Coral Reefs of the USA

Coral Reefs of the World

Volume 1

The titles published in this series are listed at the end of this volume.

Coral Reefs of the USA

Bernhard M. Riegl and Richard E. Dodge
Editors

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Small figure top: Photomicrograph of a Miocene *Porites* coral fossil in a dolostone from Navassa (Photo: R. Halley, Chapter 10).
Small figure bottom: Gag Grouper (*Mycteroperca microlepis*) in Broward County, Florida (Photo: L. Jordan, Chapter 5).
Large figure: A view across Tanapag Lagoon, Saipan, Mariana Islands (Photo: B. Riegl, Chapter 18).

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This book is dedicated to our own and the children of the USA in the hope that they will still be able to experience healthy coral reef ecosystems

Preface

Coral reefs are certainly one of the crown jewels of the USA's natural heritage and the nation is aware of that. Coral reefs receive much attention by a broad cross section of society – tourists, scientists, politicians, fishermen, conservationists are but some of those who cannot escape their charm. But there is no love-affair without some responsibility for the object of affection and the US has been very actively engaged in living up to this responsibility through a long history of research and efficient management. Being prone to boast about what it has, the USA can rightly show off its coral reefs. It possesses some of the most visited coral reefs (in Hawaii and the Florida Keys) and some of the world's biggest marine reserves (the Northwestern Hawaiian Islands= Papahanaumokuakea Marine National Monument and the Pacific Remote Islands National Wildlife Refuge Complex). It is also home to some of the world's most degraded as well as the most pristine coral reefs. Not surprisingly, its coral reef research has a long history and the coral reef research community is as vibrant and active today as it has been from the early beginnings.

This book was produced with the goal of providing an overview of coral reefs in the USA and to provide a uniform entry point for the study of any specific region. It is thus a scholarly review as opposed to a status report, such as those produced by the National Oceanographic and Atmospheric Administration (NOAA) every 4 years, which should be consulted for updates regarding biological monitoring status and trajectories of the living resources under federal jurisdiction and surveillance. In contrast, the various authors who contributed to this present book provide a sampling of published and sometimes yet unpublished knowledge of the geology, biology and oceanography of the various reef types and their inhabitants. The book is designed to provide a big picture overview of what makes each region unique (or not) and to provide a scholarly review of some key facts together with key literature. It should thus be of use both to the casual visitor seeking to generally inform him/herself of an area to be visited, and the serious scholar who wishes to receive some guidance where to begin his/her readings regarding an area of specific interest. Although most reef areas within US territorial waters are covered, it is also obvious that any such task will never be fully exhaustive and a large amount of existing literature and some information that a reader might look for will not be included. There is therefore no claim that this book is complete, it never will be, but we hope that it will be useful as an overview and entry point for each individually treated area. For any shortcomings we are to blame.

We have not included in this book the coral reefs of the Freely Associated States (the Republic of Palau, the Republic of the Marshall Islands, The Federated States of Micronesia) since we respect their political independence and therefore could not subsum them under the title "…of the USA". However, US management agencies such as NOAA and the USGS are, at least partially, involved in research and management. Information about the reef status and management issues in the Freely Associated States is provided by the various national agencies and can also be found in the NOAA Status of the Coral Reefs reports that appear every 4 years.

The organization of chapters in this present book is alphabetically by ocean and does not represent an order of listing according to any preference: first Atlantic (Florida–US Virgin

Islands–Puerto Rico–Gulf of Mexico–Navassa), then Pacific (Main Hawaiian Islands–Northwest Hawaiian Islands–Line and Phoenix Islands–Wake and Johnston Atolls–Guam and the Commonwealth of the Northern Mariana Islands–American Samoa) and finally the deep reefs of all oceans.

The editors wish to express their deep appreciation and gratitude to the authors of the various chapters for their hard work despite the exceedingly short deadline that was imposed on them in a busy time of the year. We would like to thank our publishers at Springer for believing in the project and our reviewers for providing us with excellent feedback. Reviewers for this volume were: Russel Brainard, Francine Fioust, Peter Glynn, Richard Grigg, Bob Halley, Peter Houk, Jochen Halfar, Ken Deslarzes, Greg Foster, Kristy Foster, Greg Jacoski, Jack Kindinger, Judith Lang, Barbara Lidz, Joyce Miller, Ryan Moyer, David Gulko, Christy Pattengill-Simmens, Chris Perry, Werner Piller, Sam Purkis, John Rooney, Gwilym Rowlands, Eugene Shinn, Michael Trianni, Bernardo Vargas-Angel, Andrew Wheeler, Wendy Wood and the many co-authors of the chapters who cross-checked and reviewed the other sections of their respective chapters. Other reviewers within the government agencies saw and approved the chapters by their employees and we thank them for their efforts – not all names are known to us. Maureen Trnka deserves an extra thank-you for finding literature, tirelessly digitizing graphs and formatting and reformatting manuscripts. Greg Jacoski proofread many of the chapters. We apologize if we have forgotten to thank anyone.

