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Classification of submarine canyons of the Australian continental margin

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ABSTRACT

Submarine canyons influence oceanographic processes, sediment transport, productivity and benthic biodiversity from the continental shelf to the slope and beyond. However, not all canyons perform the same function. The relative influence of an individual canyon on these processes will, in part, be determined by its form, shape and position on the continental margin. Here we present an analysis of canyon geomorphic metrics using an updated national dataset of 713 submarine canyons surrounding mainland Australia. These metrics (attributes) for each canyon are used to classify them into canyon types across a hierarchy of physical characteristics separately for shelf-incising ($n = 95$) and slope-confined (blind; $n = 618$) canyons. We find that the canyon metrics describe a wide variety of canyon form and complexity that is consistent with a population of canyons that has evolved at different rates around the Australian margin since the break-up of Gondwana. The large number of slope-confined canyons is interpreted to reflect dominance of slope mass-wasting processes over erosive turbidity flows from fluvial and shelf sources on an arid continent. The distribution of submarine canyons around the Australian margin is not regular, with clusters occurring in the east, southeast, west and southwest where the margin is steepest. The classification result provides a quantitative framework for describing canyon heterogeneity for application in studies of geological controls on individual canyons, canyon oceanography and canyon biodiversity.

1. Introduction

Submarine canyons are common geomorphic features that occur on the margins of all continents (Shepard, 1972; Harris and Whiteway, 2011; Harris et al., 2014). Their complex morphology interacts with ocean currents, tides and internal waves, setting up hydrodynamic conditions that influence benthic ecosystems and habitats (Vetter, 1994; Bosley et al., 2004; De Leo et al., 2010). Submarine canyons were first scientifically described by marine geologists, who focused on their significance as major geomorphic features of continental margins and as conduits for sediment export from coastal and shelf environments to the deep sea over geologic timescales (e.g. Shepard and Dill, 1966). More recently, the ecological significance of submarine canyons has been recognised, as features associated with enhanced primary productivity, benthic biomass and biodiversity (Huvenne and Davies, 2013).

As our knowledge and understanding of the importance of submarine canyons for biodiversity has improved, our need for a systematic approach to describing and classifying them has grown. In this paper we review the geomorphological classification of canyons and relate specific geomorphic attributes to the physical oceanographic and ecological processes that have been identified by previous workers as being important to defining differences in canyon ecosystems (e.g., Schlacher et al., 2007; Cartes et al., 2010; McClain and Barry, 2010; Vetter et al., 2010; others detailed in Section 3). In this context, we present a new submarine canyon dataset for the Australian continental margin, derive physical properties for all canyons and use these measures to classify Australian canyons as a framework for examining their geomorphic and ecological characteristics.

2. Definitions and canyon types

Here we adopt the criteria for submarine canyons proposed by Shepard (1972, 1981) who recognised that canyons may have several origins and restricted his definition to “steep-walled, sinuous valleys with V-shaped cross sections, axes sloping outward as continuously as river-cut land canyons and relief comparable to even the largest of land canyons”. This definition therefore excludes other seafloor valleys, including: delta-front troughs (located on the prograding slope of large deltas); fan valleys (the abyssal, seaward continuation of submarine canyons some of which are remarkably long; Skene and Piper, 2006; Bourget et al., 2008); slope gullies (incised into prograding slope sediments); fault valleys (structural-related, trough-shaped valleys,

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generally with broad floors); shelf valleys (incised into the shelf by rivers during sea level low stands, generally less than 120 m deep); and glacial troughs incised into the continental shelf by glacial erosion during sea level low stands, generally U-shaped in profile and having a raised sill at their seaward terminus (Shepard, 1981).

Among the submarine canyons that fit Shepard's criteria, there are two broad types: (i) Shelf-incising canyons, with the largest extending landward as shelf valleys that have a direct connection to modern river systems. A sub-category of shelf-incising canyon, termed "headless canyons", incise the shelf but do not extend across the shelf as shelf valleys nor do they connect to river systems (Greene et al., 1991); (ii) Blind (slope-confined) canyons that are confined to the continental slope with heads that terminate below the shelf break (also termed slope-sourced canyons; Brothers et al., 2013).

3. Hydrodynamic and ecological significance of canyons

The topography of submarine canyons can influence local upwelling and downwelling of water masses and generate other complex hydrodynamic processes, notably internal tides (Shepard, 1975; Hotchkiss and Wunsch, 1982; Klinck, 1996; Allen et al., 2001; Cacchione et al., 2002; Carter and Gregg, 2002). Canyons may also act as conduits for transporting sediment and nutrients from the shelf to the deep sea (Gardner, 1989a; Vetter and Dayton, 1998, 1999; Canals et al., 2006; de Stigter et al., 2007; Zuniga et al., 2009; Cunha et al., 2011; Martin et al., 2011; Puig et al., 2013). Internal tides and waves, in contrast, can resuspend sediments through focusing effects and transport them up-canyon and across the shelf break (Shepard et al., 1974a, 1974b; Gardner, 1989b; Kunze et al., 2002; de Stigter et al., 2007; Puig et al., 2013). The combined effects of these hydrodynamic processes enhance shelf-slope exchanges and vertical motions of water and materials (Allen et al., 2001; Jordi et al., 2005) and have a substantial influence on the physical and biochemical properties of submarine canyons.

