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# **Compound and hybrid clinoforms of the last lowstand Mid-Adriatic Deep: processes, depositional environments, controls and implications for stratigraphical analysis of prograding systems**

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## **ABSTRACT**

Clinofoms with a range of scales are essential elements of prograding continental margins. Different types of clinofoms develop during margin growth depending on combined changes of relative sea level, sediment supply and oceanographic processes. In studies of continental margin stratigraphy, trajectories of clinofom “rollover” points are often used as proxies for relative sea-level variation and as predictors of the character of deposits beyond the shelf-break. Typically, the analysis of clinofom dynamics and rollover trajectory often suffers from the low resolution of geophysical data, the small scale of outcrops with respect to the dimensions of clinofom packages and low chronostratigraphic resolution. Here, through high-resolution seismic reflection data and sediment cores we show how compound clinofoms were the most common architectural style of margin progradation of the late Pleistocene lowstand in the Adriatic Sea. During compound clinofom developemnt the shoreline was located landward of the shelf-break. It comprised a wave-dominated delta to the west and a barrier and back-barrier depositional system in the central and eastern area. Storm-enhanced hyperpycnal flows were responsible for the deposition of a sandy lobe in the river mouth, whereas a heterolithic succession formed elsewhere on the shelf. The storm-enhanced hyperpycnal flows built an apron of sand on the slope that interrupted an otherwise homogeneous progradational mudbelt. Locally, the late lowstand compound clinofoms has a flat to falling shelf-break trajectory. However, the main phase of shelf-break bypass and basin deposition coincides with a younger steeply rising shelf-break trajectory. We interpret divergence from standard models linking shelf-break trajectory to deep-sea sand deposition, as resulting respectively from a great efficiency of oceanographic processes in reworking sediment in the shelf, and from a high sediment supply. The

slope foresets had a large progradational attitude during the late lowstand sea level rise, showing that oceanographic processes can inhibit coastal systems to reach the shelf edge. In general, our study suggests that where the shoreline does not coincide with the shelf-break, trajectory analysis can lead to inaccurate reconstruction of the depositional history of a margin.

## INTRODUCTION

Prograding continental margins grow through the seaward migration of clinoforms: depositional surfaces composed of three different tracts forming a topset-foreset-bottomset assemblage (Steel & Olsen, 2002; Helland-Hansen & Hampson, 2009). “Rollover points” correspond with the gradient changes at the passage between topsets and foresets.

Three main clinoform types, with different scale, both spatial and temporal, are the building blocks of prograding margin (Helland-Hansen & Hampson, 2009; Patruno *et al.*, 2015a; Patruno & Helland-Hansen, 2018; Fig. 1a). Delta clinoforms (Patruno *et al.*, 2015a; Patruno & Helland Hansen, 2018), called in a more general way shoreline clinoforms by Helland-Hansen & Hampson (2009), include features produced by progradation of deltas, barrier-island and strandplains and normally have up to a few tens of metres of relief; their topset-foreset rollover, called shoreline-break, approximates the location of the shoreline (Helland-Hansen & Hampson, 2009). Subaqueous delta clinoforms have their topsets in the inner shelf, a shoreline detached topset to foreset rollover, a subaqueous delta slope foreset and a bottomset that is contiguous with the mid- to outer-shelf (e.g. Patruno *et al.*, 2015a; Patruno & Helland Hansen, 2018) (Fig. 1a). The height of the foreset of subaqueous deltas is in the order of tens of metres (Patruno *et al.* 2015a). Shelf-edge clinoforms (Patruno & Helland Hansen, 2018a), equivalent to the shelf-prism clinoforms of Patruno *et al.* (2015a) and of the shelf-slope-basin clinoforms of Helland-Hansen & Hampson (2009), typically have heights of many hundreds of metres or more. Their topset-foreset rollover, called shelf-break, coincides with the position of the shelf-edge and their foresets coincide with the continental slope (Fig. 1a).

Along a continental margin, the occurrence of the different types of clinoforms, is controlled by combined changes of relative sea-level, sediment supply and oceanographic processes at various temporal and spatial scales. The progressive outbuilding of the continental margin thus occurs through different clinoform configuration. Different clinoform types can occur together forming compound clinoforms, or they may coincide forming “hybrid clinoforms” (e.g., hybrid shorelines, shelf-edge deltas, continental-margin deltas) (Patruno & Helland Hansen, 2018) (Figs. 1b and c). A particular case of compound clinoform develops when a shoreline clinoform is associated with a shelf-edge clinoform (Fig. 1b). Amongst “hybrid” clinoforms, Patruno & Helland Hansen (2018) have distinguished shelf-edge delta clinoforms, when the shoreline reaches the shelf-edge, and the shoreline and the shelf-break correspond (Fig. 1c).

