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Stephen J. Culver *Editor*

Troubled Waters

Understanding the Science Behind our Coastal Crisis

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For family
Devinder, Katherine, David, Steve, Jessy, Will, Andie, Alice, Len, Aimee, Dave, Lew, Michelle, Jasvinder, John, Boo, Darshan, Ajit, Bill, NooNoo, Jasmine, Mira, Mike, Diana, Andy, Jo, Matt, Stephanie, Georgia, Brianna, Scarlett, Olive, Anyu, Millie, and Ben.

Preface

Academic geologists spend their careers educating future generations of geologists. We are also quite good at communicating with other geologists about our scientific research. We do it through the publication of research papers in peer-reviewed journals and through presentations at conferences attended by other geologists. Unfortunately, we are not quite so good at communicating our results and their implications to politicians, policy makers, and the public. In this book we try to correct this situation to some small degree for the very relevant subject of coastal geology. Several of our chapters concentrate on coastal North Carolina, USA (it is the natural laboratory where many of the authors have worked), but the information we convey is relevant to many other coastal systems worldwide. Thus, we include several chapters that deal with coastal systems (the coastal plain to the inner shelf) beyond the boundaries of North Carolina, in Malaysia, the Basque Country, the Western Pacific, Gabon, Wales, the Caribbean, Tanzania, Russia, Papua New Guinea, the Philippines, the Maldives, Alaska, Hawai'i, Louisiana, Florida, Oregon, and Georgia. Several authors also mention older coastal systems, up to 450 million years old. New approaches to collecting coastal geologic and oceanographic data are also treated in a couple of chapters and we recognize the importance of education of students in coastal matters in another chapter. Most importantly, we try to present the human side of geologists' work. How we conduct research, how scientific knowledge evolves as new data become available, and how we, unfortunately, sometimes take missteps along the way are all included. Our hope is that readers will come away with a better understanding of coastal systems, field and laboratory-based geologic research, and the people who conduct it. Because approximately 25 million of the world's population (~7.8 billion people) currently live on land less than 1 m above high tide level (Kulp and Strauss, 2019), and that proportion has been growing, an enhanced understanding of coastal evolution, coastal processes, and anticipated future coastal change, together with a greater understanding of geologists' research efforts (and our foibles), is relevant to us all.

I wrote much of the paragraph above in June 2018. In October 2018, the Intergovernmental Panel on Climate Change (IPCC) distributed a special report entitled "Global Warming of 1.5 °C." This report, based on extensive scientific data, explains the impacts of global warming of 1.5 °C above pre-industrial levels, what we should do about the threat of climate change, and when we should do the necessary things to avoid what can only be called global catastrophe. In the months that have followed (I am writing this paragraph in August 2019) we hear more and more serious commentators, and, indeed, the leaders of many countries, accept the fact of climate change and its (unfortunately) mind-blowing threat to humanity. As the father of two great kids and grandfather to two perfect (of course) baby grandchildren, this threat is very real to me—as it should be to all of us. As a geologist, I knew of this threat when this book was conceived in the summer of 2017, but the fall 2018 IPCC report *really* focuses the mind and spells out the dangers of doing nothing, or not enough, or not soon enough.

So, the chapters in this book take on a little more significance. They are geological in scope and they deal with coastal matters. We hear in these chapters the backstory of scientists trying to understand coastal systems around the world so we can inform those who manage these incredibly valuable natural resources. Geologists study past coastal areas that are preserved in the subsurface and also study the processes that take place in modern coastal settings. When you read in these chapters about sea-level rise, multiple powerful hurricanes, coastal erosion and flooding, saltwater intrusion, barrier island breakdown, anthropogenic coastal pollution, tsunami, and the death of coral reefs— the modern version of the canary in the coalmine, keep in mind the fact that if we humans do not act appropriately, and very soon, to reduce the rate and amount of global warming, things will only get worse. The economic costs of projected global warming will be far greater than the economic costs of reducing carbon emissions so that the Earth does not warm 1.5 ºC or more.

