1 Entering the abyss: oceanographic technology

The sea, once it casts its spell, holds one in its net of wonder forever.

J.-Y. Cousteau (1953)

1.1 First encounters

The fantasy of every marine geologist is to "pull the plug" on the oceans – to drain the water from the 70% of Earth's surface hidden beneath the waves and have a direct view of the seafloor's myriad shapes and structures. Over the last 75 years, scientists and engineers have taken advantage of innovative technologies (Figs. 1.1 and 1.2) and analytical methods to produce detailed images and geophysical

Figure 1.1 The deep-diving submersible *Alvin* preparing to dive to the axis of the Juan de Fuca Ridge. *Alvin* carries one pilot and two observers and has made more than 4700 dives to the seafloor since it was built in the 1960s. *Alvin* currently descends to a maximum depth of 4500 m; however, its titanium personnel sphere was replaced in 2013 with one that is certified to dive to 6500 m. The support ship for *Alvin* is the research vessel (R/V) *Atlantis*, operated by the Woods Hole Oceanographic Institution.

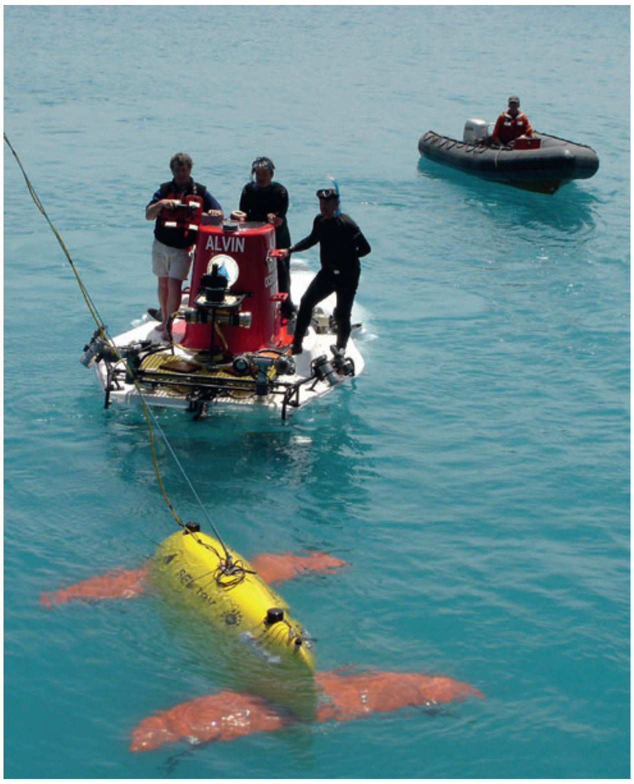

Figure 1.2 Two generations of deep-submergence vehicles meet nose to nose. *Alvin* has been central to the development of numerous deep-ocean technologies and, along with the French IFREMER submarine *Cyana*, provided some of the first access to the abyss for routine scientific observations. The yellow vehicle in the foreground is the *Sentry* autonomous underwater vehicle (AUV). It represents the latest generation of robotic underwater vehicle systems that is now being used to map the seafloor at very high resolution, and to take measurements of the chemical, biological, and physical properties the deep ocean.

representations of the deep ocean floor and ocean crust, spanning resolutions from kilometers to sub-millimeter.

Oceanographers cover disciplinary spectrums including chemistry, biology, physics, geology, and engineering; oceanography as a science is, by its nature, multidisciplinary. The iconographic oceanographer today is just as likely to be a professor soaked by spray on deck in a screaming gale, as an engineer who develops a new multi-sensor vehicle system that is innovative, progressively less inexpensive, and both small and light enough to be launched from almost any ship or submersible system in the world.

Since the early twentieth century, oceanography has relied on an increasingly sophisticated fleet of research ships that have been used as floating laboratories to study, sample, and access the oceans. These ships, and the dedicated, skilled personnel that operate them, provide the capacity to conduct complex experiments in the harsh conditions often encountered at sea. Traditionally, the technology used to study and sample the oceans has progressed from simple instruments deployed from wires and conducting cables to more intricate devices that collect better samples more efficiently. Modern sensors often provide the capability to better resolve the chemical, biological, and physical characteristics of processes or features in and at the bottom of the ocean. In the past few decades, oceanography, like many other fields of science, has benefitted from the explosion in digital electronics, new battery technologies, and robotics engineering.

New technology is rapidly changing oceanography, and the kinds of questions oceanographers can investigate, both in terms of the physical scale of various phemonena and how they change over time. Today, robots are deployed that slice through the ocean on their own for weeks or months at a time. Seafloor instrument arrays, collecting physical, chemical, and biological data, have also been installed and planned at numerous sites. During the past decade, scientists and engineers have conjured up and placed in operation a vast array of sophisticated buoys, floats, gliders, moorings, and seabed sensors that can report back 24–7 via satellite, providing monitoring in real time of the oceans as never before.

The thread of human history has been fundamentally influenced by the sea. The oceans have been sources of unknown terror – both real and imagined – the means by which empires expanded and how the outcome of global conflicts was determined, and a source of vital nutrition throughout human history. Because of these intricate and innate links between humans and the ocean there has always been a strong imperative to explore it.

Leonardo da Vinci made the first drawings of a submarine more than 500 years ago. William Bourne, a British mathematician, drew plans for a submarine in 1578, and in 1620 Cornelius van Drebbel, a Dutch inventor, was the first to actually build a submarine. Nathaniel Bowditch was an American mathematician whose *New American Practical Navigator*, published in 1802, was the first comprehensive book on maritime navigation and observations on oceanic meteorology, currents, and winds. Four centuries after da Vinci, Jules Verne still fantasized about exploring the deep in his novel *Twenty Thousand Leagues under the Sea*, published in 1875. In the 1860s, Ernest Bazin began to take photographs from a diving bell. Fellow Frenchman Louis Boutan developed one of the first underwater cameras in 1893. Around the same time, oceanography as a scientific field began in the United Kingdom with the *Challenger* Expedition (1872–1876). It was the first expedition organized specifically to gather data on a wide range of oceanic features and processes, including ocean temperatures, seawater chemistry, currents, marine life, and the geology of the seafloor.