In recent years, the trajectories of clinoform rollover points has been proposed as an important tool, stressing the role of sediment supply and accommodation space, in the interpretation of the stratigraphy of continental margins (Johannessen & Steel, 2005; Helland-Hansen & Hampson, 2009; Henriksen *et al.*, 2009; 2011). In particular, the possibility of predicting the sites of sand deposition along continental margins is supposed to depend on the recognition of different trends in the trajectory of the shelf-break. In studies based on seismic reflection line interpretation, poor imaging of shoreline clinoforms often impedes the reconstruction of the shoreline location with respect to the shelf-edge (Helland-Hansen & Hampson, 2009; Glørstad-Clark *et al.*, 2010; Holgate *et al.*, 2014). In these cases, trajectory analysis loses much of its predictive significance, since the environmental setting of clinoform rollover points is uncertain. The underestimation of the importance of shelf processes is a further issue that can limit the strength of trajectory analysis models in reconstructing spatio-temporal sediment distribution. Shelf process regime is a key factor in determining sediment distribution in time and in space along prograding continental margins, such as best illustrated by the development of compound clinoforms. Its fundamental role in determining the timing and locus of sandy sediment deposition is increasingly recognized (Dixon *et al.*, Jones *et al.*, 2015; Hodgson *et al.* 2018; Cosgrove *et al.* 2018; 2019), but is however not adequately considered in trajectory analysis models.

In the Adriatic Sea, the Po River Lowstand Wedge (PRLW) is characterized by a stack of clinothem that prograded into the Mid-Adriatic Deep (MAD). Within the PRLW, three types of elemental shelf-edge clinothem with specific topset geometry, shelf-edge and onlap-point trajectory and seismic facies are present (Pellegrini *et al.*, 2017a). Type A clinothem are characterized by moderate topset aggradation, ascending shelf-edge trajectory and mass-transport bottomset complexes. Type B clinothem show eroded topset, descending shelf-edge trajectory and bottomset distributary channel-lobe complexes. Finally, type C clinothem have maximal topset aggradation, ascending shelf-edge trajectory and fine-grained concordant bottomsets. For a detailed description of each elemental clinothem, map pattern of sediment distribution, and lateral extent of seismic facies for the 13 elemental clinothem forming the PRLW, the reader is referred to Pellegrini *et al.* (2018).

In this paper, we present a more detailed investigation, through an integrated, original interpretation of cores data and high resolution CHIRP subbottom lines, of the youngest PRLW clinothem. In particular, we focus in the interval from the B4 clinothem, which starts at about 19.5 ky BP, to the C2 clinothem which ends at about 14.4 ky BP (Fig. 2; Pellegrini *et al.*, 2017a; 2017b). The study interval thus encompasses an age interval of ~ 5.0 ky, covering the last part of the early lowstand, from unit B4 to A6, and the late lowstand C1 and C2 clinothem that formed as the sea level was already in its early phase of rise (see Pellegrini *et al.*, 2018) (Fig. 2). We highlight the variations in clinoform nature during progradation, discriminating periods of compound and “hybrid” shelf-edge

clinoform development. We reconstruct the paleogeography of the margin and discuss the processes of sediment supply and redistribution in the shelf and in the upper slope. In addition, we investigate the relationships between rollover point trajectory and shelf process-regime, deep-sea deposition and sea level variations. We show that, when the fine details of prograding clinoform units are investigated, the processes that lead to margin outbuilding are more complex than usually envisaged.

## GEOLOGICAL SETTING

During the Neogene building of the Apennine chain, foredeep basin depocenters have migrated eastward following the progressive advancement of the orogenic deformation front. The present-day Adriatic Sea is the youngest such basin and is mostly infilled with Quaternary units that prograded along the axis of the basin (Trincardi *et al.*, 1994; Dalla Valle *et al.*, 2013; Ghielmi *et al.*, 2013; Rossi *et al.*, 2015; Pellegrini *et al.*, 2018). The northern Adriatic Sea is a shallow-water shelf area that passes southward into the Mid-Adriatic Deep (MAD), a NE-SW oriented deeper water area, which straddles the axial part of the basin (Fig. 3). The most recent, late Pleistocene, south-eastward prograding clinoforms connect the northern shelf areas to the deeper MAD. Late Pleistocene succession encompasses the Last Glacial Maximum, when the PRLW prograded south-eastward for 40 km (Pellegrini *et al.*, 2018).

