CHAPTER 1
CARBONATE ROCKS AND PLATFORMS

Frontispiece Triassic carbonate rocks exposed in the Dolomites of northern Italy, cliff is ~300 m high.

Origin of Carbonate Sedimentary Rocks, First Edition. Noel P. James and Brian Jones.

Companion website: www.wiley.com/go/james/carbonaterocks

What are carbonate sedimentary rocks?

Carbonate sedimentary rocks (Frontispiece) are limestones and dolostones composed of the minerals calcite ($CaCO_3$) and dolomite ($CaMg (CO_3)_2$). They comprise roughly 20% of the surface sedimentary rocks on the planet with the oldest being ~3.5 Ga, almost as ancient as the Earth itself. Most of these rocks were once sediments that accumulated in aquatic environments that ranged from the warm, sunlit shallow seafloor to the cold, perpetually dark, deep ocean. Constituent particles precipitated directly from seawater, or were biologically formed from calcified microbes, calcareous algae, and the whole or broken skeletons of invertebrate animals. The spectrum of original sediments, ranging from muds, to deep-sea ooze, to reefs, to absurdly fossiliferous banks, is truly astonishing. Finally, carbonate rocks are not all marine. Carbonate deposits also form in association with terrestrial spring waters, in rivers and lakes, as calcareous soils, and in caves.

No one carbonate is like any other because the biosphere and the depositional environments have changed dramatically through time and space. The modern world is but a general guide as to how these amazing rocks originally formed.

Why should we care about studying these rocks?

Carbonate rocks are, because of their largely biological origin, unparalleled repositories of information about past life on our planet; they are our windows into deep time. As life has evolved, particularly in the ocean, so the composition of carbonate sediments and rocks has changed in tandem. No-one can fail to be amazed at the preservation of life that is hundreds of millions of years old and yet looks as though it was made yesterday. How can this be?

Many of the particles that comprise marine carbonate rocks are also proxies of ancient ocean composition because they were precipitated in equilibrium with ancient seawater. They contain within their skeletons mineralogic, petrographic, and geochemical vestiges of their birth. As the seas warmed and cooled, so the organisms changed in concert, thus preserving what these long-vanished oceans were like. The history of the marine realm is written in these rocks, but we must learn to read the text properly.

Carbonate rocks are profoundly important for human life as we know it. Many of our most historical and beautiful buildings are fashioned from limestone. The rocks are important freshwater aquifers worldwide. Limestones and especially dolostones also host a disproportionally large proportion of the world's metallic ores and hydrocarbons. To understand the nature of fluid flow through and the economic attributes of these rocks, we must know how they originated so that we can predict their attributes in regions that are yet to be explored.

What is the scientific approach?

Our objective is that after reading this book you will be able to interpret carbonate rocks, no matter their age and state of alteration. More specifically, we hope that you will be able to answer the fundamental questions as to how they were formed and how have they been altered after deposition before you are looking at them today. As stressed in the previous chapter, this is a profound intellectual challenge! What is the best way forward? The most useful approach seems to be one of looking carefully at the modern world of carbonate deposition (Figure 1.1) and diagenesis where we can discern the important *processes* that are operating and then apply these principles to the rock record. Ancient oceans, however, were not the same as they are today: biological evolution has been rampant through time so that the biosphere was different in the past; plate tectonics has altered the position and nature of depositional environments; and climate has induced profound changes in the atmosphere, in seawater temperature gradients, and in sea level itself. Is there any hope? The answer to that is *yes*, because knowledge of our oceans and environments is so sophisticated that we can apply our knowledge of modern analogs to interpret the products that we see in the rock record.

Figure 1.1 Students swimming over a Bermuda coral reef in ~2 m of water, the modern equivalent of many ancient limestones.

The carbonate continuum

Regardless of the age of the limestone you are trying to understand, there is always a recurring theme of deposition followed by diagenesis (Figure 1.2). Although this simple flow can be interrupted, reorganized, and recycled in many different ways, it provides an easy way in which to approach the topic.

Deposition

As emphasized above, the most obvious carbonate particles (Figure 1.3) are the broken and whole shells of invertebrates such as clams and corals that range in size from microns to meters. Biogenic components are mostly the skeletons left behind when an organism dies (e.g., a snail) or the crystallites embedded in the tissue are released when an alga expires (e.g., a green calcareous algae). Inorganic grains range from tiny crystals of mud that precipitate out of seawater or freshwater to sand-sized particles composed of numerous crystallites aggregated together (e.g., a coated grain). There are, however, many components that are formed by both biogenic and inorganic processes (e.g., a stromatolite; Figure 1.4).

