Ichnology of continental slope-channel systems: Biological, sedimentological and petroleum geological perspectives

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Highlights:* > *Review of research in ichnology of deep marine settings.* > *Review of architecture and environments in slope-channel systems.* > *Discussion of the controls on benthic ecosystems in slope-channel systems.* > *Review of the use of ichnology as a tool in understanding palaeoenvironments and turbidite facies analysis.

Abstract

Sediments of the continental slope are commonly highly bioturbated by endo- and epibenthic organisms, especially in and around submarine canyons and channels. Submarine channels act as conduits for turbidity currents and represent important sites of sediment (turbidite and mass transport) deposition. Sedimentary rocks formed in these environments are globally important as hydrocarbon reservoirs. The study of bioturbation (ichnology) can be a powerful and valuable tool in facies analysis and reservoir characterization of hydrocarbon systems, but has yet to be applied rigorously and consistently to the analysis of deep marine sediments from continental slope environments. This study reviews the architecture, depositional environments and the likely physical and chemical conditions across slope-channel systems. By integrating current understanding of sedimentology, 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 most important controls on benthic assemblages in slope-channel systems are discussed in order to develop a predictive framework for likely stresses on benthic ecosystems, and concomitantly trace fossil distributions. These physical and chemical parameters control the composition of benthic ecosystems in slope environments, and therefore control the ichnological record. Conversely, ichnology can be used as a tool to interpret depositional environments in turbidite-influenced submarine channel systems. This discussion demonstrates that ichnology is an under-utilized resource in the analysis of slope-channel systems, and has great potential to provide additional palaeoenvironmental insights when coupled with sedimentological

datasets. Future studies should focus upon the integration of ichnological data within detailed, high-resolution sedimentological and facies architectural frameworks. The combination of these data have the potential to improve our understanding of deep marine benthic ecosystems through geological time, and to further the use of ichnology in studying drill core from bioturbated slope and submarine channel hydrocarbon reservoirs.

1. Introduction

The continental slope is the comparatively steep region of the continental margin that lies between the shelf break and the continental rise (Heezen et al., 1959; Pickering et al., 1989); gradients are typically 1-7° (Vorren et al., 1998) but locally may exceed 11° (e.g. Conchonat 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 and volumetrically important depositional settings on the planet. Originally predicted to be static and lifeless (e.g. Forbes, 1844), deep water settings are now known to be among the most complex and biologically diverse environments on the planet (Gage, 1996). Far from being an environmentally stable, low-energy setting, the continental slope is affected by a variety of hydrodynamic processes including: 1) tidally driven currents; 2) deep water geostrophic currents; 3) thermohaline currents; 4) sediment gravity flows including turbidity currents and debris flows. Tidal, and sediment gravity flows are most commonly focused within submarine canyons or valleys, and levee-bound submarine channels.

Submarine canyon, valley and channel-levee systems (Fig. 1-2) are long-lived geomorphological features that can be hundreds to thousands of kilometers in length. These systems may arise at the shoreline or shelf break and cut the continental slope and may run out onto the basin floor (Fig. 1). These features may consist of one or more small channels (thalwegs), situated within a broader channel belt that is bounded by either an erosional canyon or levee (Fig. 2), though in some cases the entire confining feature acts as single broad channel, that may be several kilometres in width (e.g. Malinverno et al., 1988). At points where the slope gradient and flow energy decrease, either on the continental slope (intraslope basins) or at the base of slope, submarine channel systems commonly produce more extensive depositional features such as braid plans and fans (Fig. 1-2; Daly, 1936; Whitaker, 1974; Shepard, 1981; Pickering et al., 1989; Klaucke et al., 1998; Weimer et al., 2000; Mayall et al., 2006; Posamentier and Walker, 2006; Gamberi and Marani, 2007; Wynn et al., 2007; McHargue et al., 2011).

The fine- to medium-grained sediments (mudstones and sandstones) deposited in deep marine environments of the continental slope and basin floor are typically bioturbated by epi- and endobenthic organisms (e.g. Wetzel, 1984; 2008). Over 160 different trace fossil genera have been reported from ancient deep marine strata (Uchman, 2004). A suite of shallow-tier, near-surface grazing or farming trace fossils are often considered characteristic of submarine fan or basin floor sediments (e.g. Fig. 3; Uchman, 2004; Callow and McIlroy, 2011; Uchman and Wetzel, 2011). In contrast, the trace fossil assemblages of continental slope environments are less well characterized, due to the more limited number of ichnological studies focused upon slope settings (Hayward, 1976; Shultz and Hubbard, 2005; Heard and Pickering, 2008;

Philips et al., 2010; Callow et al., 2012; Hubbard et al., in press). Available data indicate that as well as some similarities, slope environments contain distinctive ichnological signatures that distinguish them from fan and basin floor settings.

In order to stimulate future discussion and research, this review focuses principally upon the ichnology and palaeoenvironments found within slope canyon and channel-levee systems (Fig. 1-2; e.g. Walker and Mutti, 1973; Pickering et al., 1989; Morris and Busby-Spera, 1990; Posamentier, 2003; Posamentier and Walker, 2006; Mayall et al., 2006; McHargue et al., 2011). These environments are of particular significance to sedimentologists, ichnologists and petroleum geologists due to their importance as petroleum plays (e.g. Mayall et al., 2006) and the current paucity of integrated ichnological and palaeoenvironmental data in comparison with shallow marine depositional environments.

2. Ichnology of slope-channel systems: architectural and stratigraphic perspectives

2.1. The applications of ichnology

In shallow marine settings, ichnological data are used routinely in detailed palaeoenvironmental and stratigraphic analysis, as well as intra-regional correlation and studies of petroleum reservoirs at sub-seismic and inter-well scales (e.g. Pemberton et al., 2001; McIlroy, 2004b, 2008; Gingras et al., 2007; MacEachern et al., 2007a). In contrast, there is a paucity of integrated sedimentological/ichnological studies of rocks from deep marine depositional environments, especially slope and submarine channel-levee systems (cf. Heard and Pickering, 2008; Hubbard et al., in press). In terms of ichnology, the most important rocks from these environments are those deposited by turbidity currents. Turbidites contain the highest recorded ichnodiversity, abundance and bioturbation intensity. Contourites are notoriously difficult to recognize due to the high bioturbation rates which mask diagnostic sedimentary structures (Stow, 1979; Wetzel et al., 2008). In our experience, mass transport deposits (e.g. debris flows) are typically sparsely bioturbated. For this reason, this review focuses upon turbidites and fine-grained sediments deposited in inter-turbidite periods (hemipelagite and pelagite).

2.2. The disconnect between ichnology and sedimentology

Published sedimentological studies of modern and ancient turbidites often contain little or no reliable ichnological information beyond the observation of “burrows” or “bioturbation” (e.g. Armitage et al., 2010). Conversely, most ichnological studies of turbidites fail to record accurately the detailed sedimentological context of the trace fossils. For example, many occurrences are simply described by the archaic, catch-all terms “greywacke” (*sensu* Pinkerton, 1811) and “flysch” (*sensu* Studer, 1827; e.g. Uchman, 1998, 2004). It can be concluded that despite a number of notable exceptions (e.g. Wetzel et al., 2007; Heard and Pickering, 2008; Knaust, 2009), deep marine ichnology has largely failed to keep pace with recent advances in turbidite sedimentology that have come from field analogue studies, data from drill core, seismic interpretation, numerical modeling and laboratory experiments (e.g. Prather et al., 1998; Kane et al., 2009, 2010; Mutti et al., 2009; Meiburg and Kneller, 2010). Thus, sedimentological and ichnological datasets from deep marine facies are seldom integrated, perhaps for lack of appreciation of the potential applications of trace fossils to deep marine facies analysis and palaeoenvironmental characterization.

The potential applications of ichnology to the study of slope-channel systems include: 1) high-resolution palaeoenvironmental characterization (e.g. Shultz and Hubbard, 2005; Heard and Pickering, 2008; Callow et al., 2012; Cummings and Hodgson, 2011); 2) identification of omission surfaces (e.g. Gérard and Bromley, 2008; Callow et al., 2012); and 3) assessing reservoir quality (porosity and permeability; e.g. Gingras et al., 1999; Tonkin et al., 2010). It can be difficult to address these issues comprehensively in subsurface systems by analysis of sedimentology alone, or by using existing paradigms for the interpretation of trace fossils from deep sea strata. This is because most models are based upon interface trace fossils, which are not commonly described from drill core and can have little or no impact on well-log responses. For this reason we consider that the greatest potential application of ichnology lies in the study of deep marine ichnofabrics (e.g. Wetzel, 2008; Knaust, 2009; Callow and McIlroy 2011; Callow et al., 2012).

2.3. Relevance of slope systems to the petroleum industry

Dozens of giant turbidite-hosted hydrocarbon fields are known from slope systems around the world, including the Gulf of Mexico, California, offshore West Africa, the North Sea and Brazil (Stow and Mayall, 2000). Of these, turbidite channel systems are particularly important hydrocarbon reservoirs (e.g. Mayall et al., 2006). The subsurface architectures of turbidite channel systems are well-characterized from geophysical datasets (e.g. Cross et al., 2009). However, models for their spatial and temporal development cannot be derived from seismic and well-log data alone (e.g. Deptuck et al., 2003; McHargue et al., 2011). As such, outcrop analogue studies are essential in characterizing the sub-seismic architecture of turbidite channel systems, and reservoir heterogeneity and quality. Sedimentological and facies-architectural studies have proven successful in this regard, although ichnological data have rarely been collected as part of these studies (e.g. Morris and Busby-Spera, 1988, 1990; Camacho et al., 2002; Dykstra and Kneller, 2007; Kane et al., 2007; Hubbard et al., 2008; Mutti et al., 2009).

2.4. Ichnological contributions

2.4.1. Ichnotaxonomy and ichnodiversity studies

Most ichnological studies of turbidites have focused upon ichnotaxonomy and ichnodiversity with little regard for the sedimentological context of the trace fossils (e.g. Książkiewicz, 1977; Uchman, 1998, 2004). Ichnology has been used to distinguish between 'proximal' (coarser-grained) and 'distal' (finer-grained) turbidites (Crimes, 1970, 1973, 1974, 1977; Książkiewicz, 1977; Crimes et al., 1974; Wetzel, 1991, 2008). Recent outcrop studies have begun to place ichnological observations in a more detailed facies architectural context (see section 6.3; Kane et al., 2007; Wetzel et al., 2007; Heard and Pickering, 2008; Hubbard and Shultz, 2008; Kane et al., 2009; Phillips et al., 2011; Cummings and Hodgson, 2011; Hubbard et al., in press).

2.4.2. Ethology

Much of the fundamental ichnological research that has been undertaken in the last 50 years has revolved around behaviour/ethology. One of the precepts that underlies many ichnological studies is the inference that trace fossil morphology relates to ethology. The main inferred behaviour types (described using the suffix "ichnia") are: cubichnia, repichnia, pascichnia, fodinichnia, domichnia, fugichnia, chemichnia and agrichnia (see Gingras et al., 2007). Increasingly, users of ichnology (and the *ichnia terminology) include sedimentologists and other non-specialist ichnologists. However, in many cases, the assignment of *ichnias has not been made on objective criteria, and relies upon assumptions. Instead of simply assigning trace fossils to *ichnias, it may be more enlightening to use more descriptive language where it is clear that the author is not assuming behaviour, but instead is required to rationalize their inferences of behaviour.

Ethological inferences have been applied to slope and slope-channel deposits (e.g. Heard and Pickering, 2008; Cummings and Hodgson, 2011), but in these cases, the assignment of ethological groupings is based simply on behavioural assumptions and is standard practice. It has been suggested that it is possible to use ethological groupings as indicators of depositional environments. However, given the current lack of understanding of the ethology of many deep-marine trace fossils (see Rona et al., 2009; Löwemark, 2011) and of deep marine organisms, it will be more informative to describe ichnological assemblages and inferred behaviours, rather than relying on assumptions of ethological modes.

2.4.3. Deep water ichnofacies

Trace fossils from continental slope and basin-floor environments have traditionally been considered within the ‘ichnofacies’ paradigm. This method is based upon the premise that depositional environments can be inferred from the assemblages of trace fossils found in a depositional unit (Seilacher, 1964, 1967; Frey and Seilacher, 1980; Frey et al., 1990; Bromley and Asgaard, 1991; Pemberton et al., 2001; MacEachern et al., 2007a, b; Uchman and Wetzel, 2011). In turbidites, the trace fossils often used to determine ichnofacies assignments are typically those that are confined to the bases of sandstone beds ('soles') (Fig. 3), and as such are of limited relevance to study of hydrocarbon systems from subsurface data (see Callow and McIlroy, 2011).

The 'archetypal' deep water ichnofacies are the *Zoophycos* (continental slope) and *Nereites* (basin floor) ichnofacies, which have extremely broad ranges of environment and implied water depth (Fig. 1; see MacEachern et al., 2007a; see comprehensive review in Hubbard et al., in press). In order to increase the resolution of the ichnofacies method, ichnosubfacies have been erected. The *Paleodictyon* ichnosubfacies has been used to describe thin-bedded sand-rich turbidite lobe fringes within the *Nereites* ichnofacies (Fig. 1, 3; Seilacher, 1974, 1978) and the *Ophiomorpha rudis* ichnosubfacies has been proposed to recognize sand-rich turbidite channels and channel-proximal lobes (Fig. 1; Uchman, 2009). The firmground *Glossifungites* Ichnofacies has also been described from the cohesive substrates of submarine canyon walls (e.g. Hayward, 1976), although whether these were true seafloor firmgrounds or subsurface "concealed" firmgrounds (*sensu* Bromley, 1996) is unclear.

Benjamin Kneller 29/3/16 22:30
Comment [1]: Maybe you should make the point that the classic ichofacies are dominated by interface traces, whereas some of the ichnosubfacies are not.