## DATA AND METHODS

The 2D seismic reflection grid used in this study comprises high-resolution profiles with a total length of 1500 km and covers an area of 5000 km<sup>2</sup> (Fig. 3). Seismic profiles were acquired in 2014, during the LowStand Delta (LSD14) cruise with a mini water-gun source (Sercel S15-02 of 15 inc3) and a multichannel streamer (Teledyne mini-streamer with 24 channels; 80–500 Hz frequency band width). Single-channel profiles, shot with a 300-J Sparker electro-mechanic source, and CHIRP sub-bottom lines with a 2–7 kHz outgoing signal were also acquired. The data were digitally recorded after band-pass filtering and gain adjustment. Sediment cores were collected with both a gravity- and a vibro-corer, allowing a maximum penetration of 10 m. Sediment samples (81 samples of ~142 cm<sup>3</sup> each) were collected with a core-dependent vertical spacing of 1 m or less. The samples were dried, soaked in peroxide and then wet sieved with 1 mm screens (details in Scarponi & Angeletti, 2008). Mollusks and serpulids were identified to species level whenever possible, in order to reconstruct the paleoenvironment.

The stratigraphic interval targeted in this paper, has been subdivided into different clinothems by Pellegrini *et al.*, 2017a and Pellegrini *et al.*, 2018. In this paper we follow their subdivision.

## DATA DESCRIPTION AND INTERPRETATION

### Western area

In the northern sector of the CHIRP line of Figure 4a, an area with relatively flat reflectors is present. Southward, reflectors dip at a low angle seaward, by a further area with flat reflectors and finally by relatively steep reflectors that coincide with the present-day slope of the MAD. We interpret this a compound clinoform composed of a shoreline and a shelf-edge clinoform. The shelf-edge topset, corresponding with the continental shelf, displays a very low acoustic penetration suggestive of sandy sediment. The latter is confirmed by sediment core LSD27 that collected thick clean sand in the distal part of the shelf-edge topset of C2 (Figs. 4b, 5a and 6a). The sands are rich in organic matter, shown by widespread black blobs, but are disturbed by coring operations, thus their eventual original sedimentary structures are not observable. The macrofossil assemblage consists of shallow water taxa dominated by *Anomia ephippium* and *Spisula subtruncata* along with shelf taxa (i.e., *Bittium submamillatum* and *P. minimum*) and less abundant outer shelf/upper slope *Bathyarca pectunculoides*. Assemblages consisting of mixed offshore transition and inner shelf taxa are also observed. In the deeper core segment, a relatively abundant lower shoreface to offshore transition assemblage dominated by *Spisula subtruncata* and anomids, with auxiliary *Fabulina fabula* is found. The ecological incongruent assemblages, along much of the core, are in agreement with reworking and deposition of shallower taxa and deposition in an offshore transition setting; the lowermost portion of the sediment core records shallower environments.

The low acoustic penetration in the CHIRP profile points to the presence of sand also in the area very close to the shelf-break (Fig. 4a). Here, a sandy succession, similar to that of sediment core LSD27, was sampled in the upper part of core LSD28 (Figs. 5b and 6b). The LSD28 core shows comparable macrobenthic content to LSD27 pointing to mixing of shallow water taxa (e.g., *L. mediterraneum*, *Spisula subtruncata*) with shelf to upper slope taxa (i.e., *B. pectunculoides*; *B. submamillatum*). A low acoustic penetration in the CHIRP profile continues in the upper part of the slope, and is indicative of sandy deposits as shown by sediment core LSD29 (Figs. 5c, 6c), which consists mainly of sandy heterolithics. A transition to a reflective seismic facies, indicative of fine-grained deposits, is observed in the middle part of the shelf-edge foresets, corresponding with the MAD slope. Their fine-grained nature is confirmed for the whole of the C1 and C2 clinothems, by mostly continuous low amplitude reflectors or transparent packages lacking any incision (Fig. 4b).