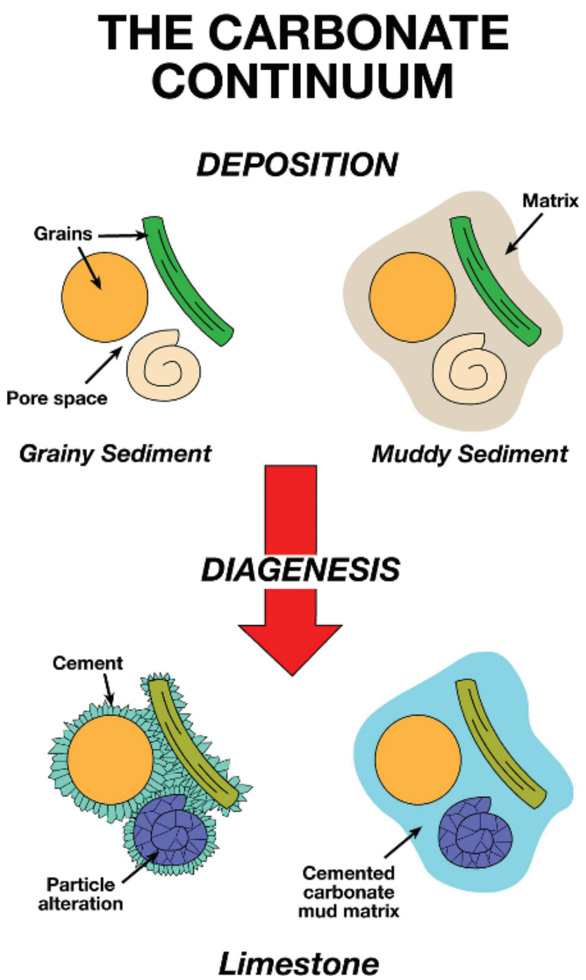

Figure 1.2 Sketch illustrating the carbonate continuum where sediment is transformed into limestone via diagenesis.

Figure 1.3 A carbonate sediment from the modern continental shelf off southern Australia composed mostly of bryozoans (B), centimeter scale.

Figure 1.4 A cross-section of laminated hemispherical stromatolites in 1.9 Ga limestones from the Pethei Group, Great Slave Lake, Arctic Canada, 10 cm scale bar at base.

The multifaceted, ongoing processes in the depositional environment not only generate particulate sediments such as carbonate sands and muds, but also construct large structures such as coral reefs. In the simplest terms, grainy sediments are composed of grains, matrix, and pore space (Figure 1.2). While grains are those particles described above, matrix is usually (for sand-sized sediment at least) composed of carbonate mud. Details of how such sediments and rocks are classified are outlined in Chapter 4. Reef rocks are classified in a different way because they are constructed of large skeletons that stack on top of one another with impressive internal cavities between, or are shed off as coarse debris (Chapter 15).

Diagenesis

Diagenesis is for the most part the processes of lithification and alteration. The term diagenesis is, for the purposes of this book, defined as the mineral, chemical, and fabric changes that carbonate sediments or rocks undergo at relatively low temperatures and pressures before they enter the realm of metamorphism.

Lithification is generally achieved by the precipitation of carbonate crystals in spaces between particles in clean sands or between the micropores of muddy sediments or matrix. Such carbonate is usually called *cement* (Figures 1.2, 1.5), not to be confused with the construction cement that is used to build houses and highways (which is quite different). Such crystals generally precipitate first on the particle surface and then grow towards the cavity centre where they can eventually fill the whole void. Cements can be precipitated in the environment of deposition, that is, at or just below the seafloor, shortly after deposition when fresh meteoric waters percolate through the rock, or much later when the whole succession is deeply buried beneath younger deposits. Most cementation and particle alteration can therefore be considered as taking place in different *diagenetic environments* that are defined by the nature of the waters involved.

Alteration is when the original composition of the sediment is changed. The range of potential modifications is wide. The simplest case is just mineralogical change where the texture and the fabric of the original deposit are largely unaltered. The more severe cases occur when the whole character of the sediment is altered such that most of the rock is composed of crystalline calcite or dolomite that obliterates the original fabric (fabric destructive).

Dolomitization of carbonate sediment or limestone is a common diagenetic process. The original calcareous material is partly or wholly transformed into dolomite (Figure 1.6). This occurs in a variety of ways and can happen at any time in the history of the deposit. The results range from complete preservation to total obliteration of texture and fabric such that the rock becomes a mass of crystals that resemble brown sugar. Whereas the latter example causes most researchers distress, hydrologists and petroleum geologists rejoice because it is generally accompanied by a profound increase in rock porosity and permeability.

