Introduction

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1 Our Blue Planet

Extending from the coastline to the deepest oceans, the submarine realm constitutes more than the 70% of our planet. The ocean comprises 1334 million cubic kilometres (320 million cubic miles) of seawater, comprising 97% of Earth's available water and covering 361 million square kilometres (139 million square miles) of seafloor (Costello et al. 2015; Trujillo and Thurman 2016). The vast majority of this seafloor cannot be directly observed by humans. Technological progress, particularly during the last century, has resulted in an explosion of knowledge on the marine realm that has radically transformed our view of the ocean and our planet in general.

The ocean is today a less remote and more fascinating place than it was 70 years ago. However, it still represents a frontier for research and resource exploitation. We have better maps of the surfaces of Mars, Venus and Earth's Moon than of our seafloor. Most of the ocean floor is mapped at a spatial resolution of only a few kilometres (Smith and Sandwell 1997), which means that the majority of the fine-scale submarine landforms are still uncharted. Surveying such landscapes is

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both expensive and time consuming; it has been estimated that it would take approximately 125 years to chart all ocean basins using the latest swath-mapping tools (Sandwell et al. 2002).

2 Submarine Geomorphology

Geomorphology is the study (-logy, from λογος) of the forms (-morpho-, from μορφη) of the Earth (geo-, from γη). Geomorphologists describe and classify the Earth's surface to investigate the complex interaction between form and process, and to unravel the evolution of landforms and landscapes through space and time.

Submarine geomorphology is the study of landforms and processes in the submarine domain. The ocean hosts a tremendous variety of forms that reflect the action of a range of tectonic, sedimentary, oceanographic and biological processes at multiple spatio-temporal scales (Fig. 1). The aim of this book is to present the state-of-the-art in the standard data and methods used in submarine geomorphology (Part 1), to introduce the most significant submarine landforms and the processes that form them (Part 2), and to highlight the applied value of submarine geomorphology to industry and ocean governance based on selected examples (Part 3). This book is written for anybody with an interest in submarine geomorphology, although it is primarily aimed for undergraduate and graduate students, and professionals with limited training in marine geosciences. Our hope is that this book will encourage an interaction with terrestrial geomorphologists as well as scientists from other disciplines that results in significant advances in submarine geomorphology.

The investigation of the form, processes and evolution of submarine landscapes has strong basic and applied value, and it is becoming a priority for many academic and research institutions, government authorities and industries globally. The seafloor is a vast reservoir of renewable and non-renewable resources, which include marine ecosystems, fisheries, hydrocarbons, freshwater, aggregates, deep sea minerals and blue energy, among others. Industries that exploit these resources are increasingly moving offshore and deeper as the shallow and more accessible resources become depleted. Sound knowledge of seafloor geomorphology is key to maritime spatial planning, the designation of marine protected areas, the construction and operation of offshore infrastructure, and the implementation of environmental monitoring programmes. Seafloor processes constitute a geohazard to key offshore infrastructure and coastal communities. The seafloor is also an important archive of global change (e.g. climate, ocean circulation, sea level).

The International Association of Geomorphologists has recognised the increasing significance of submarine geomorphology by setting up the Submarine Geomorphology working group in August 2013. This group joins other initiatives, such as S4SLIDE (Assessing Geohazards, Environmental Implications and

