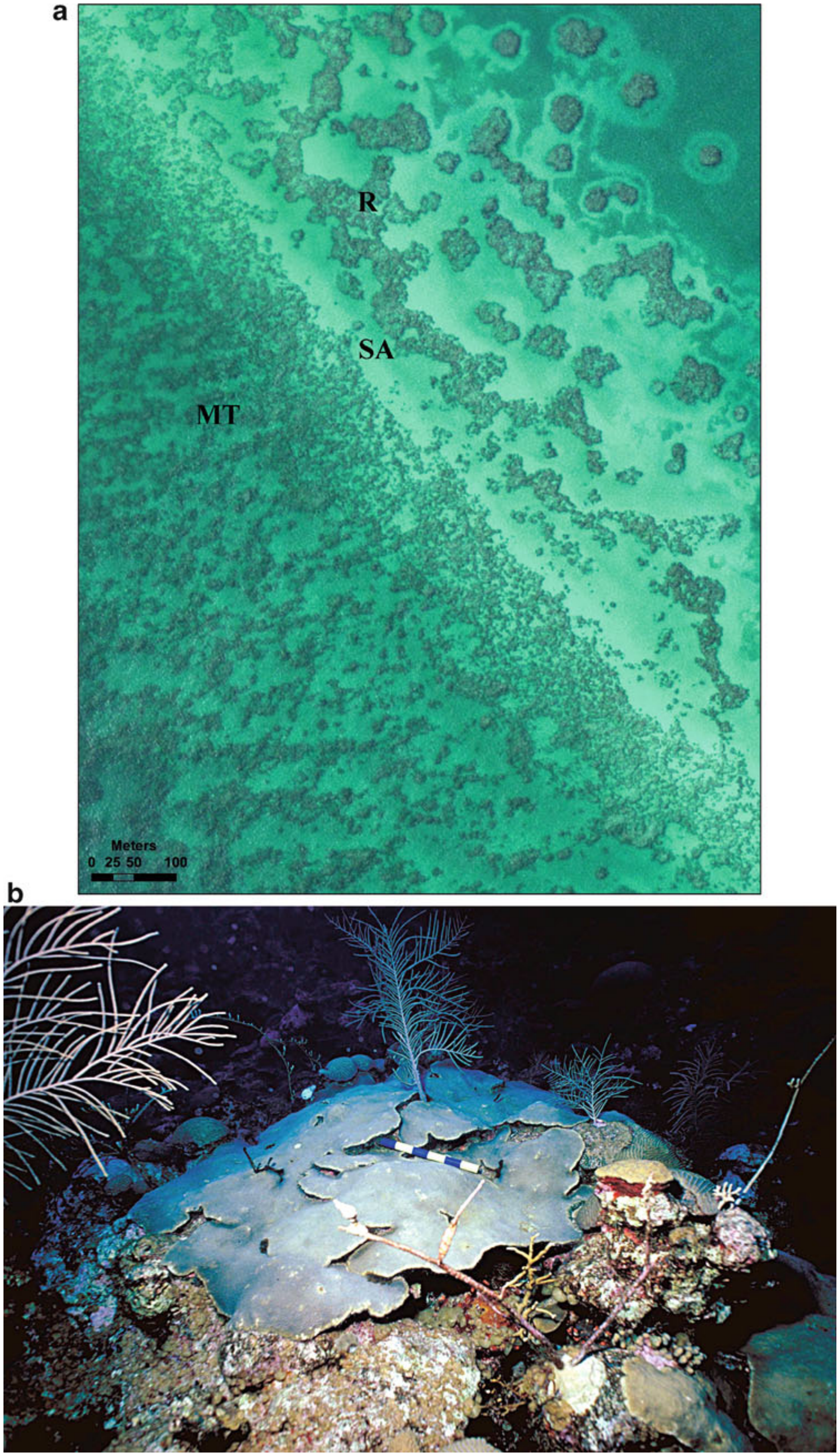


**Fig. 10.6** (**a**) Aerial photograph (Copyright 1997, Bermuda Zoological Society) of lobate rim reefs (R) at the western end of Bermuda, in the area referred to as the Ledge Flats, a sediment apron (SA) and anastomosing reef spurs and sand channels of the descending main terrace reefs (MT). (**b**) A large colony of *Montastraea franksi* showing platy growth on the deep fore-reef slope north off North Rock, 32 m depth. Scale on the coral is 30 cm long