It takes a long time to get a multiauthored book from conception to publication. So I am putting the finishing touches to this preface in the midst of the COVID-19 global pandemic. The public reaction to the virus has been unprecedented. Individuals and local, state, and national governments have joined together to fight against a ruthless and unknown threat to our way of life. I have no doubt that the doctors and scientists will find a way to combat and control the disease. Unfortunately, there is a far greater threat to humanity, and that is the anthropogenically forced global warming that drives climate change, the root cause of our coastal crisis that we discuss in this book. The effects of climate change, however, are many and go far beyond the threats to our coasts. Spread of disease, social unrest, social breakdown, and conflict readily come to mind as we battle COVID-19. But floods, droughts, crop failures, and myriad other challenges, many of them economic, will also occur. These issues are interrelated by the commonality of global warming. Indeed, the Earth is a system, analogous to a human body, but threatened by the "virus" of climate change. Perhaps we should consider the Earth to be elderly (it is 4.6 billion years old) and immunosuppressed (by the impact of humans and their burgeoning population, mainly since the Industrial Revolution). We must come together once more as individuals and local, state, and national governments to fight against global warming, an existential threat to the future of humankind. Individual responses are valuable, but not enough. Governments must act, and act in unison. And our responses should always be informed by science and driven by a communal caring for all of the inhabitants (not just human) of our third rock from the Sun.

Greenville, NC, USA Stephen J. Culver
April, 2020

Reference

Kulp SA, Strauss BH (2019) New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. Nat Commun 10:4844. https://doi.org/10.1038/s41467-019-12808-z

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Contributors

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G. Lynn Wingard Lynn Wingard received her Bachelor of Science degree from the College of William and Mary and her Master's and Ph.D. degrees in geology from George Washington University. She began working at the U.S. Geological Survey as a student intern while at George Washington, and after completing her degree she was hired as a Research Geologist. Her research focuses on reconstructing past conditions in coastal ecosystems over the last 5000 years, using mollusks and the sedimentary record preserved in cores. Much of her recent work has been in support of the Greater Everglades Ecosystem Restoration.

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Chapter 1
A Cautionary Scientific Tale and an Introduction to This Book

Stephen J. Culver

Abstract The unplanned collection of a small, nondescript rock in Senegal, west Africa leads to a story of how science and the acquisition of new knowledge does not necessarily progress in a series of straightforward steps. This cautionary tale is followed by an introduction that explains the purpose and content of this book, to explain to the general public, politicians, managers and policy makers how our coasts, important to us as places of not only inhabitation and vacation but also of natural resources and industry, are in crisis, in large part due to human activities. The human side of scientific research is emphasized and this book describes how geologists try to understand the workings of our varied coastal systems and what the future will bring for these beautiful and often wild parts of our planet.

Keywords Senegal · Sierra Leone · Late Precambrian · Shallow marine glacial deposits · *Aldanella* · Geologic research · Modern coastal environments · Climate change · Anthropogenic · Mitigating coastal hazards

A Cautionary Tale

Serendipity is a wonderful thing. It has certainly been a part of my research career. I'm a paleontologist who specializes in the study of microfossils. But I have conducted research on other matters. My first job after graduating from university was as a Lecturer (the British version of an Assistant Professor) at the University of Sierra Leone in West Africa. I held that post from 1977 to 1978 and began a lifelong interest in the geology of West Africa. By 1984 I was teaching at Old Dominion University in Virginia. That year I led a National Geographic Society-funded

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expedition to Sierra Leone, Liberia and Senegal, West Africa. It was a very small expedition, just me, a graduate student and a French geologist from Cheikh Anta Diop University (also known as the University of Dakar), Senegal.