The bottom line is that whereas carbonates can precipitate easily, they are, because of this attribute, just as readily susceptible to profound change.

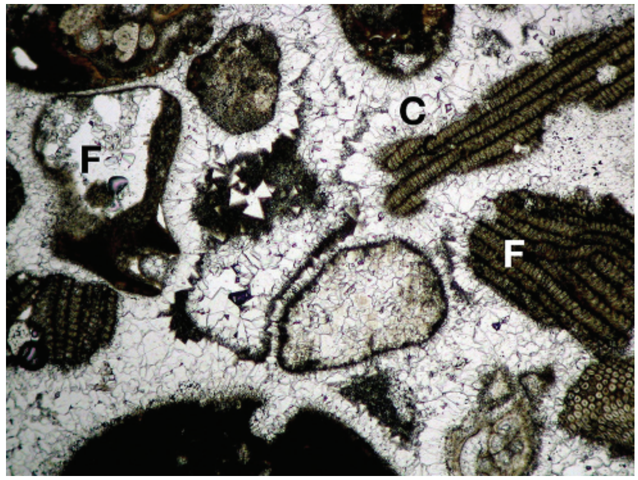

Figure 1.5 Thin-section image of a Bermuda Pleistocene limestone composed of biofragments (F) and interparticle cement (C), image width 1 cm.

Figure 1.6 Coarsely crystalline white (saddle) dolomite replacing Cambrian limestone, Main Ranges of the Rocky Mountains, Alberta, Canada; the inclined bedding is not cross-bedding but expansive hydrofracturing, centimeter scale. Photograph by W. Martindale. Reproduced with permission.

How do carbonate sediments form?

The sediments are born, not made

This deceptively simple phrase, as mentioned in the Introduction to Part I, encapsulates the main theme of carbonate deposition and highlights their differences from siliciclastic sedimentary rocks. Siliciclastic sediments are formed largely of detritus, derived from the disintegration of source rocks, which is transported to the depositional environment. Once there, the hydraulic regime dictates the nature of the facies because water movement is the primary control over transportation, deposition, and development of sedimentary structures. By contrast, carbonate sediments are *born* as precipitates or skeletons within the depositional environment. For carbonate deposition this means that:

- sediment composition is largely dictated by the skeletal composition of the resident biota;
- grain size is largely imposed by biological processes and variations in grain size and need not signal changes in the hydraulic regime;
- large structures such as platforms and reefs are self-generating and self-sustaining; and
- the temporal and spatial style of accumulation depends upon the nature of the sediments themselves.

The site of carbonate sediment production, especially in shallow illuminated aquatic environments, is commonly viewed as the *carbonate factory* (Chapter 3). Input to the factory is the Ca and CO_3 in seawater. Output is in the form of grains of all sizes and shapes that are generated by a spectrum of processes that commonly involve the direct or indirect intervention of the resident biota. Most sediments, which remain in or close to their place of formation, accumulate as widespread neritic or *subtidal* deposits or as reefs and mounds. Some of the abundant fine fraction (mud) is usually resuspended during storms and transported onshore where it forms muddy tidal flats that develop around highs on the platform and along the shoreline. As the storms wane, offshore currents will also move fine sediment seaward or basinward where it is deposited in deep water. Regardless of location, it is the factory that generates vast quantities of carbonate sediment.

The extent of marine carbonate factories is readily apparent, for example, on the satellite image that covers Cuba, the Great Bahama Bank, Florida Bay, and the Florida Shelf (Figure 1.7). On this image, areas of shallow-water carbonate sediment occur where there is no influx of detrital sediment from nearby landmasses (e.g., Florida Bay, Gulf of Batabano) or where the banks are isolated by surrounding deep oceanic waters (e.g., Great Bahama