Bernhard Riegl
Richard Dodge
Dania, Florida
December 2007

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1 Introduction: A Diversity of Oceans, Reefs, People, and Ideas: A Perspective of US Coral Reef Research

Bernhard Riegl and Richard Dodge

1.1 Historical Perspective

By virtue of its geographical extent and the size and wealth of its population, US surveyors and academics entered the scientific coral reef world soon after the study of the latter became of interest. But even earlier, the coral reefs of what are today territories of the USA have been noted and, at least cursorily, studied out of necessity since they were threats to vessels along the trade routes. Also the fossil coral reefs of the USA, of which the country has many famous examples, have received much early study and maybe even more attention than the living coral reefs. They hold a special place in sedimentology and economic geology since some of them are associated with the important oil finds that set off the early twentieth-century oil-boom in places like Texas and Utah. We will not treat these in the present volume, but restrict ourselves to the living coral reefs that can be observed in the ocean today. Recent reviews and entry points to the study of the fossil system can be found, among many others, in Stanley (2001) and Kiessling et al. (2002).

Early knowledge of, and comment on, US coral reefs dates back to the Spanish who were of course well aware of the Florida reef tract which was situated along their trade routes to and from their Caribbean possessions. Already Ponce de Leon, who explored Florida in 1513 while purportedly searching for the fountain of youth, sighted and remarked upon the reefs. Very soon, these reef-strewn shallow and treacherous waters would be the preferred haunt of pirates and buccaneers (like Edward Teach aka. the fabled "Blackbeard") attacking trade vessels while running the gauntlet in the Straits of Florida between the reefs and shallows of the Florida shelf and the Bahamas banks (whose name possibly derives from the Spanish "islas del bajamar" – isles of the low tide, or shallow sea. Or it is a derivation of a Lucayan Indian name). In the Pacific Ocean, the reefs around Hawaii were noted by Captain Cook and the place where he found his untimely death at the hands of unfriendly Polynesians is now protecting both the historical site and an adjacent coral reef (Kealakua Bay Marine Protected Area on the Big Island). Also the Mariana Islands and their reefs were known to early explorers, traders and pirates, who repeatedly called on Tinian to use the good port made by the one small section of barrier reef (that in 1944/45 would be dredged and changed into a port which allowed the delivery and offloading of the first nuclear bombs).

When Darwin published his "Structure and Distribution of Coral Reefs" in May 1842 (after having presented his theories at the Geographical Society on 31 May 1837 in a talk titled "On certain areas of Elevation and Subsidence in the Pacific and Indian Oceans as deduced from the Study of Coral Formations" which was published as an abstract in the Society's Proceedings) his ideas were rapidly taken up and vividly discussed also among scientists in the USA. J.D. Dana was at the time a scientist aboard the US Exploring Expedition headed by Captain Wilkes (an efficient but stern and not much-loved character. Captain Ahab of "Moby Dick" fame was possibly modelled on him since Melville knew Wilkes–Keating

