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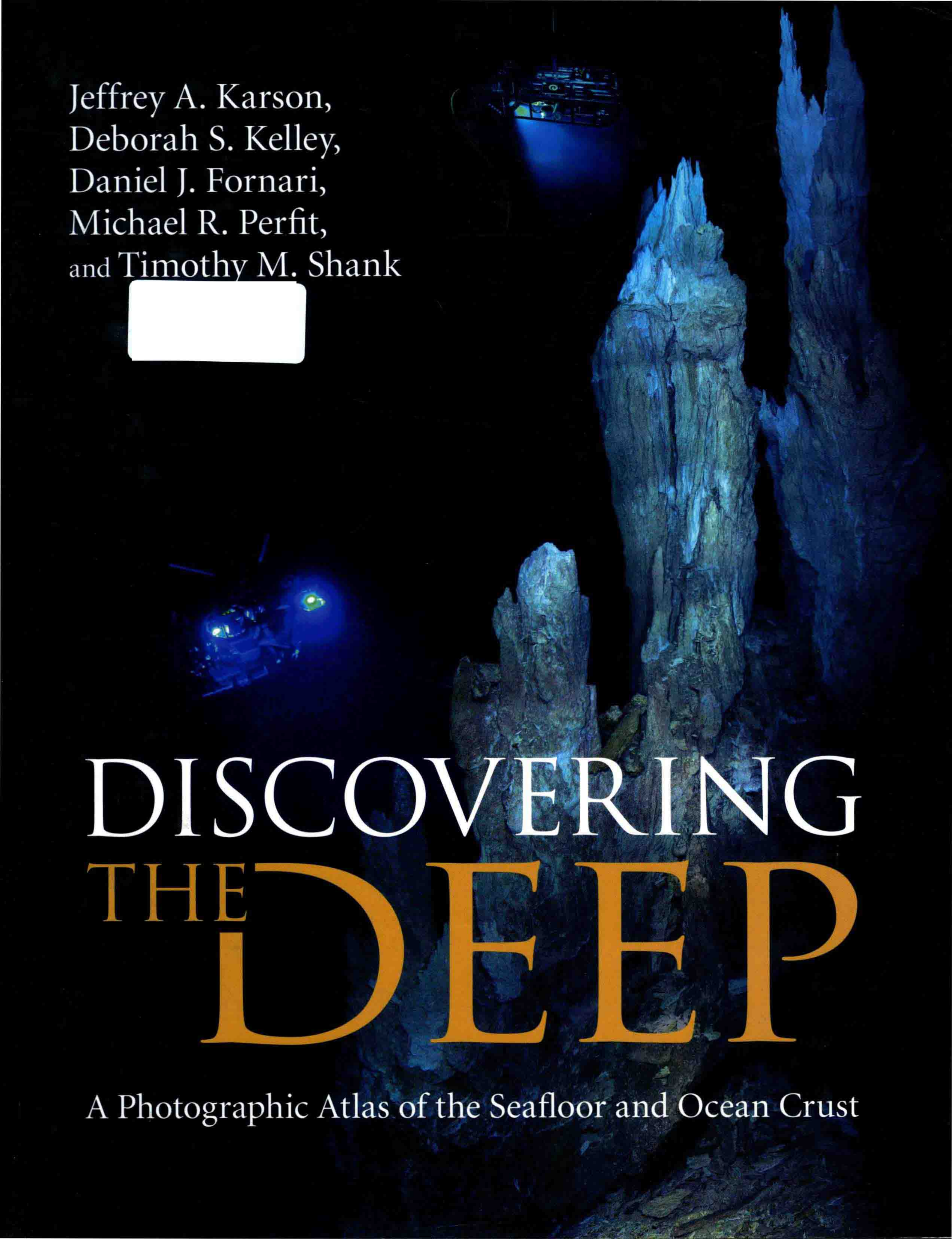

DISCOVERING THE DEEP

A Photographic Atlas of the Seafloor and Ocean Crust

Discovering the Deep

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Discovering the Deep

A Photographic Atlas of the Seafloor and Ocean Crust

The deep oceans and global seafloor are truly Earth's last frontier. They remain largely unexplored, yet are critical to our survival on this planet. This magnificent volume transports you to volcanoes, boiling hot springs, and fault zones in mountains a mile beneath the ocean surface, where bizarre landscapes host exotic life forms that rival the most imaginative science fiction.

Illustrated throughout with spectacular color photographs, the book starts with a historical summary of seafloor exploration and the developing technologies used to study this extreme environment. It then presents a series of chapters that describe the distinctive geological components of the Earth's ocean floor and the myriad environments found along mid-ocean ridges where new crust is created. It is here that discoveries of chemosynthetic biological communities revolutionized our ideas about the origins of life and the potential for life's existence elsewhere in the Universe. The authors provide elegant explanations of how the various geological and hydrothermal features of the seafloor are formed through physical, chemical, and biological processes, and present comparative examples from places where the seafloor is exposed on land.

Discovering the Deep is an indispensable reference for researchers, teachers, and students of marine science, and a visually stunning resource that will enlighten and intrigue oceanographers and enthusiasts alike. A suite of online resources, including photographs and video clips, combine with the book to provide fascinating insights into the hidden world of seafloor geology and biology using the latest deep-sea imaging and geological concepts.

Jeffrey A. Karson is Professor of Geology in the Department of Earth Sciences at Syracuse University and a Fellow of the Geological Society of America. He investigates the interplay of magmatic construction and mechanical deformation of extensional and transform fault environments from ophiolites, contemporary oceanic crust, Iceland, continental rifts, and continental margins. Professor Karson has participated in numerous field projects and seafloor research cruises worldwide. He is the author or co-author of over 150 publications on seafloor spreading and related phenomena.

Deborah S. Kelley is a Professor in the School of Oceanography at the University of Washington and also Associate Director of Science for the first US underwater high-power, high-bandwidth cabled observatory, funded by the NSF. She is the former Chair of the UNOLS Deep Submergence Science Committee. Her research examines the linkages between submarine volcanoes, underwater hot springs and how they support life in the absence of sunlight. Dr. Kelley has participated in over 35 blue water cruises routinely using robotic vehicles, and has been on over 50 *Alvin* deep-sea submersible dives, to depths as great as 4000 meters.