Early one morning I was sitting on a large rock in the Walidiala Valley, in the far southeastern corner of Senegal, 600 kilometers from the coastal capital city of Dakar and within a stone's throw of Guinea, watching my student climbing up the steep hillside in front of me slowly and carefully logging (graphically describing) the various kinds of sedimentary rocks over which he was scrambling while my French colleague collected samples. It was hot, of course, and the air was still. I stood up to walk over to a tree under which I'd left my backpack and water bottle. We carried a lot of water and so our backpacks were somewhat of a burden even though we were only a mile or two from our Land Rover. Unfortunately, our packs became heavier rather than lighter as the day progressed because we replaced the water with rocks! These were specimens that my student and I were taking back to our home laboratory in the US to study and describe in detail. I drank deeply and in the shade of the tree I took off my hat in the futile hope that a little air to the head might cool me down. As I walked back to my seat, perhaps because I had removed my hat, the sunlight reflected off a small rock and it caught my eye. It was light in color, a buff-grey, in sharp contrast to the rocks on the floor of the valley that had a reddish tinge to them. I picked it up. It was quite nondescript, maybe 10 cm in length and width and 3 or 4 cm in thickness (Fig. 1.1). For some reason I placed it in a canvas sample bag and put it in my backpack. I carefully recorded its location in my notebook and did not give it another thought for several weeks.

Our Senegalese samples that we had dispatched in a wooden box via sea freight finally arrived in the US about two months after our departure to cooler climes. My student excitedly prized open the box and sorted out his samples. And there was my little light-colored rock. The goal of our research was to build upon research I had conducted while living in Sierra Leone. We were seeking rocks that had originally been deposited by coastal and shallow marine glacial processes as much as 635

Fig. 1.1 The sample of dolostone from the Walidiala Valley, southeastern Senegal that yielded two early Cambrian fossils of the enigmatic species, *Aldanella attleborensis.* Pen for scale. (Image by Laura de Sousa)

Fig. 1.2 The author standing on and next to late Precambrian, shallow marine, glacial sedimentary rocks (laminated sandstone and shale with ice-rafted dropstones) in the Walidiala Valley, Senegal. (Image by A.W. Magee)

Fig. 1.3 Close-up of the rocks illustrated in Fig. 1.2 showing a large dropstone that fell from the base of a melting iceberg and landed on the seafloor bending and disrupting underlying sediment laminations. (Image by S.J. Culver)

(maybe as little as 560) million years ago. At that time, in the late Precambrian (modern terminology is Neoproterozoic), what is now West Africa, including the countries of Liberia and Senegal, was located over the South Pole. Continental drift, powered by the processes of plate tectonics, much later moved West Africa to its current location just north of the equator. To this day, I use specimens of these shallow marine rocks deposited around the margins of a huge ice sheet that covered the northern part of the frigid West African continent as incontrovertible evidence of climate change (Fig. 1.2). By comparing the characteristics of these rocks with the characteristics of sediments deposited in coastal and shallow marine environments around Antarctica today, we can see no difference except for the fact that the African rocks are hard (Fig. 1.3) and the Antarctic sediments are soft. No other environment

Fig. 1.4 Late Precambrian tillite from Sierra Leone. (Image by S.J. Culver)

Fig. 1.5 Late Precambrian tillite from the Walidiala Valley, Senegal. (Image by S.J. Culver)

on the surface of the Earth today exhibits sediments with same characteristics as those of shallow marine glacial environments. Thus, we use one of the basic tenets of geology, "The Present is the Key to the Past", to interpret the environment of deposition of ancient rocks.

These interpretations are valuable. For example, while I was teaching at the University of Sierra Leone, I studied late Precambrian conglomerates that had been investigated for gold deposits. The general consensus was that the conglomerates, poorly sorted sedimentary rocks composed, in this case, of sand, pebbles, cobbles and boulders up to a meter across, were deposited on the beds of rivers during the late Precambrian. Taking that idea a step further, it was thought that detrital gold might be concentrated under the pebbles and cobbles as is the case with classic placer deposits. But no gold had yet been found. By demonstrating that the conglomerates (Fig. 1.4) were glacial in origin rather than fluvial in origin, I explained why no one had struck it rich. The hydrodynamic processes that concentrate gold particles under pebbles and cobbles on the bed of a river just do not take place under a continental ice sheet or just offshore of its margins in coastal and shallow marine environments. These conglomerates were, in fact, tillites, the lithified and ancient version (see an example from the Walidiala Valley, Senegal; Fig. 1.5) of the extensive tills that were deposited under a great ice sheet in the northern states of the US and in northwest Europe during the maximum advance of the last ice age approximately 20,000–18,000 years ago.

