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Review article

Physical, biological, geochemical and sedimentological controls on the ichnology of submarine canyon and slope channel systems

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A B S T R A C T

Sediments of the continental slope are commonly bioturbated by endo- and epibenthic organisms, particularly in and around submarine canyons and channels. This study reviews the architecture and depositional environments associated with canyons and channels on the continental slope, and assesses the key physical and chemical conditions encountered in and around these conduits. Hydrodynamic energy, concentration and quality of organic carbon, dissolved oxygen concentration and sedimentation rate are identified as key controls on the composition of benthic ecosystems in slope environments. Submarine canyons and channels focus a variety of turbid and clear-water currents, all of which serve to increase the concentration of oxygen, labile organic carbon and other nutrients, which tend to elevate the abundance and biodiversity in the seafloor sediments, compared with those of the surrounding slope. Ancient slope channel and canyon systems reflect some of the variation in ichnological assemblages that is seen in modern analogues, although processes of erosion and trace fossil preservation mean that the benthic environment is often incompletely preserved in the ancient record. By integrating current understanding of sedimentology, oceanography, biology and ichnology of slope environments it is possible to provide a first order summary of the inter-relationships between ichnology and depositional environments on the continental slope. The combination of these data has the potential to improve our understanding of changes in deep marine benthic ecosystems through geological time, and to further the use of ichnology in assessing hydrocarbon reservoir presence, quality and performance from bioturbated slope, canyon and channel-levee hydrocarbon reservoirs.

1. Introduction

The continental slope is defined as the comparatively steep region of the continental margin between the shelf break and the continental rise (Heezen et al., 1959; Pickering et al., 1989). Slope gradients are typically 1–7° (Vorren et al., 1998) but may locally exceed 11° (e.g. Cochonat et al., 1993). So-called "deep water" environments beyond the shelf break (from as little as 200 m to more than 5000 m depth) represent one of the most areally important depositional settings on Earth. Originally predicted to be static and lifeless (e.g. Forbes, 1844), deep water settings of the continental slope, continental rise and basin floor are now recognized as among the most biologically rich and diverse environments on the planet (Gage, 1996; Ramirez-Llodra et al., 2010).

The continental slope is affected by a variety of hydrodynamic processes including: 1) tidally driven currents and internal waves; 2) deep water currents (e.g. contour currents and upwelling); and 3) sediment gravity flows (e.g. turbidity currents and debris flows). Currents are commonly confined within the conduits (canyons and channels) that occur almost ubiquitously on the continental slope, although some (e.g. high velocity, thick turbidity currents) may partially overspill the confining surfaces. Confinement creates strong physical and chemical gradients over relatively short distances. Such conduits include geomorphological features that have been variously described as submarine canyons, slope valleys, slope gullies, slope channels, turbidite channels and channel-levee systems (Fig. 1). These features differ in terms of their mode of formation and architecture (e.g. erosional or aggradational), but share the common element of providing a pathway for fluid and particle