Daniel J. Fornari is a marine geologist and Senior Scientist at the Woods Hole Oceanographic Institution (WHOI). He was the first Chief Scientist of Deep Submergence at WHOI, a past Director of WHOI's Deep Ocean Exploration Institute (DOEI), and was a Chair of the Ridge 2000 Program, a NSF-funded national program studying mid-ocean ridges. Dr. Fornari is the author or co-author of over 100 research publications and has participated in over 100 research cruises and as many dives in deep-sea submersibles. His research focuses on volcanic and hydrothermal processes along the global mid-ocean ridge, using a variety of surface and deep-towed sonar systems, submersibles, ROVs, and AUVs.

Michael R. Perfit is Professor of Geological Sciences at the University of Florida, where he has received several awards for excellence in teaching. He has co-authored more than 100 scientific publications on volcanism and magma genesis at oceanic spreading centers and seamounts. Dr. Perfit has participated in 30 oceanographic research cruises and taken more than 35 dives in *Alvin*. He has served as the Chair of the Deep Submergence Science Committee, and is also a Fellow of the Geological Society of America and the American Geophysical Union, and a Trustee of the Consortium for Ocean Leadership.

Timothy M. Shank is an Associate Scientist in the Biology Department of the Woods Hole Oceanographic Institution and Director of WHOI's Ocean Exploration Institute. His research focusses on ecological and evolutionary processes that affect ecosystem structure, faunal evolution, and biodiversity in the deep sea. Dr. Shank has conducted more than 57 scientific expeditions, using a wide variety of submersibles, ROV and AUV systems (including more than 50 *Alvin* dives). He is currently the Director of the Hadal Ecosystems Studies Program, pioneering the first research use of the full-ocean depth hybrid ROV (*Nereus*) in the deepest trenches.

Praise for
Discovering the Deep

"Though it's fashionable to say we know little about the mysteries of the deep, this book shows the vast wealth of understanding that pioneering researchers have already gleaned, with their probing sound waves, persistent robots and courageous submariners. This is the book I wish I'd had on my eight deep ocean expeditions, to better understand the wonders I was gazing upon. A must-own for anyone in the ocean sciences, and for those simply curious about what lies down there in the most remote realm on our planet."

James Cameron, explorer and film-maker

"*Discovering the Deep* will open your eyes to the largest and most unexplored region on Earth – the global Mid-Ocean Ridge. My own introduction to the Mid-Ocean Ridge began with the FAMOUS Expedition to the Mid-Atlantic Ridge in 1974, and this beautifully illustrated and comprehensive account shows how far we have come over the last 40 years in our understanding of this fundamental tectonic feature of the Earth and the technology required to investigate it. Not since Bruce Heezen and Charlie Hollister's classic book, *The Face of the Deep*, first published in 1971, have we seen such a comprehensive photographic atlas of what lies in the hidden depths of the sea."

Dr. Robert D. Ballard, President of the Ocean Exploration Trust

"*Discovering the Deep* is an exquisite synthesis of the complexity of natural processes, the beauty of oft unseen environments, and the critical scientific discoveries of our recent past. To read this volume is to become an enlightened traveler into the fascinating realm of the seafloor and ocean crust. No student of the natural world should be without this magnificent atlas of our planet's richly structured deep ocean environment."

Dr. Kathryn D. Sullivan, Under Secretary of Commerce for Oceans and Atmosphere and NOAA Administrator; former NASA astronaut

Foreword

An alien approaching Earth for the first time would observe a watery planet but would have no clue as to what lies beneath the blue-gray liquid surface. This book unveils and illuminates, in ways never before possible, that hidden world and the astounding processes that occur at the seafloor and within the oceanic crust. Drawing from unparalleled imagery and data from twenty-first century technology, which includes human-occupied and robotic vehicles, sophisticated sensors and analytical techniques, the authors have succeeded in "pulling the plug" on the global ocean so that the awe-inspiring terrane of the ocean floor and processes that form it are revealed.

It was 44 years ago that Bruce Heezen and Charles Hollister published their seminal book, *The Face of The Deep*, an engaging and informative text that used analog seafloor photographs to highlight and interpret the myriad processes operating in the global abyss. *Discovering the Deep* sets a new benchmark for a comprehensive treatise about visualizing the seafloor, how ocean crust forms, and the amazing life forms that thrive in one of the most extreme environments on Earth – submarine hot springs. It presents up to date, integrated multidisciplinary concepts about the mid-ocean ridge and its role in plate tectonics and developing the architecture of the oceanic crust. The authors also synthesize published data from mid-ocean ridge analogs on land – ophiolites – to better understand how oceanic crust is generated and the far-reaching implications of these processes for interpreting Earth and ocean history.

As a student of Heezen, a contemporary of Hollister, and someone who has spent most of his career studying the mid-ocean ridge using ships and the submersible *Alvin*, I was drawn into all aspects of this compelling and masterful synthesis, especially the high-resolution images of mid-ocean ridge volcanic and hydrothermal terranes and biota. The more than 500 stunning images of the seafloor, many never before published, were taken using the latest in deep-sea digital camera and lighting technology. The remarkable images provide glimpses of underwater eruptions where molten rock turns to glass almost instantly, and black-smoker vents where the most exotic life forms known on Earth live. Spanning environments from the Arctic, Atlantic, Pacific, and Indian Oceans, the authors provide captivating images of these seafloor oases, which host novel microbes that use toxic gases rising from Earth's interior as their energy source.

The authors have succeeded in presenting a holistic view of the oceanic crust from top to bottom. They present the current state of knowledge on the complex and beautiful forms of volcanic flows that pave the mid-ocean ridge crest to the massive basal layers of intrusive, plutonic, and ultramafic rocks that until recently have been difficult to sample and place in their proper geological context. The variations in style and structural complexity of these primary units are now known to be critical to the construction of all mid-ocean ridges, from ultra-slow to fast, and the hydrothermal systems and life that they support. This work ends with an important look towards the future and new technologies that will be required to address upcoming opportunities and challenges in understanding the vast oceans that make Earth habitable.