But let's get back to my little buff-colored rock. I looked at its surface under a microscope and thought it might be a limestone. But it did not fizz when I dripped a little dilute hydrochloric acid upon it. It was, in fact, dolostone, a rock that is similar in composition to limestone, but which contains magnesium. I would have preferred a limestone because limestones often contain fossils. However, limestones that later become dolomitized can preserve fossils within them and so I was still interested in this specimen. Just for the fun of it, I carried my rock to a paleontologist colleague who worked at the US Geological Survey in Washington, D.C. to look for fossils. An expert in ancient molluscs (snails, clams and their relatives), he processed it by quenching – alternating hot and cold until the rock fractured and broke. And lo and behold, two tiny fossils popped out! They were internal molds (lithified sediment infilling) of coiled snail shells preserved as phosphate and each one no bigger than a pin-head (Fig. 1.6). Similar shells, called *Aldanella*, had been described from Siberia and Newfoundland and they indicated that the rock I had collected in Senegal containing them had been deposited early in the Cambrian Period approximately 530 million years ago.

So now I had a big problem. By pure chance, the serendipity that I spoke of at the beginning of this story, I had found some fossils that were of some importance. This type and age of fossil had not been recorded previously in this part of West Africa. Thus, their presence was of significance for both dating the rocks and for understanding their paleogeographic distribution. But I did not know exactly where the fossils were from! I had not collected my little rock from its source. I had not hammered it off a cliff face of solid rock. My rock was from the "float", the collection

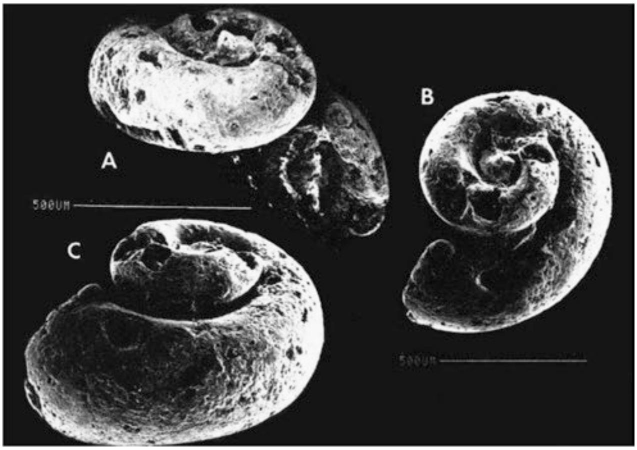

Fig. 1.6 Three scanning electron microscope images of a specimen of the early Cambrian fossil *Aldanella attleborensis* from the Walidiala Valley, Senegal. Scale bars are 500 micrometers. (Images by SJ. Culver and L. De Sousa; from C.R. Acad. Sci. Paris, t. 307, Serie II, p. 651–656, 1988)

of loose rock of all sizes that had either fallen down the valley side under the force of gravity or had been transported along the valley floor by running water during a rainy season in the not too distant past. The 635 million year-old glacial rocks sat directly upon older limestone and sandstone that together with 2 billion year-old metamorphosed basement rock of granitic composition floored the valley. So, where did my dolostone come from? Its source must have been from higher up the side of the valley – but the sedimentary logs did not record any dolostone. With my student, I had climbed up the valley side, which was partially covered by dense scrub, to check his work and I too did not see any dolostone. Overlying, and therefore younger than the glacial rocks, were red and green siltstones, with an interbedded approximately one meter-thick greyish colored chert, a very hard rock with the same composition as quartz. Overlying the siltstones was a much younger almost black rock called diabase. This dark, hard, igneous rock, which had protected the underlying sedimentary rocks from erosion, was intruded at shallow depths in the Earth's crust as a result of fracturing and faulting of rock during break-up of the supercontinent Pangea early in the Jurassic Period approximately 190 million years ago. The region that is now Senegal, Gambia, Guinea-Bissau, Guinea and Sierra Leone rifted away from what is now eastern Florida and Georgia as the continents of Africa and North America began their slow journeys that resulted in a 7000 kilometer-wide Atlantic Ocean. Indeed, the rocks deep in the subsurface below the Everglades of Florida are the same as those exposed on the surface in Sierra Leone today. If my rock was not from the valley sides, then it must have been transported down the river valley. I needed to go back to Senegal to walk up the valley to find the source, not of the ephemeral river that carved the valley over tens of thousands of years, and perhaps much longer, but of the fossils in my little buff-colored rock.