The expedition employed HMS *Challenger*, a British Navy corvette (Fig. 1.3). This small warship was converted into the first dedicated oceanographic ship. It carried laboratories, microscopes, and other scientific equipment onboard. During this 127,580 km voyage circumnavigating the globe,

Figure 1.3 HMS *Challenger* in St. Thomas harbor during the southbound leg of its global voyage from 1872 to 1876, during which the first routine oceanographic observations were made and samples of the seafloor recovered.

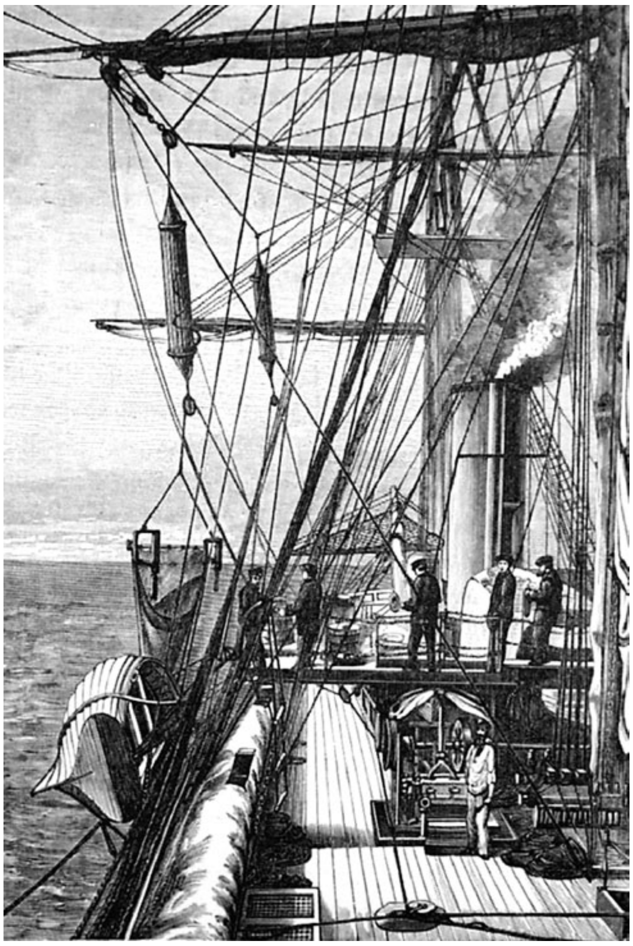

Figure 1.4 Illustration of the dredging apparatus on HMS *Challenger*. New technologies of the time included specialized ropes and mechanical winches that allowed scientists to collect some of the first samples of rocks, sediment, biology, and water from the seafloor on this first global oceanographic expedition.

new methods for dredging the seafloor and sampling ocean water were developed. New technologies, such as deep-sea winches and specialized lines for lowering equipment and measuring the depth to the ocean bottom, were tested (Fig. 1.4). One of the seminal discoveries of this expedition, among the many it produced, was that there appeared to be a shallow region in the middle of the North Atlantic basin that later proved to be the Mid-Atlantic Ridge.

German, Swedish, and other global oceanographic expeditions followed in the late nineteenth and early twentieth centuries. These paved the way for modern oceanographic research, encouraging development of new technologies and the discovery of new paradigms that fundamentally changed how we understand Earth history and ocean processes.

In 1932, William Beebe and Otis Barton descended in their bathysphere to about 1000 m off Bermuda, ushering in the era of modern deep submergence and humans' direct observations of deep-ocean and seafloor life (Fig. 1.5). Less than 30 years later, in 1960, Don Walsh and Jacques Piccard dove to 10,915 m to set the deep diving record in the US Navy bathyscape *Trieste*, touching down on the bottom of the Challenger Deep in the Mariana Trench in the western

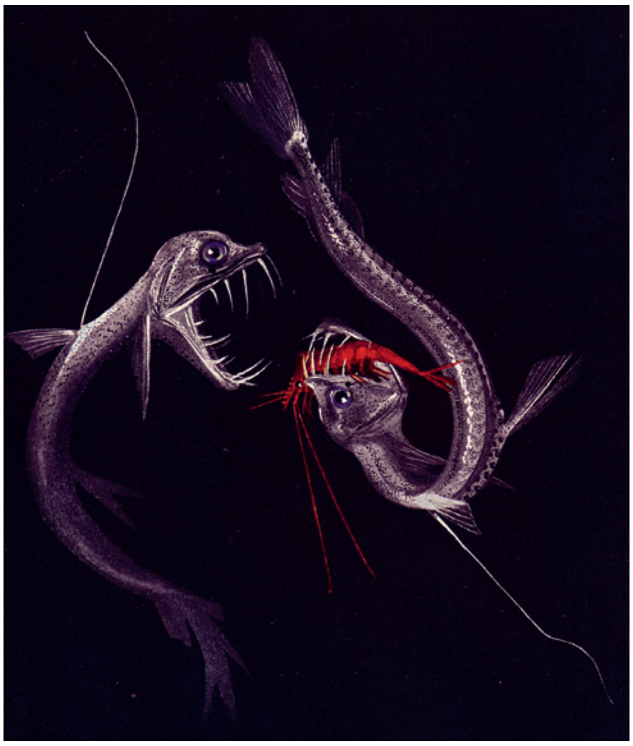

Figure 1.5 Drawing by Estelle Bostelmann of two young viper fish as observed by Beebe and Barton from their bathysphere in the depths off Bermuda. These drawings were published in a series of *National Geographic* magazine articles detailing the revolutionary descent of the explorers in 1932. Detailed drawings such as these were the common way to convey the physical characteristics of marine life and nature prior to the routine use of photography in the ocean.