The five authors of this atlas are all recognized as individuals who have made significant contributions to our understanding of the mid-ocean ridge system. They have succeeded in synthesizing the many different, but complementary data sets – weaving together a text that elegantly takes the reader on a journey from hydrothermal vents down through the oceanic crust. They tell a story that is entertaining, illuminating, and scholarly. For a layperson interested in learning more about fundamental planetary process, a student of marine geology just embarking on a career, or a seasoned investigator of oceanic crustal processes, this atlas of the seafloor and oceanic crust is sure to expand horizons and enrich understanding of how our planet works for all readers.

PAUL J. FOX
Professor Emeritus
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Preface

New Views of Earth from Below the Oceans

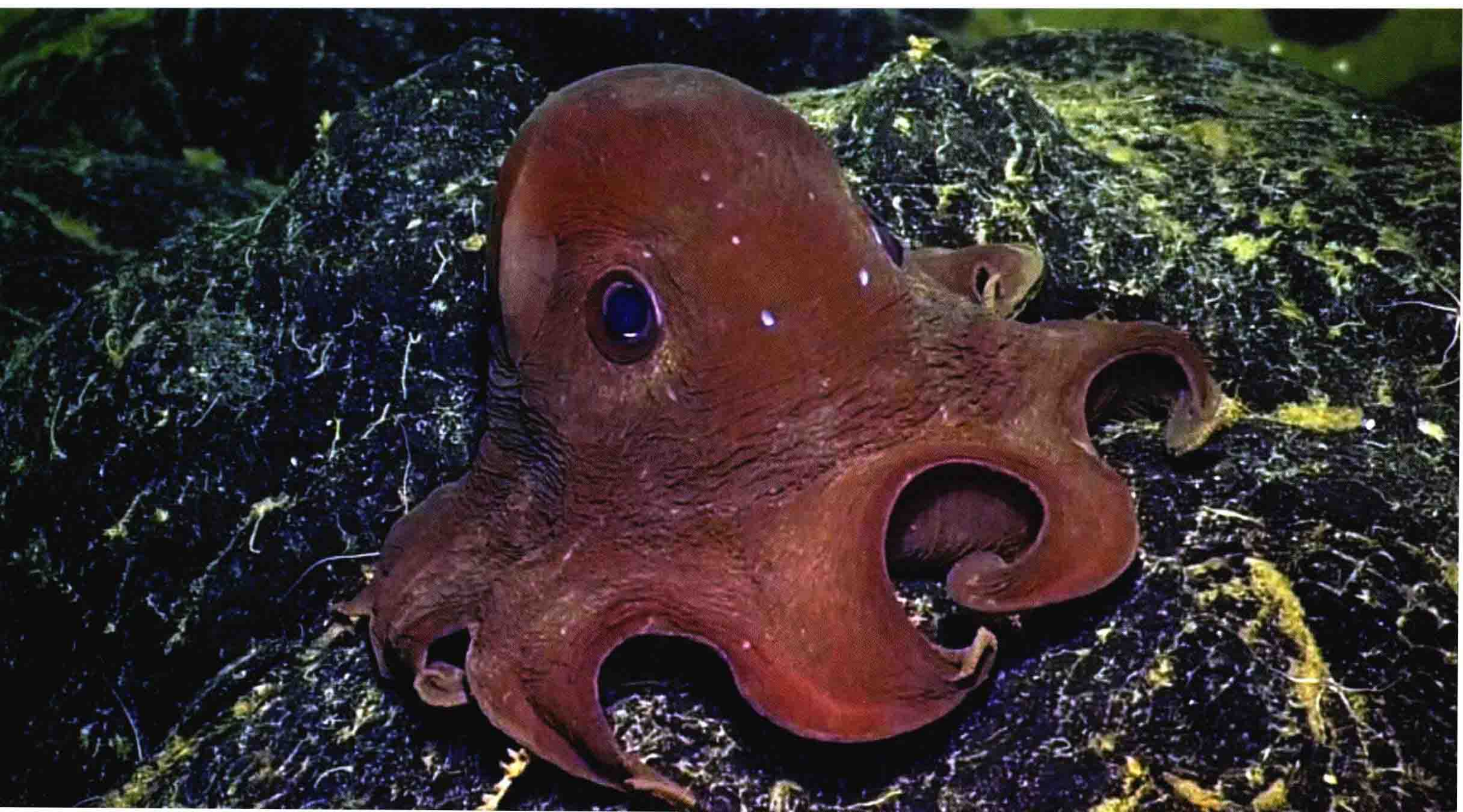
How inappropriate to call this planet Earth, when it is quite clearly Ocean.
Arthur C. Clarke (1957)

Covering 70% of our planet and reaching depths of nearly 11,000 meters (36,000 feet), the ocean is truly the last frontier on Earth. In this dark and largely unexplored environment the potential exists for profound scientific discoveries. Despite the opaque blue mask of the oceans as depicted on many maps, the Earth's crust extends continuously beneath the ocean surface. Here, the Earth beneath the sea is marked by spectacular landforms created by distinct geological phenomena and inhabited by exotic life forms (Figs. P.1 and P.2).

Since light does not penetrate the ocean depths, imaging and exploring the vast seafloor environment presents special challenges. The global seafloor is now coming into detailed focus as a result of the application of new remote-sensing technologies (Fig. P.3). In this book, we explore this expansive, hidden, and largely inaccessible part of our planet – the oceanic crust and the mid-ocean ridge system where magmatic, tectonic, and hydrothermal processes continuously generate the most extensive volcanic terrane on Earth. This work examines the links between submarine volcanoes and the life that thrives in this extreme environment. At the mid-ocean ridge crest, chemosynthetic ecosystems provide the closest analogs to life on early Earth and offer insights into how life began on our planet. This has implications for the search for life elsewhere in the solar system and beyond.