I wrote another proposal, this time to the National Science Foundation, and a couple of years later I returned to the Walidiala Valley, this time with two colleagues from the U.S. Geological Survey. On arrival I saw immediately that the place had changed dramatically. The dense brush that had covered the valley sides had been burned off (Fig. 1.7), perhaps by wildfires but more probably by the local villagers in order to expand the area where crops could be planted. And there, at the same

Fig. 1.7 A hillside in the Walidiala Valley, Senegal showing burnt vegetation in the left foreground and geologists moving past newly exposed rock outcrops (Image by J. Repetski)

elevation on both sides of the valley was a horizontal buff-colored rock unit, a little scorched from fire, from 1 m to 7 m in thickness, above the glacial rocks. I was both surprised and extremely happy to see this. This must be the source rock for my little snail shells! A couple of years earlier, my student and I had climbed up the hillside and had, by chance, chosen a route through the brush that happened to be over a thin part of the dolostone where it was hidden by vegetation.

With this new knowledge about the source of my "float" rock, I could now submit a research paper describing and illustrating these fossils to a peer-reviewed scientific journal. After review and editorial comments my coauthors and I revised the paper and a year or so later it was finally published.

An Introduction to This Book

So why have I recounted a cautionary scientific tale? Well, first of all, the only people who read my paper on the fossils I had found in the Walidiala Valley were fellow paleontologists interested in the early Cambrian when many groups of animals and various kinds of single-celled organisms first acquired hard parts, in this case, coiled shells. In other words, we scientists communicate through our publications in specialized journals with liked-minded people with similar interests. Most of what scientists publish is never seen let alone read by anyone else. The proverbial "man in the street" has little idea what scientists are doing and why the many avenues of research might be important. Indeed, importance, is not always self-evident. Remember, for example, the conglomerates in Sierra Leone and the lack of gold.

Second, you'll see that serendipity is a big part of this story. It was by chance that I picked up my little buff-colored rock. It was by chance that my student and I missed the source dolostone during our traverse up the valley sides. I had not planned for returning to a valley almost devoid of vegetation. And I'm sure chance had something to do with my grant proposal being funded. I could have received reviews from anonymous scientists who did not like what I had written. But, instead, the reviews were good, and I received the funding that enabled me to return to my field site. It was also by chance that I knew paleontologists at the U.S. Geological Survey who could collaborate with me. And that was the result of my being a postdoctoral researcher in the Department of Paleobiology at the Smithsonian Institution at a time when the Survey's paleontologists were housed in the Smithsonian's Natural History Museum along with Paleobiology's paleontologists. This was the result of a (successful) effort to encourage collaboration between the paleontologists of two of the most important scientific institutions in the US.

Third, you'll understand now that the research I published on the little snail shells was not only the result of chance finds but that it was the result of basic, curiosity-driven science. That is one way to undertake research, but it is well removed from what we are taught about at school – the scientific method. Geologists are expected nowadays to undertake hypothesis-driven research. The geologist develops a hypothesis about a topic of interest, often based on previously conducted research. S/he then tests the hypothesis by trying to falsify it. It is possible to falsify a hypothesis, but it is not possible (in geology, usually) to prove a hypothesis. Take, for example, the hypothesis that all ants have six legs. One cannot prove that is the case because it is not possible to count the legs on every ant that is alive today and, of course, the legs on every ant that was alive in the past. Now consider the hypothesis that all sheep are white. Observations are then made, and one single observation of a black sheep falsifies the hypothesis. This then leads to the next, interesting scientific question, “Why are some sheep are black?”