Two genetically-related progradational clinoform sets, one at the shelf-edge, and another further inland, show that compound clinoforms developed during the deposition of clinothems B4 and A5a (Fig. 4b). In these clinothems, the shoreline clinoforms have foresets with high amplitude reflectors. The shelf-edge topset is aggradational, and is characterized by either high or medium amplitude reflectors that are mostly continuous, but become discontinuous and truncated approaching the shelf-break. The foresets of the shelf-edge clinoforms of the compound B4 and A5b clinoforms have mostly

continuous low amplitude reflectors or consist of transparent packages. They lack any incision and are interpreted as evidence of a relatively fine-grained, mud-prone unchannelized slope setting.

A single clinoform is shown by the seismic line of figure 4b during the deposition of unit A5b. It is interpreted as a “hybrid shelf-edge clinoform” (*sensu* Patruno & Helland-Hansen, 2018) that occurred when the shoreline corresponded with the shelf-break. A single “hybrid” shelf-edge clinoform setting persisted during the deposition of unit B5 and unit A6. All the “hybrid” shelf-edge clinoforms have foresets, corresponding with the MAD slope, with transparent seismic facies or highly discontinuous reflectors with relatively high amplitude. They can be the proof of sandy sediment deposited in a sometimes channelized slope setting.

### **Central area**

The northern sector of the CHIRP profile shows reflectors dipping with a low angle towards the south (Fig. 7a). They are followed, going deeper southward, by an area, with flat reflectors, that connects further south with the relatively steep reflectors of the MAD slope. We interpret this setting as the evidence of compound clinoforms, where shoreline foresets, imaged in the northern sector of figure 7a, occupy the seaward side of a low relief bathymetric high, fully visible in the line of figure 7b. The high is here assumed to represent a barrier with a shoreline flanked landward by a back-barrier area. During clinothem C1 and C2, the barrier was part of a shoreline clinoform that was flanked seaward by a shelf-edge clinoform resulting in a compound clinoform setting (Fig. 7a). The CHIRP profile (Fig. 7a) shows that the shoreline foresets have very faint internal reflections with poor acoustic penetration indicative of sandy sediment. The CHIRP penetration and reflectivity increases southward, suggesting that finer grained deposits are present in the shelf-edge topsets. As a matter of fact, in sediment core LSD09 (Figs. 5d and 6d), the shelf-edge topsets of unit C1 mostly consist of heterolithics made up of few-centimetres-thick couplets of thin silty to sandy layers and mud levels. The sandy intervals consist of discontinuous lenses resulting from traction processes also shown by cross laminated intervals. The relatively rich macrofossil assemblage in the topmost segment of the core is dominated by outer shelf and upper slope taxa (i.e., *Kelliella miliaris*, *Bathyarca pectunculoides* and *Parvicardium minimum*) and shelf euribathic species, associated with taxa of shallower environments (i.e., *Bittium* spp., *Turritella communis*). Macrobenthic remains are very rare along the deeper segments of the sediment core. As a whole, an offshore depositional environment with a contribution of sediment reworked from a nearby shallow-water area and the addition of slope taxa during subsequent sea-level rise, is thus substantiated for the preserved shelf-edge topset of unit C1. A seismic facies lacking internal reflections characterizes the proximal part of the shelf-edge topsets (Fig. 7a). Erosional surfaces are frequent within the otherwise aggradational topset package (Fig. 7a). A reflective facies develops seaward and then continues into the shelf-edge slope foresets

in the MAD slope (Fig. 7a), which upper part, was sampled by core INV12-05, during clinothem C2 (Fig. 5e and 6e). The core shows the mud-prone nature of the shelf-edge foresets which mainly consist of heterolitics, with 3-4 cm-thick silty and muddy couplets with a predominance of mud over sand and silt, intercalated between gray mud intervals. The paucity of macrobenthic remains does not allow any environmental inference. Low amplitude continuous reflectors characterize the whole of C1 and C2 shelf-edge foresets (Fig. 7b).

A compound clinoform setting developed also during the deposition of clinothems B4 and A5a (Fig. 7b), as shown by two genetically-related clinoform sets, one at the shelf-edge, and another further inland. The shelf-edge topsets of clinothems B4 and A5a, located seaward from the transparent seismic facies of the shoreline foresets, form an aggradational package and are characterized by either high or medium amplitude, mostly continuous reflectors (Fig. 7b). The shelf-edge foresets of clinoforms B4 and A5b clinothems consist of mostly continuous reflectors with low amplitude.