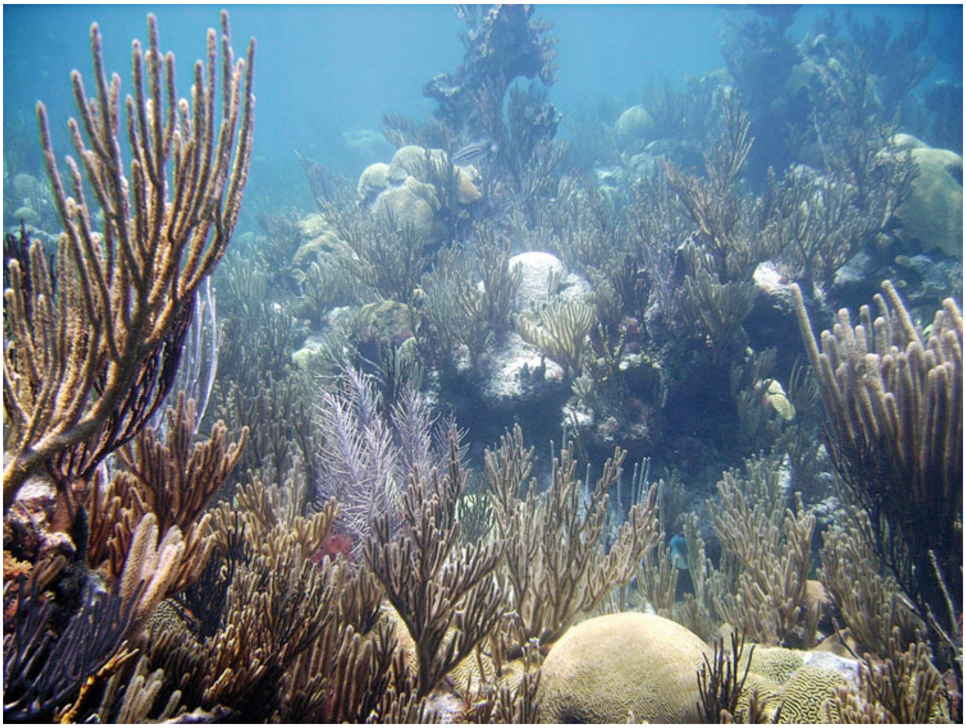

**Fig. 10.7** Rim reefs with domal *Diploria* spp, *Porites astreoides* in the middle ground and octocorals, *Plexaura flexuosa* (purple), *Plexaura homomalla* (black), a single *Pseuopterogorgia* and probably *Antillogorgia* (foreground near centre, light purple), 5-8 m depth, on the western rim, July 2007

