Atlas of Bedforms in the Western Mediterranean

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This atlas is dedicated to our colleague and friend, Juan Acosta. Juan studied Geology (Madrid, 1972) and joined the Marine Geology group of the Spanish Institute of Oceanography in 1973. Since then he has accompanied several generations of marine geologists in Spain, combining marine research (his vocation) and resource management (a duty). To highlight just a few things from his extensive curriculum, Juan participated as a Spanish delegate in the Second United Nations Conference on the Law of the Sea (UNCLOS) (Geneva, 1975); in the first Spanish Antarctic campaign (1986); in the study of the fixed link between Morocco and Spain across the Strait of Gibraltar; in many precursor studies on marine protected areas; in the achievement of the 3D bathymetry of the Spanish continental shelf; and in the study of the birth of a new volcanic island (El Hierro, 2011). In the preparation of the FORMED research project, Juan proposed the compilation of this atlas and he has actively collaborated in editing it even after his retirement in 2014. Above all, however, we want to emphasize the pleasure of working with Juan at the office, in oceanographic surveys and in meetings, due to his positive thinking and his friendliness. He has always made things easier for the people around him.

Gracias amigo!

Contents

Introduction to the Atlas

Bedforms are depositional morphologies generated by the interaction between a mobile bottom and the force induced by a fluid. The study of bedforms was first undertaken in the field of aeolian and river geomorphology and subsequently has spread to the coastal zone and the marine environment in general. The technological revolution brought about by the use of multibeam echo-sounders, with swath-bathymetric data coverage and previously unimaginable precision, has transformed our small-scale view of the seabed; whereas we initially considered seafloor bottoms to be predominantly flat, we now know that bedforms are ubiquitous throughout marine environments. In parallel to this technological and scientific development, we are changing our perception of the sediment dynamics of the marine environment: significant sediment movement near the bottom was previously thought to be confined to very shallow depths but is now known to occur throughout the continental margin and even in deep basins. This conceptual "revolution" has occurred in a relatively short period of time (30 years) and has led to the incorporation of new terminology for describing bedforms and sediment transport mechanisms and to a great increase in knowledge of the mechanisms that generate and/or maintain bedforms.

Bedforms can be composed of gravel, sand or mud and of siliciclastic or carbonate sediment. They have a wide range of spatial and temporal scales. In shallow water, the common types are ripples, megaripples and nearshore bar systems with a variety of morphological characteristics (shore-parallel, crescentic, etc.). On the continental shelf, the forms described include shoreface-connected ridges, sorted bedforms, sand banks, sand waves, sand ridges, dunes and ribbons. Finally, on prodeltas, on the outer continental shelf and slope, on submarine canyons and in deep areas of the ocean, the presence of large-scale sediment waves and cyclic steps is reported.

The profusion of bedforms has led to various attempts in classifications based on morphological, sedimentological or genetic criteria, although a generic classification that covers all sedimentary environments is still missing. Among the most commonly used classifications are that of Ashley (1990) on large-scale flow-transverse sandy bedforms in fluvial and shallow marine sediment and that of Wynn and Stow (2002) on sediment waves in deep water regions. The basic factors traditionally considered to determine the type of bedform are sediment size and current intensity. Several diagrams containing sediment size, bedform morphology and current intensity have been proposed for both shallow (Allen 1984; Middleton and Southard 1984; Boguchwal and Southard 1990) and deep (Stow et al. 2009) waters. These diagrams are preferably used to interpret the hydrodynamic conditions of relict structures and the geological record, because two parameters allow the third one to be deduced (for example, the intensity of the current can be deduced from the morphology and sediment). However, these diagrams include only certain types of bedforms (usually transverse) and are excessively simple. Additionally, the use of cross-bedding stratification to the classification and interpretation of bedforms provides a useful tool for studying bedforms in the geological record (Rubin 1987). Interpretation of the genesis of bedforms is often complex: in addition to near-bottom currents, other mechanisms such as waves, internal waves and density flows can be involved. A dimensionless parameter combining terms such as speed, height and wave period, sediment density and grainsize, fluid density and viscosity, and bottom slope may well be more appropriate (Fredsoe and Deigaard 1992). In the proper interpretation of bedform formation, an important additional question is which of the observed morphologies are dynamic at present and which are relict features inherited from past environmental conditions.