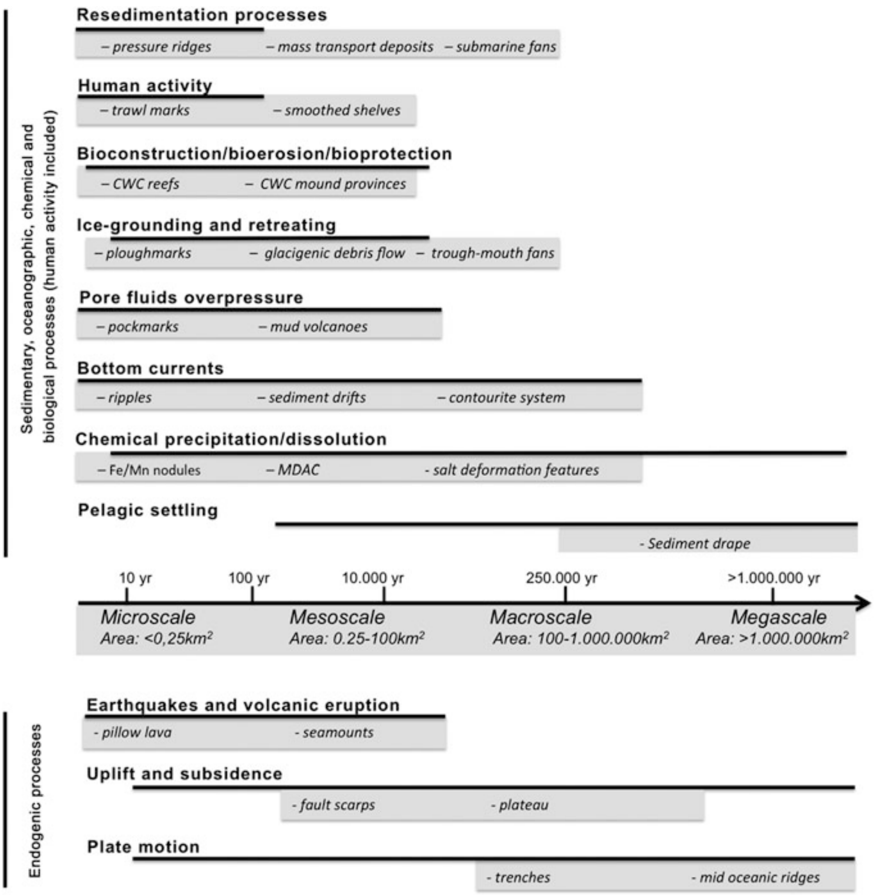

Fig. 1 A list of the main drivers of seafloor geomorphic changes in submarine environments (see Chapter "Drivers of Seafloor Geomorphic Change") and examples of resulting landforms at different spatial and temporal scales. The *black line* associated to each process refers to the temporal scale (see the *black arrow* for reference values), indicating the process lifespan required to create representative landforms. The *grey boxes* include an example of representative landforms for each spatial scale (see the *grey box* under the *black arrow* for reference values) (CWC = Cold-Water Corals; MDAC = Methane Derived Authigenic Carbonates)

Economic Significance of Subaqueous Landslides across the World's Continental Margins; funded by IGCP-640), and INCISE (International Network for submarine Canyon Investigation and Scientific Exchange), in bringing together scientists, students and professionals working on various aspects of submarine geomorphology, and to stimulate discussions with geoscientists from related fields of research.

3 History of Submarine Geomorphology

Submarine geomorphology is a relatively young scientific discipline. This is largely a result of the difficulties inherent to the investigation of the ocean floor. Submarine geomorphology has relied heavily on ‘remote sensing’ of the ocean floor, primarily through the use of acoustic waves. Developments in submarine geomorphology have therefore been closely linked to developments in geophysics.

The first pioneers to measure the depth of the ocean did so using plumb lines. A time consuming and inaccurate method, this involved a weight attached to cable that was lowered to the seafloor while the ship was stationary. The length of the cable was used to estimate the depth of the ocean floor. The first known attempt to measure ocean depth in this manner was by Ferdinand Magellan in the central Pacific around 1500 AD, but his attempt failed because the plumb line he used was too short. Lt. Matthew Fontaine Maury published the first deep-sea bathymetric map based on measurements with plumbs in 1855 (Fig. 2). This map covers the North Atlantic Ocean and is based on sparse soundings. Maury included a bathymetric profile between Mexico and NW-Africa along an area with a relatively high density of soundings. This profile showed numerous important morphological features, such as

Fig. 2 Maury’s map of the North Atlantic, Italian edition from 1877. The map content is identical to that of the original edition published in 1855. (Reprinted from Sound images of the ocean, Wille 2005, with permission from Springer.)

the Mid-Atlantic Ridge and the first indications of typical continental margin and abyssal plain morphologies. Another 100 years had to pass before these features could be understood in the frame of the theory of plate tectonics.

The first great oceanographic expeditions also took place in the second half of the 19th century. The Challenger Expedition, for example, circumnavigated the globe from 1872–1876 and made nearly 500 deep soundings using a lead weight attached to a hemp rope. During this time, several attempts were made to mechanise depth soundings and make them less time consuming and expensive. This was partly driven by the need to lay down the first transatlantic cables. One technique was developed by William Thomson and consisted of a motorised drum of piano wire with a lead and a dial. Another instrument was the gravity-measuring bathometer developed by Siemens (1876), but it failed to achieve the accuracy of plumb lines and was never routinely used.