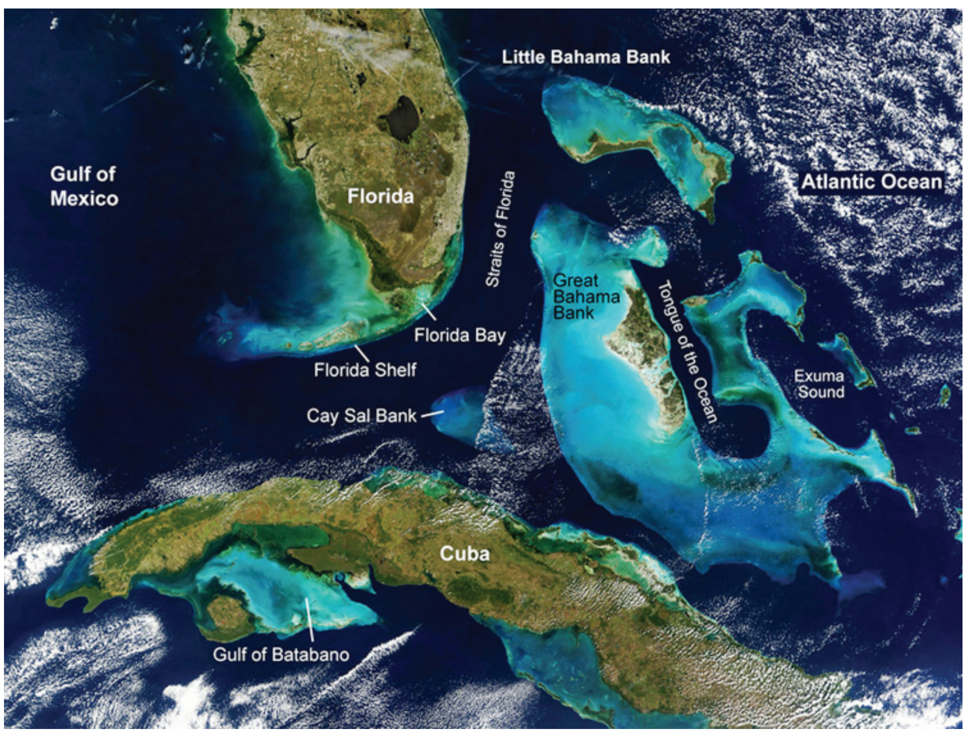

Figure 1.7 A satellite view of southern Florida, Cuba, and the Bahama Banks. The light blue areas, mostly <5 m deep, are regions of carbonate sediment formation. Source: Jones (2010). Reproduced with permission of the Geological Association of Canada.

Table 1.1 Sedimentary aspect of modern warm- and cool-water carbonate components and their ancient counterparts.

Component	*Modern, warm-water*	*Modern, cool-water*	*Ancient counterpart*
Large elements of reefs or biogenic mounds	Corals (with photosymbionts)	ABSENT	Corals, stromatoporoids, stromatolites, coralline algae, sponges, rudist bivalves, Archaeocyathans
Whole organism forms granule-size particles	Large benthic foraminifers (with photosymbionts)	ABSENT	Large benthic foraminifers (e.g., Fusilinids)
Remain whole or break apart into several pieces to form sand- and gravel-size particles	Bivalves, red algae	Bivalves, red algae, brachiopods, barnacles	Red algae, brachiopods, cephalopods, trilobites
Whole skeletons that form sand- and gravel-size particles	Gastropods, small benthic foraminifers	Gastropods, small benthic foraminifers	Gastropods, small benthic foraminifers
Spontaneously disintegrate upon death to form many sand-sized particles	Green (Codiacean) and red algae	Red algae, bryozoans, echinoderms	Phylloid algae, pelmatozoans and other echinoderms, bryozoans
Concentrically laminated or micritic sand-sized grains	Ooids, peloids	ABSENT	Ooids, peloids
Medium sand-sized and smaller particles in basinal deposits	Planktic foraminifers, coccoliths, pteropods	Planktic foraminifers, coccoliths, pteropods	Planktic foraminifers and coccoliths (post-Jurassic), stylolinids
Encrust on or inside hard substrates, to build up thick deposits or fall off upon death to form sand grains	Encrusting foraminifers, red algae, bryozoans, serpulid worms	Encrusting foraminifers, red algae, bryozoans	Red algae, calcimicrobes, encrusting foraminifers, bryozoans
Spontaneously disintegrate upon death to form lime mud	Green algae (Dasycladaceans)	Red algae, bryozoans, serpulid worms	Dasyclad green algae
Trap, bind, and facilitate precipitation of fine-grained sediment to form mats, stromatolites, and thrombolites	Bacteria and other microbes	Bacteria and other microbes	Calcimicrobes and microbes (especially pre-Ordovician)

Bank). Such factories can cover vast areas, for example the Great Bahama Bank has an area of ~96,000 km^2 and the Great Barrier Reef complex in Australia has an area of ~344,400 km^2. It should be noted, however, that some carbonate factories in past geological time covered even greater areas such as the vast shallow so-called epeiric seas that veneered most of continental North America during the Paleozoic.