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1992). Dana heard of Darwin's theories (reading about them in a newspaper while in Australia) and became an ardent supporter. The US Exploring Expedition went to the most forlorn corners of the territories, such as Rose Atoll near Samoa (next to be visited 80 years later by Mayor in 1920). This expedition also started the tradition of collaboration between US government agencies, then the Navy, and civilian research, now embodied by agencies like NOAA (the National Oceanographic and Atmospheric Administration). Dana (1843) was the first to show that cold currents prevented reef growth preferentially on the eastern sides of oceans and he charted many of the Hawaiian Islands for the first time (Grigg 2006). Consurrently, A.E. Verrill studied the taxonomy of corals at Harvard and also jointly published with Dana (Verrill 1864, 1866, 1872). In the meanwhile, the British Challenger expedition (1873–1876) visited the reefs in what was to become American Guam and the Hawaiian Islands. Dana remained loyal to Darwin's views of subsidence as the driver of atoll formation and defended them against competing ideas that pre-existing platforms are the foundation of atolls (Dana 1885). Another titan of early US reef science, Alexander Agassiz, who had been a member of the Challenger Expedition, was in correspondence with Darwin and keenly interested in the discussion regarding reef formations. Having made a fortune from Michigan copper, he himself funded an almost decade-long series of exploring expeditions to all major coral reef areas of the world. He sailed on the *Blake* and the *Albatross* from 1893 to 1902. Agassiz was the first to study the Florida Keys and Marquesas reefs in detail and came to the conclusion that they had grown on a bank until reaching the surface and found no evidence of atoll-like subsidence. Wanting to know more about reefs, he then proceeded to explore the reefs of the Pacific, among them the Great Barrier Reef and the US territories in the Mariana Islands and Samoa. At the same time as Agassiz worked in the Florida Keys, and produced one of the first habitat maps of a coral reef at the Dry Tortugas (Agassiz 1883), the eminent Harvard zoologist and geologist T.W. Vaughan also entered the field and subsequently published a series of works. Vaughan's work in Florida, the Bahamas, Cuba and Australia led him to propose antecedent control of reef formation (i.e. reefs can only form on pre-existing structures and are thus pre-defined in their position and shape) in the form of flooded platforms (Vaughan 1914a, b). He also published the first exhaustive monograph on the corals of Hawaii and Laysan (Vaughan 1907). Verrill (1868) had earlier produced a review of corals on the American west coast, as well as of the North Pacific (Verrill 1866). Also at Harvard, R.A. Daly developed his Glacial Control Theory along similar lines of thinking and pioneered a better understanding, and eventually uniform acceptance, of glacio-eustatic processes (i.e. that sea level is driven primarily by water retention/ mobilisation in ice during cold/warm-ages) and their control on shelf morphology and coral reefs (Daly 1910, 1915, 1916, 1917, 1934, 1948). Daly also studied beachrocks in the Tortugas and the reefs of American Samoa (Daly 1924). The idea that all coral formation was uniquely defined by sea level and erosional forces was not accepted by W.M. Davis, Daly's predecessor at Harvard who stayed scientifically active after his early retirement and strongly argued for cycles of uplift and subsidence for which he provided an eloquent platform in his "Coral Reef Problem" (Davis 1928). In 1904, A.G. Mayer (name changed to Mayor in 1918) had received permission from the Carnegie Institution in Washington to establish the Tortugas Marine Laboratory on Loggerhead Key in the Dry Tortugas (Mayer 1903). After its opening in 1905 it rapidly turned into an important center of tropical marine research, attracting many renowned American and international scientists and from which a resultant wealth of marine biological research poured forth (Shinn and Jaap 2005). At the laboratory R.C. Wells (1922) was among the first to study CO_2 saturation state, a hot topic in today's greenhouse world. Mayer studied the thermal tolerances of reef animals and showed how closely they live to their upper tolerance limits (Mayer 1914, 1918). Daly studied beachrock (Daly 1920), and T.W. Vaughan and J.W. Wells studied the corals (Vaughan 1910, 1914a, b, 1915, 1916a, b; Wells 1932). Mayor himself studied reefs all over the Caribbean and the Pacific, among others those of American Samoa (Tutuila, the Manu'a Islands and Rose atoll) (Mayer 1914, 1918, 1924). The transects established by Mayor are still being used for reef monitoring in Pago Pago harbour (Chapter 20, Birkeland et al.). While in Samoa, Mayor undertook research that sounds surprisingly modern – among many other things he studied the survival of corals in seawater of changed pH and how acidification would act on coral death by bleaching. Inspired by Mayor, C.H. Edmondson pioneered ecological and physiological studies in Hawaii (Edmondson 1928, 1933, 1946; Chapter 12, Jokiel). During these early days of the century, the Tanager Expedition of 1923/24 explored the Hawaiian and NW Hawaiian Islands and started Hawaii as a hub of coral reef science which it has remained to this day. Also, some of the first established large-scale marine reserves were declared in the NW Hawaiian Islands when President Roosevelt in 1909 declared them (with the exception of Midway) protected as the National Wildlife Bird Reservation (more to protect birds, which were being flagrantly over-exploited at the period, than coral reefs). In 1940, this became the Hawaiian Islands National Wildlife Refuge and in 2006 the Northwest Hawaiian Islands (=Papahnaumokuakea) National Monument, now the largest coherent coral reef reserve in the world.

In the 1930s, J.E. Hoffmeister and H.S. Ladd contributed to the discussion how coral reefs form their findings that extensive shoals can be developed by volcanic activity leading to emergence and erosion (Hoffmeister and Ladd 1935, 1944, 1945). Hoffmeister then went on to study the Florida Keys reefs and, together with H.G. Multer, the Key Largo Limestone which is the rock the upper Florida Keys are made from (Hoffmeister and Multer 1964, Hoffmeister et al. 1967, Multer and Hoffmeister 1969; Chapter 2, Lidz et al.). In the Pacific, a large contribution to the study of coral reefs and island geology was made by H. Stearns who, prior to World War II, had investigated sea level by studying the shore benches of Hawaii (Stearns 1935) and Guam (Stearns 1940, 1941) and had a detailed look at coral reefs in his treatise of Samoan geology (Stearns 1944). He also regarded the antecedent platform as essential for the formation of a reef (Stearns 1946).