Benjamin Kneller 29/3/16 22:30
Comment [2]:

Benjamin Kneller 29/3/16 22:30
Comment [3]: Does this mean that the organisms burrowed down to a level where the sediment was firm? It seems to me more likely that firm sediment was exposed by erosion, then bioturbated; I think this should be made explicit

2.4.4. Deep water ichnofabrics

In comparison with interface trace fossils, ichnofabric-forming trace fossils from turbidites (cf. Bromley, 1996; McIlroy 2004a; Callow and McIlroy, 2011; Fig. 4-5) have received less attention from ichnologists (but see Knaust, 2009; Callow et al., 2012; Hubbard et al., in press). Ichnofabric analysis involves the collection of data from vertical cross sections at the bed or bed-set scale, incorporating lithology, bioturbation intensity, burrow size, ichnodiversity, abundance, cross-cutting relationships and depth of burrowing (Bromley and

Ekdale, 1986; Taylor and Goldring, 1993; Taylor et al., 2003; McIlroy, 2004b, 2008). Ichnofabric data can be collected from natural or cut cross-sections either in the field or in core, and has been used to refine the facies characterization of basin-floor fans in core from the Jurassic of the North Sea (Knaust, 2009), as well as a channel-levee system from the field in the Rosario Formation of Mexico (Callow et al., 2012). A recent review of available data on trace fossil occurrences within turbidites highlighted the most frequently encountered ichnofabric-forming trace fossils in Palaeozoic, Mesozoic and Cenozoic turbidites (Callow and McIlroy, 2011; see Fig. 4-5). While differences exist between typical Palaeozoic, Mesozoic and Cenozoic assemblages (e.g. abundance of *Ophiomorpha* and *Scolicia* in post-Palaeozoic turbidites), turbidite ichnofabrics show remarkable stasis, particularly in terms of inferred trophic mode throughout the Phanerozoic (Callow and McIlroy, 2011).

2.4.5. Trace fossils and reservoir quality

Bioturbation exerts various effects on reservoir quality (porosity and permeability; Weber, 1982; Gingras et al., 1999, 2007; Bednarz and McIlroy, 2009, in press; Cunningham et al., 2009; Tonkin et al., 2010). The effects on these fundamental petrophysical parameters vary with grain size and lithology of the host sediment, but may also be modified by the burrowing and feeding behaviour of trace-making organisms (Francois et al., 2002). While some common deep marine ichnotaxa can increase porosity and permeability by improving grain sorting (e.g. phycosiphoniform trace fossils; Bednarz and McIlroy, 2009; Fig. 5A-B), others produce conduits or ‘pipeworks’ for fluid flow (e.g. *Ophiomorpha* and *Thalassinoides*; Fig. 4C-D), while some ichnotaxa (e.g. *Scolicia*; Fig. 4A-B) decrease grain sorting and porosity/permeability (see Gingras et al., 2007; Tonkin et al., 2010). Other possible impacts on reservoir quality include the *in situ* production of authigenic clays by biological weathering (McIlroy et al., 2003), sometimes in the form of clay rims (Needham et al., 2005). The combined effects of bioturbation on the quality of turbiditic reservoirs are complex, and have not yet been considered in detail. These effects cannot be incorporated into reservoir quality models until such a time as the distribution of ichnotaxa across channel, levee, lobe and fan systems is more completely understood and the porosity-permeability data can be up-scaled to the scale of reservoir intervals.

2.4.6. Neoichnology

Due to the inherent difficulties of studying burrowed sediments from modern deep marine systems, progress in deep marine neoichnology has lagged behind advances in shallow marine and non-marine neoichnology (e.g. Davis et al., 2007; Gingras et al., 2008). Current understanding is limited to seafloor observations and bottom photographs, as well as analysis and X-radiography of box and gravity cores (e.g. Ekdale, 1977, 1980; Wetzel, 1983, 1984, 2008; Ohta, 1984; Young et al., 1985; Smith et al., 2000; Rona et al., 2009). In contrast with shallow marine systems, the palaeobiology of many key deep marine trace fossils is poorly understood (e.g. *Paleodictyon*; Rona et al., 2009). Due to the relatively small number of studies and limited sampling density, modern studies have scarcely considered spatial variations in the compositions of benthic faunas across slope canyon or channel-levee systems (Wetzel, 1984; Gerino et al., 1999). Similarly, sedimentological studies of modern submarine canyons have also failed to fully characterize the ichnology of sediment cores (e.g. Babonneau et al., 2002; Armitage et al., 2010). Shallow sediment cores from submarine canyon systems represent an under-exploited resource for ichnologists studying bioturbation of deep marine systems, and present an interesting and readily available dataset for future research.

3. Slope-channel system architecture

The architecture and evolution of submarine canyons and channels, and canyon-confined turbidite systems have been studied in modern and ancient slope systems by field studies (e.g. Camacho et al., 2002; Beaubouef, 2004; Dykstra & Kneller, 2007; Hubbard et al., 2008), bathymetric and shallow-seismic profiling (e.g. Pirmez et al., 2000; Babonneau et al., 2002), and well-log and core analysis (e.g. Samuel et al., 2003). Given the intrinsic variability of continental slope systems it is difficult to provide a comprehensive review of slope morphology and architecture that can be applied equally to all systems. Instead, we discuss the architectural and geomorphological elements of slope-channel systems, and use this to predict palaeoenvironmental conditions, and the potential controls on benthic ecology and ichnology across slope-channel systems.

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Comment [4]: Cerro Toro, AAPG Bulletin.

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Comment [5]: San Fernando, Shell Atlas

Slope canyons and channels can run from the shoreline (shoreline attached canyons) or shelf break to the basin floor (Fig. 1). Canyons and slope channels may be initiated or enlarged by mass failure and erosive turbidity currents, and may pass down-slope and evolve stratigraphically into levee-confined systems (Fig. 1-2; Hall et al., 2008; Piper and Normark, 2009; Kane and Hodgson, 2011). Channels and canyons act as important conduits for sediment and fluid transport in gravity-driven flows including turbidity currents (Whitaker, 1976; Mutti and Normark, 1987).

Accommodation is the principal control on the architecture of slope-channel systems, and is determined by the difference between the actual down-current profile of the channel and its hypothetical equilibrium profile (see Pirmez et al., 2000; Samuel et al., 2003; Kneller, 2003). The equilibrium profile of a system is a function of sediment grain size, flow thickness and flow density (Samuel et al., 2003; Kneller, 2003). Creation of accommodation (steepening the equilibrium profile) is favoured by decreasing flow density or flow thicknesses and/or increasing grain size, leading to deposition within the channel and in overbank areas, including levees (e.g. Camacho et al., 2002; Dykstra and Kneller, 2007; Kane et al., 2007; Kane and Hodgson, 2011). Erosion is favoured by reduction in gradient of the equilibrium profile caused by increasing flow density or thickness, and decreasing grain size. Graded systems form where the down-current channel profile matches the equilibrium profile and tend for form sinuous meandering channel belts (e.g. Kolla et al., 2001), marked by lateral accretion deposits, within channel-bounding levees (Fig. 2; e.g. Morris and Busby-Spera, 1990; Dykstra and Kneller, 2007, 2009).

Field and seismic studies have revealed a common pattern of submarine channel systems, evolving downslope from erosional on the upper slope, to graded and aggradational systems on the mid to lower continental slope (Fig. 2), though with some notable exceptions (e.g. Congo; Babonneau et al., 2002). Various studies have shown a temporal evolution of channel systems tending from erosional to aggradational over both long and short time scales (Fig. 2;

e.g. Beauboeuf and Friedman, 2000; Sprague et al., 2002; Samuel et al., 2003, Deptuck, 2003; Mayall et al., 2006). Deeply incised, erosion-dominated submarine canyons are most common on the upper slope (Fig. 1-2; e.g. Babonneau et al., 2002, Smith et al., 2007). Slope canyons typically pass down-slope into leveed channel systems and as the canyon is filled by sedimentation, canyons pass stratigraphically up into levee-confined systems (Fig. 1-2; Babonneau et al., 2002; Samuel et al., 2003). Changes in the location of the local gravity base (e.g. channel avulsion, filling of intraslope basins) or channel mouth, or in turbidity current flow characteristics, can result in changes from aggradation to erosional systems (Fig. 2; Pirmez et al., 2000; Kneller, 2003; Samuel et al., 2003). Relative sea level has also been inferred to play an important role in controlling accommodation, erosion and sedimentation in slope-channel systems, through changes in sediment supply to deep ocean basins (e.g. Hübscher et al., 1997; Deptuck et al., 2003; Di Celma et al., 2010; cf. Carjaval and Steel, 2006). It has been suggested that erosion and channel belt development occurs during regressive phases associated with maximum sediment supply, while channel aggradation occurs during transgressive phases, associated with reduced sediment supply (e.g. Mutti, 1999; Wilgus et al., 1988; Hübscher et al., 1997; Deptuck et al., 2003).

Benjamin Kneller 29/3/16 22:30
Comment [6]: M&PG

In addition to flow characteristics, factors such as faulting, salt and shale mobility, and deep clear-water currents also control the geomorphology and development of slope systems through time (see Pickering et al., 1989; Pirmez et al., 2000; Tinterri and Magalhaes, 2011). The characteristics of a submarine channel system are the principal controls on depositional environments, benthic ecosystems and therefore, ichnology.

3.1. Slope-channel system architecture

Detailed reviews of slope-channel architecture can be found elsewhere (see McHargue et al., 2011). We briefly review the architectural elements that are likely to contain distinctive and predictable ichnological signatures that are controlled by the environmental parameters.

Deep water slope-channel facies elements are classified on the basis of their facies assemblages, geometry, vertical and lateral stacking patterns, and the distribution of their confining surfaces (e.g. Sprague et al., 2002; Dykstra and Kneller, 2007). In the Sprague et al. scheme individual channel-fill bodies ('channels' in their terminology) are grouped into channel complexes, which are in turn grouped into channel complex sets. Channel-fill bodies, channel complexes and channel complex sets have predictable net fining-upward trends due to the filling of accommodation space, and the associated change from erosional to aggradational character during the lifetime of a submarine channel system (Fig. 2; Morris and Busby-Spera, 1988, 1990; Babonneau et al., 2002; Dykstra and Kneller, 2007). The facies associations that constitute individual channel fill bodies or channel complexes can be defined as axial, off-axis or marginal (McHargue et al., 2011). These facies associations differ in the abundance of amalgamated beds, bed thickness and sandstone to mudstone ratio.

Axial facies commonly form the thickest part of the channel belt deposits, representing deposition within individual channel thalwegs, and are typically dominated by coarse-grained, thick-bedded and amalgamated sandstones or conglomerates. Marginal depositional settings are dominated by thin-bedded facies with lower proportions of sand and less amalgamation

Benjamin Kneller 29/3/16 22:30
Comment [7]: There is a bit of confusion here between the final depositional architecture in 3D and the configuration of depositional settings on the sea floor.

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Comment [8]: If 'coarse-grained' is hyphenated, why isn't 'thick-bedded'?

(see McHargue et al., 2011; Hubbard et al., in press). Overbank facies associations consist of heterolithic sediments, occur outside the region of channel confinement, and are typically more fine-grained than axial and marginal facies (i.e. levees).

Two scales of confinement are commonly recognized within submarine channel systems. Small aggradational levees (internal levees) may form in overbank regions of individual thalwegs that may meander within a channel belt that is bounded by an external levee (Fig. 2; see Kane and Hodgson, 2011 for recent review of levee terminology); internal levee deposits may thus bound channel-fill bodies or channel complexes. Internal levees result from deposition from flows over-banking from channels that were confined within the main channel belt, but where the over-banking flows did not interact significantly with the broader bounding surface (levee or erosional confinement). It has been suggested that internal levees form in association with reduced sediment supply and aggradation of the channel belt within the confines of the external levee (see Hübscher et al., 1997; Deptuck et al., 2003). External levees are formed when larger flows escape the confines of the channel belt, which has been suggested to be associated with the highest rates of sediment supply (see Hübscher et al., 1997; Deptuck et al., 2003) – or simply larger flows; at least some external levees are associated with systems where the entire width of the space between the external bounding surface acts as a single channel (e.g. Laurentian Fan Valley, Piper et al., 1988; Var Canyon, Malinverno et al., 1988). External levees exhibit laterally continuous beds showing systematic trends in decreasing bed thickness and sandstone to mudstone ratio perpendicular to the channel axis, while internal levees are characterized by complex palaeocurrents, laterally discontinuous beds and a lack of clear trends in bed thickness (see Kane and Hodgson, 2011).

Benjamin Kneller 29/3/16 22:30

Comment [9]: I think this is wrong; this almost certainly refers to terraces, not internal levees – with no trend in bed thickness there would be no levee (which is by definition a morphological feature)

The height of external levees relative to the base of the channel is variable (tens to hundreds of metres), and commonly decreases down-slope (Babonneau et al., 2002; Wood and Mize-Spansky, 2009; but cf Pirmez et al., 2000). On the mid to upper slope the floor of the channel may lie below the level of the surrounding sea floor beyond the lateral limit of the levee, while in lower slope and base of slope environments channels can become super-elevated above the level of the surrounding sea floor (Fig. 2). The sedimentary fill of channel-levee complexes may be broadly similar to the fill of erosional canyon systems (Walker, 1985; Beauboeuf, 2004; Arnott, 2007; Hubbard et al., 2008; Kane et al., 2009).

Benjamin Kneller 29/3/16 22:30

Comment [10]: What do you mean by ‘complex’? Surely this depends on whether you are looking at distal systems (where a channel-levee is one or more ‘channels’ in Sprague terms), the mid fan, where it may be a channel complex) or inner fan to slope where it may be a channel complex set. This needs clarifying.

Due to the predictable evolution of stacking patterns in slope systems, the average grain size, proportion of amalgamated beds and average bed thickness all tend to decrease upwards in stratigraphic sections through channel-fill bodies, channel complexes and channel complex sets. Fine-grained sandstones, siltstones and mudstones are deposited as hemipelagic/pelagic drapes over the system during phases of slope-channel system abandonment and/or autocyclic cessation of turbidite deposition. Abandonment facies may be overlain and incised by subsequent channel bodies if re-activation of the system occurs, thereby commencing another cycle in the fill of the submarine canyon or channel (e.g. Dykstra and Kneller, 2007). Such reactivation may occur due to either an increase in sediment supply (Hübscher et al., 1997) or due to a change in the base of slope when an intraslope basin becomes completely filled (Fig. 2; Winker & Booth, 2000; McHargue et al., 2011). Previous studies have shown that the sub-environments within a single channel fill can have distinctive ichnological assemblages that can aid in facies interpretation when used in conjunction with detailed sedimentology (see Heard and Pickering, 2008; Callow et al. 2012: Hubbard et al., in press).

Having defined the key architectural elements of slope-channel turbidite systems and outlined the typical spatial and temporal evolution of a slope-channel system (Fig. 2), it is possible to assess the likely conditions within these depositional environments, and predict the probable impact of these parameters on ichnological assemblages.