Ask anyone to name Earth's most prominent natural features, and you will get some familiar answers: the Grand Canyon, Mt. Everest, the Amazon River. Ask an oceanographer or marine geologist, and you will get a single response: the mid-ocean ridge. Discovered and initially

Figure P.1 The deep ocean hosts astonishing life forms that thrive in some of the harshest conditions on Earth – the deep seafloor. At 1500 m depth (4920 ft) beneath the ocean surface a 0.5 m diameter "Dumbo" octopus traverses a lobate lava flow on Axial Seamount, Juan de Fuca Ridge.



mapped just 60 years ago, this ~60,000 km long chain of active volcanoes, rift valleys, and fault zones is the planet's most dynamic and continuous tectonic feature, and it is here where most of the volcanism on Earth occurs (Figs. P.4 and P.5). Recognition of the mid-ocean ridge paved the way for placing the historical concept of "continental drift" into a global tectonic context. This led to the development of the plate tectonics paradigm, which provided the foundation for understanding Earth's evolution and the effective exploration of its mineral, hydrocarbon, and biological resources.

The mid-ocean ridge is an essential research environment for the twenty-first century, where investigations will continue to change our concepts of biological and biogeochemical processes. Less than 40 years ago, submarine hot springs (hydrothermal vents) were found along the mid-ocean ridge at the Galápagos Spreading Center in the eastern equatorial Pacific. That discovery revolutionized biological and oceanographic sciences, revealing for the first time the bizarre assemblages of animals and symbiotic microbes that thrive in the dark, high-pressure abyss in an exotic chemical system. It is within this alien environment that chemosynthesis was first discovered, a remarkable biochemical process that allows organisms to obtain their energy not from sunlight but from volcanic gases. Its occurrence in the deep ocean has led to important new research, some of which has significant implications for biomedical and industrial applications. There is no doubt that the next 50 years of oceanographic research will yield new discoveries that have the potential to fundamentally alter the understanding of evolution of life on Earth and how that knowledge can be used to benefit society.

Most of the seafloor lies at depths greater than several thousand meters (more than a mile) beneath the ocean's surface. This environment contrasts starkly with familiar features on land. It is a place with no sunlight; light is absorbed by the upper few hundred meters of ocean water, effectively casting the deep seafloor in perpetual darkness. The temperature in the deep ocean is typically only a few degrees above the freezing point of water. Unlike our airy atmosphere, the ambient environment in the deep ocean is defined by denser, liquid water with crushing pressures of hundreds to over a thousand atmospheres, which equates to tons per square inch. The ocean basins contain incredibly flat abyssal plains hundreds of kilometers wide, interrupted by rugged mountainous features and deep canyons with vertical relief of thousands of meters. Much of the deep seafloor is buried or partially covered by a nearly continuous layer of tiny carbonate or silicic shells of organisms that once lived in warm, sunlit surface waters and then slowly rained down on to the seafloor below. This muddy blanket remains nearly undisturbed because there is no rainfall, rivers, or glaciers to disrupt it (Fig. P.6).

From this quiescent sediment-covered abyss emerge the jagged mountainous features of the most volcanically and seismically active part of our planet: the mid-ocean ridges.