Interestingly, the morphology of bedforms is basically the same in all marine environments and, except for the effect of gravity waves, which is restricted to the shallower area, the mechanisms proposed to explain the formation of bedforms are quite similar from shallow to deep water areas, suggesting the existence of common processes of interaction between the fluid and the mobile seabed. In an initial approximation, we can consider that the main groups of mechanisms that can generate or maintain bedforms in different marine environments are the following: (1) waves, tides and wind-induced currents (e.g. Swift et al. 1978; Van Dijk 2005; Li and King 2007); (2) thermohaline oceanic currents, contour currents and other specific bottom currents (e.g. Wynn and Stow 2002; Masson et al. 2004); (3) density flows (e.g. cascading) and turbidity currents (e.g. Trincardi and Normark 1988; Lee et al. 2002); and (4) internal waves (e.g. Flood 1988; Puig et al. 2007; Ribó et al. 2016). However, knowledge of the sediment transport processes associated with the generating mechanisms of bedforms is incomplete, and the predictive ability of the models is limited (Davies and Thorne 2008). While we can make appropriate predictions of small-scale bedforms such as ripples based on the size of the sediment and statistics of the current intensity near the bottom (e.g. Nielsen 1992; Wiberg and Harris 1994), these relationships are more ambiguous when it comes to larger bedforms (Gallagher et al. 2005). Currently, the mechanisms that generate shallow bedforms are interpreted as self-organization processes (Coco and Murray 2007).

The study of bedforms is important for the advancement of knowledge of bottom boundary-layer processes, such as sediment transport and variations in the circulation system caused by the changes in the roughness of the seabed. However, bedforms can also be used as indicators of the position of ancient shorelines, to infer the hydrodynamic processes that have taken place in the past, and to interpret the geological record (even on other planets!). Many bedforms have developed above larger sedimentary bodies and they are used as a criterion for inferring whether these bodies are dynamic. The implications of this dynamism on biogeochemical cycles and habitat distribution still deserve focussed research with new technological advances. From the application point of view, bedforms can create specific habitats that must be known in order to optimize the management of the marine environment and, as some of them are often exploited by fishing activities. Some bedforms may also offer exploitable mineral resources (e.g. sand deposits for beach nourishment) or have applications in the oil industry as analogues of possible reservoir rock. Finally, the dynamism of bedforms may have impacts on coastal and offshore structures such as harbours, estuaries and offshore wind farms.

Advances in our knowledge of bedforms have mainly resulted from a huge effort to obtain high-resolution bathymetric records and boundary-layer hydrodynamic and sediment transport measurements over the past decades. We must now collect and analyse in depth the existing information on a regional scale, provide an overview of the morphology of bedforms and identify gaps in our knowledge of the formation mechanisms. This book fits into this goal. The inventory of the bedforms on the Spanish Mediterranean continental margin was one of the objectives of the FORMED research project (CGL2012-33989). We asked our colleagues to collaborate in the preparation of this atlas by providing their expertise on specific topics or examples of bedforms from the western Mediterranean Sea. The aim of this book is to illustrate the characteristics of present-day bedforms, from the shoreline to deep-sea environments, and it also includes short reviews of the main mechanisms that generate such bedforms. The atlas is aimed at the research community, in addition to students, the public at large and companies with interests in the marine environment. The book is divided into seven parts composed of a number of short chapters: (I) Bedform Analysis and Main Physical Processes (eight chapters), (II) Bedforms in the Coastal Zone (eight chapters), (III) Bedforms in Prodeltas and Sorted Bedforms (seven chapters), (IV) Bedforms in the Continental Shelf (six chapters), (V) Bedforms and Benthos (four chapters), (VI) Bedforms in Submarine Canyons (six chapters) and (VII) Slope and Deep-sea Bedforms (seven chapters). We hope that the contents of the book can give the reader a comprehensive, though not exhaustive, view of the diversity of bedforms and associated processes and of the morphological and temporal scales in the enclosed tideless western Mediterranean Sea.

This book would not have been possible without the support and cooperation of all the authors. We especially appreciate the work of reviewers, who greatly improved the original manuscripts.

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