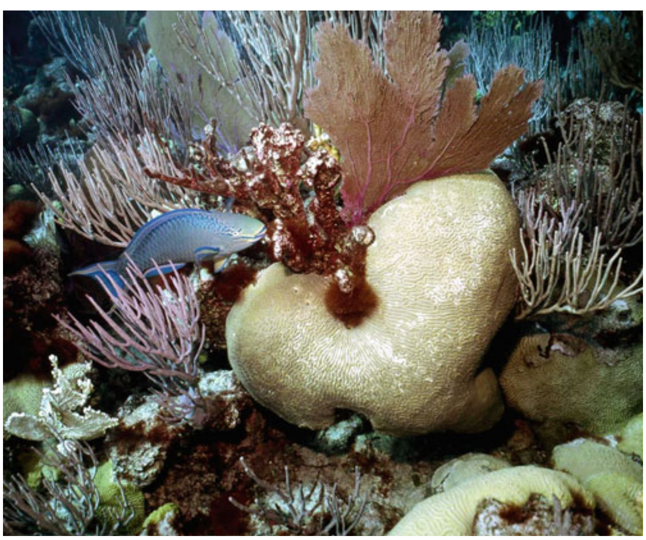

**Fig. 10.8** Outer lagoon patch reef with large *Diploria strigosa*, branching *Millepora alcicornis* and octocorals, 5 m depth, Three-Hill Shoals, North Lagoon; queen parrotfish is about 50 cm in length

addition, support a rich sessile invertebrate biota of octocorals, zoanthids, sponges, anemones, tunicates and bivalves, as well as a variety of calcareous algae (Fig. 10.8).

### Inshore

Hard bottom coral communities, with up to 5% coral cover, are common in Harrington, Great and Little Sounds. However, of Bermuda's inshore waters only Castle Harbour has significant coral reef development; linear reefs occur around the western and southern shorelines (Fig. 10.9) and steep-sided patch (pinnacle) reefs are present in the north-western and south-eastern areas.

Dredging for airport construction in 1941–1943 had deleterious effects on all reefs in Castle Harbour, reducing cover to only about 5% on linear reefs and 13% on pinnacle reefs (Dodge and Vaisnys 1977; Dryer and Logan 1978; Logan 1992). Prior to the dredging, the waters of Castle Harbour were pristine and supported healthy reefs (Dryer and Logan 1978). *Isophyllia sinuosa* and *D. labyrinthiformis* are the dominant corals on the tops of the pinnacle reefs, which have both low cover and diversity, whereas the steep flanks have relatively high cover by branching species of *Oculina* and *Madracis*. Recent surveys of Castle Harbour reefs by Cook et al. (1994) and Flood et al. (2005) indicate that *D. labyrinthiformis*, an efficient sediment-shedder, remains dominant on reef tops and there is active recruitment of *D. strigosa*, *Agaricia fragilis* and *Siderastraea* spp. Logan et al. (1994) showed that growth rates of post-dredging-age colonies of both *Diploria* spp are, surprisingly, higher in Castle Harbour than on lagoonal and platform-margin reefs. *Madracis auretenra* (misnamed in earlier studies as *M. mirabilis*) continues to rank high in coverage on the pinnacle reef flanks but *Oculina diffusa* appears to have declined since the 1978 survey (Flood et al. 2005).

**Fig. 10.9** Castle Harbour, showing lobate fringing linear reefs along the northwestern shore of the Harbour; the airport runway, the Causeway with Longbird swingbridge are in the background. Dark blue areas of water are sites of dredging for the fill used to create the airport lands. The image is oriented with N at the top

### Algal-Vermetid Cup Reefs

Algal-vermetid cup reefs (Fig. 10.10a, b) occur as a discontinuous tract on the outer edge of the platform rim, particularly along the south-eastern side where there are three distinct zones running more-or-less parallel to the shoreline. From the shore outwards, the first zone is bioconstructional lips attached to headlands, the second is the actively-growing tract at the edge of the near-shore platform and the third and oldest zone is drowned cup reefs lying at depths of 10–12 m (Meischner and Meischner 1977). These may have been at sea-level about 7,000 years ago and the bioconstructional lips will eventually become the actively-growing tract as headlands are eroded. Cup reefs are generally circular to oval in shape and less than 30 m in maximum dimension. In profile they have an elevated rim enclosing a shallow mini-lagoon with occasional small coral heads, and tapering to a narrow undercut base at 8–10 m depth (Logan 1992). Void space is high in these reefs at both micro- and macro-scales (Logan et al. 1984). The main constructive agents are crustose coralline algae and the partially-embedded vermetid gastropod *Dendropoma corrodens*, with occasional encrusting *Millepora alcicornis*, all of which are adapted to turbulent conditions in high wave energy environments (Thomas and Stevens 1991). The algal-vermetid cup reefs represent an unusual reef type rarely found elsewhere in the world.