4. Ecology of slope-channel systems

4.1. Environmental conditions in slope-channel systems

4.1.1. Environmental conditions and ichnology

The ichnological assemblage in a sedimentary bed is a record of the sum of the activities of a community—or more commonly many communities—of infaunal and epifaunal organisms. Bioturbation may be caused by organisms that were either living at the site of deposition during sedimentation, or which colonized the bed after deposition (McIlroy, 2004a, 2008). The geological expression of these biological communities is in the form of ichnocoenoses (time averaged ichnological assemblages; see McIlroy, 2004b). Ichnocoenoses, being the ichnological proxies for biological communities, can be used as indicators of palaeoenvironmental conditions, and—when integrated with process-based sedimentology—for depositional setting. Environmental parameters are considered to have the greatest influence on biological communities, and thus—taphonomic biases apart (Crimes, 1973;

Benjamin Kneller 29/3/16 22:30
Comment [11]: How can they be 'time-averaged' in a literal sense?

Bromley and Asgaard, 1991; Orr, 1994)—on ichnological assemblages. Significant environmental variables include hydrodynamic energy, nature and rate of sediment supply and sedimentation, suspended sediment concentration, degree of sediment erosion, bottom- and pore-water oxygenation, nutrient quality and availability, substrate consistency (Boucot, 1981; Wetzel, 1991). These variables differ significantly between the many environments associated with slope canyon and channel-levee systems (see Griggs et al., 1969; Vetter and Dayton, 1998; Gerino et al., 1999).

Benjamin Kneller 29/3/16 22:30
Comment [12]: This is a bit vague; ditto throughout

4.1.2. Currents

Slope settings are subject to a variety of different hydrodynamic processes including: episodic, gravity-driven mass transport processes such as slumps, slides and debris flows; turbidity currents, including sustained unidirectional gravity flows driven by terrestrial runoff (hyperpycnal flows); contour and deep geostrophic bottom currents; and currents driven by tidal processes (Shepard et al., 1974; Damuth and Emebley, 1981; Nelson et al., 1993; Mulder et al., 2003; Piper and Normark, 2009). Currents on the continental slope thus vary significantly in terms of their frequency, hydrodynamic energy, direction, velocity, mechanism of generation, turbulence, tractional- and suspended-sediment load.

Turbidity currents and hyperpycnal flows transport significant quantities of sediment, nutrients and oxygen from shelf margin environments to deeper parts of a basin (e.g. Mulder et al., 2003). As such, they exert significant controls on the composition of benthic fauna in areas affected by these processes. In levee- or canyon-confined turbidite systems the highest energy and strongest currents (i.e. turbidity currents) are found in a relatively narrow axial zone, although over-spilling can deposit relatively coarse grained sediment and detrital organic matter beyond the confined regions in off-axis and overbank settings (e.g. Piper & Normark, 1983; Khripounoff et al., 2003). Nonetheless, strong gradients in hydrodynamic energy are found within a few kilometres of the axis of the turbidite channel or canyon axis.

Bidirectional (up and down canyon), oblique and sustained unidirectional flows are recorded in modern slope canyons down to depths of 4000m (Shepard et al., 1974; Vetter and Dayton, 1998). Bidirectional currents may originate from tidal processes operating within the canyons, with the periodicity depending upon factors including slope and canyon morphology, the depth of the canyon axis and the tidal range at the ocean surface (Shepard et al., 1974; Caccione et al., 2002; Paull et al., 2003; Bosley et al., 2004). Deep tidal currents have been recorded with velocities of up to 40cms^{-1} in open ocean settings and 110cms^{-1} in submarine canyons (e.g. Shepard and Marshall, 1969). Such currents may alternatively be produced by internal waves, which are driven by surface tides amplified by the funnelling effect of canyon topography (Shepard et al., 1974; Garrett and Kunze, 2007). Currents driven by internal waves and tides have also been shown to cause erosion in the deep ocean (e.g. Lonsdale et al., 1972; Matsuyama et al., 1993; van Haren and Gostiaux, 2010). Bidirectional tidal periodicities recorded in ripple cross lamina sets indicate the importance of tides in both the transport and deposition of fine-grained sediment and the mobilization of particulate organic material (Xu et al., 2002; Dykstra, 2011).

Contour currents and deep water geostrophic currents have the potential to control the composition of benthic communities and bioturbation through the transport of nutrients and oxygenated bottom waters (e.g. Stow, 1979; Wetzel et al., 2008; Faugères & Mulder, 2011). This may be reflected in the intense bioturbation associated with contourite deposits (Stow, 1979; Wetzel et al., 2008), although low net rates of sedimentation relative to bioturbation can increase the observed bioturbation intensity.

In summary, it is clear that currents and hydrodynamic energy on the continental slope exert a major control on benthic macrobiotic and microbial communities.

4.1.3. Nutrients and Oxygen

Oxygen and nutrient availability are important controls on benthic communities and behaviour of burrowing organisms. Most modern continental slopes lie at depths below the oxygen minimum zone (OMZ, 200-700m; Levin, 2003). The majority of the organic nutrients supplied to these deep water setting through pelagic fall-out are relatively refractory due to remineralization of the most labile organic matter in the upper water-column (e.g. Hartwig, 1976 and references therein) and due to prior degradation (microbial and metazoan) along the transport pathway (Aller, 1982). Phytoplankton blooms cause marine snow events, and can lead to deposition of organic-rich sediments in continental slope settings, leading to dysoxia or anoxia if seafloor oxygen is consumed in the metabolism of sedimentary organic matter (e.g. Riedel et al., 2008). Similarly, dysoxia can develop beneath high-productivity water columns (e.g. upwelling zones), with high flux of particulate organic material (e.g. phytodetritus and faecal pellets) to the seafloor (e.g. Logan et al., 1995; Holmkvist et al., 2010).

Submarine channel and canyon systems are associated with elevated nutrient and oxygen concentrations (Blake and Hilbig, 1994; Rhoads and Hecker, 1995). Increased particulate nutrient fluxes and high levels of oxygenation are a consequence of both turbidity currents and intra-canton tidal currents (Vetter and Dayton, 1998; Gerino et al., 1999; *contra* Pickerill, 1981). Turbidity currents entrain large amounts of well-oxygenated water and commonly contain organic-rich and nutrient-rich materials that are deposited at the tail of the flow. The input of nutrients and oxygen may therefore provide an explanation for the high metazoan biomass recorded from submarine canyons (e.g. de Leo et al., 2010). Away from a channel or canyon axis, and further down-slope, it is predicted that conditions will become increasingly dysoxic and poorer in nutrients due to decreased influence of turbidity and tidal currents (Wetzel, 1983).

4.1.4. Sedimentation Rate

Erosion and sediment bypass during turbidity current events are likely to be the dominant processes occurring close to the axis of a submarine channel and in the erosive upper parts of canyon systems. These processes represent significant challenges to epi- and endobenthic communities (Wetzel, 1991). Deposition in channel-proximal settings is commonly dominated by coarse-grained sandstone or conglomerate (Dykstra and Kneller, 2007). Coarse-grained turbidites typically have little associated fine-grained siliciclastic or detrital organic material, and are therefore unsuitable substrates for infaunal deposit-feeding organisms. When deposition does occur within the axes of slope channels and canyons, it is likely to involve very coarse-grained bedload, or deposition at rates too high to allow colonization of the substrate by all but the most deeply burrowing organisms (e.g. Hubbard and Shultz, 2008; cf.

Benjamin Kneller 29/3/16 22:30
Comment [13]: You haven't made it clear whether you are talking about instantaneous or time-averaged rates, and how these might change with time.
I think it is also necessary to differentiate between periods of net erosion (that presumably leave no record), net bypass (that may or may not leave some record), and net deposition (which may still involve sufficient erosion that there is little record. You could discuss the depth of burrowing and preservation potential of specific niches.
Overall, I think sedimentation rate is a far bigger issue where there is more or less continuous sedimentation, such as on overbank areas (terraces/levees)

Benjamin Kneller 29/3/16 22:30
Comment [14]: Meaning?

Wetzel and Wijayananda, 1990). This may be especially true during deposition of slump and debris flow deposits in the axial portions of canyon or channel systems (e.g. Samuel et al., 2003; Jenner et al., 2007); furthermore slumps and debris flows commonly experience partial consolidation, resulting in firmgrounds on the their upper surfaces, with characteristic ichnofaunas (see below).

The intense hydrodynamic regime, high rates of erosion and the potential for significant sediment bypass associated with turbidity currents, mean that the ichnodiversity of axial settings may not adequately reflect the relatively nutrient- and oxygen-rich bottom waters that characterize inter-turbidite periods. The fine-grained pelagic and hemipelagic sediment deposited during between turbidite events may also typically eroded by, and incorporated into subsequent turbidity currents and turbidites (e.g. Phillips et al., 2010). In these environments, bypass surfaces at the bases of channels in several depositional systems are colonized by deep burrows (aff. *Ilmenichnus*; Callow et al., 2012) that penetrate exhumed or concealed firmgrounds (see Lewis and Ekdale, 1992; Gérard and Bromley, 2008; Hubbard and Shultz, 2008; Knaust, 2009).

Benjamin Kneller 29/3/16 22:30

Comment [15]: I think more to the point is that any turbidite mud that was deposited from or between large flows would be eroded. Currents in these environments are probably so frequent that there is no time for hemipelagic sedimentation.

4.1.5. Predictions

A first order assessment of the predicted and known changes in key environmental conditions (current energy, oxygenation, nutrient availability and sedimentation rate) from the axis of a slope-channel system, across overbank and terrace environments to the channel-bounding levees is shown in Table 1. These conditions allow us to predict the likely changes in biological (and ichnological) assemblages between these environments, but the real trends need to be assessed through field studies of ancient slope systems (e.g. Heard and Pickering, 2008; Callow et al., 2012), as well as studies of modern slope-channel systems.

The increased levels of oxygenation and bioavailable nutrients in and around submarine canyons have the potential to increase biomass, diversity, depth of burrowing and size of organisms. Such environments appear to offer suitable habitats for suspension and deposit-feeding organisms. However, periodic events (gravity flow events), coupled with high rates of erosion and/or sedimentation have the potential to both remove the benthic fauna, and obliterate the ichnological record of all but the deepest burrowing organisms (see Callow et al., 2012). Following dramatic events, these environments then offer suitable substrates for recolonization by highly motile organisms, or those with pelagic larval stages. The ichnological record of these settings is expected to be sparse, due to the pressures of the hydrodynamic regime, sedimentation rate, and the taphonomic biases due to sediment erosion.

Benjamin Kneller 29/3/16 22:30
Comment [16]: With respect to what?

Benjamin Kneller 29/3/16 22:30
Comment [17]: See above

Off-axis environments including terrace, overbank and internal levee appear to offer an ideal location for benthic organisms to become established and thrive. These settings experience increased nutrient supply, elevated levels of oxygen, but are not subjected to the same selective pressures as the most axial environments. Rates of sedimentation are lower, erosion is less significant and more rare, and the hydrodynamic regime is less intense. Abundant biomass and diverse benthic communities are predicted to leave a rich ichnological record, dominated by deposit-feeding organisms.

Benjamin Kneller 29/3/16 22:30
Comment [18]: With respect to what?

In distal levees, the surrounding continental slope and during phases of channel abandonment it is predicted that levels of oxygenation and bioavailable nutrients will be low. These settings are also dominated by low rates of sedimentation, and low hydrodynamic energies. Low rates of sedimentation have the potential to produce complex ichnofabrics, produced by multiple ichnocoenoses, resulting in high bioturbation intensities controlled as much by by sedimentation rate as bioturbation rate. Erosion is minimal in these settings, and there is no taphonomic bias against the preservation of shallow-tier trace fossils.

Benjamin Kneller 29/3/16 22:30
Comment [19]: As it probably is on levees

4.2. Ecology of modern slope systems

Current understanding of deep marine biology and biodiversity is scant and information is even more limited for submarine channel and canyon systems. However, available data indicate that submarine canyon and channel systems create heterogeneities in slope environments that enhance biodiversity (McClain and Barry, 2010). Communities living in and around modern canyon and slope channel systems contain distinctive faunal assemblages that are characterized by higher species diversity and biomass than the surrounding continental slope (Griggs et al., 1969; Rowe, 1971; Vetter and Dayton, 1998; Duineveld et al., 2001; Ingels et al., 2009; Vetter et al., 2010). This increased biomass has been related to elevated and frequent supply of nutrients, perhaps in the form of terrestrial organic matter (e.g. Morse and Beazley, 2008; Sarda et al., 2009). Sampling has revealed lateral changes in benthic communities within canyons on scales of <100m (McClain and Barry, 2010). Time averaging of ichnofabrics in such settings is likely to be significant (e.g. Lewis and Ekdale, 1992). In contrast, other studies have not revealed higher biomass and diversity within a canyon compared to adjacent sea-floor, despite higher organic carbon supply (see Cúrdia et al.,

Benjamin Kneller 29/3/16 22:30
Comment [20]: Perhaps not as scant as you are making out!

Benjamin Kneller 29/3/16 22:30
Comment [21]: What does 'time-averaging' mean in this context?

2004; Garcia et al., 2007; de Leo et al., 2010). Neoichnological studies show that the mode of bioturbation differs between channel, inter-channel and channel-distal environments, with higher ichnodiversity in settings that are subject to greater turbidity current influence (Wetzel, 1984). Higher rates of biodiffusive mixing (deposit feeding and sediment reworking organisms) have been measured from within canyons relative to canyon margins (Gerino et al., 1999).

Data relating to the hydrodynamic and chemical conditions of submarine channel versus non-channel settings have been obtained by measuring oxygen consumption, transmissometry, current velocity, sediment accumulation rate (pelagic) and direct imaging of the seafloor (Wetzel and Wijayananda, 1990; Duineveld et al., 2001; Hargrave et al., 2004 Garcia et al., 2008). Sediment dredges, burrow casting and X-ray scanning of box and gravity cores have been used to study bioturbation, biomass and burrow volume in deep sea settings, including submarine channel systems (Gerino et al., 1999; Seike et al., 2012). These data reveal that relative to the continental slope, submarine canyons have: 1) increased levels of organic matter and particulate organic carbon (POC); 2) more significant and frequent sediment reworking and resuspension by currents; 3) higher current velocities; 4) increased rates of biological oxygen consumption; and 5) increased rates of secondary production (Griggs et al., 1969; Vetter and Dayton, 1998; Gerino et al., 1999; Duineveld et al., 2001).