During the Japanese presence in what were later to become, for a time, US territories, namely the Mariana Islands and Palau, their very active coral reef scientists established a research station in Palau, which led to a wealth of research in the region that influenced later US research (Burke 1951). Yabe and Sugiyama (1935) provided full taxonomic accounts of the corals. Yabe (1942) and Asano (1942) showed that the shapes of many Pacific reefs were defined by subaerial solution (i.e. the exposed parts of islands being weathered away). This idea was later developed by F.S. McNeil (1954) who stressed the importance of organismic growth during submergence but the equal importance of subaerial erosion for the formation of lagoons and the shape of the reefs. This original model was further developed by E. Purdy (1974) to interpret reef shape in general by the "antecedent karst model" (karst being the rugose and gnarly form limestones take due to dissolution by freshwater when lifted out of the sea) suggesting preferential reef accretion on topographic highs. This has now been generally accepted (Hopley 1981). McNeil's paper marks a watershed in reef science inasmuch it clearly shows that reefs do not all have a similar evolution and that structure (its stratigraphic and sedimentologic make-up) and morphology (its surficial aspect) must not be confused. General, ubiquitously applicable theories subsequently lost their appeal and a wide array of empirical studies of form and process began (Hopley 1981).

The post-war period in the Pacific led to important government-funded work in the US territories. Groundbreaking geological investigations took place in the US and occupied territories, such as the Mariana Islands, under the Pacific Islands Mapping Program of the US Geological Survey (Whitmore 2001). H.S. Ladd conceived the idea of a long-term geologic mapping program in the Pacific Islands, which achieved many landmark studies on fossil and modern reefs (Cloud et al. 1956, Tracey et al. 1964, Emery et al. 1954, Emery 1962, Schlanger 1963, 1964). A further government-sponsored boost to US coral reef science was provided by the desire for a Pacific nuclear test ground that led to deep drilling at Bikini (775 m core) and Enewetak (2,307 and 2,530 m cores) which reached the Eocene basalt base of the atoll. These investigations also included studies of the coral fauna (Wells 1954a, b). Further drilling and seismic explorations at Midway, Enewetak, Funafuti, Kwajalein and Nukufetau furthered the understanding of the structure of US Pacific reefs and were of great marine geological importance in general (Ladd et al. 1953, 1970; Ladd and Schlanger 1960, Menard 1986, Tracey 2001). The Office of Naval Research also sponsored biological investigations in the Pacifc, which allowed F. Bayer to conduct extensive research on Pacific octocorallia, research he also conducted in the Atlantic. The eminent botanist F.R. Fosberg had been involved in the USGS's Pacific Islands mapping initiative, and, worried that much information would only remain in unpublished reports, founded the Atoll Research Bulletin in 1951, which has remained a mainstay of US coral reef literature (now edited by the eminent sedimentologist I. Macintyre).

Durham (1947) evaluated the coral fauna on the American West coast and the E. Pacific, which was later continued by P. Glynn in many papers (p. ex. 1997, 371). In the 1950s, coral reef studies came to full bloom in Florida and R.N. Ginsburg developed the principles of comparative sedimentology in the Florida Keys (Ginsburg 1953, 1956, 1957; Ginsburg and Lowenstam 1958, Ginsburg and Shinn 1964). Many US American scientists began working throughout the nearby Caribbean and a number of marine laboratories were established. In Jamaica T.F. Goreau produced seminal papers regarding the ecology and physiology of corals (Goreau and Goreau 1959, 1960). Connell (1973, 1978), in Australia, followed in Jamaica by Jackson and Buss (1975), applied aspects of competition and disturbance theories as community-shaping processes to coral reefs.

In 1964, H.G. Multer used a portable trailer-mounted rig to drill fossil and modern reefs in the Florida Keys, and I. Macintyre introduced submersible drilling in 1974, which revolutionized reef framework studies. Saturation, at least in a diving sense, was achieved in 1970, when the Tectite II program allowed 12 missions of 5 scientists each to spend 2 weeks in an underwater habitat in the US Virgin Islands (Miller et al. 1971) and became a precursor to today's Aquarius habitat in the Florida Keys, maintained by the University of North Carolina. Enos and Purkins (1977) provided the first exhaustive overview of facies and habitats throughout the Florida Keys, and Enos (1974) provided the first complete sediment facies map of the Florida–Bahamas plateau. Marszalek (1977) mapped the habitats of the entire Florida Keys. Shinn and co-workers published much about reefs in Florida and the Bahamas (and elsewhere) while Wells (1932, 1954a, b, 1956) worked up the taxonomy of living and fossil corals in US waters and worldwide. The Third International Coral Reef Conference in Miami in 1977, the Seventh ICRS in Guam in 1992, the eighth ICRS 1996 in Panama (hosted by the Smithsonian Institution) allowed the US to welcome the international reef science community and present its own progress. Over the past 30 years, such a plethora of coral reef work was produced by US scientists that a full review here is impossible. It is also not necessary, since key aspects are mentioned in the following chapters.