Of particular importance to canyon ecology are enhanced nutrient levels (e.g. chlorophyll-a, organic carbon and nitrogen, lignin) in the water column and sediment (Palanques et al., 2005; Garcia et al., 2008; Zuniga et al., 2009; Tesi et al., 2010; Kiriakoulakis et al., 2011; Martin et al., 2011; van Oevelen et al., 2011; De Leo et al., 2012) and the vertical profiles of light availability (turbidity), temperature, salinity and oxygen (Bosley et al., 2004; S.J. Rennie et al., 2009; Zuniga et al., 2009; Martin et al., 2011; De Leo et al., 2012). Together with large depth ranges, steep walls, rocky outcrops and mixed sediment types, these factors contribute to high spatial and temporal heterogeneity of canyon habitats which may in turn facilitate high marine biodiversity (Schlacher et al., 2007; McClain and Barry, 2010).

Refuge and food supply are two determining factors of habitat quality. Submarine canyons commonly have heterogeneous substrate types that offer habitats for various benthic species (e.g., Vetter et al., 2010; Cunha et al., 2011; De Mol et al., 2011; Paterson et al., 2011). In addition, canyons can provide natural refuge from fishing activities (Yoklavich et al., 2000) and harbour relic species (Gili et al., 2000; Palanques et al., 2005). Increased food supply in the vicinity of canyon heads and the upper reaches of canyons can lead to strong primary and secondary production (Vetter, 1994; Skliris and Djenidi, 2006; Cartes et al., 2010; Vetter et al., 2010). The aggregation effect of the food web enhances species diversity (Gili et al., 2000; Genin, 2004; van Oevelen et al., 2011). Numerous studies have demonstrated the significant biodiversity values of submarine canyons for:

- benthic macrofauna such as polychaetes (e.g., Rowe et al., 1982; Vetter, 1994; Vetter and Dayton, 1998; Cartes et al., 2010; Louzao et al., 2010; Cunha et al., 2011; Paterson et al., 2011; Currie and Sorokin, 2014; De Leo et al., 2014);
- benthic megafauna such as sponges and cold-water corals (e.g., Rowe, 1971; Vetter and Dayton, 1999; Hargrave et al., 2004; Schlacher et al., 2007; Cartes et al., 2010; De Leo et al., 2010; Ramirez-Llodra et al., 2010; Vetter et al., 2010; De Mol et al., 2011);
- phytoplankton (e.g., Skliris and Djenidi, 2006; Mendes et al., 2011);
- zooplankton such as krill (e.g., Greene et al., 1988; Allen et al., 2001; Skliris and Djenidi, 2006; Robison et al., 2010);
- fish and invertebrates such as rockfish, Pacific ocean perch and giant squid (e.g., Vetter and Dayton, 1999; Yoklavich et al., 2000; Brodeur, 2001; De Leo et al., 2010; Vetter et al., 2010; Guerra et al., 2011; De Leo et al., 2012); and
- whales (e.g., Hooker et al., 1999; S. Rennie et al., 2009).

4. Submarine canyons in Australia

The distribution of submarine canyons on the Australian margin was first mapped at the national scale by Heap and Harris (2008). A total of 423 submarine canyons was identified on all margins of the continent, with the greatest number ($n = 127$) along the southeast margin where the continental shelf and slope are both relatively narrow and steep. In contrast, only seven canyons were identified on the broad shelf of the northern margin (Heap and Harris, 2008). This contrast in the distribution of canyons in relation to the shelf and slope of the Australian margin was further highlighted by Porter-Smith et al. (2012) in a morphometric analysis of 257 canyon catchments.

In addition to these continent-wide studies, Australian submarine canyons have been mapped at local to regional scales along the south-western (Von Der Borch, 1968; Exon et al., 2005), south-south-eastern (Hill et al., 1998; Gingele et al., 2004; Hill et al., 2005; Mitchell et al., 2007) and north-eastern (Puga-Bernabeu et al., 2011, 2013, 2014; Webster et al., 2012) margins with a focus on canyon geology, geomorphology and sedimentology. Canyon-specific studies of local patterns in benthic biodiversity (e.g. Schlacher et al., 2007; Currie et al., 2012; Currie and Sorokin, 2014) and of canyon oceanography (e.g. Perth Canyon; S. Rennie et al., 2009) have contributed to an improved understanding of canyons as sites of enhanced productivity. However, the drivers of broader regional patterns in biodiversity within and between canyons remain poorly understood.

Many canyons on the Australian margin are influenced to some degree by either the Leeuwin Current (western to southern margins) or the East Australian Current (eastern margin), in addition to more localised oceanographic phenomena such as the Ningaloo Current (central western margin), the Flinders Current (southern margin), and dense shelf water cascades such as documented for Bass Strait (Godfrey et al., 1980) and southwest Australia (Pattiaratchi et al., 2011). Many canyons are located within the new national network of Commonwealth Marine Reserves (CMRs) and are recognised as Key Ecological Features (KEFs) in the management plans for these reserves (Commonwealth of Australia, 2013a, b). In particular, it is the role that canyons play in channelling nutrient-rich waters and thereby promoting productivity that is highlighted in the profile descriptions of these canyon KEFs. It follows then that to support the management of these marine reserves and to better understand the ecological processes associated with submarine canyons, an integrated analysis of canyons and oceanography is required.

5. Data sources and methods

5.1. Bathymetry datasets

Our analysis covers the full extent of the Australian Exclusive Economic Zone (excluding the external territorial seas and extended continental shelf; Fig. 1), an area of 6.82 million km^2. The study area is arbitrarily divided into eight geographic regions, as defined by Heap and Harris (2008) (Fig. 1). The eight regions are used here to facilitate the presentation and comparison of the canyon mapping and classification results.

To map the submarine canyons on the Australian margin we used three bathymetry datasets. Dataset 1 is the national-scale bathymetry