Production in the carbonate factory is intimately linked to the resident biota. Thus, as animals and plants have evolved through geologic time, so too has the nature of the sediments changed. Some comparisons are obvious (Table 1.1); for example, the contrast between the Proterozoic microbial-dominated stromatolite factory and the Jurassic invertebrate-dominated coral factory is readily apparent. Other comparisons, especially those involving shorter time spans, are subtle with the differences being less obvious; for instance, the difference between Permian brachiopod-rich and Cretaceous bivalve-rich sediment.

Where are carbonates produced and where do they accumulate?

The marine realm

Marine carbonates have the potential to accumulate anywhere in the ocean except on the deepest abyssal plains and trenches where hydrostatic pressure is so high and seawater temperature is so low that they generally dissolve before reaching the seafloor (see Chapter 2). The main limiting factor in carbonate production in most places is abundant dirt, because too much siliciclastic sediment: (1) swamps the carbonates; (2) clogs the feeding apparatus of many calcareous organisms; and (3) decreases light penetration, a critical factor for photosynthetic biota. It used to be thought that carbonates were strictly warm-water tropical deposits but we now realize that whereas water temperature is important, carbonate production can extend from the equator well into polar waters. In summary, most carbonate sediment is produced in bright, relatively clear, near-surface ocean waters.

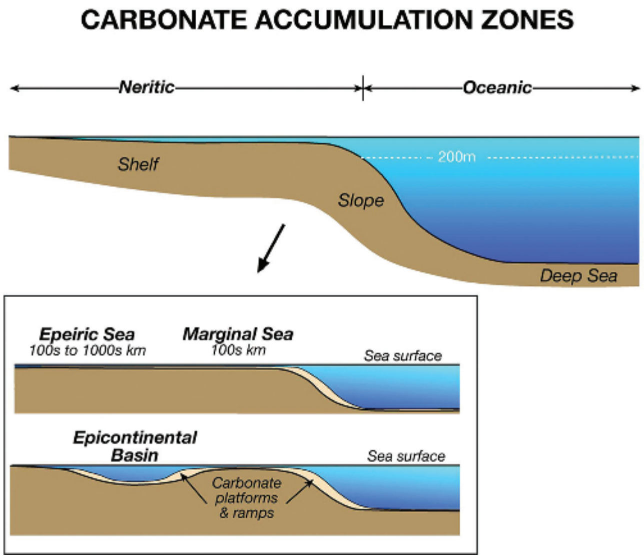

Figure 1.8 Sketch illustrating the different areas of carbonate sedimentation.

Carbonate production can take place on the shallow seafloor or in the shallow water column. The two major sediment-producing environments are the *neritic zone*, the part of the seafloor from the shoreline to the continental shelf edge at ~200 m water depth, or the *oceanic zone*, the shallow part of the water column to ~200 m depth (Figure 1.8). The major organisms in these two zones respectively are seafloor-dwelling (*benthic*) or water-column dwelling (*planktic*).

Carbonate deposition or accumulation in the neritic zone today is mostly benthic (both biogenic and physicochemical) with a minor pelagic component. The opposite is true in deep ocean basins where, even though some sediment can be washed into deep water via sediment gravity flows from neritic environments, most sediment is pelagic in the form of calcareous plankton that, upon death, sink to the deep seafloor; there is only a minor contribution from deep-water calcareous benthos.

Areas of neritic carbonate sedimentation (Figure 1.8) are either on the continents (intracontinental basins) or in the open ocean as spectacular shallow banks (e.g., Bahama Banks; Figure 1.7). Epicontinental carbonates accumulate in a variety of shallow basins, along continental margins, and in epeiric seas. An epeiric sea is defined as a vast shallow sea that was connected to the open ocean and stretched for hundreds to thousands of kilometers across a continent; sadly, there are no modern analogs to these environments. These are different from the more common, marginal seas that covered continental margins. Whereas epeiric seas were beyond the reach of oceanic tides, marginal seas were well within the zone of such tides. The difficulty of interpreting carbonates deposited in epeiric seas is explored in Chapter 20.

The terrestrial realm

Not all carbonate sedimentary rocks are of marine origin; many originate on land in the terrestrial realm. The most extensive deposits accumulate in lakes. Settings range from marginal marine to truly terrestrial far from the ocean in large shallow structural basins, in rift valleys, or in mountain valleys. The most impressive lacustrine carbonates occur when the lakes are fed by internal drainage.

Calcareous soils are widespread in space and time. Such pedogenic horizons can develop in both siliciclastic and carbonate soils, generally under semi-arid climates. The interaction of soil and soil-related processes around the margins of lakes can also profoundly modify lacustrine deposits leading to palustrine carbonate deposits.