1.2 Diverse Country, Diverse Oceans, Diverse Reefs

As diverse as its inhabitants and geography, the coral reefs of the USA show almost all the variability of which these systems are capable. The reader of this book can therefore vicariously travel through almost all types of carbonate depositional systems within which coral reefs can be embedded, as well as experience much of the biological differentiation experienced by coral reefs as a result of geographic position (Pacific versus Atlantic), latitude or different oceanographic and climatic control.

Coral reefs occur in US territories on one of the most stable passive margins (i.e. one where no plate subduction or collision occurs, which keeps tectonic deformation relatively minor) which, in Florida, has created one of the largest and thickest carbonate platforms found in the ocean today. That platform shows all transitions from a rimmed platform (where a reef at the edge encloses a carbonate platform with very gentle bathymetry), to an unrimmed platform (where the carbonate platform is unprotected by shelf-edge reefs), to a homoclinous ramp (where the seafloor slopes uniformly towards the deep – unlike in the platforms, which have an abrupt change in topography at the shelf-edge), to a distally steepened ramp (where the uniform slope is distally accentuated), and shows many of the responses coral reefs are capable of producing in response to shelf morphology (Chapter 2, Lidz et al.; Chapter 4, Hine et al.; Chapter 11, Fletcher et al.; Chapter 13, Rooney et al.).

On the other extreme, coral reefs also exist in one of the world's most active ocean margins, where the Pacific plate gets pulled underneath the overriding West Philippine Plate, in the Commonwealth of the Northern Mariana Islands and Guam. There, we clearly see the effects of tectonic activity on the establishment of coral reefs, and how they can be used as indicators of isostatic sealevel variation (when sealevel changes in an entire ocean basin), variably caused by uplift or the ocean reacting to plate adjustments due to loading/unloading of iceshields (Chapter 18, Riegl et al.).

In the Hawaiian Islands and Samoa, we see the effect of oceanic hotspots (melt-anomalies in earth's mantle that break the ocean's crust to form oceanic islands) on reef development, and clear illustrations of some of Darwin 's own coral reef theories in action (Chapter 11, Fletcher et al.; Chapter 13, Rooney et al.; Chapter 14, Grigg et al.; Chapter 20, Birkeland et al.). Samoa demonstrates the effects of volcanism on modern, Holocene, reef building, which has been influenced by eruptions as well as emergence and subsidence of the islands. Both in Hawaii and Samoa, we observe carbonate sedimentation in a mid-oceanic island setting.

True atolls and submerged carbonate banks are found in the northwestern Hawaiian Islands and Rose atoll in American Samoa, and the Pacific Remote Islands (like the Line Islands, Johnston atoll, etc.; Chapter 15, Maragos et al.; Chapter 17, Lobel and Lobel).

In the US Virgin Islands, and parts of the territory of Puerto Rico, we experience reef building in the context of what used to be a large carbonate shelf in the Oligocene to Pliocene (from about 28 to 5 million years ago; Van Gestel et al. 1999), but since has acquired a strong tectonic overprint with rifting, faulting and volcanism that has generated a variety of landforms made up by different rock types that all have different influences on reef building (Chapter 7, Hubbard et al.; Chapter 8, Rogers et al.; Chapter 9, Ballantine et al.).

US territories stretch from the tropics to beyond the latitudinal limits of coral reef distribution, which has provided for much biological interest since early on and the opportunity to study latitudinal attenuation of reef building and biodiversity (Vaughan 1914; Chapter 4, Hine et al.; Chapter 5, Banks et al.; Chapter 14, Grigg et al.). Zonation and within-reef differentiation has been an important subject of US coral reef science since the 1950s and continues to be so. Physiological studies regarding the environmental tolerances of corals also have a long history and some key advances regarding upper and lower limits of thermal tolerances were obtained on US coral reefs (Mayer 1914, Coles and Jokiel 1977). US coral reefs are far flung, and connectivity between them is a big issue. Johnston atoll is arguably one of the most remote coral reefs in the world (Maragos and Jokiel 1986). The entire Hawaiian island chain exists in a relatively isolated setting and much has been hypothesized regarding where its tropical fauna originates from and how it is maintained (Chapter 14, Grigg et al.; Chapter 15, Maragos et al.; Chapter 17, Lobel and Lobel). Thus a host of connectivity studies, using variable techniques, have been conducted. Naturally, a fair amount of endemism can be observed in these isolated settings, which has proven a fruitful subject of study (Chapter 12, Jokiel; Chapter 14, Grigg et al.; Chapter 15, Maragos et al.; Chapter 17, Lobel and Lobel). The coral reefs in the US Caribbean, on the other hand, all exist in relative close proximity to each other in an ocean where almost ubiquitous connectivity has been postulated – but is increasingly being questioned (Chapter 6, Banks et al.; Baums et al. 2005, Vollmer and Palumbi 2007).