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Pacific. In the intervening years, basic and applied oceanographic research played a significant role in the outcome of World War II. This, in turn, led to the recognition of the strategic and societal importance in understanding the physics, geology, biology, and chemistry of the ocean, and the subsequent investment in basic oceanographic sciences by government funding agencies worldwide.

In the 140 years since the *Challenger* Expedition, oceanographic science and technologies have advanced significantly, allowing scientists to develop and pursue new hypotheses for the underlying, interacting processes that govern how the oceans and Earth work. Scientists now use sophisticated vehicles and imaging systems to reveal the wonders of the abyss, especially the realm below 400 m where sunlight does not penetrate. These discoveries have provided keys to understanding Earth history and planetary processes and the fundamental importance of the mid-ocean ridge (MOR), ocean trenches, transform faults, seamounts, and the great variations in terrain making up the continental margins throughout the global ocean (Fig. 1.6). We have realized da Vinci's and Verne's dreams of exploring the ocean depths and routinely taking humans to the deep seafloor.

The methods used to "reveal" the seafloor can be roughly grouped as either acoustic or optical, with each having vastly different resolution capabilities. To better appreciate the significant technological advances that have been applied to exploration of the deep ocean and seafloor, we provide some historical context for acoustic and optical imaging systems employed to map and image seafloor features.

The following historical discussion illustrates how far oceanography has advanced in a short period of time. The chronology emphasizes the important impacts that technological advances have made toward understanding oceanic crustal architecture, hydrothermal and volcanic features present on the ocean floor, and the novel biological communities that thrive at depth in the absence of sunlight.

1.2 Acoustic imaging

1.2.1 Echo sounding

In the early twentieth century, in response to the *Titanic* disaster, the German physicist Alexander Behm developed echo sounding – a method of transmitting sound waves through water to reflect off objects. Echo sounding proved to be incapable of locating icebergs on the sea surface, but scientists found it was an excellent tool to measure the depth of the ocean. Sound waves, traditionally ranging in frequency from 3.5 kilohertz (kHz) to 12 kHz, were transmitted into the ocean, reflected off the seafloor, and recorded at the surface by microphones or hydrophones. The deeper the seafloor beneath the ocean's surface, the longer the sound waves took to echo back.

Strategic requirements during World War II, particularly how seafloor topography provided hiding places for submarines to avoid detection, as well as the influence of seafloor features on acoustic propagation, provided a major impetus for developing sonar, originally an acronym for "**so**und **na**vigation and **r**anging." From the post-World War II era to the 1970s, a higher-resolution echo sounder, called a precision depth recorder (PDR), provided the standard means for academic scientists and the military to survey the ocean floor and measure its depth (Fig. 1.7). The sound

Figure 1.6 R/V *Vema* of the Lamont-Doherty Geological Observatory of Columbia University (now Lamont-Doherty Earth Observatory) operated from 1953 to 1981. *Vema* collected a wide range of oceanographic data during its many voyages, which spanned over a million miles and paved the way for a revolution in our understanding of the Earth and oceans.

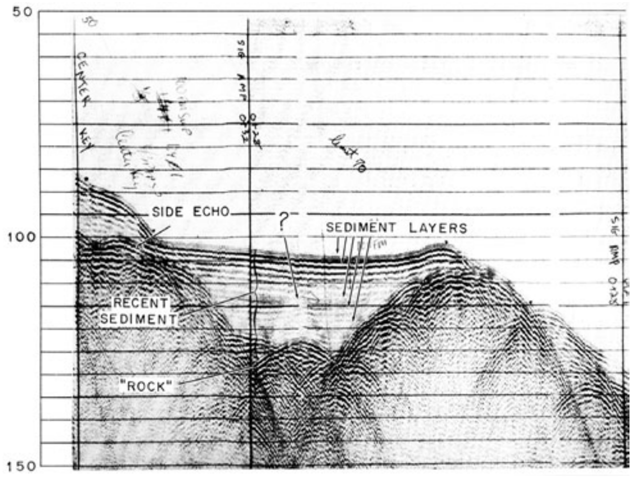

Figure 1.7 Precision depth recorder (PDR) record made using a 3.5 kHz echo sounder. Depth in fathoms (a fathom is 6 feet, or almost 2 meters) is on vertical axis, time (which was linked to the ship's location) is on horizontal axis. Complex reflection patterns generally indicate that there is rugged seafloor topography on either side of the ship.

beam of PDR systems is transmitted from the ship through the water and reflected off the bottom. The depth is calculated using the round-trip time through the water, as measured on the PDR and divided in half, multiplied by the speed of sound in seawater (average ~1500 m/s). Because of the wide beam of sound energy transmitted from the surface transducer mounted on the ship's hull, this type of early bathymetric mapping system had spatial resolution of the order of hundreds of meters at depths below 3000 m, so the measured depths were really an average of the depth over the ensonified area.

In the 1950s, Bruce Heezen and Marie Tharp from the Lamont Geological Observatory of Columbia University in New York used thousands of US Navy soundings and other bathymetric data to compile their now classic physiographic maps of the ocean basins (see Fig. 2.5). These maps revolutionized the way scientists viewed the seafloor and led to the discovery of the global MOR system and its role in seafloor spreading and plate tectonics. That, in turn, provided new frameworks for explaining how the continents and ocean basins evolved. William "Bill" Menard at the Scripps Institution of Oceanography in California used similar approaches to map large areas of the central and eastern Pacific, recognizing the importance of the MOR and seafloor spreading on the geologic evolution of the western margins of South, Central, and North America (Menard, 1964, 1967; Menard and Atwater, 1969).