In view of the lack of detailed morphological maps of the ocean, scientists in the late 19th century joined forces to study the ocean floor systematically. During the 7th International Geographic Congress in Berlin in 1899, a proposal was made to develop an international agreement on nomenclature and systematic terminology for sub-oceanic relief features. In response to this proposal, a commission was formed and charged with the preparation of a bathymetric map of the oceans. In 1903, His Serene Highness Prince Albert I of Monaco offered to organise and finance the production of a map series named ‘la Carte générale bathymétrique des océans’ (the General Bathymetric Chart of the Oceans, GEBCO) (Carpine-Lancre et al. 2003). This was the origin of GEBCO, which nowadays operates under the joint auspices of the International Hydrographic Organization (IHO) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO. GEBCO today offers a 30 arc minute grid (ca. 1 km), which is an important reference map for the morphology of the world’s oceans.

A milestone in the investigation of submarine geomorphology was the development of ocean echo sounders in the early 20th century. These instruments allowed measuring water depth from moving vessels by means of acoustic waves. The invention of echo sounders happened independently at two places (Wille 2005). The Canadian engineer Reginald A. Fessenden started the development of an acoustic echo ranging device in Boston in 1912. German physicist Alexander Behm built his first echo sounder in Kiel in 1913. Both workers were stimulated by the loss of the Titanic after a collision with an iceberg in 1912. The main aim of both developments was the detection of icebergs and obstacles with acoustic waves. Alexander Behm failed with his approach to detect icebergs with horizontal sound propagation, but vertical soundings allowed very precise measurements of water depth. Several ships were equipped with echo sounders soon afterwards. A first echo sounding line crossing the Atlantic Ocean was collected on the USS Stewart in 1922 using an acoustic echo sounder devised by Dr Harvey Hayes, a U.S. Navy scientist. The German Meteor Expedition (1925–1927) systematically surveyed the South Atlantic Ocean by crossing it 13 times between 20° north and 55° south using echo sounding equipment and other oceanographic tools. In total, they collected about 67,000 soundings along lines spaced at 600 km. This expedition showed for the first time that ocean floors have irregularities as great as suberial landscapes. The continuity of the Mid-Atlantic Ridge was proven beyond doubt during this expedition. Sediment coring during this cruise also led to the first estimates of sedimentation rates in the deep ocean. The first operational multibeam sounding system was installed on the USNS Compass Island (Glenn 1970). For the first time, detailed bathymetric maps of the ocean floor became available, which revolutionised our understanding of seafloor morphology and seafloor processes (see Chapter "Multibeam Echosounders").

The first marine seismic measurements were conducted in 1938 (Ewing and Vine 1938). Ewing was one of the pioneers in the development of seismic reflection and refraction systems for the exploration of ocean basins. Early measurements were done from stationary vessels with explosives as source. Early marine seismic measurements imaged thick sedimentary successions on the continental shelves, which quickly drew the attention of the hydrocarbon industry.

Major technical achievements in the investigation of the oceans were made during World War II, mainly in relation to the detection and safe navigation of submarines. Some of the engineers moved to academic institutions and private companies after the end of the war, thus making the newly developed techniques available to civil society. An important step for the investigation of submarine geomorphology was the invention of sidescan sonars, which permitted the acquisition of seafloor images at significantly high resolutions (see Chapter "Sidescan Sonar"). The Geological Long-Range Inclined Asdic GLORIA came in service in the late 1960s, and it was used to map large portions of the seafloor, including the entire Exclusive Economic Zone of the continental United States. These and other surveys significantly contributed to the improved morphological analysis of continental margins and other seafloor features such as Mid-Ocean Ridges (Laughton 1981).

The increasing availability and quality of seafloor maps led to pioneering work on various aspects of submarine geomorphology. Francis Parker Shepard, an American sedimentologist, became well known for his work on the origin of continental margins and submarine canyons (especially along the US continental shelves and slopes), as well as the first global statistical study of seafloor morphology. Jaques Bourcart carried out similar work offshore France, particularly in the Mediterranean Sea. The global hypothesis for ocean margin morphology was developed by a meteorologist—Alfred Wegener—whose hypothesis of continental drift is now an integral part of seafloor spreading and plate tectonics. The theory of seafloor spreading was consolidated by the work on flat-topped seamounts (guyots) by Harry H. Hess, and the mapping carried out by Bruce C. Heezen and Marie Tharp.[1] The famous seafloor map published by Heezen and Tharp in 1977 is a

[1]In the early years of their cooperation, Bruce C. Heezen used to collect the data aboard the research vessels while Marie Tharp drew the maps, as women were excluded from seagoing activities at that time. It was only in 1965 that Marie Tharp was able to join a data collection expedition. As quoted in "The Floor of the Sea" by William Wertenbaker (1974), Bruce Heezen related the following story concerning the realisation that a rift valley existed in the middle of the Mid-Atlantic Ridge: "*Marie's job for me was to decide what a structure was... In three of the transatlantic profiles she noticed an unmistakable notch in the Mid-Atlantic Ridge, and she*

Fig. 3 The Bruce Heezen-Marie Tharp world ocean floor map, painted by Heinrich Berann. *Photograph* Library of Congress

masterpiece that illustrates all the major morphological elements of plate tectonics (Fig. 3). This map is surprisingly accurate even in areas where no data were available at that time. Heezen's work is extremely diverse—it extended to all parts of the world and covered both broad and fine scale submarine geomorphology. Reported in more than 300 publications, Heezen's work has left an indelible mark on submarine geomorphology.