Benjamin Kneller 29/3/16 22:30

Comment [22]: This is all a bit vague (and hardly a surprise). I think you could be much more specific

4.3. Ichnology of ancient slope-channel systems

The growing body of data regarding changes in ichnology and ichnofabrics across the facies elements of slope-channel systems can be applied to high resolution facies analysis and reservoir characterization (see Heard and Pickering, 2008; Knaust, 2009; Philips et al., 2010; Cummings and Hodgson, 2011; Callow et al., 2012). In spite of the differences between slope systems of various ages, it is possible to identify a number of trends in trace fossil distributions.

A number of trace fossils have widespread palaeoenvironmental distributions within slope-channel systems. These include *Planolites*, *Phycosiphon incertum* and other similar phycosiphoniform traces (Fig. 4-5; Bednarz and McIlroy, 2009; Callow and McIlroy, 2011) as well as *Planolites* (Hubbard and Shultz, 2008; Heard and Pickering, 2008; Callow et al., 2012). Trace fossil assemblages dominated by the putative arthropod trace fossils *Thalassinoides* and *Ophiomorpha* (Fig. 4C-D) are mostly confined to sand-rich turbidites from channel axial settings in submarine channels and fans (Kane et al., 2007; Heard and Pickering, 2008; Phillips et al., 2011; Callow et al., 2012). This dominance appears to be reflected in higher ratios of vertical/horizontal trace fossils in axial than in off axis settings (see Kane et al., 2007). Ichnodiversity and bioturbation intensity are also commonly lower in sand-rich, axial turbidites than in off-axis environments (Heard and Pickering, 2008; Hubbard and Shultz, 2008; Phillips et al., 2011; Callow et al., 2012). Channel axes have been noted to contain unusually deep (up to several metres), vertical or oblique, U-shaped trace fossils, often in semi-consolidated, cohesive mudstones (Fig. 4F). These trace fossils have been described by a number of different names including *Diplocraterion*, *Arenicolites*, *Chondrites* and aff. *Ilmenichnus* (see Gérard and Bromley, 2008; Hubbard and Shultz, 2008; Knaust, 2009; Callow et al., 2012). Regardless of their taxonomic position these deep, paired, sand-filled burrows appear to be diagnostic of bypass surfaces and concealed firmgrounds at the base of submarine channels (see Gérard and Bromley, 2008). The irregular echinoid trace *Scolicia* also appears to be characteristic of settings close to the axes of slope-channels (Heard and Pickering, 2008; Callow et al., 2012).

Other trace fossils that have commonly been reported from off-axis settings include *Asterosoma*, *Taenidium*, *Zoophycos*, *Helminthopsis*, *Paleodictyon* and *Chondrites* (Fig. 4-5; Heard and Pickering, 2008; Hubbard and Shultz, 2008). The recorded ichnodiversity of off-axis settings is higher than settings close to the channel axis (Heard and Pickering, 2008; Phillips et al., 2011; Callow et al., 2012; Hubbard et al., in press). Distal down-slope environments including fan- and lobe-fringe environments are characterized by diverse assemblages of shallow tier and graphoglyptid ichnotaxa (see Crimes, 1977; Heard and Pickering, 2008; Cummings and Hodgson, 2011). The most distal depositional environments of channel-bounding levees and the surrounding continental slope appear to be characterized by low ichnodiversity and bioturbation intensity often with diverse assemblages of graphoglyptids (Fig. 3; Heard and Pickering, 2008; Cummings and Hodgson, 2011). These distal settings are dominated by small, shallow tier to surface traces of vermiform organisms (e.g. *Phycosiphon*, *Chondrites*, *Lophoctenium* and *Nereites*) that show simple ichnofabrics often lacking complex cross-cutting relationships (Fig. 5; see Heard and Pickering, 2008; Phillips et al., 2011; Callow et al., 2012).

In summary, environments close to the axis of a turbidite channel system tend to be characterized by diverse ichnological assemblages that include the large ichnotaxa *Ophiomorpha, Thalassinoides* and *Scolicia* (Fig. 4) which are produced by large macrofaunal

Benjamin Kneller 29/3/16 22:30
Comment [23]:

Benjamin Kneller 29/3/16 22:30
Comment [24]: This seems at odds with what you say above about diversity being lower in sand-rich axial environments

endobenthos. The environmental distribution of these trace fossils may be controlled by the delivery of oxygen and nutrients by turbidity currents through slope channels and canyons. Away from the channel axis the low abundance, low diversity trace fossil assemblages are dominated by trace fossils that were likely produced by vermiform organisms that were better adapted to poorly oxygenated, lower nutrient conditions.

The variability of slope-channel systems from different oceanographic settings and different ages means that differences are likely to be present, which are currently difficult to assess given the paucity of detailed studies (see Callow and McIlroy, 2011). However, as outlined here, the available data appears to suggest that the broad trends in the benthic fauna and in the ichnological record are consistent through a number of modern and ancient slope deposits.

5. Conclusion

Ichnology represents a hitherto under-utilized tool that can be combined with sedimentological analysis to refine facies interpretations and improve subsurface predictability in deep marine slope depositional systems. The use of ichnofabric analysis has great potential to be applied to the study and characterization of facies and reservoir quality of hydrocarbon reservoirs from core. Sedimentological, oceanographic, ichnological and modern biological studies have greatly improved our understanding of deep marine sedimentary environments and benthic ecosystems although current ichnological suffers from a lack of integration to deep marine facies models and hydrocarbon reservoirs. Theoretical considerations, modern benthic ecology and detailed studies of ancient slope successions collated herein have revealed systematic ichnological trends owing to the strong hydrodynamic and productivity gradients on modern slopes. We propose that likely key controls upon trace fossil distribution and ichnofabric development across a range of environment in slope depositional systems, include nutrient availability, hydrodynamic energy, oxygenation and sedimentation rate. The next phase of ichnological innovation in deep marine facies analysis will come through ichnological and sedimentological investigations of well exposed turbidites in the field to build robust models for the facies and reservoir characterization of turbidite-hosted hydrocarbon systems.

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References

Aller, R.H., 1982. The effects of macrobenthos on chemical properties of marine sediment and overlying water, in: McCall, D.L., Tevesz, M.J.S. (Eds.), Animal-sediment relations. Plenum, New York, pp. 53-102.

Armitage, D.A., Piper, D.J.W., McGee, D.T., Morris, W.R., 2010. Turbidite deposition on the glacially influenced, canyon-dominated southwest Grand Banks Slope, Canada. Sedimentology 57, 1387-1408.

Arnott, R.W.C., 2007. Stratal architecture and origin of lateral accretion deposits (LADs) and conterminuous inner-bank levee deposits in a base-of-slope sinuous channel, lower Isaac Formation. Marine and Petroleum Geology 24, 515-528.

Babonneau, N., Savoye, B., Cremer, M., Klein, B., 2002. Morphology and architecture of the present canyon and channel system of the Zaire deep-sea fan. Marine and Petroleum Geology 19, 445-467.

Beaubouef, R.T., 2004. Deep-water leveed channel complexes of the Cerro Toro Formation, Upper Cretaceous, southern Chile. American Association of Petroleum Geologists Bulletin 88, 1471-1500.

Beaubouef, R.T., Friedman, J., 2000. High resolution seismic/sequence stratigraphic framework for the evolution of Pleistocene intra-slope basins, western Gulf of Mexico: depositional models and reservoir analogs, in: Weimer, P., Slatt, R.M., Coleman, J., Rosen, N.C., Nelson, H., Bouma, A.H., Styzen, M.J., Lawrence, D.T. (Eds.), Deep water reservoirs of the world. GCSSEPM Foundation, Houston, pp. 40-60.

Bednarz, M., McIlroy, D., 2009. Three-dimensional reconstruction of “Phycosiphoniform” burrows: implications for identification of trace fossils in core. Palaeontologia Electronica 12, 1-15.

Blake, J.A., Hilbig, B., 1994. Dense faunal assemblages on the continental slope off Cape Hatteras, North Carolina. Deep-Sea Research II 41, 875-899.

Bosley, K. L., Lavelle, J. W., Brodeur, R. D., Wakefield, W. W., Emmett, R. L., Baker, E. T., & Rehmke, K. M., 2004. Biological and physical processes in and around Astoria submarine canyon, Oregon, USA. Journal of Marine Systems, 50, 21-37.

Boucot, A.J., 1981. Principles of benthic marine paleoecology. Academic Press, New York.

Bromley, R.G., 1996. Trace fossils. Biology, taphonomy and applications. Chapman & Hall, London.

Bromley, R.G., Ekdale, A.A., 1986. Composite ichnofabrics and tiering of burrows. Geological Magazine 123, 59-65.

Bromley, R.G., Asgaard, U., 1991. Ichnofacies: a mixture of taphofacies and biofacies. Lethaia 24, 153-163.

Cacchione, D. A., Pratson, L. F. & Ogston, A. S., 2002. The shaping of continental slopes by internal tides. Science, 296, 724-727.

Callow, R.H.T. and McIlroy, D., 2011. Ichnofabrics and ichnofabric forming trace fossils in Phanerozoic turbidites. Bulletin of Canadian Petroleum Geology 59, 103-111.

Callow, R.H.T., McIlroy, D., Kneller, B., Dykstra, M., 2012. Integrated ichnological and sedimentological analysis of a Late Cretaceous channel-turbidite system: the Rosario Formation, Baja California, Mexico. Marine and Petroleum Geology, doi: 10.1016/j.marpetgeo.2012.02.001

Camacho, H., Busby, C.J., Kneller, B., 2002. A new depositional model for the classical turbidite locality at San Clemente State Beach, California. American Association of Petroleum Geologists Bulletin 86, 1543-1560.

Carvajal, C.R., Steel, R.J., 2006. Thick turbidite successions from supply-dominated shelves during sea-level highstand. Geology 34, 665-668.

Cochonat, P., Bourillet, J. F., Savoye, B., & Dodd, L., 1993. Geotechnical characteristics and instability of submarine slope sediments, the nice slope (N-W Mediterranean Sea). Marine Georesources & Geotechnology, 11, 131-151

Crimes, T.P., 1970. The significance of trace fossils in sedimentology and palaeoecology with examples from Lower Palaeozoic strata, in: Crimes, T.P., Harper, J.C. (Eds.), Trace Fossils. Seel House Press, Liverpool, pp. 101-126.

Crimes, T.P., 1973. From limestones to distal turbidites: a facies and trace fossil analysis in the Zumaya flysch (Paleocene-Eocene), North Spain. Sedimentology 20, 105-131.

Crimes, T.P., 1974. Colonisation of the early ocean floor. Nature 248, 328-330.

Crimes, T.P., 1977. Trace fossils of an Eocene deep-sea fan, northern Spain. In: Crimes, T.P., Harper, J.C. (Eds.), Trace Fossils 2. Seel House Press, Liverpool, pp. 71-90.

Crimes, T.P., Marcos, A., Perez-Estaún, A., 1974. Upper Ordovician turbidites in western Asturias: A facies analysis with particular reference to vertical and lateral variations. Palaeogeography, Palaeoclimatology, Palaeoecology 15, 169-184.

Cross, N.E., Cunningham, A., Cook, R.J., Taha, A., Esmaie, E., El Swidan, N., 2009. Three-dimensional seismic geomorphology of a deep-water slope-channel system: the Sequoia field, offshore west Nile Delta. American Association of Petroleum Geologists Bulletin 93, 1063-1086.

Cummings, J.P., Hodgson, D.M., 2011. Assessing controls on the distribution of ichnotaxa in submarine fan environments, the Basque Basin, northern Spain. Sedimentary Geology 239, 162-187.

Cunningham, K.J., Sukop, M.C., Huang, H., Alvarez, P.F., Curran, H.A., Renken, R.A., Dixon, J.F., 2009. Prominence of ichnologically influenced macroporosity in the karst Biscayne aquifer: stratiform “super-K” zones. Geological Society of America Bulletin 121, 164-180.

Cúrdia, J., Carvalho, S., Ravara, A., Gage, J.D., Rodrigues, A.M., Quintino, V., 2004. Deep macrobenthic communities from Nazaré submarine canyons (NW Portugal). Scientia Marina 68, 171-180.

Daly, R.A., 1936. Origin of submarine ‘canyons’. American Journal of Science 31, 607-610.

Damuth, J., Emebley, R.W., 1981. Mass-transport complexes on Amazon cone: western equatorial Atlantic. American Association of Petroleum Geologists Bulletin 65, 629-643.

Davis, R.B., Minter, N.J., Braddy, S.J., 2007. The neoichnology of terrestrial arthropods. Palaeogeography, Palaeoclimatology, Palaeoecology 255, 284-307.

Deptuck, M.E. Steffens, G.S. Barton, M., Pirmez, C., 2003. Architecture and evolution of upper fan channel belts on the Niger Delta slope and in the Arabian Sea. Marine and Petroleum Geology 20, 649-676.

Di Celma, C., Cantalamessa, G., Didaskalou, P., Lori, P., 2010. Sedimentology, architecture, and sequence stratigraphy of coarse-grained, submarine canyon fills from the Pleistocene (Gelasian-Calabrian) of the Peri-Adriatic basin, central Italy. Marine and Petroleum Geology 27, 1340-1365.

Duineveld, G., Lavaleye, M., Berghuis, E., de Wilde, P., 2001. Activity and composition of the benthic fauna in the Whittard Canyon and the adjacent continental slope. Oceanologica Acta 24, 69-83.

Dykstra, M., 2011. Deep-water tidal sedimentology, in: Davis, R., Dalrymple, B. (Eds.), Tidal Sedimentology. Springer, Dordrecht, pp. 371-396.

Dykstra, M., Kneller, B., 2007. Canyon San Fernando: A Deep-Marine Channel-Levee Complex Exhibiting Evolution From Submarine-Canyon Confined to Unconfined, in: Nilsen, T.H., Shew, R.D., Steffens, G.S., Studlick, J.R.J. (Eds.), Atlas of Deep-Water Outcrops. AAPG Studies in Geology 56. AAPG and Shell Exploration and Production, Tulsa, pp. 226-230.

Dykstra, M., Kneller, B., 2009. Lateral accretion in a deep-marine channel complex: implications for channelized flow processes in turbidity currents. Sedimentology 56, 1411-1432.

Ekdale, A.A., 1977. Abyssal trace fossils in the worldwide Deep Sea Drilling Project cores, in: Crimes, T.P., Harper, J.C. (Eds.), Trace Fossils 2. Seel House Press, Liverpool, pp. 163-182.

Ekdale, A.A., 1980. Graphoglyptid burrows in modern deep-sea sediment. Science 207, 304-306.