1.2.2 Satellite oceanography

As in many fields, oceanographic science has instigated and benefitted from revolutionary advances in technology over the past half-century. A notable example, at the most basic level, is resolving the topography of the ocean basins, which is essential to understanding their evolution. The application of new satellite and ship-based mapping technologies in the early 1970s, developed largely in response to the Cold War, allowed scientists to map bathymetric features at unprecedented resolution throughout the global ocean.

Satellite-based geophysical data, especially gravity and magnetic studies, complemented sonar data to achieve a holistic understanding of the evolution of ocean basins. Gross topography of the global seafloor was produced at a resolution of about 1 km per pixel (Fig. 1.8). Even with

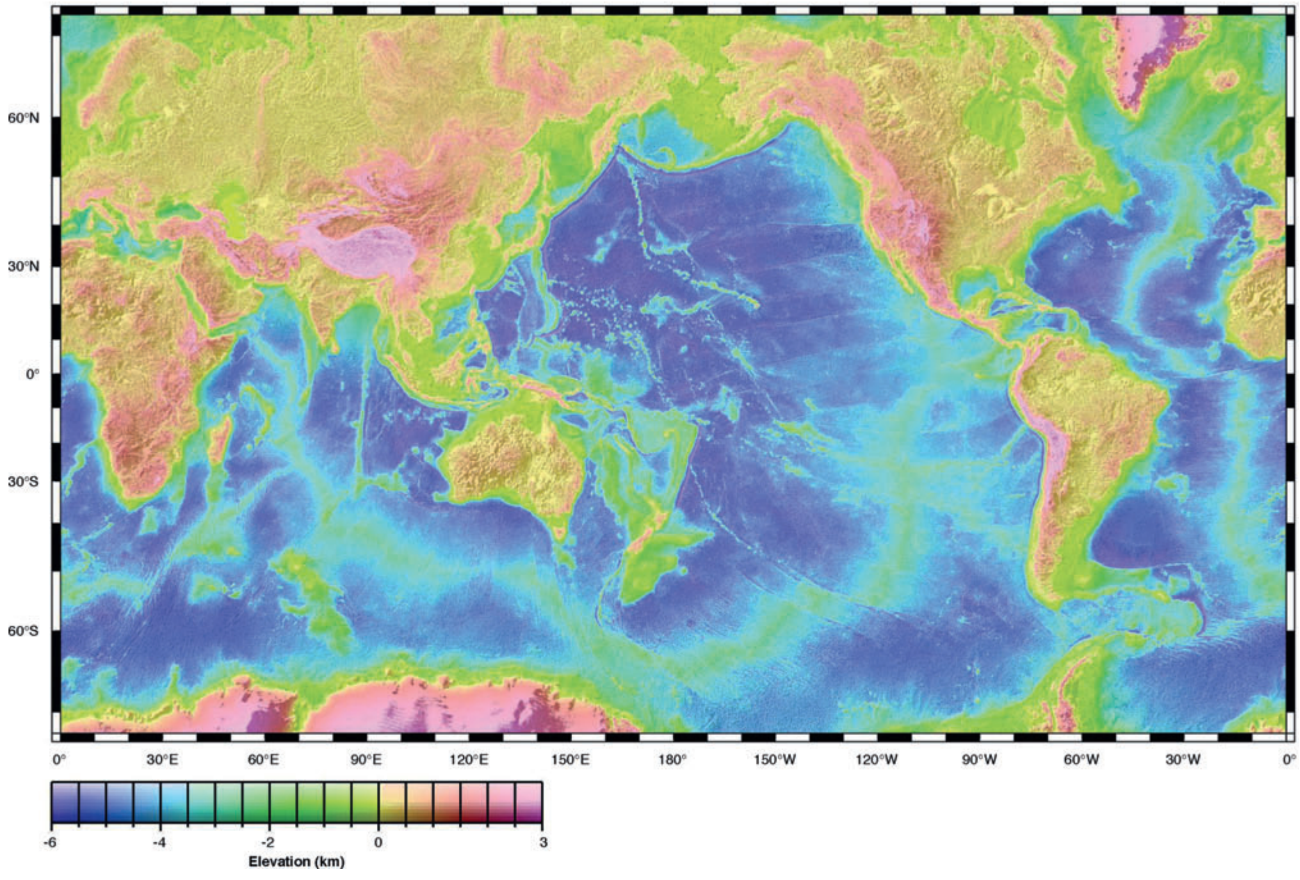

Figure 1.8 The digital bathymetric map of the global ocean seafloor compiled from satellite altimetry data and available depth sounding and gravity data produced by Walter Smith and David Sandwell (Smith and Sandwell, 1997). The spatial resolution of features mapped using these data ranges from 1 to 12 km. These images provide the most accurate and holistic view of the topography of ocean basins "with the water drained out." Compare this figure with the Heezen and Tharp compiled bathymetry shown in Fig. 2.5.

these coarse regional data, it is possible to resolve detailed topography of the global *and* local seafloor as well as the gravity signature of the crust and upper mantle with remarkable clarity. These perspectives permit the study of areas that span hundreds of thousands of square kilometers using satellite geophysical data, and areas of thousands of square kilometers using ship-based surveys.

Early oceanographic surveys, prior to 1970, did not have the benefit of routine, continuous satellite navigation. Thus, it was often difficult to return to exactly the same location to conduct time-series or repeat surveys or sampling. Features mapped on one expedition might not be relocated for sampling on subsequent cruises, or at times features might be repeatedly mapped or misidentified because of navigational errors. A critical technological development that helped to advance seafloor mapping and imaging was the deployment of the Global Positioning System (GPS) satellites in constellations that yielded global coverage of all oceans. GPS now provides critical location information that allows the position of ships to be determined to within 10 m on the sea surface. This accuracy in geodetic positioning meant that an entire range of oceanographic survey data could now be accurately placed (within a few meters) and compared to higher-resolution surveys and detailed observations using newly developed deep-submergence vehicles, effectively revolutionizing the ability to map and image the seafloor.