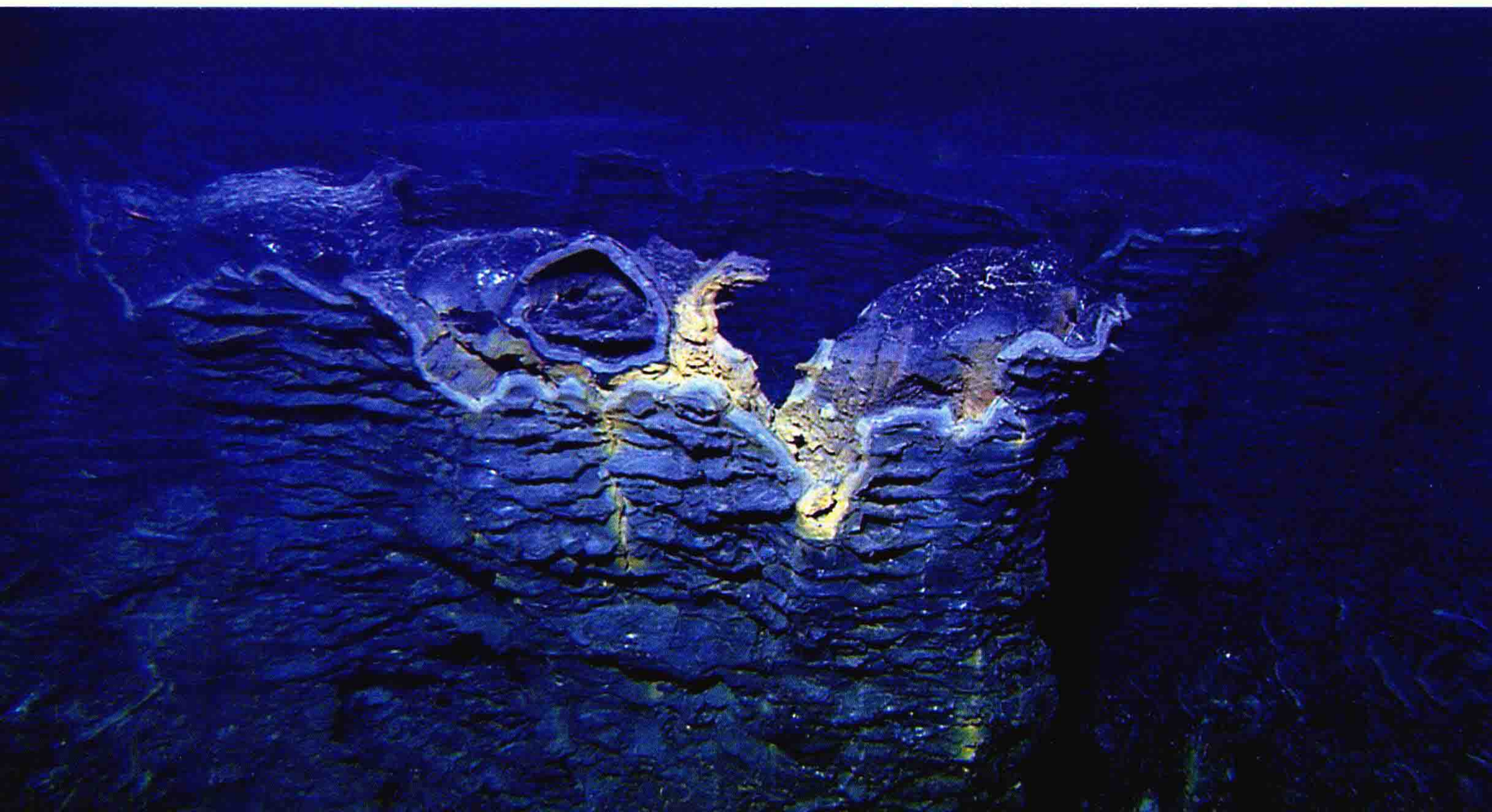


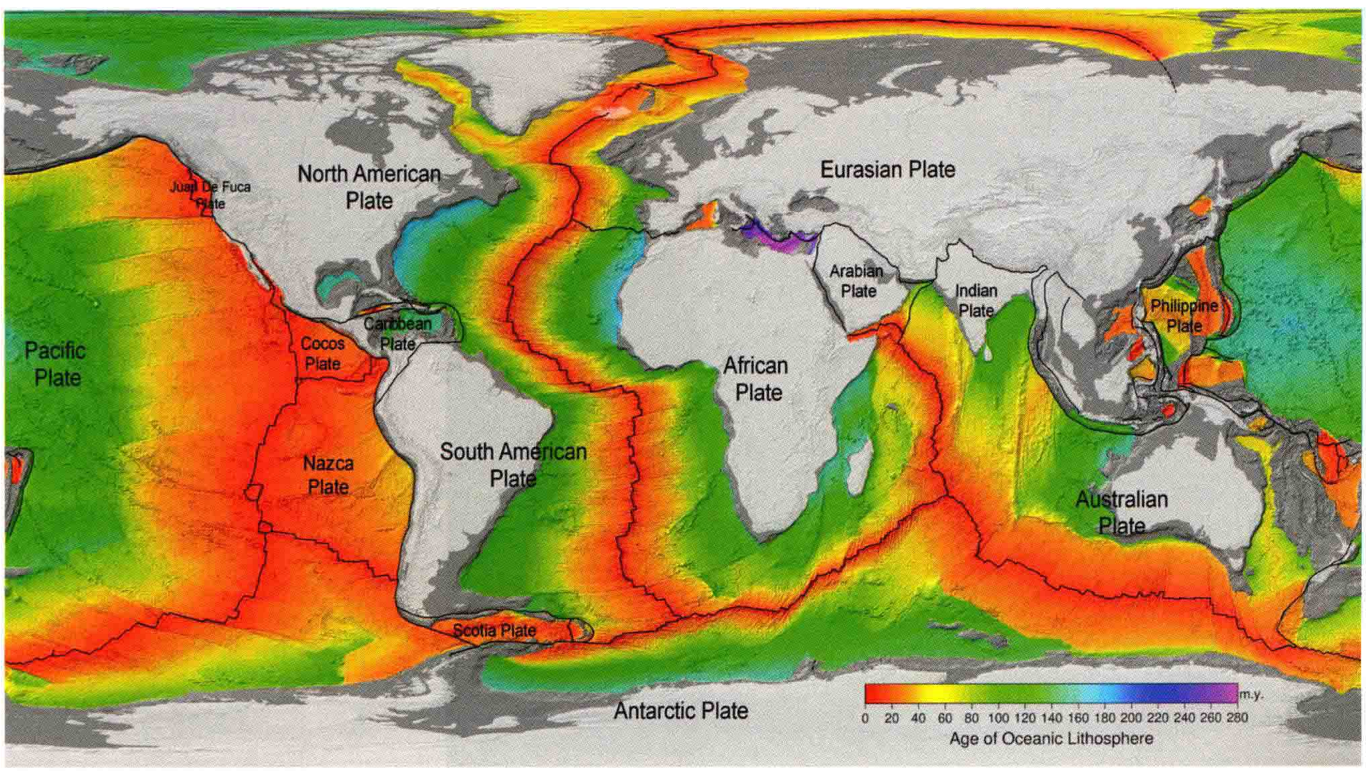
Figure P.2 Frozen lava columns mark the drain out and subsequent cataclysmic collapse of lava lake ceilings formed during ponding of 1200 °C (2192 °F) melt at the MOR. At a mile or more beneath the ocean surface, the near freezing seawater rapidly quenches the molten lava, forming glass-covered flows that reflect the dynamic nature of submarine eruptions.

These broad and rugged volcanic mountain ranges snake their way around the Earth in a complex, interconnected network of fault zones, rift valleys, and volcanic ridges. This mountain range is unlike those on the continents. Mountain belts on land are mostly formed by violent collisions that occur as continental masses impact upon one another as a consequence of the movement of tectonic plates. This involves the titanic "bulldozing" of continental basement rocks and overlying sedimentary rocks into complexly faulted and folded belts of metamorphic rocks that are uplifted, even as erosion works to cut them down. In stark contrast, mid-ocean ridges are formed by processes related to the divergence and pulling apart of the rigid outer shell of the Earth: the lithosphere. The magmatism and faulting at these ridges create new swaths of the Earth's surface in a process referred to as "seafloor spreading." The ridges are elongate features that are not so much uplifted as they are left as high-standing regions flanked by older, cooler seafloor that has subsided as it ages and is transported away from either side of the spreading axis. Through much of Earth history, seafloor spreading has created about 60% of Earth's crust, with older lithosphere recycled, or "subducted," back into the mantle through plate tectonics at active margins where deep-sea trenches occur. Thus, seafloor spreading is a primary process on a planetary scale.

Across most of the seafloor, life forms familiar to humans do not exist; there are no forests, savannahs, or tundra with their characteristic ecosystems. The absence of light penetration means organisms that rely on photosynthesis cannot thrive on the deep-ocean floor. Without light to support the base of the food chain, larger organisms such as fish and

Figure P.3 The remotely operated vehicle *ROPOS* surfaces in the Pacific Ocean after a dive to 2500 m (8200 ft) on the Juan de Fuca Ridge. Robotic vehicles similar to this one explore the depths using high-bandwidth fiber-optic cables, thereby permitting detailed exploration of over 98% of the global seafloor down to 6500 m (21,320 ft) depth.