## Other Major Members of the Coral Community Zone

As in many other tropical locations with coral reefs, seagrass beds and submerged macroalgae beds are closely associated spatially and ecologically with the corals. However, the spatial distribution of the reefs and contact potential of reef dwellers with seagrass and macroalgae habitats appears to be greater in Bermuda than elsewhere in the North Atlantic (JWK, pers. obs.). This coral community zone includes most of the Bermuda Platform and seagrasses and calcareous green macroalgae are widespread (Fig. 10.11a, b). Numerous studies document the ecological services provided by these species and communities as well as the ecological connectivities among them.

**Fig. 10.10** (**a**) Near-shore algal-vermetid cup reef at low tide, about 6 m across, showing exposed rim and mini-lagoon, Elbow Beach, South Shore; note outer cup reef tract in background where waves are breaking. (**b**) Waves breaking over a line of algal-vermetid cup reefs in foreground, with rim reefs of nearshore platform behind. Dark smudge near centre of the image is Seabright sewage outfall

## Seagrass Beds

Fewer seagrass species occur in Bermuda than in the Greater Caribbean; five genera and six species are reported for Bermuda: *Ruppia maritima, Thalassia testudinum*, *Syringodium filiforme*, *Halophila decipiens* and both *Halodule bermudensis* and *Halodule wrightii*. *Ruppia maritima* is restricted to land-locked brackish or marine ponds. In recent studies only four species are found in open waters, *S. filiforme*, *T. testudinum*, *H. decipiens* and *Halodule* sp. (not identified).

At least one seagrass species has been found at about 24% of about 530 sites that are distributed across the Platform. *Syringodium filiforme* was most commonly encountered, followed by *H. decipiens* and then *T. testudinum* and *Halodule* sp. (KAC, JWF. WFK, SAM, unpub. obs.). Prior to those studies the annual seagrass, *H. decipiens* was considered