A single clinoform characterizes clinothems A5b, B5 and A6 and is interpreted as corresponding with “hybrid shelf-edge clinoforms” (*sensu* Patruno & Helland-Hansen, 2018) with the shoreline located at the shelf-break (Fig. 7b). The “hybrid” shelf-edge clinoforms have foresets, corresponding with the MAD slope, with transparent seismic facies or highly discontinuous reflectors with relatively high amplitude (Fig. 7b). They can be the proof of sandy sediment deposited in a sometimes channelized slope setting.

### **Eastern area**

The CHIRP and sparker lines (Figs. 8a and b) show an elevated area at the seafloor that is the eastern continuation of the barrier developed in the central area (Figs. 7a and b). In the lower part of the C1 clinothem, the reflectors dip seaward in the southern barrier side, then become relatively flat before steepening in coincidence with the MAD slope. This setting is interpreted as a compound clinoform, with a shoreline clinoform that corresponds with the barrier, and a shelf-edge clinoform further seaward. In the barrier area, the topset of the shoreline clinoform, has a highly reflective seismic facies that greatly reduces subbottom acoustic penetration (Fig. 8a) and is indicative of sandy deposits. A thick sand succession in core LSD37 (Figs. 5f and 6f) with oligotypic assemblages mainly represented by *Lentidium mediterraneum* with auxiliary *Abra alba* and *Spisula subtruncata* characteristic of very shallow marine environments was sampled in proximity of the barrier. Whereas in the topmost segment, the malacological content consists of assemblages of species with contrasting ecological requirements: bay to shoreface taxa (*L. mediterraneum*; *S. subtruncata*) mixed with shelf or deeper taxa (e.g., *Parvicardium minumum*; *B. pectunculoides*, *Abra longicallus*). The fossil assemblage is suggestive of strong physical and biological reworking in shelf settings of shallow water taxa (see also Scarponi *et al.*, 2017a).



At the seafloor, large parts of the shoreline foresets are cut by an erosional surface that further southward cuts the shelf-edge topsets and foresets of clinothem C1 (Fig. 8a). The erosional surface continues at the present-day shelf-break where it cuts the slope foresets of clinothem C2. Further erosion surfaces cut the older part of the shelf-edge topsets of C1 and C2 clinothems (Fig. 8a). The facies of the shoreline foresets of clinothem C1, sampled by core LSD35 consists of various types of heterolithics and thick sand (Figs. 5g and 6g).

The backbarrier environment, sampled by core LSD36 (Figs. 5h and 6h), consists of thick sandstone units sandwiched between two heterolithics units with both sandy and silty layers. The malacological content represented by low diversity associations with a few specimens of *L. mediterraneum* and of *Abra segmentum* or hydrobiids is indicative of shallow water eurythermal and euryhaline protected environments (Scarponi *et al.*, 2017b).

The foresets of the C1 and C2 clinothems have mostly continuous low amplitude reflectors and lack any incision and thus they are best interpreted as the expression of a fine-grained unchannelized slope setting. A compound clinoform setting developed also during the deposition of clinothems B4 and A5a (Fig. 8b), as shown by two genetically related clinoform sets, one at the shelf-edge, and another further inland. The shelf-edge topsets of clinothems B4 and A5a, located seaward from the transparent seismic facies of the shoreline foresets, form an aggradational package and are characterized by either high or medium amplitude reflectors that are mostly continuous but often become discontinuous and truncated approaching the shelf-break (Fig. 8b). The shelf-edge foresets of clinoforms B4 and A5b clinothems consist mostly of continuous and low amplitude reflectors.

The seismic line (Fig. 8b) shows that clinothem A6 has convex-upward reflectors that downlap into older reflectors in the landward side of the barrier. This setting suggests that the main phase of barrier upbuilding corresponds with the clinothem A6. The latter represents an “hybrid” shelf-edge clinoform when the barrier was located at the shelf-break. A shoreline was also located at the shelf-edge during the deposition of B5 but was not associated with the building of any barrier and back-barrier area. In this case, therefore the “hybrid” shelf-edge clinoform had the shoreline coinciding with a strandplain environment.