An additional benefit of GPS technology and advances in ship-based sensors and control systems is that ship positions could now be very accurately controlled in real time, allowing them to maintain geodetic position in a range of oceanographic conditions throughout the globe. Called dynamic positioning, or DP for short, it provides for autonomous vessel positioning though a combination of computer-controlled systems. These are tied to both GPS navigation input at high data rates and simultaneous autonomous control of ship propulsion systems in response to the magnitude of current, wind, and wave forces acting on the vessel. Dynamic positioning is now a routine capability used in most oil and gas deep-water exploration and drilling activities and is essential for many remotely operated vehicle operations, where vessel position must be maintained in order to carry out seafloor surveys and sampling. The benefits of GPS and DP navigation are many and they translate directly to our ability to navigate deep-submergence vehicles (which cannot use GPS below the ocean surface) with a high degree of both precision and accuracy in geodetic space.

More recently, because of advances in sonar technology and attitude sensing of vehicle motions, ultra-short baseline navigation for the spectrum of deep-sea vehicles has revolutionized the ease with which vehicles can be navigated without sacrificing the precision and accuracy needed to produce quantitative map-based imagery of the seafloor.

1.2.3 Multibeam sonar

Post World War II technological advances in both computing and acoustics led to the development of multiple beam bathymetric sonars by the US Navy. These systems relied on not just one acoustic pulse, but multiple pulses sent and received by acoustic transducers and receivers configured as arrays on ships' hulls, gathering a swath of bathymetric information as the ship moved through the water at 8–10 knots (kts). The Navy system, called SASS (Sonar Array Bathymetry Survey System), transformed how scientists mapped the global ocean seafloor. SASS data played a major role in mapping the Mid-Atlantic Ridge at the site of the FAMOUS (French–American Mid-Ocean Undersea Study) expedition in 1974 (Ballard and Van Andel, 1977a), in the first major science expedition for the human-occupied submersible *Alvin*, and in the Galápagos Rift, where the first low-temperature hydrothermal vent communities were discovered in 1977 (Corliss *et al.*, 1979) (see Section 4.14).

Academic scientists have had access to multibeam sonar systems since the early 1980s, when they were first used to map the topography of the northern East Pacific Rise crest over a distance of more than 1000 km (Macdonald *et al.*, 1992; Macdonald, 1998). Since that time, the early hull-mounted multibeam systems, which had 12 beams in an array oriented across the keel of research ships, have evolved into arrays of more than 200 beams using frequencies up to 30 kHz (Fig. 1.9).

Shallow-water multibeam systems operating at higher frequencies, generally above 100 kHz, for use at depths shallower than 1000 m, provide even greater precision and accuracy for coastal seafloor mapping and locating water column features such as rising methane bubble plumes. Advances in sonar processing and acoustic array technologies have also increased the swath that multibeam sonar systems can cover in a single pass. Older systems were able to yield swaths of integrated bathymetric data that were approximately as wide as the mean water depth over which the survey was being carried out. Modern systems with more than 200 beams cover swaths that are three to four times the water depth.

Multibeam bathymetry systems afford stunning improvements in the resolution of seafloor features (Fig. 1.10). While the old PDR echo sounders could resolve the seafloor depth to within a few tens of meters, that depth was an average over the footprint of the beam on the seafloor. At depths greater than a few thousand meters, the diameter of the older sonar footprint is several hundred meters, resulting in greatly diminished spatial resolution. In steep terrains, such as the escarpments bounding transform faults or fracture zones, even multibeam bathymetry cannot resolve small (10 to 50 m) steps in the relief.

By comparison, a modern 30 kHz multibeam hull-mounted bathymetry system can resolve the topography of the seafloor down to depths of about 4000 m with a vertical resolution of about 10 m and spatial precision of

Figure 1.9 An illustration showing the swath coverage of multibeam sonar used on many modern oceanographic vessels. Multibeam sonar can resolve seafloor bathymetric variations of 10 m vertically over horizontal distances that range from 25 to 100 m, depending on the frequency of the system. Continuous bathymetric maps with spatial resolution of 50 to 80 m and vertical resolution of 10 to 15 m covering a thousand square kilometers can be acquired in only 10 to 12 days. The yellow signals from the ship to shore depict the real-time satellite transmission of data and images that are used for "telepresence" (see Section 1.7).

about 25 m. As an example of how important accurate bathymetric mapping is, HMS *Challenger* made the first lead-line sounding to the bottom of the Mariana Trench in 1875 and recorded a depth of 8,184 m. In 2010, a multibeam system was used to map the Challenger Deep, yielding the deepest part to be 10,984 m, with an accuracy of ±25 m (Gardner *et al.*, 2014).

Today, multibeam sonar mapping is a prerequisite for almost any type of seafloor research. In some cases, investigators choose to map relatively small areas – as small as 100 square kilometers – specifically targeting structural or volcanic features they plan to explore later in more detail using various types of deep-submergence vehicle systems. In other cases, efforts to map larger areas of seafloor with multibeam sonar have produced exceptionally detailed maps revealing large seafloor features and how changes in morphology reflect a host of ocean crustal formation processes (see, for example, the MOR segments mapped in specific areas during the RIDGE and Ridge 2000 Programs from the early 1990s to 2012; www.ridge2000.org).

1.2.4 Sidescan sonar

While bathymetric sonar provides quantitative measures of the vertical relief of seafloor features, sidescan sonar – where the sound is projected laterally to either side of a ship, towed vehicle, or robotic vehicle – can be used to provide a fine-scale textural perspective of the seafloor. This type of imaging of the seafloor is often called "backscatter" data because the spatial distribution of dark to light patterns in the recorded image depends on the type of ocean floor being surveyed as well as the slopes in the terrain. The scattering of the sound waves from irregularities on the seafloor and whether the bottom is composed of rock or sediment, and the distribution of those materials, creates characteristic acoustic reflectivity patterns in sidescan imagery. Faults – large and small – as well as constructional volcanic features and lava flows, and variations in seabed "roughness" all reflect sound energy differently. Therefore, sidescan sonar images commonly resolve more subtle variations in seafloor morphology than bathymetric sonars, and as such are valuable for interpreting both tectonic processes and field relationships on the ocean floor.