The ocean is a prolific and ongoing source of carbonate sediment and calcareous beach sediment can be blown into spectacular sand dunes called aeolianites. These dune complexes form along the shores of both warm-tropical and cool-temperate oceans.

The features that set terrestrial systems apart from marine carbonates are the dissolution and precipitation products associated with their interaction with fresh water, namely karst and springs. Karst features such as caves are produced by subsurface dissolution via water mixing and can contain impressive calcareous precipitates in the form of speleothems (e.g., stalagmites and stalactites). Carbonate springs, essentially carbonate saturated warm- or cold-subterranean waters that emerge onto land, precipitate carbonate in the form of tufa or travertine.

Tectonic settings and the nature of carbonate platforms

Carbonate accumulation through time in an area of crustal subsidence can lead to the formation of impressive rock bodies. Some of the more important are exposed in mountain belts such as the Rockies and the Alps, whereas others remain buried in the subsurface and are important hydrocarbon reservoirs. The term that is usually used for such structures is *carbonate platform* (Figure 1.9). This is a general term because there are three recurring end-members in the rock record: rimmed platforms; open platforms; and inclined platforms (usually referred to as *ramps*). The structures can be attached to land (e.g., Great Barrier Reef) or be detached and isolated in the open ocean or basin (e.g., Great Bahama

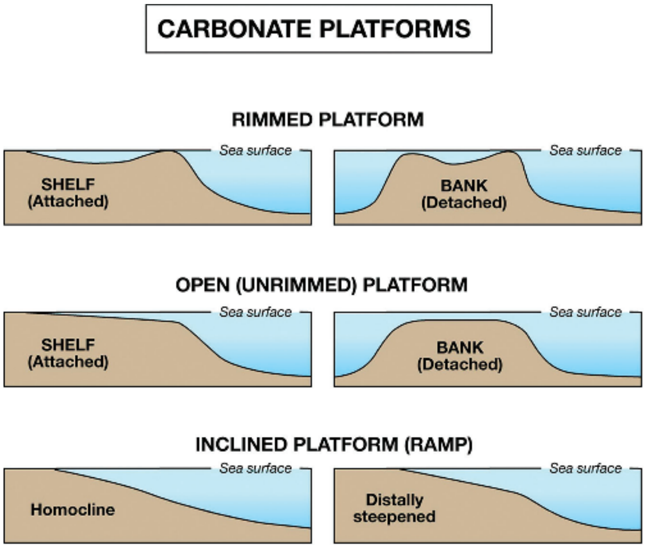

Figure 1.9 Sketch illustrating the three main types of carbonate platforms.

Bank). A flooded craton many hundreds to thousands of kilometers across is called an *epeiric platform* when covered by shallow seawater (an epeiric sea) (Figure 1.8). A *bank* is an isolated platform surrounded by deep ocean water and cut off from terrigenous clastic sediments and terrestrial runoff. An *atoll* is a specific type of bank commonly developed on a subsiding volcano. Carbonate atolls and banks may be dominated by reefs such that their geological expressions are termed *reef complexes*.

The size, geometry, thickness, and stratigraphy of carbonate bodies are largely determined by tectonic setting, either extensional (Figure 1.10) or compressional (Figure 1.11). A few platform types can be present in each realm.

Extensional

Intracratonic. Such platforms are located in relatively shallow basins on the craton with low subsidence rates. They are relatively thin successions with subhorizontal boundaries that are largely determined by eustasy. Climate is important; interbedded siliciclastics occur in humid climates and coeval evaporites in arid climates. Platforms are rimmed around the basin margin with the basin center evaporites or shales giving a concentric or bull's eye facies pattern to the deposits. Platforms are generally progradational and <1 km thick. The Paleozoic Michigan Basin, the Permian Basin of North America, and the Cenozoic Murray Basin in Australia are excellent examples.