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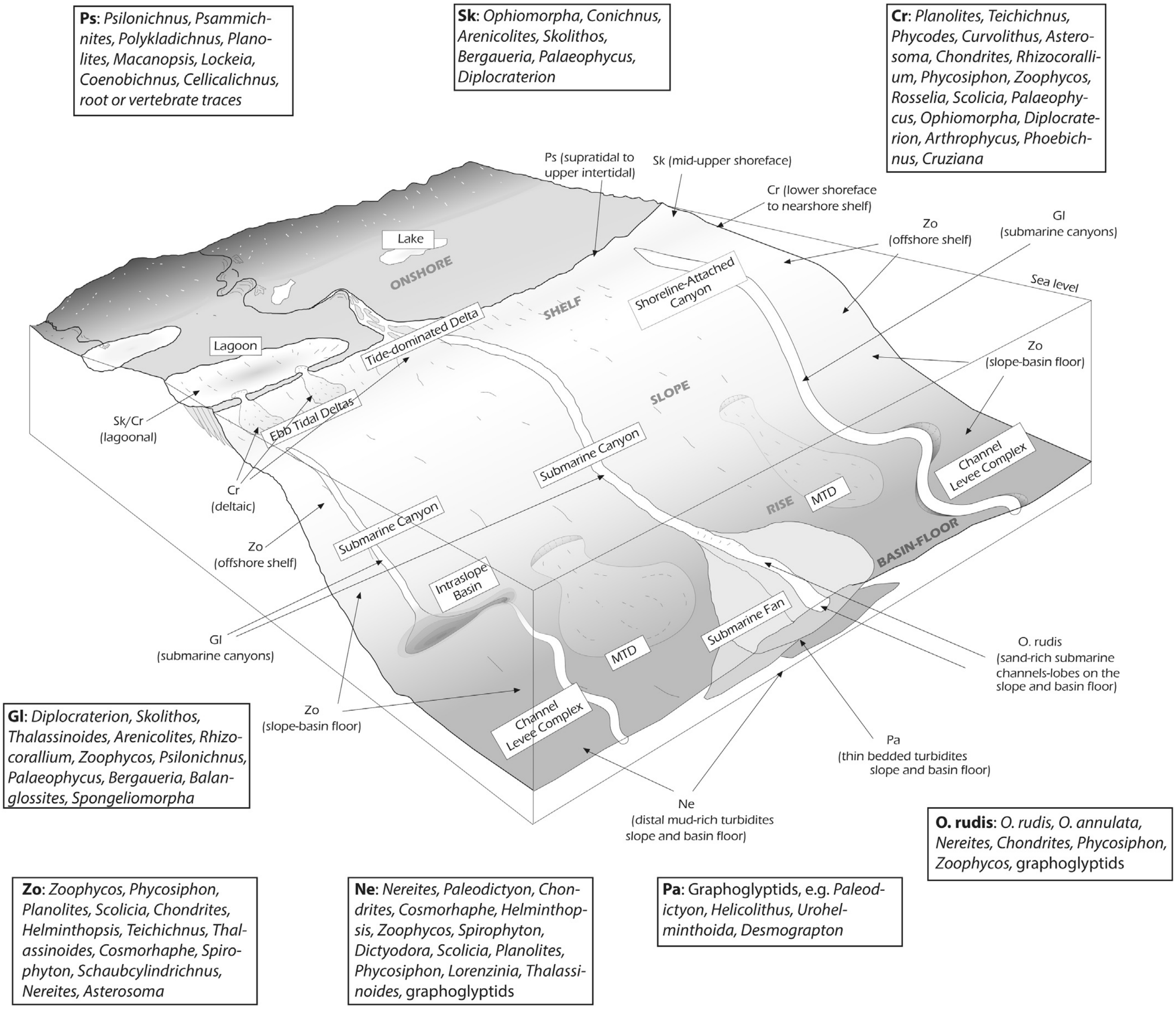

Figure 1. Diagram showing the spatial distribution of marine ichnofacies and depositional environments from marginal marine settings to abyssal plains, and ichnofossils that are common or distinctive components of each ichno(sub)facies. Cr: *Cruziana* ichnofacies. Ne: *Nereites* ichnofacies. Pa: *Paleodictyon* ichnosubfacies. *O. rudis*: *Ophiomorpha rudis* ichnosubfacies. Ps: *Psilonichnus* ichnofacies Sk: *Skolithos* ichnofacies. Zo: *Zoophycos* ichnofacies. The *Ophiomorpha rudis* (sand-rich channels) and *Paleodictyon* (fan-fringe) ichnosubfacies have helped to increase the palaeoenvironmental resolution of deep marine ichnofacies. Modified after McIlroy (2004a). Commonly occurring ichnofossils are after Seilacher (2007), MacEachern et al. (2012) and Buatois and Mangano (2011).

transport down (or up) the continental slope. In this review, the term “canyon” is used to refer to systems that are erosionally incised into underlying strata with limited development of bounding levees (i.e. typical of upper slope settings), “channel” is used to refer to a less erosional or aggradational system that may be bounded largely by overbank deposits such as submarine levees (i.e. the channel-levee systems that are typical of lower slope and continental rise), and “conduit” is used as a general term to include slope channels and canyons.

Hydrocarbon fields hosted in ancient slope systems are known from around the world, including the Gulf of Mexico, California, offshore West Africa, the North Sea and Brazil (Stow and Mayall, 2000; Weimer and Slatt, 2006). Amongst these, canyon and channel systems are particularly important (e.g. Mayall et al., 2006, 2010). Reservoir elements include the coarse-grained sediments that are typical of the conduit fill (e.g. Mayall et al., 2006) and finer-grained overbank sediments such as levees (e.g. Clemenceau et al., 2000). The subsurface architectures of slope channel and canyon systems may be broadly characterized by seismic and wireline log datasets (e.g. Posamentier, 2003; Cross et al., 2009), but outcrop analogue and modern seafloor studies are essential in characterizing sub-seismic architecture, and reservoir heterogeneity and quality. However, the role of bioturbation in influencing reservoir performance has yet to be assessed.

The fine- to coarse-grained sediments (mud and sand) of the continental slope, rise and basin floor (largely turbidites, contourites, mass transport deposits, pelagic and hemipelagic sediments) are typically bioturbated by epi- and endobenthic organisms, especially in and around submarine canyons, channels and their associated levees (Fig. 3; Wetzel, 1984, 2008; Uchman, 2004; Callow and McIlroy, 2011; Uchman and Wetzel, 2011). However, ichnological data have not as a rule been systematically