Figure P.4 For more than 4 billion years the oceans and the volcanic processes within them have co-evolved. The plate boundaries and locations of MORs today are vastly different from where they were located in early Earth history. This present-day view shows the age of the ocean basins based on magnetic data. It highlights the spreading centers that wrap around the globe like the seams on a baseball (thin black lines within the red colors that denote the youngest crust). This dynamic system forms the largest volcanic mountain chain on Earth and hosts the youngest seafloor.



marine mammals find slim pickings at depth. But within this unlikely place, significant biomass exists, and it is where Earth's life probably first appeared. Most of the life forms inhabiting this remote ecosystem are believed to be micrometer-sized microbes living in cracks and crevices in the rocks beneath the seafloor.

Nowhere is the connection between volcanism and life more evident than along mid-ocean ridges, where hot springs at over 300 °C (572 °F) host some of the most amazing life forms on the planet (Fig. P.7). These include single-cell organisms that thrive at temperatures up to 122 °C (251 °F), and vibrant red tubeworms, 3 m long, which grow at rates of 50 cm/yr and contain hemoglobin in their blood – the same compound found in human blood.

Figure P.5 Mid-ocean ridges are spectacular features exemplified by seafloor spreading processes that create major rift zones or valleys along the spreading axes. Largely hidden beneath the darkness of the sea, these areas were historically difficult to image. In places such as Iceland, however, where volcanism has been ongoing for millions of years, the volcanoes that make up the island are considered to be the subaerial continuation of the Mid-Atlantic Ridge. The rift shown here is part of a spreading system that separates the North American Plate from the Eurasian Plate.

Hydrothermal vents are sites where superheated seawater, modified by chemical reactions with hot subsurface rocks, gushes out from the seafloor. Entrainment of volcanic gases and metals leached from the surrounding rocks into the

Figure P.6 Sediment-covered abyssal plains make up more than 50% of the Earth's surface. These low-relief areas preserve a remarkable historical record of the evolution of the ocean basins, climate change, and mountain formation and demise. In this nutrient-poor environment, animals such as brittle stars forage on organic particles that rain down from above, as well as on plankton and bacteria.

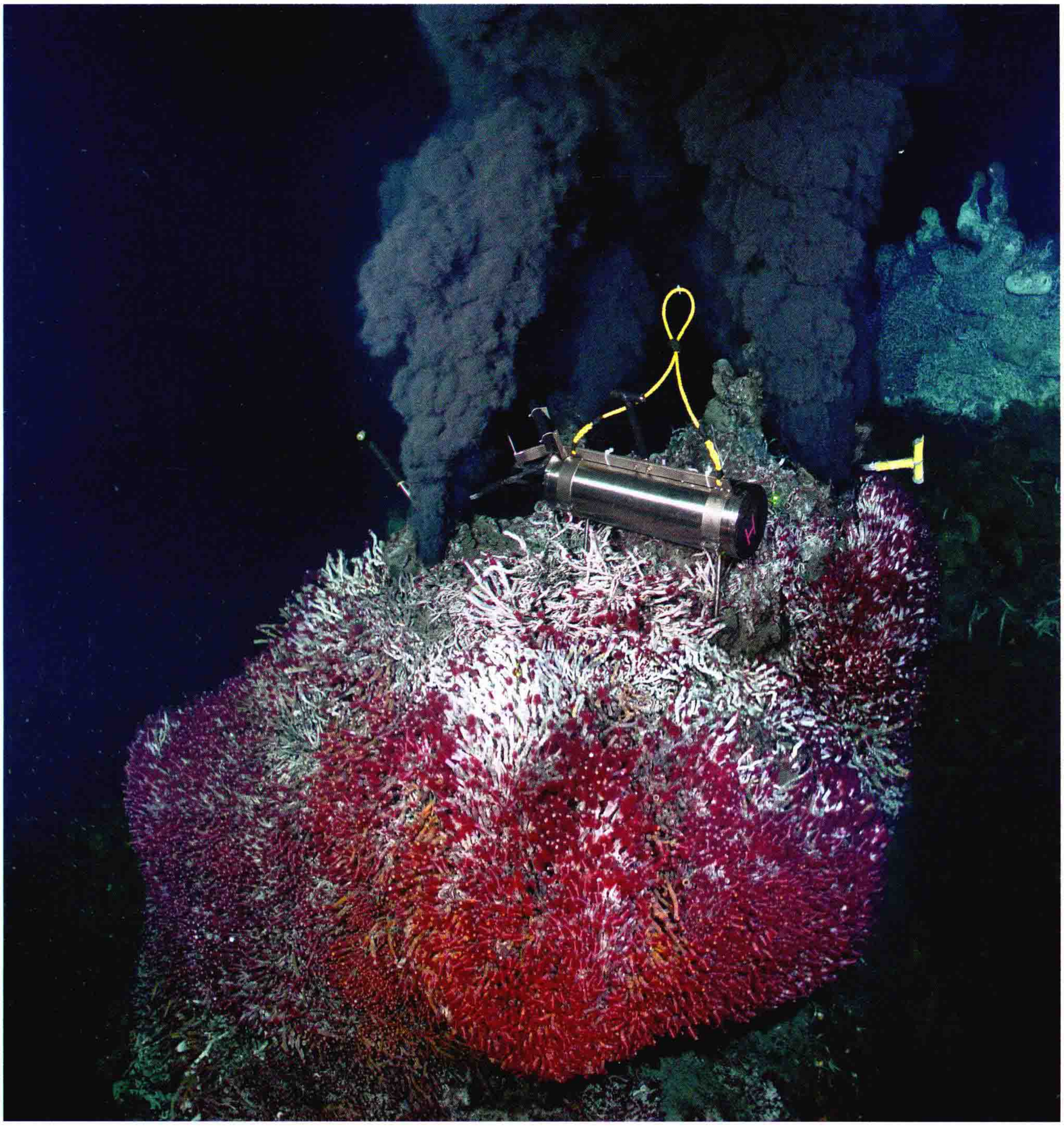


Figure P.7 The discovery of high-temperature hot spring systems in 1979 was made at a MOR spreading center, the East Pacific Rise at 21° N. These high-temperature vents issue jets of metal-rich superheated fluids from the seafloor and are one of the most profound scientific discoveries ever made. Within these extreme environments, characterized by darkness and hundreds of atmospheres of pressure, life was found to not only survive, but flourish. The lush and vibrant communities of tubeworms, sprouting bright red plumes, in areas typically devoid of much color was a startling discovery. Equally surprising was the presence of microorganisms thriving, in the absence of sunlight, by metabolizing volcanic gases at temperatures in excess of 90 °C (194 °F). With the advent of genomic sequencing, we are now gaining insight into the vast diversity of microbes that live on and within the seafloor.