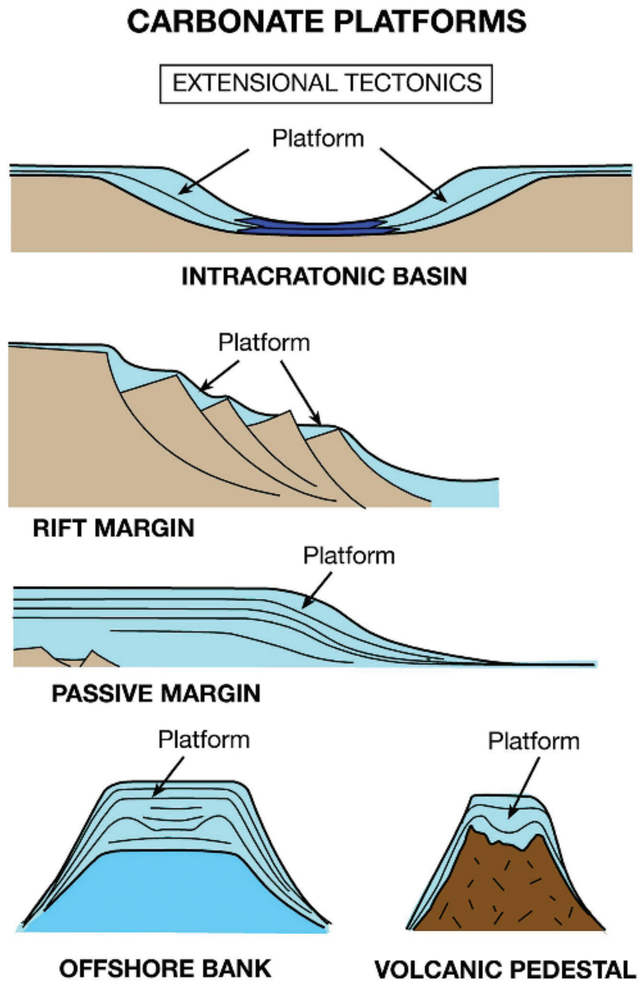

Figure 1.10 Sketches of carbonate platforms and atolls in different extensional tectonic regimens.

Rift basins. Carbonate platforms can develop on footwall highs or rotated fault blocks. Deposits are wedge-shaped and thicken down into hanging-wall dip slopes. They thin onto footwall highs. The footwall areas are commonly reef- or shoal-rimmed margins. A good example of these deposits is the Cenozoic along the Gulf of Suez.

Passive continental margins. These are some of the most extensive carbonate platforms in the rock record. Platforms are generally thick with their bathymetry inherited from underlying rift successions. Platforms can be immense: many thousands of kilometers in length and many hundreds of kilometers in width. Subsidence rates are generally low and so progradation is typical with facies belts parallel to the coastline. Stratigraphic geometries are generally subhorizontal because of domination by eustatic sea-level fluctuations (eustasy). The Paleozoic continental margin of eastern North America and the

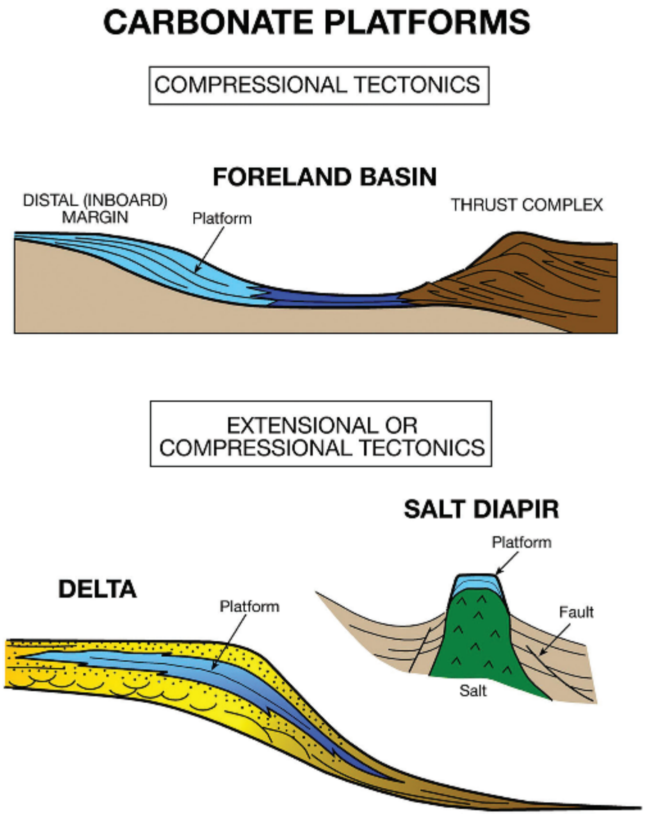

Figure 1.11 Sketches of carbonate platforms in compressional and extensional–compressional tectonic regimens.

Cenozoic northwest shelf of Australia are good examples of these systems.

Offshore banks. Large carbonate banks surrounded by deep basins are generally located in passive margin settings. As above, subsidence rates are usually low and progradational successions can dominate stratigraphy. These structures can have strongly differentiated margins with erosional or steep reefal windward margins and low-relief progradational leeward margins. The Bahama Banks is the quintessential example of a modern offshore carbonate bank.