Sidescan sonar, developed in the 1960s, added a new dimension to precision depth recording and multibeam sonar surveying, providing quantitative data on the texture, spatial dimensions, and geomorphology of seafloor features. The Scripps Institution of Oceanography at the University of California, San Diego, had assembled an exceptional group of scientists and engineers interested in developing new seafloor mapping technologies. Their leader was a marine geophysicist, regarded by many as the father of academic deep-submergence vehicle systems: Dr. Fred Spiess. Among his many accomplishments, Dr. Spiess developed the *Deep Tow* system, a deep-sea vehicle hosting an array of down-looking and side-looking sonars (Fig. 1.11). The sonars operated at different frequencies, optimizing the acoustic backscatter of the seafloor to gain a lateral perspective of the terrain. In addition, because this sonar used higher frequency sound at about 100 to 200 kHz, it also revealed the fine-scale textural and structural fabric of the terrain, which greatly enhanced the quality of images of geological features on the seafloor.

Over the years, *Deep Tow* went through numerous system upgrades as new technologies were developed. It hosted sensitive temperature sensors with a camera and lights, so that it could collect photographic images and use them to confirm the nature of specific features mapped using various sonar systems. *Deep Tow* is commonly credited with providing the roadmap to discovering hydrothermal vents at the Galápagos Rift. During an expedition in May 1976 to the Galápagos Rift, cameras on *Deep Tow* imaged fields of what were subsequently interpreted to be large clams, and

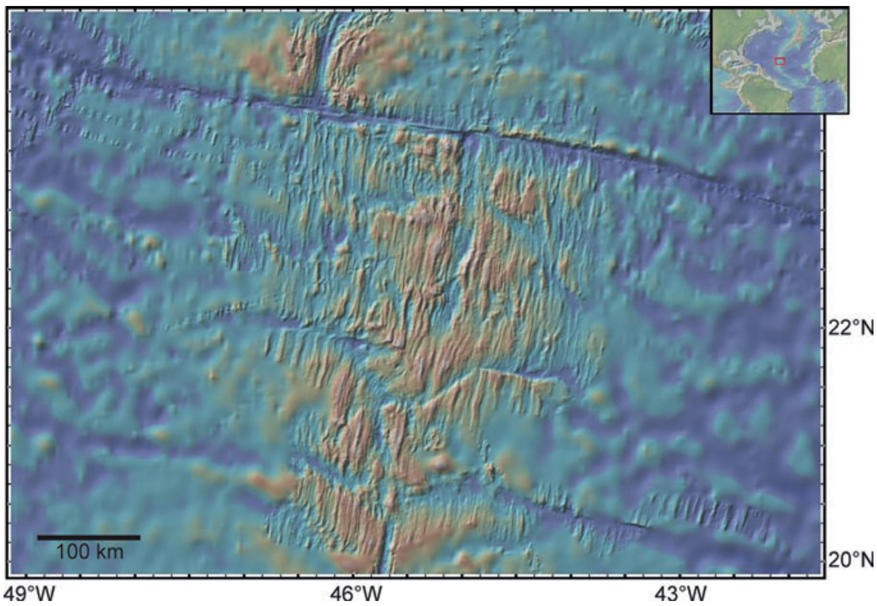

Figure 1.10 A bathymetric map of the Mid-Atlantic Ridge in the 20–24° N region showing the prominent rift valley, rough topography of the ridge flanks, and discontinuities along-axis. The map is a combination of data sets including coarser 1 km gridded data derived from satellite altimetry along the east and west edges of the map and 100 m gridded multibeam data in the center along the ridge axis. Lighter colored areas are shallower depths of the MOR crest and upper flanks.

its sensors registered bottom-water temperature anomalies of 0.25 °C, both of which were completely unexpected on the deep seafloor. The images and data it collected were a crucial antecedent to the follow-on discoveries of hydrothermal vents at the Galápagos Rift in 1977 that were made by geologists diving in the research submersible *Alvin* (Lonsdale, 1977; Corliss *et al.*, 1979) (see Section 4.14).

Over the last 40 years, *Deep Tow*'s success encouraged the development of an array of sidescan sonar vehicles capable of mapping both large areas and specific features of the seafloor, providing key information on its structure and geological history and the discovery of seafloor biological communities.

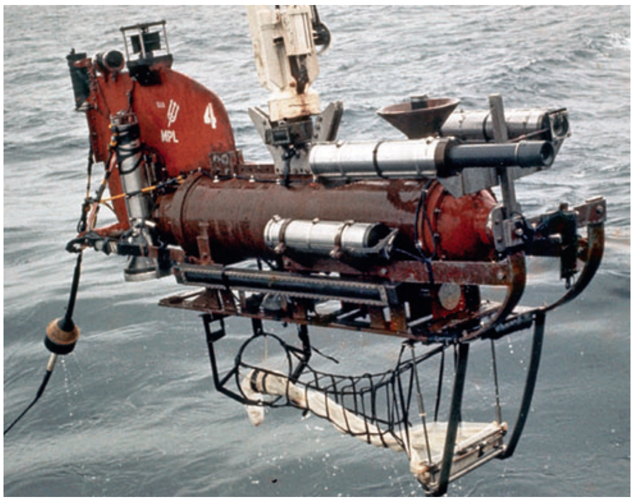

Figure 1.11 The *Deep Tow* vehicle, as configured in the mid 1970s, was developed by Dr. Fred N. Spiess and colleagues at the Scripps Institution of Oceanography's Marine Physical Laboratory.