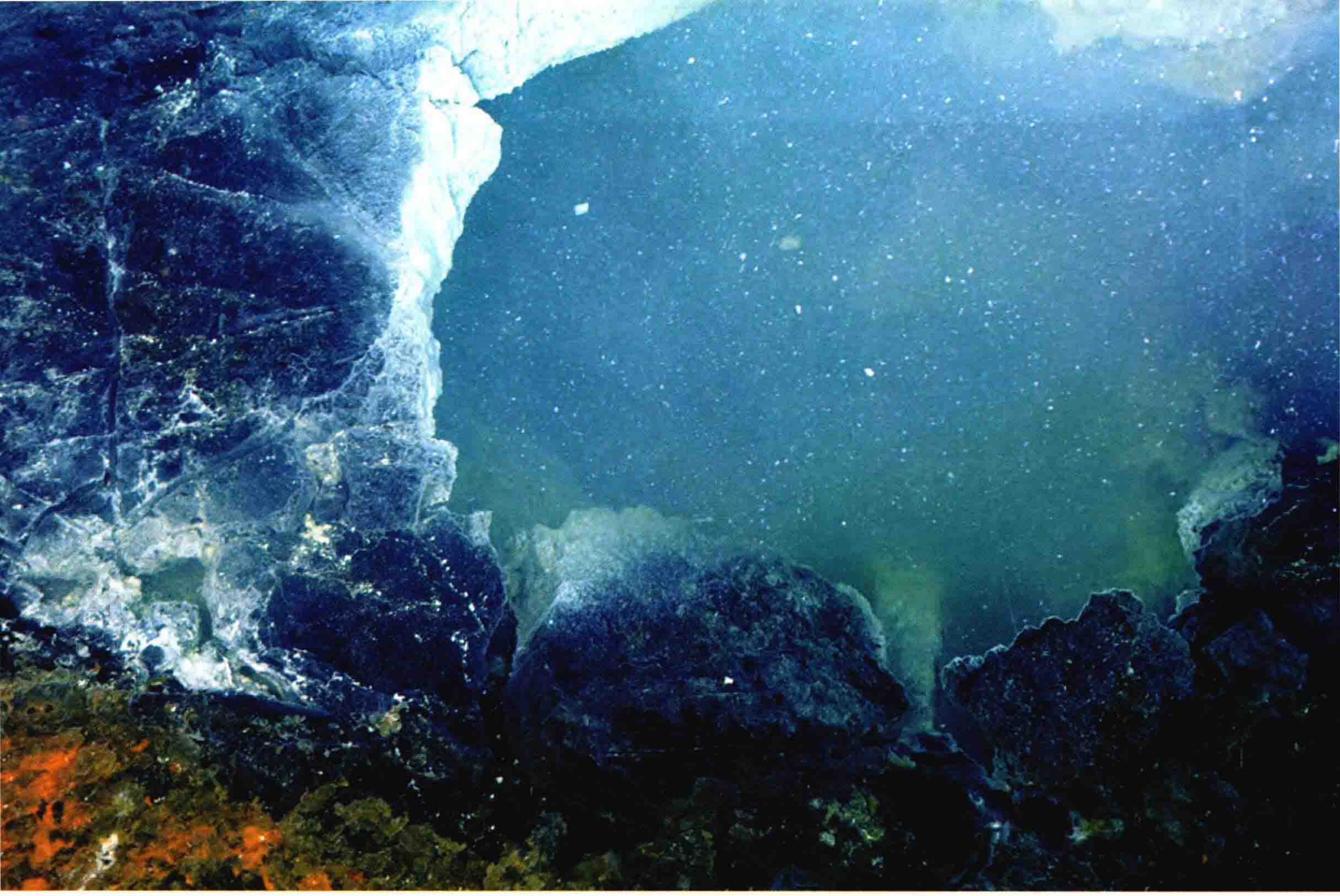


Figure P.8 One of the most spectacular events in crustal formation is the release of billions of microbes from the seafloor during and following seafloor volcanic eruptions. The microbes form whitish sulfide-rich particles that are ejected in dense, billowing streams from the seafloor – called snowblowers, such as the one imaged here following the 2011 eruption on Axial Seamount.

hydrothermal fluids provides nutrients that sustain the microbial base of a "chemosynthetic" food chain. Larger organisms feeding off these microbes are forced to live close to the hydrothermal vents where their food source is concentrated. Perhaps even more spectacular are dramatic outpourings of massive white microbial biomass from the crust during and following seafloor volcanic eruptions. These are reminiscent of blizzards of snow (Fig. P.8). Many of these microorganisms are archaea that optimally grow at temperatures in excess of 80 °C (176 °F). They are thought to be some of the most ancient of extant organisms. Understanding the processes occurring in the dynamic environments along mid-ocean ridges is key to comprehending not only the origins of the seafloor, but also life on our planet.

Highlighted by hundreds of high-resolution seafloor images, this book explores the formation of the oceanic crust at mid-ocean ridge spreading centers and the diverse processes occurring there. They include: hydrothermal phenomena, volcanism that creates the uppermost layer of ocean crust, crystallization and flow of magma to form the lowermost layers of the ocean crust, and tectonic processes that create the distinctive geology and physical properties of oceanic lithosphere. The compelling stories of how new ideas about mid-ocean ridges developed provide the background to understand the importance of this branch of science and an appreciation of the complexity of the diverse processes occurring in the deep ocean and beneath the seafloor.

The future of Earth's inhabitants unquestionably relies on the oceans and the Earth beneath them. Marine scientists using twenty-first-century oceanographic techniques are poised to explore and develop a deeper understanding of these scientific frontiers. Through these studies new insights into oceanic crustal evolution will emerge; from creation at mid-ocean ridges to destruction beneath subduction zones and the life that thrives, survives, and expires within these environments. Join us in our exploration to discover the deep.