Volcanic pedestals and island arcs. These platforms reflect their association with volcanic edifices, namely biogeographic isolation, variable subsidence, steep volcanic slopes, and tectonic instability. These relatively small platforms (Figure 1.10), 10–50 times smaller than continental platforms, range from fringing reefs around volcanoes to atolls composed of thick successions on top of thermally subsiding ocean volcanoes. Successions are typically aggradational and are surrounded by deep-water facies. The steep margins are characterized by numerous slumps and redeposited carbonates. Thicknesses are highly variable from <100 m to >1000 m. Sequence boundaries are subhorizontal over the top and reflect eustasy. Biotas are highly endemic because of geographic isolation and typically of low diversity, with some components surviving longer than their cousins on continental margin platforms. They are common today in the tropical Indo-Pacific and in mountain belts where they have been obducted landward onto a craton (e.g., Mesozoic of Oman or Paleozoic of the Appalachians).

Compressional

Foreland. Platforms in foreland basin settings on the craton are either on the crest of advancing thrusts or along the passive inboard margin (Figure 1.11). Platforms on thrust tops are generally ribbon-like in plan view and relatively thin on rising thrust complexes with tectonics imparting an irregular unpredictable motif to carbonate sequences. Seismicity results in numerous redeposited slope deposits. Platforms on the inner distal margin are best developed when there is a semi-arid climate and minor input of siliciclastic sediment from the adjacent exposed craton. High subsidence rates result in locally thick successions (which can be >1 km) that onlap down into the axial trough with the platforms which generally, but not always, parallel the inboard shoreline. Platforms have a ribbon-like geometry and can eventually be buried by siliciclastics from the relentlessly advancing thrust sheets. The late Paleozoic Cordillera foreland basin in western North America and the Cenozoic foreland basin of the Alps are good examples.

Extensional and compressional

Salt diapirs. Platforms may be located on rising salt diapirs (Figure 1.11) and have ameboid to arcuate shapes. The internal geometry is generally complex and caused by a combination of the rise and fall of the diapir and subsurface salt dissolution. The sequences are generally shallowing upward, aggradational, and relatively thin (<500 m). The Persian Gulf off Abu Dhabi is an area with numerous such platforms.

Deltas. Platforms are typically irregular in this situation because of the complex interrelationships with siliciclastic deposition. They usually have an arcuate or lenticular shape and limited stratigraphic thickness. Platforms can coexist with coarse and intermittent siliciclastic sedimentation in arid settings. Only carbonate benthic communities that can tolerate fine sediment can thrive under humid climates that produce continuous fine-grained siliciclastic sediment. Good examples are the Mesozoic of Sicily and Pyrenees of Spain together with the Holocene of Borneo.

How do we study carbonate sediments and rocks?

To fully understand the sedimentology and diagenesis of carbonate rocks the researcher must be a natural scientist who is willing to use the main tools of stratigraphy, paleontology, petrography, and geochemistry to get at the answers.

It is probably a good idea to have several excellent books on paleontology at hand, particularly those that discuss not only the taxonomic attributes but also the ecological aspects of marine organisms. These books are very useful when working at the outcrop scale and searching for macrofossils.

There is no question, however, that the real understanding of the rocks comes from thin-section petrography. There are several excellent books (see the Further reading list) that illustrate microscopic attributes of the main rock-forming components and their alteration. Most workers have such books open and at hand near the microscope when describing and interpreting thin-sections. A key skill is being able to recognize organisms from random two-dimensional cuts through their skeletons.

Diagenetic aspects of the rocks can be greatly enhanced through the application of additional techniques. Stains are particularly useful for differentiating calcite and dolomite and for visualizing the iron contents of precipitates. Some trace elements, especially manganese, cause calcites and dolomites to luminesce when bombarded with electrons. Cathodoluminescence (CL) is particularly useful for determining the precipitation and alteration history of crystals and skeletons. Some features are just too small to be revealed by standard petrography and so scanning electron microscopy (SEM) of either broken or polished and etched surfaces can be extremely helpful.

Geochemistry is also a required research tool. The most useful trace elements are Sr, Ba, Fe, Mg, and Mn. Strontium is especially good for tracing the diagenetic evolution of young sediments and unraveling the genesis of dolomite. Sr isotopes have also been used for dating of carbonate rocks (especially in the Tertiary). Carbon and oxygen stable isotopes, because they are so abundant in carbonates and in the waters from which they precipitated, are indispensible in diagenetic studies. Most of these techniques and their utility are explained in Part III of the book.

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