Different types of seafloor, comprising sediments, rocks, lava surfaces (see Chapter 5), fissures and faults, reflect sound differently, and variable slopes also impact patterns of reflectivity in sidescan sonar data. The imagery produced by sidescan sonar helps achieve another important way of "draining the water" out of the oceans, thereby revealing variations in seafloor textures that are important for studying the evolution of different areas and the processes affecting them.

More recent sidescan sonars, using frequencies from 12 to 200 kHz, reveal the texture of the ocean floor and MOR crests and flanks in both stark and subtle ways that multibeam bathymetry does not portray (Fig. 1.12). Some sidescan sonar systems (e.g., GLORIA, SeaMARC-2, MR1–2) (Figs. 1.13 and 1.14) are towed a few hundred meters below the ocean's thermocline, the boundary between the shallow mixed layer and the deep ocean, where there is a steep temperature gradient from the surface down to several hundred meters that impacts sound velocity and acoustic raypaths. The swath width of these systems can be 10–20 km. These systems ensonify large areas of seafloor with lateral resolution varying between about 8 and 50 m per pixel. Other sidescan sonar systems (e.g., TOBI, SeaMARC-1, DSL-120A, IMI-30) are towed within a few hundred meters of the seafloor, and have correspondingly greater resolution that ranges between 1 and 5 m per pixel, but with narrower swaths between about 1 and 5 km wide (Blondel, 2009) (Fig. 1.15).

Sidescan systems have also been designed to operate on remotely operated vehicles (ROV) and particularly on autonomous underwater vehicles (AUV), whose stability provide an excellent platform for collecting these types of acoustic data. Recent examples of how important near-bottom sidescan data are to the study of seafloor volcanic eruptions include data from the East Pacific Rise near

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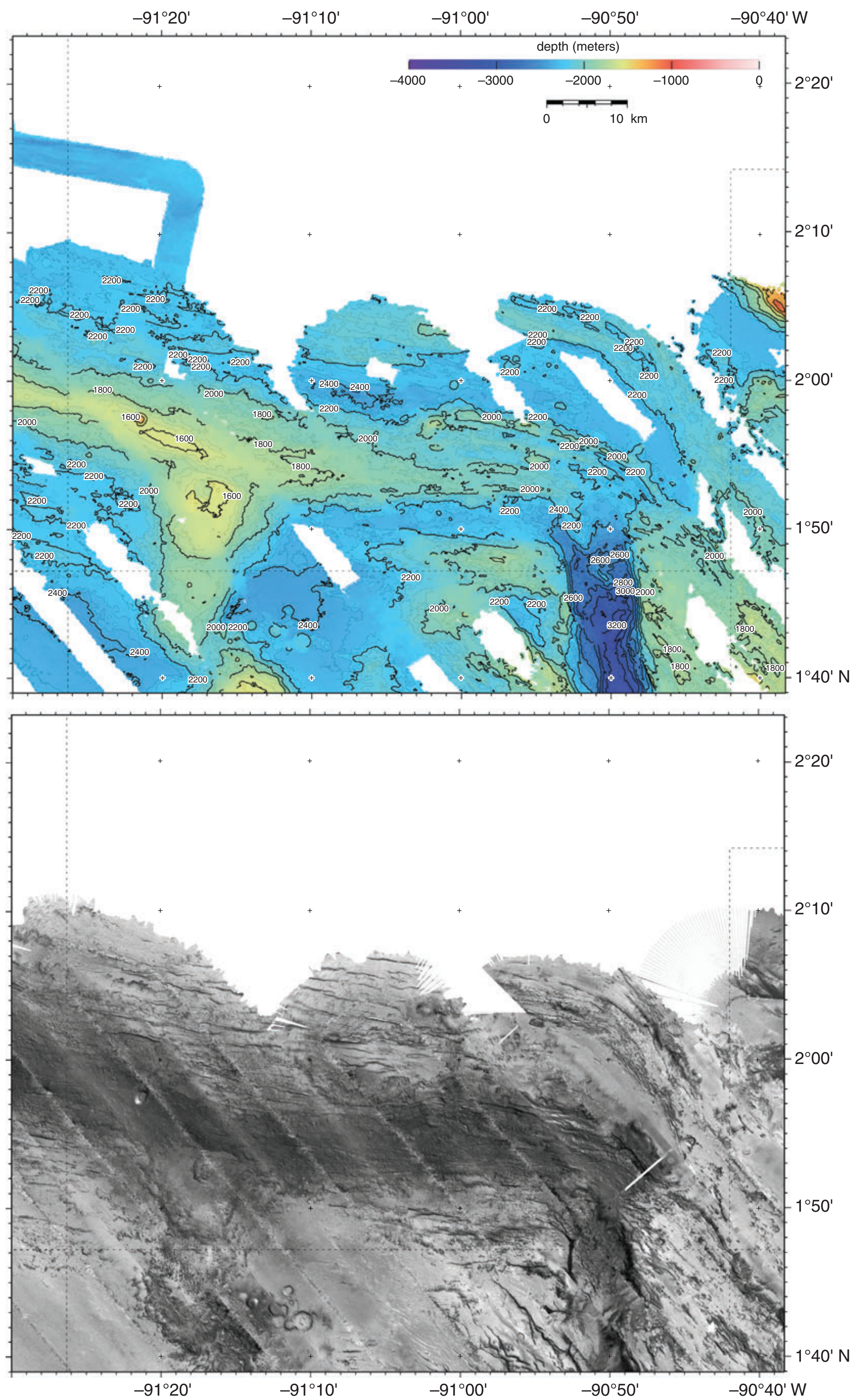

Figure 1.12 Sidescan sonar data provide important backscatter maps that depict both large- and small-scale seafloor structures, which are important for proper interpretation of the geologic history of seafloor terranes. MR1 sidescan sonar (bottom) and compiled multibeam bathymetry maps of the Galápagos Spreading Center (GSC) (top). The E-W swath of high backscatter (dark gray) in the bottom sidescan image is the GSC axis and upper flanks where lava flows are exposed at the seafloor and are thus more reflective to the sound energy. The linear features parallel to the GSC in the sidescan swath are abyssal hills and low-relief faults that are not well resolved in the bathymetry. Light gray areas are sediment covered, so have low-reflectivity. Small seamounts and volcanic-flow fronts occur south of the GSC near 91° 20′W and are part of the seamount province in this region.