Fourth, this book will, hopefully, demonstrate the fact that geologic research, like any other endeavor, has a human side. We all have our styles, strengths, weaknesses, and foibles. And, of course, we can all make mistakes. One fact that pleases me, even though I have disagreed, sometimes strongly, with other scientists, is that in 46 years of undertaking geologic research I have not come across a single case of a fellow geologist being willfully misleading in his/her research activities. That is a pretty strong statement and one that should give us all much comfort. It is very important to point out, however, that this does not mean that we should not question scientists’ research and conclusions. As I suggested in the Preface, we should all do a little research, nowadays probably on the web (making careful judgements on the veracity of sites we visit), and in doing so allow ourselves to make educated judgements on what to accept, what to question and what to reject. And our acceptance, questioning and rejection should be based on data and not belief.

In summary, geologic research, often involving a significant field component, can be exploratory and descriptive or it can be hypothesis-driven. Either way, science progresses. New scientific data can often answer a question and lead to one or more new scientific questions. Scientists rarely have all of the answers. We are always learning new things. It is understandable, therefore, when other professionals, such as environmental managers or policy makers, become frustrated by the diffidence of scientists and their unwillingness to become dogmatic about whatever topic is the subject of discussion. This apparent “changing of the mind” can lead to accusations of “bad science” or even of scientists feathering their nests with grant funds. All you need to do is look at how most geologists dress and the cars that we drive and you’ll know that grant funds have not led to a life of luxury.

What is this book about? Well, it’s not about West Africa, not about 635 million year-old shallow marine glacial deposits, and not about tiny fossils of snail shells. But it is about how geologists conduct research and progress their science. More specifically, it is about coastal geology and it is a sincere effort to communicate what coastal geologists do and why they do it. It is an effort to explain the relevance of what we do to the lives of people living in coastal communities, to the tourists who visit our shores, to the people who manage our coastal economies and, indeed, the relevance of our work to the well-being of national economies and, therefore, the populations of entire countries.

The coast is the zone where the marine realm and the terrestrial realm intersect. It is a dynamic place, one that is affected by climate change and where the processes of sea-level rise and storm dynamics demonstrate the power of the ocean over the relatively long term and short term, respectively (Figs. 1.8, 1.9, and 1.10). But the coast,

Fig. 1.8 Storm-driven erosion of a bluff on the Chowan River estuary, North Carolina. (Image by Burrell Montz)

Fig. 1.9 A back-barrier marsh on Ocracoke Island, North Carolina, showing hurricane-driven overwash sand covering much of the marsh vegetation. (Image by A.C. Kemp)

Fig. 1.10 Highway12 just north of Rodanthe, North Carolina, looking south, showing the artificial dune on the left that was overwashed by water and sand during a nor'easter. Note the location of the white dashed line down the middle of the road. In the right distance, bulldozers are clearing sand off the highway. (Image by S.J. Culver)

defined narrowly, does not tell the whole story. The coastal zone is affected, for example, by the waters that come down the rivers and by the nature and amount of sediment that characterizes the inner shelf. In return, coastal processes can affect the characteristics of the coastal plain, for example by intrusion of saline water miles inland in surface and subsurface waters. Hence, this book documents aspects of a zone much broader than the coast, encompassing the coastal plain to the inner shelf.

We have heard much in the media about climate change. The authors of this book recognize that climate change is a natural process. How can we not recognize and accept this? The entire history of the Earth that we read in the rocks is about change. Refer again to the Cautionary Tale and glacial deposits in what is now equatorial Africa. But even greater changes have characterized our Earth. For example, if you travelled in a time-machine back to the early Earth, 3.5–4 billion years ago (the Earth is ~4.6 billion years old), and you got out, you would suffer an awful but quite rapid death because the atmosphere at that time contained no oxygen for you to breathe. Free atmospheric oxygen arrived millions of years later during the Great Oxygenation Event (2.4–2.0 billion years ago) and only by about 540 million years ago did it reach concentrations high enough to lead to the evolution of the animal groups that are still with us today.