Faugères, J-C., & Mulder, T., 2011. Contour currents and contourite drifts. In Hüneke, H. & Mulder, T. (Eds), Developments in Sedimentology, Vol. 63*,* Amsterdam: The Netherlands, 149-214

Forbes, E., 1844. Report on the Mollusca and Radiata of the Aegean Sea, And on their distribution, considered as bearing on geology. Report of the British Association of the Advancement of Science for 1843, 129-193.

Francois, F., Gerino, M., Stora, G., Durbec, J-P., Poggiale, J-C., 2002. Functional approach to sediment reworking by gallery-forming macrobenthic organisms: modeling and application with the polychaete *Nereis diversicolor*. Marine Ecology Progress Series 229, 127-136.

Frey, R.W., Seilacher, A., 1980. Uniformity in invertebrate ichnology. Lethaia 13, 183-207.

Frey, R.W., Pemberton, S.G., Saunders, T.D.A., 1990. Ichnofacies and bathymetry: a passive relationship. Journal of Paleontology 64, 155-158.

Gage, J.D., 1996. Why are there so many species in deep-sea sediments? Journal of Experimental Marine Biology and Ecology 200, 257-286.

Gamberi, F., Marani, M., 2007. Downstream evolution of the Stromboli slope valley (southeastern Tyrrhenian Sea). Marine Geology 243, 180-199.

Garcia, R., Koho, K.A., de Stigter, H.C., Epping, E., Koning, E., Thomsen, L., 2007. Distribution of meiobethos in the Nazaré canyon and adjacent slope (western Iberian Margin) in relation to sedimentary composition. Marine Ecology Progress Series 340, 207-220.

Garcia, R., Van Oevelen, D., Soetart, K., Thomsen, L., De Stigter, H.C., Epping, E., 2008. Deposition rates, mixing intensity and organic content in two contrasting submarine canyons. Progress in Oceanography 76, 192-215.

Garrett, C., Kunze, E., 2007. Internal tide generation in the deep ocean. Annual Review of Fluid Mechanics 39, 57-87.

Gérard, J., Bromley, R., 2008. Ichnofabrics in clastic sediments. Applications to sedimentological core studies. A practical guide. J. Gérard, Madrid.

Gerino, M., Stora, G., Weber, O., 1999. Evidence of bioturbation in the Cap-Ferret Canyon in the deep northeastern Atlantic. Deep-Sea Research II 46, 2289-2307.

Gingras, M.K., Pemberton, S.G., Mendoza, C.A., Henk, F., 1999. Assessing the anisotropic permeability of *Glossifungites* surfaces. Petroleum Geoscience 5, 349-357.

Gingras, M.K., Pemberton, S.G., Henk, F.B., MacEachern, J.A., Mendoza, C., Rostron, B., O'Hare, R., Spila, M., Konhauser, K., 2007. Applications of ichnology to fluid and gas production in hydrocarbon reservoirs, in: MacEachern, J.A., Bann, K.L., Gingras, M.K., Pemberton, S.G. (Eds.), Applied Ichnology. SEPM Short Course Notes 52. Society for Sedimentary Geology, Tulsa, pp. 131-145.

Gingras, M.K., Dashtgard, S.E., MachEachern, J.A., Pemberton, S.G., 2008. Biology of shallow marine ichnology: a modern perspective. Aquatic Biology 2, 255-268.

Griggs, G.B., Carey, A.G., Kulm, L.D., 1969. Deep-sea sedimentation and sediment-fauna interaction in Cascadia Channel and on Cascadia Abyssal Plain. Deep-Sea Research 16, 157-170.

Hall, B., Meiburg, E., Kneller, B., 2008. Channel formation by turbidity currents. Journal of Fluid Mechanics 615, 185-210.

Hargrave, B.T., Kostylev, V.E., Hawkins, C.M., 2004. Benthic epifauna assemblages, biomass and respiration in The Gully region on the Scotian shelf, NW Atlantic Ocean. Marine Ecology Progress Series 270, 55-70.

Hartwig, E.O., 1976. Nutrient cycling between the water column and a marine sediment. I. Organic carbon. Marine Biology 34, 285-295.

Hayward, B.W., 1976. Lower Miocene bathyal and submarine canyon ichnocoenoses from Northland, New Zealand. Lethaia 9, 149-162.

Heard, T.G., Pickering, K.T., 2008. Trace fossils as diagnostic indicators of deep-marine environments, Middle Eocene Ainsa-Jaca basin, Spanish Pyrenees. Sedimentology 55, 809-844.

Heezen, B.C., Tharp, M., Ewing, M., 1959. The floors of the oceans: I. The North Atlantic. Geological Society of America Special Paper 65, 1-126.

Holmkvist, L., Arning, E.T., Küster-Heins, K., Vandieken, V., Peckmann, J., Zabel, M., Jørgensen, B.B., 2010. Phosphate geochemistry, mineralization processes, and *Thioploca* distribution in shelf sediments off central Chile. Marine Geology 277, 61-72.

Hübscher, C., Spieb, V., Breitzke, M., Weber, M.E., 1997. The youngest channel levee system of the Bengal fan: results from digital sediment echosounder data. Marine Geology 141, 125-145.

Hubbard, S.M., Shultz, M.R., 2008. Deep burrows in submarine fan-channel deposits of the Cerro-Toro Formation (Cretaceous), Chilean Patagonia: Implications for firmground development and colonization in the deep sea. Palaios 23, 223-232.

Hubbard, S.M., Romans, B.W., Graham, S.A., 2008. Deep-water foreland basin deposits of the Cerro Toro Formation, Magallanes basin, Chile: architectural elements of a sinuous basin axial channel belt. Sedimentology 55, 1333-1359.

Hubbard, S.M., MacEachern, J.A., Bann, K.L., In Press. Slopes, in: Knaust, D., Bromley, R.G. (Eds.), Trace fossils as indicators of sedimentary environments. Elsevier.

Ingels, J., Kiriakoulakis, K., Wolff, G.A., Vanreusel, A., 2009. Nematode diversity and its relation to the quantity and quality of sedimentary organic matter in the deep Nazaré Canyon, western Iberian margin. Deep Sea Research Part I: Oceanographic Research Papers 56, 1521-1539.

Jenner, K.A., Piper, D.J.W., Campbell, D.C., Mosher, D.C., 2007. Lithofacies and origin of late Quaternary mass transport deposits in submarine canyons, central Scotian Slope, Canada. Sedimentology 54, 19-38.

Kane, I.A., Hodgson, D.M., 2011. Sedimentological criteria to differentiate submarine channel levee subenvironments: exhumed examples from the Rosario Fm. (Upper Cretaceous) of Baja California, Mexico, and the Fort Brown Fm. (Permian), Karoo Basin, S. Africa. Marine and Petroleum Geology 28, 807-823.

Kane, I.A., Kneller, B.C., Dykstra, M., Kassem, A., McCaffrey, W.D., 2007. Anatomy of a submarine channel-levee: An example from Upper Cretaceous slope sediments, Rosario Formation, Baja California, Mexico. Marine and Petroleum Geology 24, 540-563.

Kane, I.A., Dykstra, M., Kneller, B.C., Tremblay, S., McCaffrey, W.D., 2009. Architecture of a coarse-grained channel-levee system: the Rosario Formation, Baja California, Mexico. Sedimentology 56, 2207-2234.

Kane, I.A., McCaffrey, W.D., Peakall, J., Kneller, B.C., 2010. Submarine channel levee shape and sediment waves from physical experiments. Sedimentary Geology 223, 75-85.

Khripounoff, A., Vangriesheim, A., Babonneau, N., Crassous, P., Dennielou, B., Savoye, B., 2003. Direct observation of intense turbidity current activity in the Zaire submarine valley at 4000m water depth. Marine Geology 194, 151-158.

Klaucke I., Hesse R., Ryan B.F., 1998. Seismic stratigraphy of the Northwest Atlantic Mid-Ocean Channel: growth pattern of a mid-ocean channel-levee complex. Marine and Petroleum Geology 15, 575-585.

Kneller, B., 2003. The influence of flow parameters on turbidite slope channel architecture. Marine and Petroleum Geology 20, 901-910.

Knaust, D., 2009. Characterization of a deep-sea fan system in the Norwegian Sea by means of ichnofabrics. Marine and Petroleum Geology 26, 1199-1211.

Kolla, V., Bourges, P., Urruty, J.M., Safa, P., 2001. Evolution of deep-water Tertiary sinuous channels offshore Angola (West Africa) and implications for reservoir architecture. American Association of Petroleum Geologists Bulletin 85, 1373-1405.

Kolla, V., Posamentier, H.W., Wood, L.J., 2007. Deep-water and fluvial sinuous channels – characteristics, similarities and dissimilarities, and modes of formation. Marine and Petroleum Geology 24, 388-405.

Książkiewicz, M., 1977. Trace fossils in the flysch of the Polish Carpathians. Palaeontologia Polonica 36, 1-208.

de Leo, F.C., Smith, C.R., Rowden, A.A., Bowden, D.A., Clark, M.R., 2010. Submarine canyons: hotspots of benthic biomass and productivity in the deep sea. Proceedings of the Royal Society, B 277, 2577-2585.

Levin, L.A., 2003. Oxygen minimum zone benthos: adaptation and community response to hypoxia. Oceanography and Marine Biology: an Annual Review 41, 1-45.

Lewis, D.W., Ekdale, A.A., 1992. Composite ichnofabric of a mid-Tertiary unconformity on a pelagic limestone. Palaios 7, 222-235.

Logan, G.A., Hayes, J.M., Hieshima, G.B., Summons, R.E., 1995. Terminal Proterozoic reorganization of biogeochemical cycles. Nature 376, 53-57.

Lonsdale, P., Normark, W.R., Newman, W.A., 1972. Sedimentation and erosion on horizon guyot. Geological Society of America Bulletin 83, 289-316.

Löwemark, L., 2011. Ethological analysis of the trace fossil *Zoophycos*: hints from the Arctic Ocean. Lethaia doi: 10.1111/j.1502-3931.2011.00282.x

McClain, C.R., Barry, J.P., 2010. Habitat heterogeneity, disturbance, and productivity work in concert to regulate biodiversity in deep submarine canyons. Ecology 9, 964-976.

MacEachern, J.A., Bann, K.L., Pemberton, S.G., Gingras, M.K., 2007a. The ichnofacies paradigm: high resolution paleoenvironmental interpretation of the rock record, in: MacEachern, J.A., Bann, K.L., Gingras, M.K., Pemberton, S.G. (Eds.), Applied Ichnology. SEPM Short Course Notes 52. Society for Sedimentary Geology, Tulsa, pp. 27-64.

MacEachern, J.A., Pemberton, S.G., Bann, K.L., Gingras, M.K., 2007b. Departures from the archetypal ichnofacies: effective recognition of physico-chemical stresses in the rock record, in: MacEachern, J.A., Bann, K.L., Gingras, M.K., Pemberton, S.G. (Eds.), Applied Ichnology. SEPM Short Course Notes 52, Society for Sedimentary Geology, Tulsa, pp. 65-93.

Malinverno, A., Ryan, W. B. F., Auffret, G., & Pautot, G., 1988. Sonar images of the path of recent failure events on the continental margin off Nice, France. Sedimentologic Consequences of Convulsive Geologic Events, Geological Society of America, Special Paper, 229, 59-76.

Matsuyama, M., Ohta, S., Hibiya, T., Yamada, H., 1993, Strong tidal currents observed near the bottom in the Suruga Trough, central Japan. Journal of Oceanography 49, 683-696.

Mayall, M., Jones, E., Casey, M., 2006. Turbidite channel reservoirs – Key elements in facies prediction and effective development. Marine and Petroleum Geology 23, 821-841.

McHargue, T., Pyrcz, M.J., Sullivan, M.D., Clark, J., Fildani, A., Romans, B., Covault, J., Levy, M., Posamentier, H., Drinkwater, N., 2011. Architecture of turbidite channel systems on the continental slope: Patterns and predictions. Marine and Petroleum Geology 28, 728-743.

McIlroy, D., 2004a. Some ichnological concepts, methodologies, applications and frontiers, in: McIlroy, D. (Ed.), The Application of Ichnology to Palaeoenvironmental and Stratigraphic Analysis. Geological Society, London, Special Publication 228, pp. 3-27.

McIlroy, D., 2004b. Ichnofabrics and sedimentary facies of a tide-dominated delta: Jurassic Ile Formation of Kristin Field, Haltenbanken, Offshore Mid-Norway, in: McIlroy, D. (Ed.), The Application of Ichnology to Palaeoenvironmental and Stratigraphic Analysis. Geological Society, London, Special Publication 228, 237-272.

McIlroy, D., 2008. Ichnological analysis: the common ground between ichnofacies workers and ichnofabric analysts. Palaeogeography, Palaeoclimatology, Palaeoecology 270, 332-338.

McIlroy, D., Worden, R.H., Needham, S.J., 2003. Faeces, clay minerals and reservoir potential. Journal of the Geological Society, London 160, 489-493.

Meiburg, E., Kneller, B.C., 2010. Turbidite currents and their deposits. Annual Review of Fluid Mechanics 42, 135-156.

Morris, W.R., Busby-Spera, C.J., 1988. Sedimentologic evolution of a submarine canyon in a forearc basin, Upper Cretaceous Rosario Formation, San Carlos, Mexico. American Association of Petroleum Geologists Bulletin 72, 717-737.

Morris, W.R., Busby-Spera, C.J., 1990. A submarine-fan valley-levee complex in the Upper Cretaceous Rosario Formation: implications for turbidite facies models. Geological Society of America Bulletin 102, 900-914.

Morse, J.W., Beazley, M.J., 2008. Organic matter in deepwater sediments of the northern Gulf of Mexico and its relationship to the distribution of benthic organisms. Deep-Sea Research II 55, 2563-2571.

Mulder, T., Syvitski, J.P.M., Migeon, S., Faugeres, J.-C., Savoye, B., 2003. Marine hyperpycnal flows: initiation, behavior and related deposits. A review. Marine and Petroleum Geology 20, 861-882.

Mutti, E., 1999. An introduction to the analysis of ancient turbidite basins from an outcrop perspective (Vol. 39). Amer Assn of Petroleum Geologists.

Mutti, E., Normark, W.R., 1987. Comparing examples of modern and ancient turbidite systems, in: Legget, J.K., Zuffa, G., Graham, G., Trotman, A. (Eds.), Marine clastic sedimentology: concepts and case studies. Graham & Trotman, London, pp. 1-38.

Mutti, E., Bernoulli, D., Ricci Lucci, F., Tinterri, R., 2009. Turbidites and turbidity currents from Alpine 'flysch' to the exploration of continental margins. Sedimentology 56, 267-318.