Figure 1.13 The Hawaii Mapping Research Group, MR1 sidescan sonar system during deployment. The system operates at 12–13 kHz and collects large-area sidescan imagery swaths (10–20 km width) which have a resolution of 2–5 m per pixel.

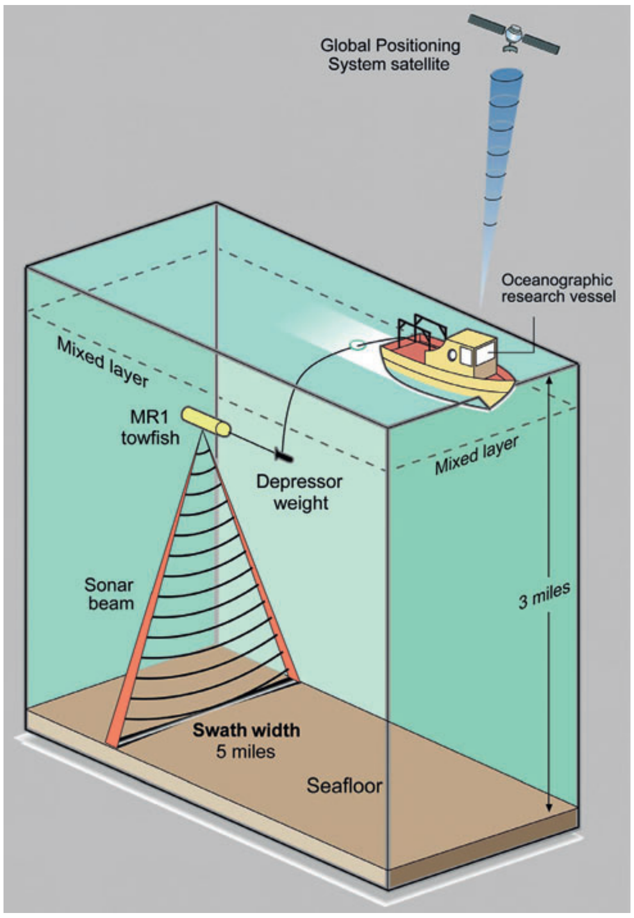

Figure 1.14 Illustration depicting the geometry of sidescan sonar acquisition using the near-surface towed MR1 system operated by the Hawaii Mapping Research Group at the University of Hawaii. The sonar towfish is towed below the thermocline to avoid acoustic ray-path problems. The towfish is also towed behind a depressor weight to minimize the effects of surface sea state and motion that are transmitted mechanically down the tow cable.

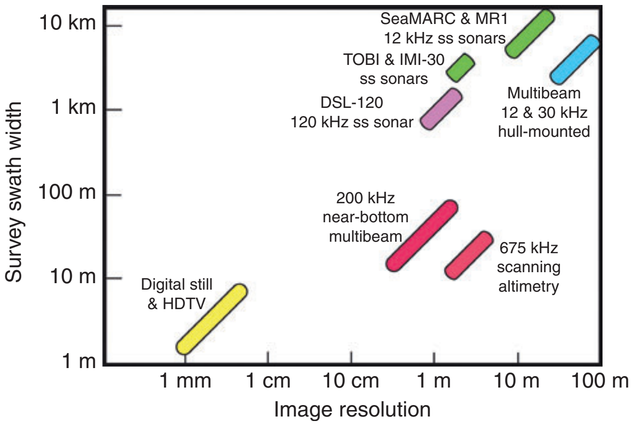

Figure 1.15 Plot showing the variations in image resolution as a function of the survey method and swath width of modern sonar systems used for oceanographic research compared to the resolution obtained from digital cameras and high-definition TV (HDTV).

9°50′ N where "before and after" DSL-120 sidescan sonar revealed the significance of channelized lava flows (Fig. 1.16) in distributing lava at a fast-spreading MOR during the 2005–2006 eruptions (e.g., Soule *et al.*, 2007, 2012) (see Chapter 5, Figs. 5.20, 5.31, 5.33 and 5.40).

Ultra-high-resolution sidescan data acquired by AUVs revealed the detailed distribution of new seafloor created by a submarine volcanic eruption on Axial Seamount in 2011 on the Juan de Fuca Ridge (Caress *et al.*, 2012). Results from near-bottom AUV-based sidescan sonar surveys that have raised public awareness of deep-sea mapping techniques and new technologies include the discovery of the wreckage of an Air France aircraft found in about 4 km of water on the east flank of the equatorial Mid-Atlantic Ridge by the REMUS AUVs in April 2011 (see Section 1.4.3).

1.3 Twentieth-century developments in deep-sea optical imaging technology

In the early 1950s, Harold Edgerton, an engineering professor at MIT, developed the deep-sea strobe light, providing the "sunlight" required to take photographs of the deep ocean and seafloor for the first time. That development, coupled with the engineering efforts of Maurice "Doc" Ewing and Lamar Worzel at the Lamont Geological Observatory and J. Brackett Hersey, Allyn Vine, and David Owen at Woods Hole Oceanographic Institution, led to the first generation of deep-sea cameras (Ewing *et al.*, 1946; Hersey, 1967). These systems (Fig. 1.17) were simple by today's standards, but they provided key photographic evidence of animals and seafloor features over small areas in the deep ocean. They were also indispensible in carrying out crucial deep-sea search missions, such as those required after the tragic accident that sank the Navy submarine *Thresher* in 1963 and the loss of an atomic bomb off the coast of Spain in 1966 (Fig. 1.18).