Also, the health trajectories of US coral reefs differ among oceans. The Caribbean has seen spectacular die-back of its dominant reefbuilder *Acropora palmata* (Chapter 3, Jaap et al.; Chapter 8, Rogers et al.; Chapter 9, Ballantine et al.). The cumulative effects of diseases possibly as a result of, or at least following, the die-off of the long-spined sea urchin *Diadema antillarum* (Lessios et al. 1984) and problematic levels of algal growth have decimated previously flourishing Caribbean reefs. Although reefs in the Pacific have also been badly affected by plagues of the coral-eating starfish *Acanthaster planci,* for example in Guam and the CNMI, no similar species-specific mortality of a dominant reef-builder has been observed (Chapter 19, Richmond et al.) and some reefs seem to exhibit significant resilience (Chapter 20, Birkeland et al.). It is interesting to note that early Holocene coral communities in the Mariana Islands exhibit a very similar community to what is found on their reefs today, while the comparable coral community composition in the Caribbean has been dramatically altered (Chapter 5, Banks et al.; Chapter 7, Hubbard et al.; Chapter 18, Riegl et al.). But the coral reefs of the Pacific face other threats. The Hawaiian Islands currently face major problems with introduced noxious species that may eventually turn out to threaten the very existence of these coral reefs as we know them today (Chapter 12, Jokiel). Of course Caribbean reefs are also threatened by introduced species, however, impacts there are yet less obvious than in the Pacific (Chapter 8, Rogers et al.; Chapter 9, Ballantine et al.; Chapter 10, Miller et al.). Unique impacts have been created on many US coral reefs in the Caribbean and the Pacific through their use as military facilities and bombing ranges. Most of these lands have been handed to civilian, mostly conservation, authorities, but interesting "case studies" remain (Chapter 9, Ballantine et al.; Chapter 16, Maragos et al.; Chapter 17, Lobel and Lobel). While much management effort is expended throughout the US territories, examples of overfishing are unfortunately easy to find (Chapter 8, Rogers et al.; Chapter 10, Miller et al.; Chapter 12, Jokiel; Chapter 14, Grigg et al.; Chapter 16; Maragos et al.; Chapter 20, Birkeland et al.). However, the US also possesses some of the world's most pristine reefs and is making strong efforts to protect them (Chapter 14, Grigg et al.; Chapter 16, Maragos et al.).

Some US coral reef scientists have been at the forefront of decrying the negative effects of anthropogenic impacts (Jackson 2001, Jackson et al. 2001, Pandolfi et al. 2005) and key scientific advances now allow a better understanding of the negative effects of nutrient enrichment, overfishing, rising temperatures, and ocean acidification, disease epizootics, to name but a few. The study and forecasting of such impacts is and increasingly important theme in US and international coral reef science.

In short, the coral reefs of the USA are interesting, well-studied and therefore a deserving subject for a synoptic scientific review. Alternatively, a closer look at them is justified merely by their biological wealth and beauty. They are certainly one of this country's most cherished and most valuable natural treasures.

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2
Controls on Late Quaternary Coral Reefs of the Florida Keys

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2.1 Regional Setting and Early Cultural History

The Florida Keys is an arcuate, densely populated, westward-trending island chain at the south end of a karstic peninsular Florida Platform (Enos and Perkins 1977; Shinn et al. 1996; Kindinger et al. 1999, 2000). The "keys" mark the southernmost segment of the Atlantic continental margin of the United States. The islands are bordered by Florida Bay to the north and west, the Atlantic Ocean to the east and southeast, Gulf of Mexico to the west, and Straits of Florida to the south. Prevailing southeasterly trade winds impinge on the keys, creating a windward margin. The largest coral reef ecosystem in the continental United States rims this margin at a distance of ~5–7 km seaward of the keys and occupies a shallow (generally <12 m), uneven, westward-sloping shelf (Parker and Cooke 1944; Parker et al. 1955; Enos and Perkins 1977). The platform is tectonically stable at present (Davis et al. 1992; Ludwig et al. 1996; Toscano and Lundberg 1999). The reefs and 240-km-long island chain parallel the submerged shelf margin, corresponding roughly to the 30-m depth contour that marks the base of a fossil shelf-edge reef (studies cited use the same criterion). The modern reef tract extends west-southwest from Soldier Key southeast of Miami (25°60′ N, 80°20′ W) to the Dry Tortugas in the Gulf of Mexico (24°40′ N, 83°10′ W). Reef-tract habitats lie within the protective domain of the Florida Keys National Marine Sanctuary (Fig. 2.1a–c; Multer 1996).

Prehistoric Paleoindians inhabited the Floridan Peninsula around 12 ka (Zeiller 2005). The Archaic Period of human progress followed (from ~7 to 2 ka) as aboriginal tool making became more sophisticated. The Formative or Ceramic Period (from ~2 ka to AD 1513) was next as the creation of pottery for transportation and storage of food and water became important. The Historic Period began in 1513. By the mid-1500s, Florida had become part of a Spanish monopoly in the Americas. Conquistadors first settled in La Florida in St. Augustine on the East Coast in 1567. In 1763, England took Canada from France, and Spain ceded all of La Florida to England. Spain again took possession of La Florida in the 1783 Treaty of Paris (Zeiller 2005).