Needham, S.J., Worden, R.H., McIlroy, D., 2005. Experimental production of clay rims by macrobiotic sediment ingestion and excretion. Journal of Sedimentary Research 75, 1028-1037.

Nelson, C.H., Baraza, J., Maldonado, A., 1993. Mediterranean undercurrent sandy contourites, Gulf of Cadiz, Spain. Sedimentary Geology 82, 103-131.

Ohta, S., 1984. Star-shaped feeding traces produced by echiuran worms on the deep-sea floor of the Bay of Bengal. Deep Sea Research Part A. Oceanographic Research Papers 31, 1415-1432.

Orr, P.J., 1994. Trace fossil tiering within event beds and preservation of frozen profiles: An example from the Lower Carboniferous of Menorca. Palaios 9, 202-210.

Paull, C. K., Ussler, W. I. I. I., Greene, H. G., Keaten, R., Mitts, P., & Barry, J., 2002. Caught in the act: the 20 December 2001 gravity flow event in Monterey Canyon. Geo-Marine Letters, 22, 227-232.

Peakall, J., Amos, K., Keevil, G.M., Bradbury, P.W., Gupta, S., 2007. Flow processes and sedimentation in submarine channel bends. Marine and Petroleum Geology 24, 470-486.

Pemberton, S.G., Spila, M., Pulham, A.J., Saunders, T., MacEachern, J.A., Robbins, D., Sinclair, I., 2001. Ichnology, sedimentology of shallow to marginal marine systems: Ben Nevis, Avalon Reservoirs, Jeanne d'Arc Basin. Geological Association of Canada, Short Course Notes 15.

Phillips, C., McIlroy, D., 2010. Ichnofabrics and biologically mediated changes in clay mineral assemblage from a deep-water, fine-grained, calcareous sedimentary succession: an example from the Upper Cretaceous Wyandot Formation, offshore Nova Scotia. Bulletin of Canadian Petroleum Geology 58, 203-218.

Phillips, D., McIlroy, D., Elliott, T., 2011. Ichnological characterization of Eocene/Oligocene turbidites from the Grès d'Annot Basin, French Alps, SE France. Palaeogeography, Palaeoclimatology, Palaeoecology 300, 67-83.

Pickerill, R.K., 1981. Trace fossils in a Lower Palaeozoic submarine canyon sequence – the Siegas Formation of northwestern New Brunswick, Canada. Marine Sediments and Atlantic Geology 17, 36-58.

Pickering, K.T., Hiscott, R.N., Hein, F.J., 1989. Deep marine environments: clastic sedimentation and tectonics. Unwin Hyman, London.

Pinkerton, J., 1811. Petralogy: a Treatise on Rocks, two volumes. White, Cochran & Co., London.

Piper, D.J.W., Normark, W.R., 2009. Processes that initiate turbidity currents and their influence on turbidites: a marine geology perspective. Journal of Sedimentary Research 79, 347-362.

Piper, D. J. W., A. N. Shor, and J. E. Hughes-Clarke, 1988. The 1929 "Grand Banks" Earthquake, slump and turbidity current, *in* H. E. Clifton, ed., Sedimentologic consequences of convulsive geologic events: GSA Special Paper 229, 77-92.

Piper. DJ.W., & Normark, W.R., 1983. Turbidite depositional pallerns and flow characteristics. Navy submarine fan, California Borderland. Sedimentology, 30, 681-694.

Pirmez, C., Beauboeuf, R.T., Friedmann, S.J., Mohrig, D.C., 2000. Equilibrium profile and base level in submarine channels: examples from Late Pleistocene systems and implications for the architecture of deepwater reservoirs, in: Weimer, P., Slatt, R.M., Coleman, J., Rosen, N.C., Nelson, H., Bouma, A.H., Styzen, M.J., Lawrence, D.T. (Eds.), Deep water reservoirs of the world. GCSSEPM Foundation, Houston, pp. 782-805.

Posamentier, H.W., 2003. Depositional elements associated with a basin floor channel-levee system: case study from the Gulf of Mexico. Marine and Petroleum Geology 20, 677-690.

Posamentier, H.W., Walker, R.G., 2006. Deep-water turbidites and submarine fans, in: Posamentier, H.W., Walker R.G. (Eds.), Facies models revisited. Society for Sedimentary Geology Special Publication 84, pp. 397-520.

Prather, B.E., Booth, J.R., Steffens, G.S., Craig, P.A., 1998. Classification, lithologic calibration, and stratigraphic succession of seismic facies of intraslope basins, deep-water Gulf of Mexico. American Association of Petroleum Geologists Bulletin 82, 701-728.

Rhoads, D.C., Hecker, B., 1994. Processes on the continental shelf off North Carolina with special reference to the Cape Hatteras region. Deep-Sea Research II 41, 965-980.

Riedel, B., Zuschin, M., Stachowitsch, M., 2008. Dead zones: a future worst-case scenario for Northern Adriatic biodiversity, in: Briand, F. (Ed.), Climate warming and related changes in Mediterranean marine biota. CIESM Workshop Monographs 35, pp. 73-77.

Rona, P.A., Seilacher, A., de Vargas, C., Gooday, A.J., Bernhard, J.M., Bowser, S., Vetriani, C., Wirsen, C.O., Mullineaux, L., Sherrell, R., Grassle, J.F., Low, S., Lutz, R.A., 2009. *Paleodictyon nodosum*: A living fossil on the deep-sea floor. Deep-Sea Research II 56, 1700-1712.

Rowe, G.T., 1971. Observations on bottom currents and epibenthic populations in Hatteras submarine canyon. Deep Sea Research and Oceanographic Abstracts 18, 569-576.

Samuel, A., Kneller, B., Raslan, S., Sharp, A., Parsons, C., 2003. Prolific deep-marine slope channels of the Nile Delta, Egypt. American Association of Petroleum Geologists Bulletin 87, 541-560.

Sarda, R., Gil, J., Taboada, S., Gili, J.P., 2009. Polychaete species captured in sediment traps moored in northwestern Mediterranean submarine canyons. Zoological Journal of the Linnean Society 155, 1-21.

Seike, K., Jenkins, R.G., Watanabe, H., Nomaki, H., Sato, K., 2012. Novel use of burrow casting as a research tool in deep-sea ecology. Biology Letters doi: 10.1098/rsbl.2011.1111.

Seilacher, A., 1964. Biogenic sedimentary structures, in: Imbrie, J., Newell, N. (Eds.), Approaches to Paleoecology. John Wiley & Sons, New York, pp. 296-316.

Seilacher, A., 1967. Bathymetry of trace fossils. Marine Geology 5, 413-428.

Seilacher, A., 1974. Flysch trace fossils: evaluation of behavioural diversity in the deep sea. Neues Jahrbuch für Geologie und Paläontologie, Monatshefte 4, 233-245.

Seilacher, A., 1978. Evolution of trace fossil communities in the deep sea. Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen 157, 251-255.

Shepard, F.P., 1981. Submarine canyons: multiple causes and long time persistence. American Association of Petroleum Geologists Bulletin 65, 1062-1077.

Shepard, F.P., Marshall, N.F., 1969. Currents in La Jolla and Scripps submarine canyons. Science 165, 177-178.

Shepard, F.P., Marshall, N.F., McLoughlin, P.A., 1974. “Internal waves” advancing along submarine canyons. Science 183, 195-198.

Shultz, M.R., Hubbard, S.M., 2005. Sedimentology, stratigraphic architecture, and ichnology of gravity flow deposits partially ponded in a growth-fault-controlled slope minibasin, Tres Pasos Formation (Cretaceous), southern Chile. Journal of Sedimentary Research 75, 440-453.

Smith, C.R., Levin, L.A., Hoover, D.J., McMurtry, G., Gage, J.D., 2000. Variations in bioturbation across the oxygen minimum zone in the northwest Arabian Sea. Deep-Sea Research II 47, 227-257.

Smith, D. P., Kvitek, R., Iampietro, P. J., & Wong, K., 2007. Twenty-nine months of geomorphic change in upper Monterey Canyon (2002–2005). Marine Geology, 236, 79-94.

Sprague, A.R., Patterson, P.E., Hill, R.E., Jones, C.R., Campion, K.M., Van Wagoner, J.C., Sullivan, M.D., Larue, D.K., Feldman, H.R., Demko, T.M., Wellner, R.W. Geslin, J.K., 2002. The physical stratigraphy of fluvial strata: A hierarchical approach to the analysis of genetically related stratigraphic elements for improved reservoir prediction. Abstract AAPG Annual Meeting.

Stow, D.A.V., 1979. Distinguishing between fine-grained turbidites and contourites on the Nova Scotian deep water margin. Sedimentology 26, 371-387.

Stow, D.A.V., Mayall, M., 2000. Deep-water sedimentary systems: new models for the 21st Century. Marine and Petroleum Geology 17, 125-135.

Studer, B., 1827. Remarques géognostiques sur quelques parties de la chaine septentrionale des Alpes. Annales Sciences Naturelles Paris 11, 1-47.

Taylor, A.R., Goldring, R., 1993. Description and analysis of bioturbation and ichnofabric. Journal of the Geological Society, London 150, 141-148.

Taylor, A.R., Goldring, R., Gowland, S., 2003. Analysis and application of ichnofabrics. Earth-Science Reviews 60, 227-259.

Tinterri, R., Magalhaes, P.M., 2011. Synsedimentary control on foredeep turbidites: an example from Miocene Marnoso-Arenacea Formation, northern Apennines, Italy. Marine and Petroleum Geology 28, 629-657.

Tonkin, N.S., McIlroy, D., Meyer, R., Moore-Turpin, A., 2010. Bioturbation influence on reservoir quality: A case study from the Cretaceous Ben Nevis Formation, Jeanne d'Arc basin, offshore Newfoundland, Canada. American Association of Petroleum Geologists Bulletin 94, 1059-1078.

Uchman, A., 1998. Taxonomy and ethology of flysch trace fossils: revision of the Marian Książkiewicz collection and studies of complementary material. Annales Societatis Geologorum Poloniae 68, 105-218.

Uchman, A., 2004. Phanerozoic history of deep-sea trace fossils, in: McIlroy, D. (Ed.), The Application of Ichnology to Palaeoenvironmental and Stratigraphic Analysis. Geological Society, London, Special Publication 228, 125-139.

Uchman, A., 2009. The *Ophiomorpha rudis* ichnosubfacies of the *Nereites* ichnofacies: Characteristics and constraints. Palaeogeography, Palaeoclimatology, Palaeoecology 276, 107-119.

Uchman, A., Wetzel, A., 2011. Deep-sea ichnology: The relationships between depositional environment and endobenthic organisms, in: Hüneke, H., Mulder, T. (Eds.), Deep-Sea Sediments. Developments in Sedimentology, Volume 63. Elsevier, Amsterdam, pp. 517-556.

van Haren, H., Gostiaux, L., 2010. A deep-ocean Kelvin-Helmholtz billow train. Geophysical Research Letters 37, doi:10.1029/2009GL041890.

Vetter, E.W., Dayton, P.K., 1998. Macrofaunal communities within and adjacent to a detritus-rich submarine canyon system. Deep-Sea Research Part II: Topical Studies in Oceanography 45, 25-54.

Vetter, E.W., Smith, C.R., de Leo, F.C., 2010. Hawaiian hotspots: enhanced megafaunal abundance and diversity in submarine canyons on the oceanic islands of Hawaii. Marine Ecology 31, 183-199.

Vorren, T.O., Laberg, J.S., Blaume, F., Dowdeswell, J.A., Kenyon, N.H., Mienert, J., Rumohr, J., Werner, F., 1998. The Norwegian–Greenland Sea continental margins: morphology and late Quaternary sedimentary processes and environment. Quaternary Science Reviews 17, 273-302.

Walker, R.G., 1985. Mudstones and thin-bedded turbidites associated with the Upper Cretaceous Wheeler Gorge conglomerates, California: A possible channel-levee complex. Journal of Sedimentary Petrology 55, 279-290.

Walker, R.G., Mutti, E., 1973. Turbidite facies and facies associations, in: Middleton, G.V., Bouma A.H. (Eds.), Turbidites and deep-water sedimentation. SEPM Pacific Section Short Course, Anaheim, pp. 119-157.

Weber, K.J., 1982. Influence of common sedimentary structures on fluid flow in reservoir models. Journal of Petroleum Technology 34, 665-672.

Weimer, P., Slatt, R.M., Coleman, J., Rosen, N.C., Nelson, H., Bouma, A.H., Styzen, M.J., Larence, D.T., (Eds.) 2000. Deep-water reservoirs of the world. Gulf Coast Section SEPM 20th Bob F. Perkins Research Conference.

Wetzel, A., 1983. Biogenic structures in modern slope to deep-sea sediments in the Sulu Sea Basin (Philippines). Palaeogeography, Palaeoclimatology, Palaeoecology 42, 285-304.

Wetzel, A., 1984. Bioturbation in deep-sea fine-grained sediments: influence of sediment texture, turbidite frequency and rates of environmental change, in: Stow, D.A.V., Piper, D.J.W. (Eds.), Fine-grained sediments: deep water processes and facies. Blackwell Scientific Publications, Oxford, pp. 595-608.

Wetzel, A., 1991. Ecologic interpretation of deep-sea trace fossil communities. Palaeogeography, Palaeoclimatology, Palaeoecology 85, 47-69.

Wetzel, A., 2008. Recent bioturbation in the deep South China Sea: a uniformitarian ichnologic approach. Palaios 23, 601-615.

Wetzel, A., Wijayananda, N.P., 1990. Biogenic sedimentary structures in outer Bengal Fan deposits drilled during Leg 116. Proceedings of the Ocean Drilling Program, Scientific Results 116, 15-24.

Wetzel, A., Blechschmidt, I., Uchman, A., Matter, A., 2007. A highly diverse ichnofauna in Late Triassic deep-sea fan deposits of Oman. Palaios 22, 567-576.

Wetzel, A., Werner, F., Stow, D.A.V., 2008. Bioturbation and biogenic sedimentary structures in contourites, in: Rebesco, M., Camerlenghi, A. (Eds.), Contourites. Developments in Sedimentology 60. Elsevier, Amsterdam, pp. 183-202.

Whitaker, J.H., 1974. Ancient submarine canyons and fan valleys, in: Dott, R.H., Shaver, R.H. (Eds.), Modern and ancient geosynclinal sedimentation. SEPM Special Publication 19, pp. 106-125.