So, the composition of the Earth's atmosphere has changed since early Earth History and climate has always changed but we also now know that human activities are an increasingly important driver of current climate change. This book will not debate this fact – it has been well demonstrated elsewhere (see IPCC reports, for example). But readers of the following chapters will see that climate change is a fact of life and that the geological record of the recent past is important as it provides us with an understanding of the nature and scale of environmental changes we should anticipate in the future. Thus, we have changed around that basic tenet of geology referred to earlier in this Introduction ("The present is the key to the past") to, "The past is the key to the future". If our data-based projections for the future are realistic, accepting that there are uncertainties and that science progresses, our projections will become more accurate as new data are collected and new models are run. We will have a chance of adapting to the warming world mentioned in the Preface and to mitigating the coastal hazards that come our way (Figs. 1.11 and 1.12).

We start the book with a chapter by Dave Mallinson that introduces the reader to coastal North Carolina, USA (Fig. 1.13) and, in particular, to what lies beneath the Outer Banks barrier islands and the sounds behind them. Andy Kemp and Ben Horton then explain the science behind sea-level studies based on research experience from all over the world. We then return to the Outer Banks and this book's editor describes an event of major change that occurred 1200 years ago that might well happen again in the not too distant future. Pete Parham's chapter describes his sea-level studies in Malaysia that come at the question in a completely different way from that of Kemp and Horton. Next we hear from J.P. Walsh about new ways to investigate coastal processes, including the high-tech approaches to that tried and true scientific activity, geologic mapping. Edu Leorri then recounts some of his coastal pollution research in the Basque Country and gives us his perspective on a topic de jour, the proposed new geologic interval of time known as the Anthropocene.

Fig. 1.11 Highway 12 on Pea Island, North Carolina, looking north showing an eroded dune on the right and bulldozed sand on the left during a nor'easter. (Image by S.J. Culver)

Fig. 1.12 Houses in the ocean at Rodanthe, North Carolina, during a nor'easter storm. The house with the blue shutters featured in the movie, "Nights in Rodanthe", starring Diane Lane and Richard Gere. The house was later moved by truck to another location. (Image by S.J. Culver)

We return to North Carolina and Alex Manda's stories on water resource issues. Of course, the availability of water is a basic societal need – recall that the capital of South Africa, Cape Town, came perilously close to running out of water in 2018 (water levels of major dams dropped to 13.5% of capacity). The next chapter, by Kathleen Farrell, is about her experiences drilling into the subsurface of the Mississippi Delta and the Georgia and North Carolina Coastal Plain, the source for much of this region's ground water supply. We then travel to the west coast of the US and hear from Andrea Hawkes about coastal change driven by earthquakes. Andrea then takes us back to Malaysia and describes her experiences as a graduate student studying the geologic record of the horrifying tsunami of December 2004 caused by a megathrust earthquake off Sumatra, Indonesia. We stay in warmer realms with Lynn Wyngard's chapter on the value of coastal mangrove forests and threats to the unique Everglades environment and David Lagomasino's chapter on remote sensing of mangrove forests in Gabon, Tanzania and the Philippines. Following is Pam Hallock's extremely educational but, unfortunately, disturbing