Acknowledgments

We conceived this book with the goal of engaging a wide readership and exposing them to the mysteries and fantastic visual perspectives we now have of deep-sea processes and features at the mid-ocean ridge. Our objective was to unveil the deep seafloor and the details of how oceanic crust is generated so that its beauty and complexity could be revealed and appreciated, for both its aesthetic and scientific value. This book represents the compilation and synthesis of a vast amount of information collected over the past 60 years by our mentors, colleagues, and scientific associates here in the USA and internationally, and by each of us during the nearly 150 years, collectively, we have been involved in studying the seafloor and ocean crust.

Each of us owes a debt of gratitude to numerous individuals who facilitated access to imagery, as well as field and geochemical data that are crucial to the stories we present about how the oceanic crust forms and the many interrelated processes associated with seafloor spreading. The images presented in this book were taken from numerous research submersibles, HOVs, ROVs, AUVs, and towed digital camera systems. We have utilized imagery from a variety of sources. They include 35 mm images acquired by these vehicles throughout the 1990s and, over the past decade, high-definition images taken with more advanced imaging systems, which used the latest advances in deep-sea metal halide and LED lighting employed by scientists, engineers, and filmmakers. We have identified the source of the imagery and at the end of the book provide detailed credit information, and, where possible, we have included the vehicle type, facility operator, engineering or film group that provided the images, and, where appropriate, the funding agency that supported the research. The images we present were taken primarily with the US submersible *Alvin* (WHOI), the French *Nautile*, and Russian *MIRs*; US ROVs *Jason* (WHOI), *Tiburon* (Monterey Bay Aquarium Research Institute, MBARI), *Hercules* (University of Rhode Island), the Canadian *ROPOS* (Canadian Scientific Submersible Facility), German *Quest* (MARUM, University of Bremen), Norwegian *Bathysaurus* (University of Bergen), and the WHOI *TowCam*, a towed digital camera system. We are indebted to our colleagues, the vehicle pilots, and vessel and deep-submergence system operators for their collaboration and generosity in making these extraordinary images available to us.

We also acknowledge the numerous colleagues who helped us with key aspects of this work, reading and commenting on early drafts of chapters, and encouraging us to finish this volume despite the nearly 10-year gestation period it took to complete. Steven Ross provided important editorial comments on initial drafts of all chapters and we are very grateful for his input and encouragement as we finished the book. Lonny Lippsett also provided editorial advice on early drafts of various chapters, and we are grateful for his insights and guidance. Janyne Ste. Marie expertly indexed the entire book. The following individuals deserve our personal and professional appreciation: Jean-Marie Auzende, Robert Ballard, Rodey Batiza, Francoise Boudier, Christian Broski, Dave Butterfield, James Cameron, Suzanne Carbotte, David Caress, John Chadwick, William W. Chadwick, Jr., Walter Cho, Anna Cipriani, David Clague, Lawrence Coogan, James Cowen, John Delaney, Alden Denny, Cornel de Ronde, Colin Devey, John Dewey, Henry Dick, Dolly Dieter, Margo Edwards, Mitch Elend, Don Elthon, Bob Embley, David Epp, Javier Escartín, P. Jeff Fox, Gretchen Früh-Green, Allison Fundis, Allison Gale, David Garrison, Denny Geist, Chris German, Kathy Gillis, Marguerite Godard, Hunter Hadaway, Karen Harpp, Nick Hayman, Rachel Haymon, Taylor Heyl, Jim Holik, Susan Humphris, Steve Hurst, David Jousselin, Emily Klein, Ken Kostel, Marv Lilley, Lonny Lippsett, Amanda Loman, Richard Lutz, Ken Macdonald, Brian Midson, D. Jay Miller, John Mutter, Adolphe Nicolas, Mark Olsson, Rolf Pederson, Sven Petersen, Meagan Pollock, Barbara Ransom, Volker Ratmeyer, Ian Ridley, Ken Rubin, Bill Ryan, Keith Shepherd, Alexander Shor, George Shor, John Sinton, Debbie Smith, Matt Smith, S. Adam Soule, Mark Stoermer, Philip Taylor, Maurice Tivey, Meg Tivey, Maya Tolstoy, Doug Toomey, Robert Varga, Karen Von Damm, Rachel Walters, Dorsey Wanless, William Wilcock and Maria Wilhelm.

The archives at both Woods Hole Oceanographic Institution and the Scripps Institution of Oceanography were instrumental in providing historical images, and many other individuals provided us with the excellent illustrations from their publications.

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Finally, we are grateful for the patience and commitment by our publisher Cambridge University Press and Susan Francis, who has encouraged us throughout this too-long process, and her colleagues Laura Clark, Zoë Pruce and Jessica Murphy, who helped edit and produce the book.

JAK thanks the collaborators, post-docs, and graduate students who shared so much time in the field and at sea investigating black rocks in cold, wet places. Thanks also to those mentors who provided introductions and encouragement in areas that contributed so much to this book: John Dewey and Bill Kidd (ophiolites and kinematics), Jeff Fox (seafloor geology), Bruce Rosendahl (East African Rift), Kent Brooks (East Greenland), and Kristján Sæmundsson and Bryndís Brandsóttir (Iceland). My undying gratitude goes to Eileen and my family for their love, encouragement, and infusions of energy in support of my efforts.

DSK offers special thanks to her family, Steve, Ann, and John, and especially to her mother, Hazel, who supported her during her long absences at sea and during her long onshore hours finishing this book. DSK also offers a special thank you to long-time mentor, collaborator, and friend Dr. John Delaney, for his scientific and educational vision that led to the collection of many of the images used in this book and the science behind them.

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TMS extends his deep appreciation to his mother; for her strength, unconditional love and support in all aspects of his career and life, and to his father, who showed him the gift of following life's passion and the levity to persevere through challenging times. He expresses immense gratitude and love for his two brothers Michael and Mark, and for the love and understanding of his two daughters, Emma and Callie, and wife Leslie, who supported him during his combined four years of research and discovery at sea. Thanks also goes to the many mentors, colleagues, and members of his laboratory who supported and enriched his research and life over the years and not only made this book possible but a living entity.

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