Whitaker, J.H., 1976. Submarine canyons and deep-sea fans. Benchmark Papers in Geology 24. Dowden Hutchinson & Ross, Inc., Stroudsberg.

Wilgus, C. K., Hastings, B. S., Kendall, C. G. S. C., Posamentier, H. W., Ross, C. A., & Van Wagoner, J. C., 1988. Sea-level changes: an integrated approach. Society of Economic Paleontologists and Mineralogists. 407pp.

Winker, C.D. & Booth, J.R., 2000. Sedimentary dynamics of the salt-dominated continental slope, Gulf of Mexico: integration of observations from seafloor, near-surface, and deep subsurface. In P. Weimer, Slatt, R.M., Coleman, J., Rosen, N.C., Nelson, H., Bouma, A.H., Styzen, M.J. & Lawrence, D.T. (eds). Deep water reservoirs of the world. Houston, GCSSEPM Foundation**:** 1059-1086.

Wood, L.J., Mize-Spansky, K.L., 2009. Quantitative seismic geomorphology of a Quaternary leveed-channel system, offshore eastern Trinidad and Tobago, northeastern South America. American Association of Petroleum Geologists Bulletin 93, 101-125.

Wynn, R.B., Cronin, B.T., Peakall, J., 2007. Sinuous deep-water channels: Genesis, geometry and architecture. Marine and Petroleum Geology 24, 341-387.

Young, D.K., Jahn, W.H., Richardson, M.D., Lohanick, A.W., 1985. Photographs of deep-sea Lebensspuren: a comparison of sedimentary provinces in the Venezuela Basin, Caribbean Sea. Marine Geology 68, 269-301.

Xu, J.P., Noble, M., Eittreim, S.L., Rosenfeld, L.K., Schwing, F.B., Pilskaln, C.H., 2002. Distribution and transport of suspended particulate matter in Monterey Canyon, California. Marine Geology 181, 215-234.

Figure Captions

Figure 1 – Diagram showing the spatial distribution of ichnofacies and depositional environments from marginal marine to deep marine environments. Cr: *Cruziana* Ichnofacies. Ne: *Nereites* Ichnofacies. Pa: *Paleodictyon* Ichnosubfacies. *O*. *rudis*: *Ophiomorpha rudis* ichnosubfacies. 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 techniques. Modified from McIlroy (2004a).

Figure 2 – Summary block diagrams (1-3) and stratigraphic insets (4-6) showing the stratigraphic evolution, and down-dip changes in architecture of an idealized submarine channel-levee system. A: Schematic overview of submarine channel system, running from the shelf break to the basin floor. The approximate location of block diagrams 1-3 are shown. 1&4) The upper slope is initially characterized by erosional systems and large amounts of sediment bypass. The canyon fill consists of coarse-grained, amalgamated channel bodies bounded by internal levees, and mass transport complexes. Limited external levee development occurs after the original erosive channel is filled by sediment. The fill of the canyon and channel-levee system fine upwards, and is incised by new coarser-grained, amalgamated channels during reactivation of the system. 2&5) Mid-slope systems are characterized by an initially erosive phase, and a later aggradational phase as the accommodation space (initial channel incision) is filled and bounding levees develop to

confine the system laterally. The system is incised by the next set of channels during reactivation. 3&6) Lower slope systems are associated with limited erosion and aggradation of the levee-bound channel above the level of the surrounding continental slope. Due to changes in stratigraphic architecture and physical and chemical conditions, changes in ichnological assemblages can be predicted both spatially and stratigraphically during the lifetime of a submarine channel system.

Figure 3 – Examples of the detailed, delicate and geometric surface and shallow-tier trace fossils that are common on sandstone soles within turbidite units. Interface traces such as these are often reported from slope and basin floor deposits where they are preserved in positive hypichnial relief and are considered diagnostic for the *Nereites* ichnofacies and the *Paleodictyon* ichnosubfacies. A: The spiralling graphoglyptid trace fossil *Spirorhaphe involuta*. B: The mesh- or net-like graphoglyptid *Paleodictyon* isp., of unknown biological origin (see Rona et al., 2009). C: Shallow-tier grazing trail of *Helminthorhaphe* (*Helminthoida*) *crassa* from the Late Cretaceous Rosario Formation, Mexico. D: The graphoglyptids *Paleodictyon* isp. (P) and *Desmograpton* isp. (D). D: The graphoglyptid *Paleomeandron elegans* cross cut by later, deeper-tier *Ophiomorpha rudis*. E: The graphoglyptid *Helicorhaphe* isp. from the Late Cretaceous Rosario Formation, Mexico. Scale bars 1cm, lens cap 6cm in diameter.

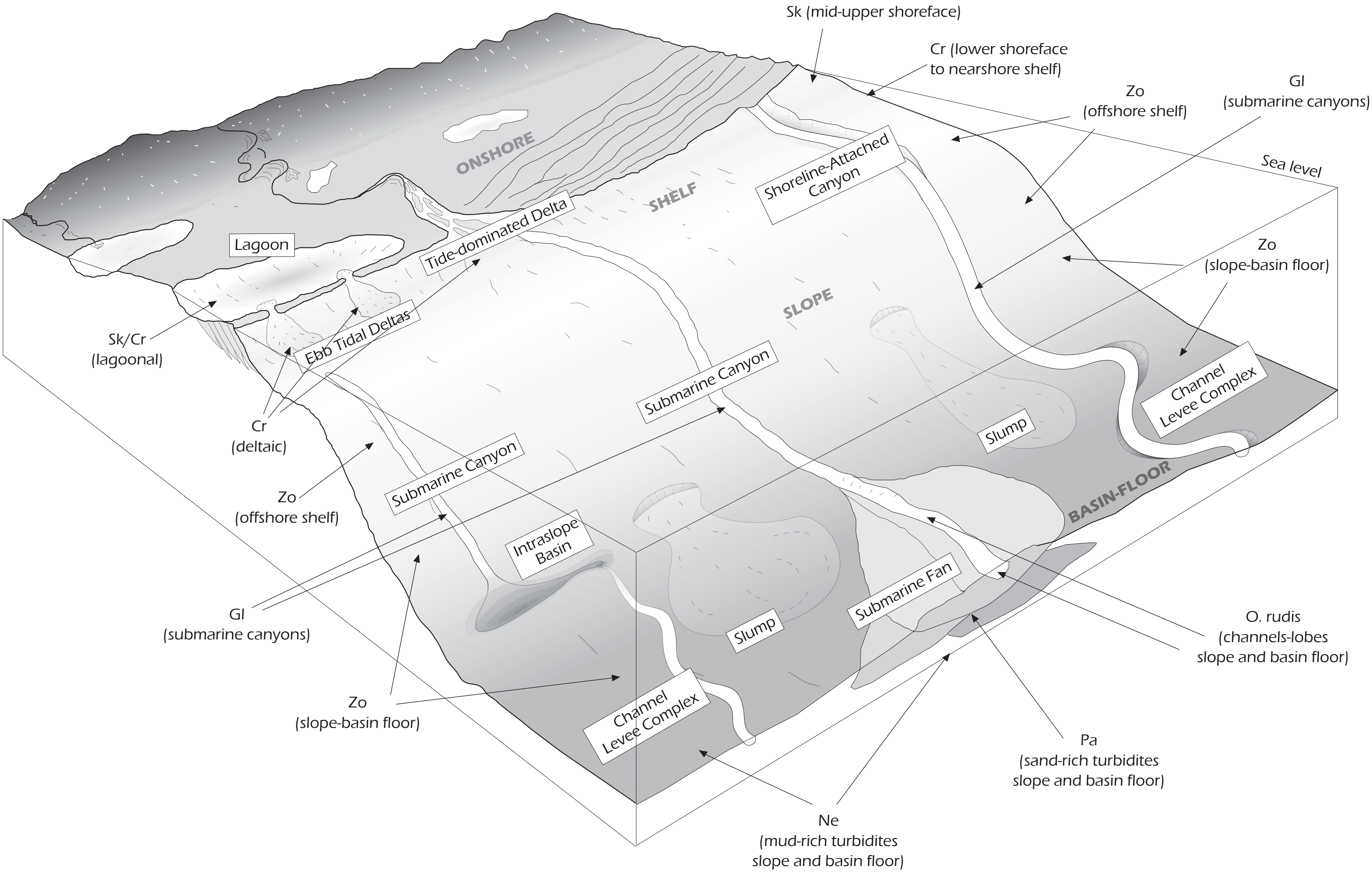
Figure 4 – Ichnofabrics that are common in slope-channel turbidite sediments. A-B: *Scolicia* sp. ichnofabrics at the interface between ripple cross-laminated fine sandstone and an

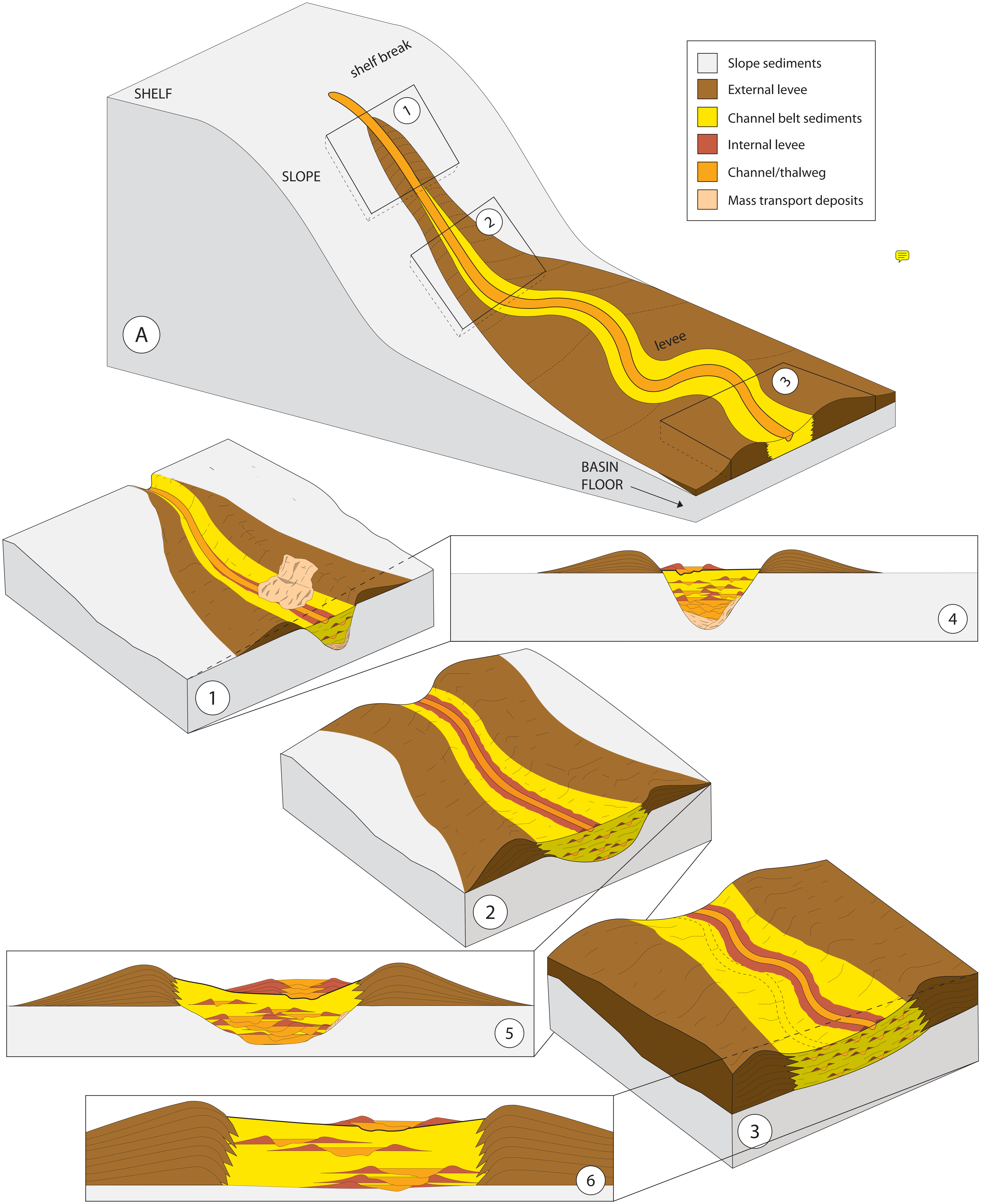
overlying siltstone. *Scolicia* can be associated with a variety of other ichnotaxa including *Ophiomorpha* (O). From the Late Cretaceous Rosario Formation, Baja California, Mexico. C: Mud-rich pellet-lined vertical shafts and horizontal galleries of *Ophiomorpha rudis*, which is typically considered to be the burrow of an endobenthic crustacean. From the Eocene Juncal Formation, California. D: Sand-filled, unlined vertical shafts and horizontal galleries known as *Thalassinoides*, also commonly attributed to burrowing decapod crustaceans. Core from Cenozoic of Russia, locality and well unknown. E. Simple, unlined, tube-like, sand-filled burrow of *Planolites* (Pl) are common across many depositional environments within slope-channel settings. Here *Planolites* cross-cuts an older phycosiphoniform ichnofabric consisting of dark cores and lighter halos. F: Sand-filled, paired, vertical to oblique U-shaped burrows referred to aff. *Ilmenichnus* at an erosion/emission surface on a block in a mass transport complex within a submarine canyon. From the Late Cretaceous Rosario Formation, Mexico. Scale bars 1cm, lens cap 6cm in diameter.

Figure 5 - Ichnofabrics that are common in slope-channel turbidite sediments. A: *Phycosiphon incertum* (Pi) ichnofabric composed of dark, mud-rich cores surrounded by concentric, lighter sand-rich halos. Large sub-cylindrical *Thalassinoides* (Th) and sand-filled *Planolites* (Pl) are also present. This typical ‘frogspawn’ ichnofabric is characterized by vertical loops and twists and a concentric halo. B: An ichnofabric dominated by phycosiphoniform (Ph) burrows (*sensu* Bednarz and McIlroy, 2009). The phycosiphoniform ichnofabric is broadly similar to *Phycosiphon incertum*, but the burrows are typically larger, show vertically stacked pairs of burrows and halo that is located below the causative burrow. C: Vertical to oblique,

dendritically branched, mud-filled trace fossils of *Chondrites* sp. From the Late Cretaceous Rosario Formation, Mexico. D: Oblique section through a *Nereites* (N) burrow, characterized by a lenticular, mud-rich core, surrounded by a light, bilobate, sand-rich halo. Unlike *P. incertum* and phycosiphoniforms, *Nereites* shows no vertical, loops, twists or meanders. E: Horizontal cross section through two *Asterosoma* lobes. No central shaft is visible in this section. F: Oblique lobes composed of concentric, mud-rich spreiten represent a cross section through the complex trace fossil *Zoophycos* (Z). The *Zoophycos* lobe cuts a mottled *Phycosiphon* and *Chondrites* ichnofabric. From the Mesozoic of Yorkshire, UK. Scale bars 1cm.