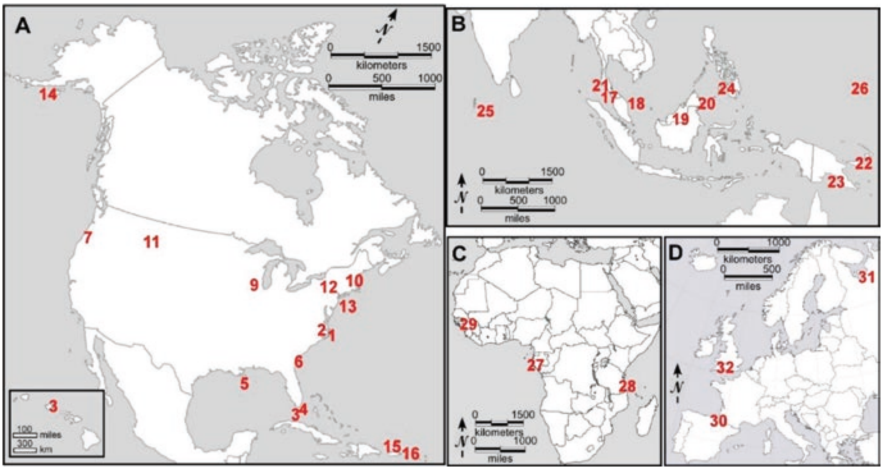

Fig. 1.13 (**a**–**d**) Maps showing the location of studies mentioned in this book
1. Pamlico Sound, Outer Banks, Roanoke Island, North Carolina, USA
2. Suffolk Scarp, Buckridge Preserve, Plymouth, Chowan estuary, North Carolina, USA
3. Florida Keys, USA
4. Florida Bay, USA
5. Mississippi Delta, Louisiana, USA
6. Coastal Georgia, USA
7. Coastal Oregon, USA
8. Coconut Island, Kaneohe Bay, Hawai'i, USA
9. Beloit, Wisconsin, USA
10. Dartmouth, New Hampshire, USA
11. Missoula, Montana, USA
12. Hamilton, New York, USA
13. Long Island, New York, USA
14. Sitkinak Island, Alaska, USA
15. Parguera, Puerto Rico
16. St. Croix, US Virgin Islands
17. West coast, Peninsular Malaysia
18. East Coast Peninsular Malaysia
19. Sarawak, Malaysia coast, Borneo
20. Sabah, Malaysia coast, Borneo
21. West coast, Thailand
22. New Britain Island, Papua New Guinea
23. Fly River Delta, Papua, New Guinea
24. Southern Negros, Philippines
25. The Maldives
26. Belau, western Caroline Islands
27. Libreville, Gabon
28. Rufiji Delta, Tanzania
29. Southeast Senegal
30. Bilbao, The Basque Country
31. White Sea, Russia
32. Swansea Bay, South Wales, UK

chapter on the threat of global warming to the well-being of coral reefs worldwide. Stan Riggs then describes his love affair with coastal geology and education over 70 years; many, many students have had successful careers as geologists due to the things they have learned (not just geological) under Stan's "soggy groggy" tutelage. In the penultimate chapter, oceanographer and educator Joy Moses Hall reflects on the chapters in this book and provides thoughts that will, hopefully, encourage and enable the reader to both embrace and coexist with the inevitable coastal change that will come our way. We end with an Afterword – a brief essay by the editor that describes an unforgettable experience during his doctoral student days that greatly impressed upon him the incredible power of the oceans. It is that power, and the changes that it effects, that makes the coastal zone such an interesting and exciting place to live, work, study and play.

Important Postscript (More Caution!)

I've noted above that science progresses. We learn new things and old interpretations might need to be modified or even rejected. Sometimes we might not like what we learn. My story about the two tiny fossil snail shells in the buff-colored rock took another turn in 2007 in a paper that I coauthored with a multinational team of geologists. In the 23 years since I had collected that rock, no other fossils had been found in samples from the dolostone outcrop (although few people had looked at those specific outcrops, similar rocks, in similar stratigraphic sequences, and of similar age, occur on several continents, and none -to my knowledge- have yielded fossils like the two I had found in Senegal). Furthermore, phosphate had not been recorded in the Walidiala Valley dolostone and yet the fossils were phosphatized. The weight of evidence led us to conclude that it was "unwise" to use the two fossils to assign an early Cambrian age for the dolostone when all other evidence suggests the dolostone was of late Precambrian age. What have I learned from this? Never pick up a loose rock!

You might think that is the end of this tale, but it is not! In 2013 a research paper argued that *Aldanella* was not a snail (class Gastropoda, phylum Mollusca). Amazing fossils of *Aldanella attleborensis* from Pennsylvania and Siberia, even though they are more than 500 million years old, preserve phosphatized soft parts including hair-like structures called chaetae that were part of a locomotory organ that indicates a swimming lifestyle. These are not characteristics of early gastropods (although some tiny members of this group called pteropods began to swim in oceanic surface waters ~72–79 million years ago and continue to do so today). It was suggested in the 2013 paper that *Aldanella* belonged to an enigmatic group of extinct organisms called the hyoliths (class Hyolitha, phylum Mollusca). So, my tiny coiled fossils, now in the collections of the Smithsonian Institution, are not even snail shells! Serendipity can be very complicated! But we learn new things and science progresses.