The United States acquired Florida from Spain by treaty in 1821 largely for the potential military advantage that the Florida Keys offered (see articles in Gallagher et al. 1997, and selected human-interest notes in Appendix 2.A). The government recognized a need to protect shipping between the Atlantic and Gulf Coasts, and the keys were natural sites for military bases for this purpose. The US Army and US Navy established bases on several islands, and upon admission to the Union as the 27th State in 1845, forts were built at Key West (Fort Zachary Taylor) and the Dry Tortugas (Fort Jefferson). The Florida Keys played major roles in the Second Seminole War (1835–1842), the Spanish-American War (April–August 1898), World War I (1916–1918, when Key West first became a major naval training base), World War II (1941–1945), the Cuban Missile Crisis (1962), the war on drugs

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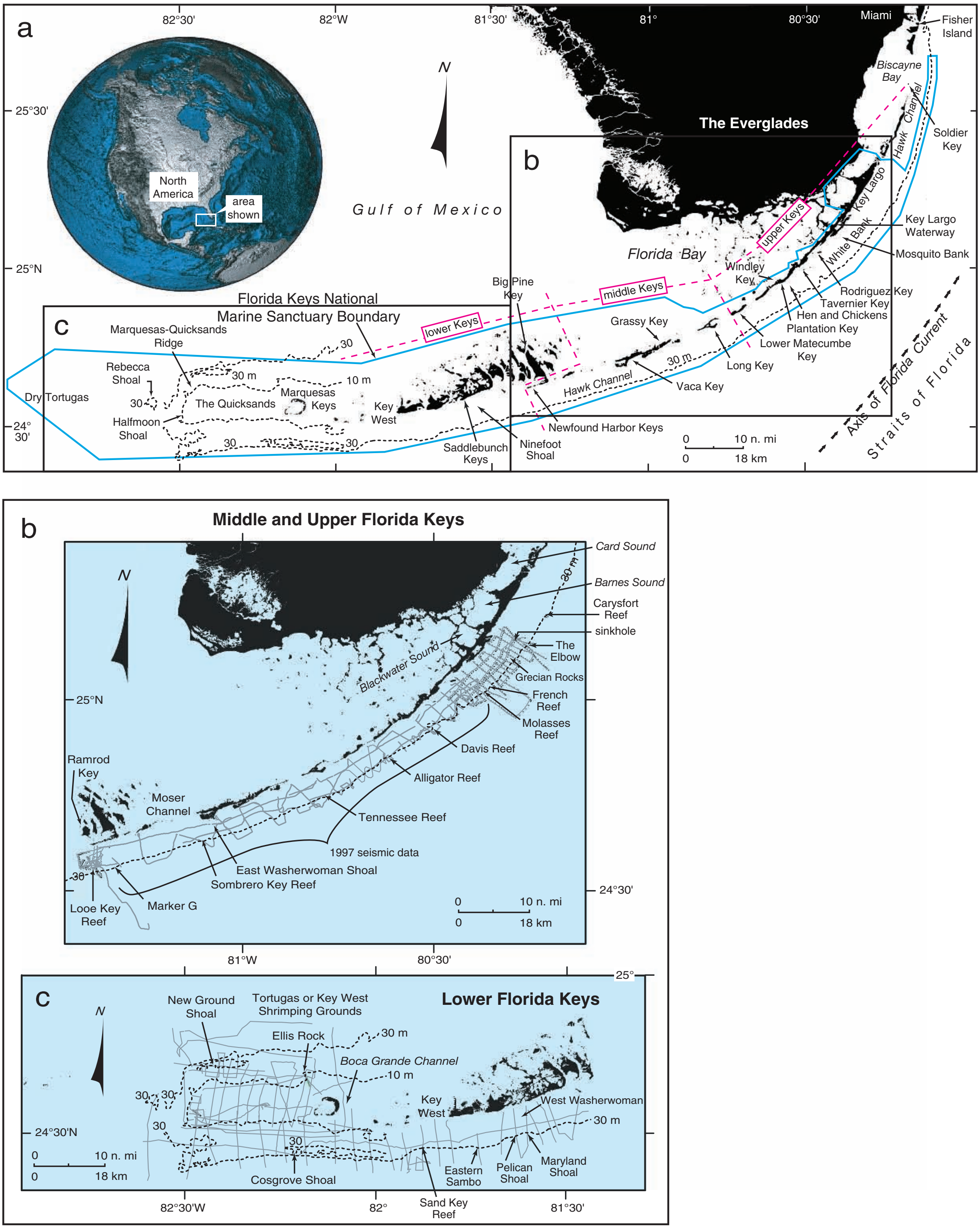