Table 1 – Table showing predicted and observed physical and chemical conditions (oxygenation, nutrients, sedimentation rate and hydrodynamic energy) from an idealized transect across a slope-channel system on the mid continental slope. The environments range from the axis of a channel belt to the external levee and the surrounding continental slope. These physical and chemical parameters directly control the composition of epi- and endobenthic communities and are reflected in the ichnological assemblages from these depositional environments.


Sk (mid-upper shoreface)
Cr (lower shoreface to nearshore shelf)
Zo (offshore shelf)
Gl (submarine canyons)
Sea level
ONSHORE
SHELF
SLOPE
BASIN-FLOOR
Shoreline-Attached Canyon
Tide-dominated Delta
Lagoon
Ebb Tidal Deltas
Sk/Cr (lagoonal)
Cr (deltaic)
Zo (offshore shelf)
Submarine Canyon
Submarine Canyon
Zo (slope-basin floor)
Channel Levee Complex
Slump
Intraslope Basin
Slump
Submarine Fan
Gl (submarine canyons)
Zo (slope-basin floor)
Channel Levee Complex
O. rudis (channels-lobes slope and basin floor)
Pa (sand-rich turbidites slope and basin floor)
Ne (mud-rich turbidites slope and basin floor)


shelf break
SHELF
SLOPE
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levee
BASIN
FLOOR
Slope sediments
External levee
Channel belt sediments
Internal levee
Channel/thalweg
Mass transport deposits
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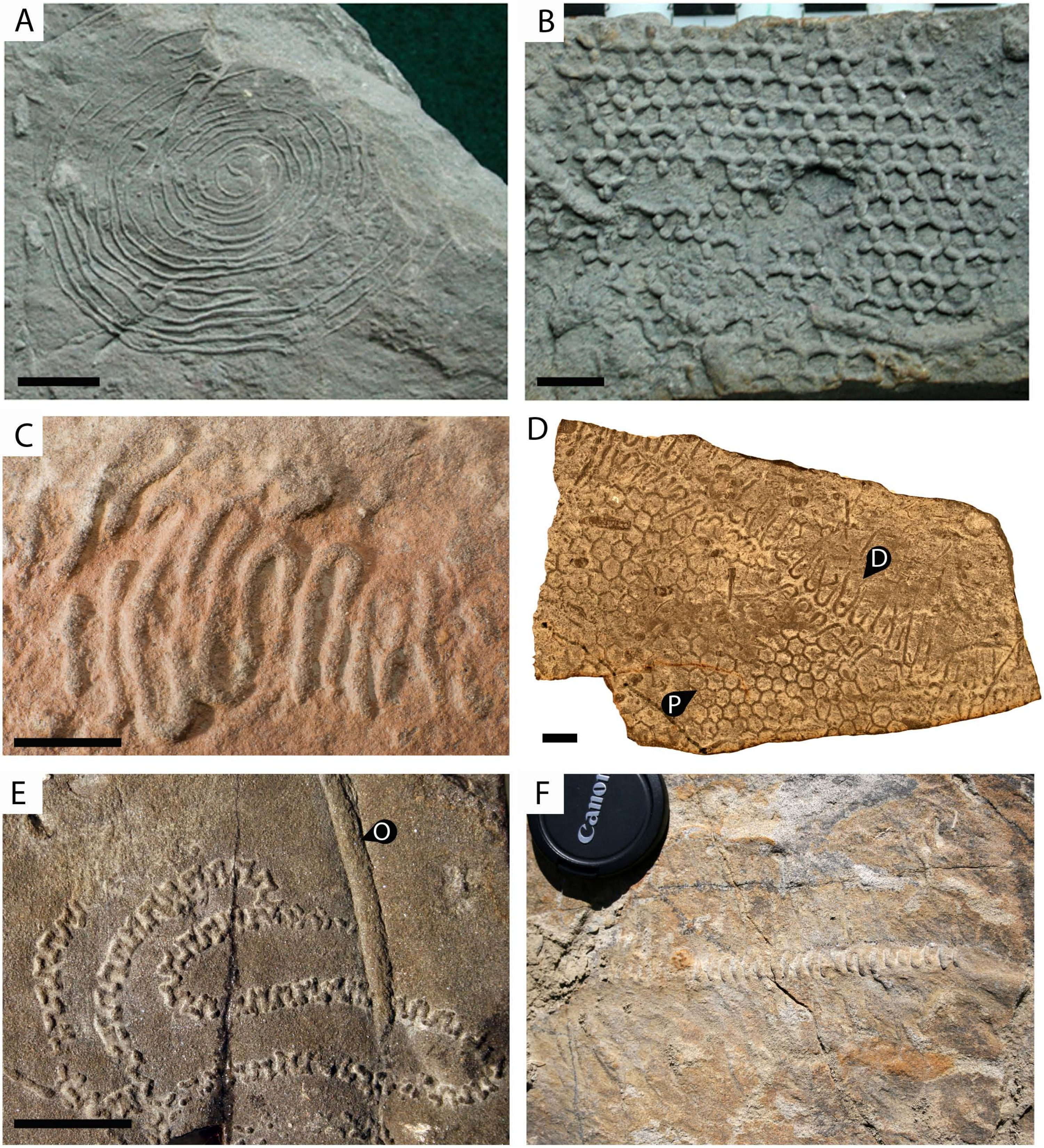
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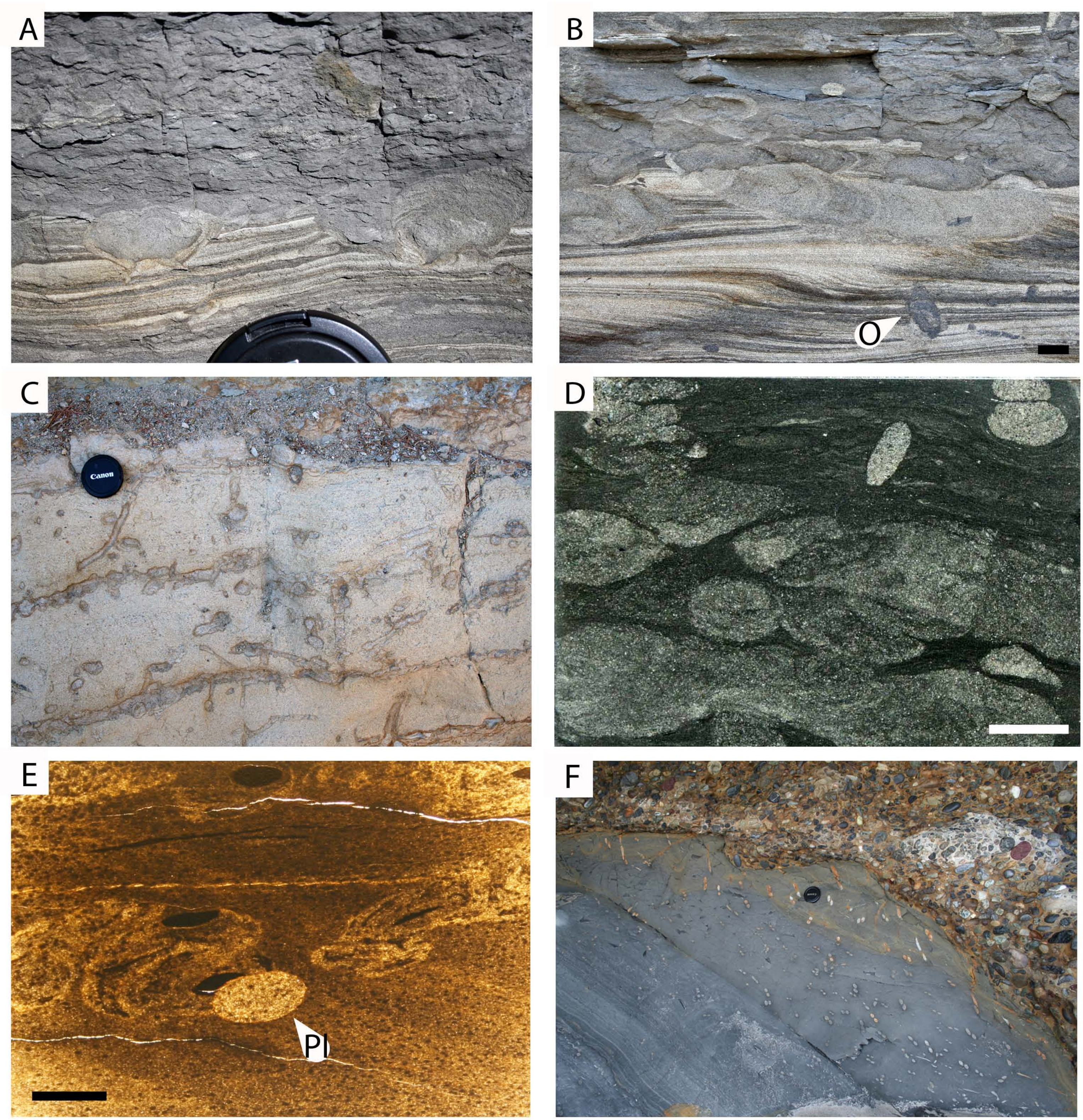
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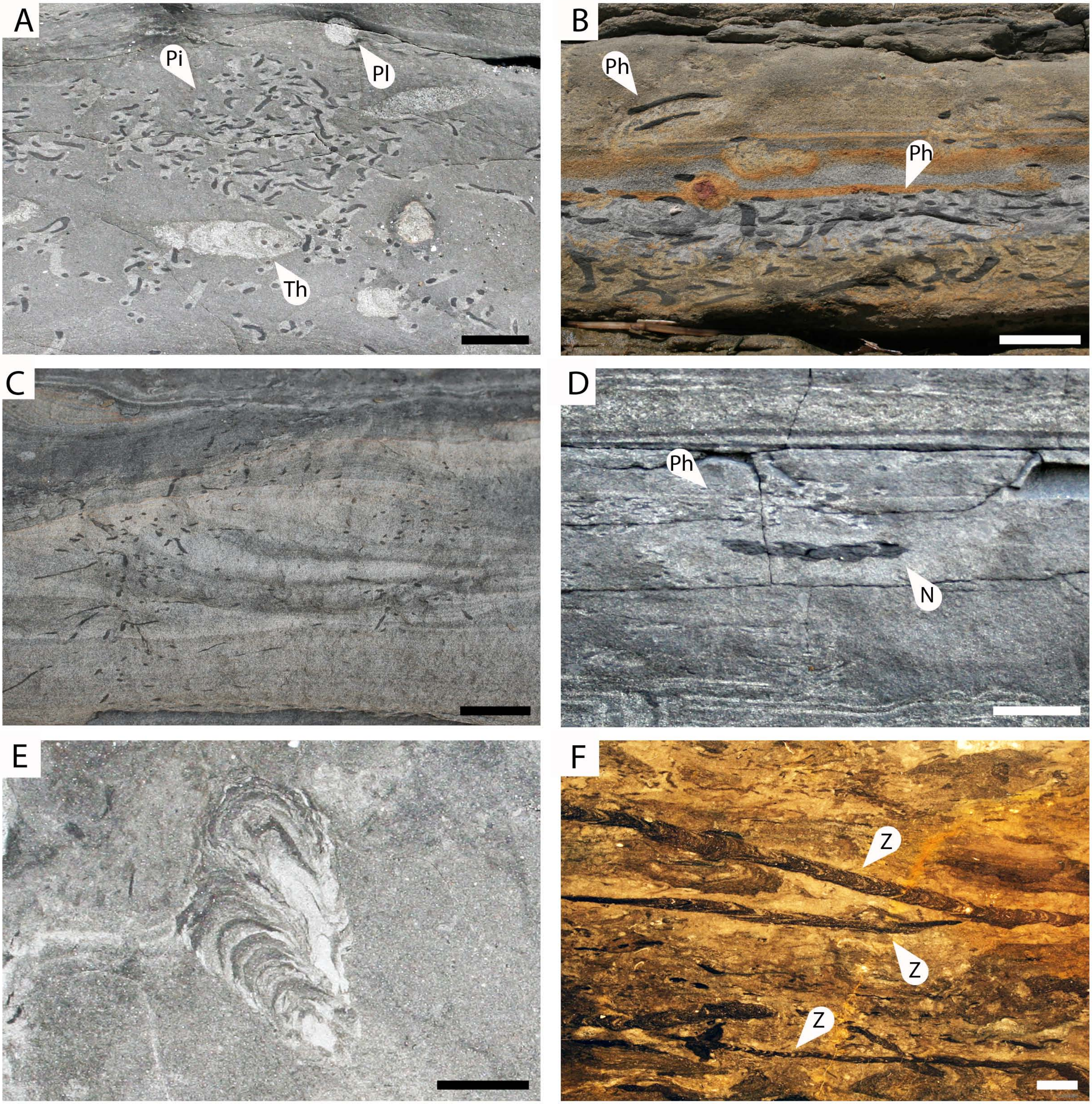
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Designation	Setting	Oxygenation	Nutrient Supply	Sedimentation Rate	Hydrodynamics
Axis	**Channel Thalweg**	Good	Refractory from pelagic. Labile from upwelling and turbidity currents.	Erosive, bypass or high. MTDs.	Internal tides, turbidity currents, mass transport.
Off Axis	**Channel Belt**	Good	Refractory from pelagic. Labile from upwelling and turbidity currents.	High, limited erosion.	Internal tides, turbidity currents.
Off Axis	**Internal Levee**	Good-moderate	Refractory from pelagic. Labile from upwelling and turbidity currents.	Moderate-high, limited erosion.	Internal tides, turbidity currents.
Marginal	**External Levee Proximal**	Moderate	Refractory from pelagic. Labile from upwelling and turbidity currents.	Moderate. Slumping.	Less frequent, lower energy turbidity currents
Marginal	**External Levee Distal**	Moderate-poor	Refractory from pelagic. Labile from upwelling and turbidity currents.	Moderate-low, decreases distally	Rare, low energy turbidity currents.
Marginal	**Basin Slope**	Variable to poor	Refractory from pelagic. Labile from upwelling.	Low, pelagic.	Contour currents, geostrophic currents.