A milestone in marine geosciences was the initiation of the Deep Sea Drilling Program (DSDP) in 1966 using the Drilling Vessel Glomar Challenger (Chapter "Seafloor Sediment and Rock Sampling"). Ocean drilling is not a direct method for investigating submarine geomorphology, but the analysis of rock and sediment sampling contributes to the understanding of the processes shaping the seafloor. DSDP was followed by the Ocean Drilling Program (ODP, 1983–2003), the Integrated Ocean Drilling Program (IODP, 2003–2013), and the ongoing International Ocean Discovery Program (IODP, since 2013). All of these programs are truly international and multidisciplinary endeavors that significantly contribute to the understanding of the ocean floor and planet Earth in general.

(Footnote 1 continued)

*decided they were a continuous rift valley and told me. I discounted it as girl talk and didn't believe it for a year". "*Marie was the grand dame of ocean exploration*," said Bill Ryan, Doherty Senior Scholar at Lamont-Doherty and a long-time colleague of Tharp's. "*She didn't just make maps; she understood how the Earth works*".*

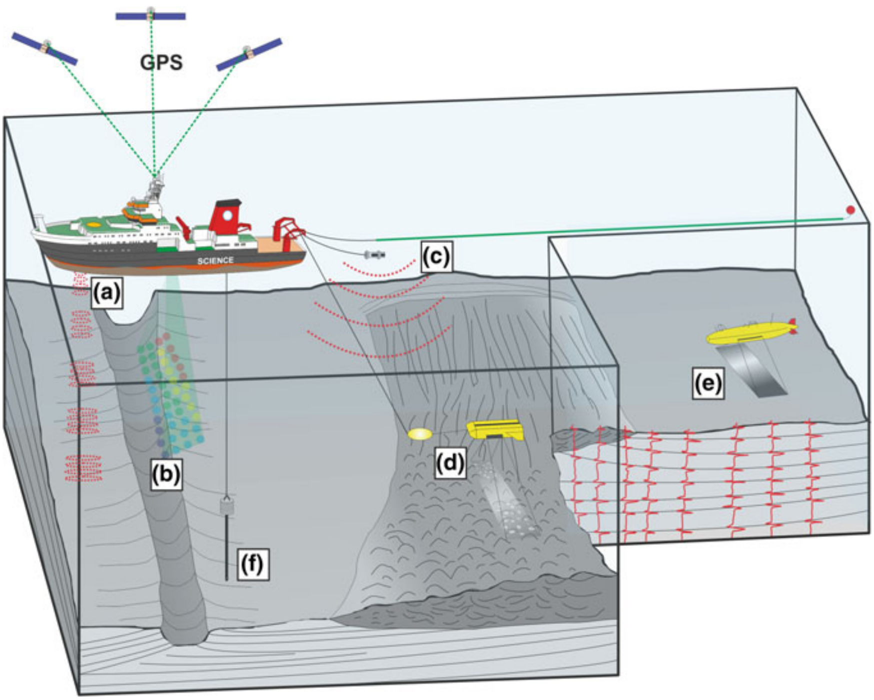

Fig. 4 Typical setup for a submarine geomorphological survey. (*a*) Sub-bottom profiler, (*b*) multibeam echosounder, (*c*) reflection seismic system, (*d*) sidescan sonar, (*e*) autonomous underwater vehicle, (*f*) sediment sampling (gravity corer)

Several technological advances in the last few decades have allowed investigating submarine geomorphology in increasing detail. Major advances include the use of underwater vehicles (see Chapter "ROVs and AUVs"), the accurate navigation of surface vessels and underwater vehicles, and improved resolution and penetration of acoustic imaging tools. As a result, modern submarine geomorphic investigations are based on a wide range of techniques (Fig. 4). The main strength of these techniques is that they provide an insight into both the exterior and interior structures of submarine landforms. The first part of this book presents the most commonly used techniques for data collection in submarine geomorphology.

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