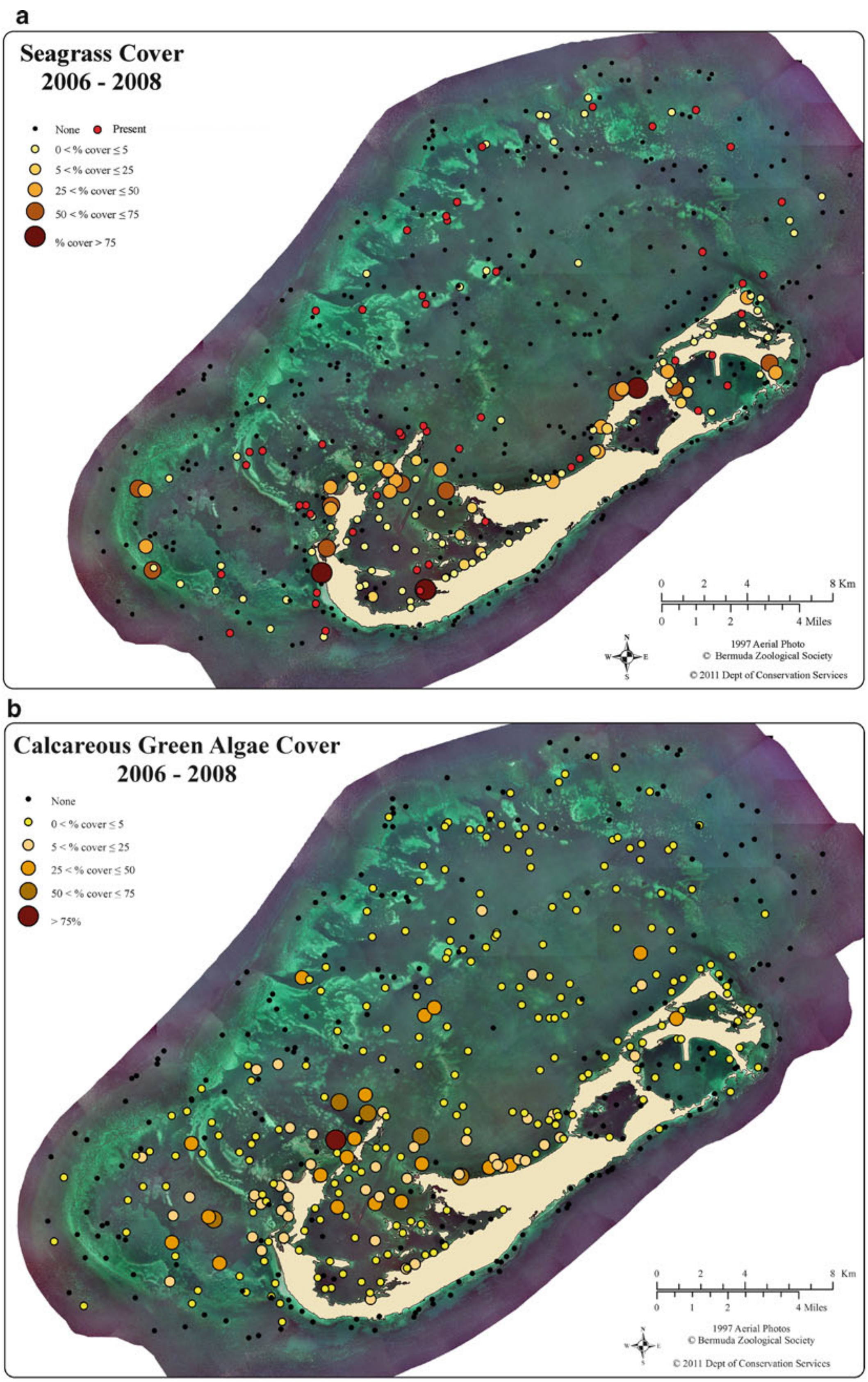


**Fig. 10.11** Presence, absence and average percent bottom cover based on 530 benthic transect sites of 50 m by 0.5 m (**a**) Seagrass. Dense cover always includes either or both of *Thalassia testudinum* and *Syringodium filiforme*. (**b**) Calcareous green macroalgae. Based on KAC, JWF, JWK, SAM unpub. data

rare and *T. testudinum* was considered the dominant species. *Halophila decipiens* grows in deeper or murkier water than the other species.

Seagrasses form dense and spatially extensive beds in only a few locations (Fig. 10.11a). Murdoch et al. (2007) described the recent disappearance of reef-associated meadows in the North Lagoon.

## Calcareous Green Algae Beds

Calcareous green algae form a second macrophyte dominated sea-bottom community. These were observed at 57% of about 530 survey sites on the Bermuda Platform (Fig. 10.11b) but were rarely encountered along the South Shore (KAC, JWF, JWK, SAM, unpub. obs.), a higher energy area with coarse mobile sediments. The most common genus was *Penicillus*, followed by *Udotea* and *Halimeda*. The last two sometimes formed dense beds with more than 75% cover.

## Summary

Corals and coral reefs have played a central role in the complete history of Bermuda. They formed the platform and the islands, and then they protected those islands.

In some locations reefs have been considered nuisances and were removed, without much regard to the importance of the integrity of the reef system to its own viability and to the viability of Bermuda. Certainly, with more awareness of their past, present and future importance, destruction will decrease and protection will increase. Bermuda's corals occur at the very northern limits of coral reefs in the Atlantic Ocean so that they are surviving under conditions that may exemplify limiting environmental conditions for reef development. Understanding these reefs will become of critical importance in anticipating the effects of global climate change.

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