Fig. 2.1. **a** Index map of South Florida and the Florida Keys. Dashed red dogleg line separates areas of Pleistocene ooid bank (Miami Limestone) of the lower Keys and coral reef (Key Largo Limestone) of the westernmost middle Keys. An ooid bank also formed at the east end of the reef and today underlies the city of Miami (Halley and Evans 1983). Note major tidal passes in middle Keys. Dotted line (30-m-depth contour) marks the shelf margin, which lies within the Florida Keys National Marine Sanctuary boundary (blue line). **b** Index map shows locations of major Holocene coral reefs and USGS geophysical surveys (gray lines) for a portion of the upper and all of the middle Keys. Sinkhole at the northeast end is discussed in Shinn et al. (1996). **c** Index map shows survey lines for the lower Keys, Marquesas Keys, and The Quicksands areas. Contours are in meters

(1970s), and the Mariel Boatlift (1980). Financier Henry Flagler's Overseas Railroad transported tourists south to Key West and agricultural produce north from Cuba to Miami for 23 years before the Labor Day hurricane of 1935 destroyed both train and railway tracks (Parks 1968). The keys and other areas of South Florida today remain favored destinations for Caribbean immigrants seeking asylum in the US. But for the past three decades, the coral reefs have fueled the economy of the keys, providing lucrative commercial fisheries and colorful easily reachable habitats that draw tourists from around the world.

Accessibility of the shallow and emergent late Quaternary sequences to scientists makes the Florida windward margin one of the best-studied modern carbonate platforms. In the early years, Florida reefs intrigued researchers interested in the tropical marine-carbonate environments. Shinn and Jaap (2005) recount some of the classic carbonate studies that were carried out in the Dry Tortugas. Louis Agassiz mapped benthic communities in the Tortugas (Agassiz 1880). His son Alexander published the map (Agassiz 1883). In an effort to protect shipping, Louis also examined reefs for the Lighthouse Service (the US Coast Survey, predecessor of the US Coast Guard) with the intent of determining how to prevent the reefs from growing. Reefs took a heavy toll on shipping and in those days were considered a costly nuisance. Failing to discover how to halt reef growth, Louis decided the logical solution was installation of lighthouses. A 46-m-high structure was completed on Loggerhead Key in the Tortugas in 1858 and still functions today, though with updated illumination. In 1905, Alfred Goldsborough Mayer, a student of Alexander Agassiz, built and directed the Carnegie Institution's Dry Tortugas Laboratory on Loggerhead Key. To help justify the laboratory, he documented the so-called black-water event (a red tide) of 1879 that killed fish and essentially all acroporids at the Tortugas (Mayer 1903). He published his landmark treatise on medusae (Mayer 1910) and contributed to research on temperature tolerance of corals and other marine organisms (Mayer 1914, 1918). Without the aid of drilling, T. Wayland Vaughan, a close friend of Mayer, correctly deduced that the Tortugas was an elliptical atoll-like structure built primarily of Pleistocene coral, which spurred his interest in reef geology, ecology, and coral growth rates (Vaughan 1914a, b, 1915a, b, 1916). After Mayor's death in 1922 (Mayer changed the spelling of his name to Mayor in 1918), William H. Longley (who with Hildebrand 1941, pioneered the first underwater color photography of tropical Atlantic fishes), then David Tennent (sea-urchin embryology) directed the Carnegie Laboratory until its closure in 1939 for economic reasons. Today, little is left of the facility. A memorial plaque designed by Mayor's artist wife was erected near the site a year after Mayor died. The monument stands in lone testimony to the benchmark tropical marine-biology research that Mayor had envisioned and that he and his colleagues had achieved (Stephens and Calder 2006).

Prior to being designated a National Marine Sanctuary in 1990, reefs in the vicinity of the Florida Keys were drilled in the search for oil. Hydrocarbons are being produced from Lower Cretaceous limestone, anhydrite, and dolomite that compose the Sunniland Formation of Florida (Winston 1969, 1972). Seventeen exploratory wells were drilled in south and central Florida and in the keys beginning at about the time oil was discovered at the Sunniland Field in 1943 (Fig. 2.2; Dustan et al. 1991). All wells had oil shows, but no show was economically viable. All wells left magnetic signatures due to borehole casing. Most offshore well sites evolved into 'artificial reefs' as sessile organisms colonized discarded wires and casings, and great numbers of fish congregated in borehole cavities that formed havens in otherwise featureless seafloor sites (Shinn et al. 1989a, 1993). Conclusions drawn from the well-site studies were that none of the environments sustained permanent biological damage during the one-time perturbations of drilling, even to depths of several thousand meters, and that the biological impact was negligible. Conclusions could not be drawn from those studies for wells that would become producing wells with longer-term on-site perturbations.

2.2 Overview of Large-scale Geologic Parameters

South Florida is built of thousands of meters of Cenozoic limestone deposited on top of an igneous Mesozoic basement (e.g., Applin and Applin 1965;