## **DISCUSSION**

### **Lowstand compound clinoforms: shoreline, shelf and slope processes**

Variations of sediment partitioning between the different physiographic domains of progradational margins dictate whether hybrid or compound clinoforms form. The partitioning of sediment between the shoreline area, the continental shelf and the continental slope, is a function of relative sea-level changes, the rate and calibre of river sediment supply, the strength of basin processes (Swenson *et al.*, 2005; Pratson *et al.*, 2007; Helland-Hansen & Hampson, 2009; Patruno *et al.*, 2015a; Patruno &

Helland-Hansen, 2018). The formation of compound clinoforms is evidence that oceanographic processes have relatively high energy (Swenson *et al.*, 2005; Pratson *et al.*, 2007; Patruno & Helland-Hansen 2018; Cosgrove *et al.*, 2018). Compound clinoforms were the main components of the PRLW progradational architecture during the studied clinothem, suggesting that basinal processes of transport, erosion and deposition, dominated by waves and both long- and across-shore currents, were very efficient during the last sea level lowstand.

In the central and eastern part of the study area, during clinothem C1, compound clinoform formation was associated with erosion and bypass, indicated by the erosion of the upper, proximal part of the shoreline clinoform foresets (Figs. 8a) and of the landward part of many of the shelf-edge clinoform topsets and foresets (Figs. 7a and 8a). Here, the preserved shelf-edge topsets have a lithology that consists of sandy heterolithics with thin and often discontinuous sand levels (Fig. 5c and 6d). Concomitantly, a mostly aggradational shelf-edge topset developed in the western area, where thick massive sands were deposited (Fig. 5a and b, 6a and b).

A schematic representation of the environmental setting, and the sedimentary processes active during the development of clinothem C1 and C2, derived through the integrated interpretation of the data presented in this paper, is shown in figure 9. We interpret the aggradational sandy shelf-edge topset in the western area to reflect a position proximal to the entry point of the major river, while finer-grained sediments accumulated in the central and eastern area, located away from the major sediment source (Fig. 9). The association of the western area with a river is also confirmed by the abundance of organic matter in the massive sands in core LSD27. In the river entry point region, in the CHIRP profile and in the seismic line (Figs. 4a and b), channels are rarely seen, thus we suggest that the related delta was mostly wave-dominated (Fig. 9). This is in agreement with the delta positioned very close to the shelf-break and thus being impacted by strong waves that, travelling over a very narrow shallow-water area, experienced only a minor energy loss (Porębski & Steel, 2006; Yoshida *et al.*, 2006; Uroza & Steel, 2008). We interpret the thick sands in the shelf-edge topset of the eastern area (Fig. 5a and b, 6a and b) as being mainly the result of riverborne sediment subject to extensive reworking (Fig. 9). In particular, we envisage a storm-flood depositional setting (Bhattacharya & MacEachern, 2009; Collins *et al.*, 2017), whereby sediment introduced within the basin by hyperpycnal flows during peak fluvial discharge were moved further offshore by concomitant offshore-directed downwelling storm flows. We conclude that storm-enhanced hyperpycnal flows were responsible for the formation of a sandy lobe in front of the main river of the MAD (Fig. 9). Storm-generated offshore-directed sediment-gravity flows, can flow below the storm wave base (Macquaker *et al.*, 2010; Schieber, 2016; Poyatos-More *et al.*, 2016). Such kinds of flows are here interpreted as responsible for sediment transfer to the shelf-edge and beyond, thus forming the apron

of sandy heterolitic sands sampled in core LSD29 in the shelf-edge foresets, corresponding with the slope of the western area (Fig. 9).

The central area, and presumably also the eastern one, for which sediment cores are not available in the shelf topset, were located seaward from an area away from the direct river input. Longshore anticlockwise currents and possibly smaller rivers fed the sediment for the construction and aggradation of a coastal barrier system, during fair-weather periods, shown by the CHIRP profiles (Figs. 7a and 8a) s (Fig. 9). Storm events eroded the shoreline as shown by the shoreline foreset erosion (Fig. 8a) and promoted offshore-directed sediment-gravity flows, responsible for the sandy heterolithics sampled in core LSD09 in the shelf-edge topset (Fig. 5d, 6d and 9). Within the latter heterolithics, the discontinuous sandy and silty layers are the result of the turbulence of the storm wave-induced sediment-gravity flows as suggested by Birghenheir *et al.* (2017) for similar layers in the Late Cretaceous Mancos Shales. The topsets of the shelf-edge clinoform of the C1 and C2 clinothems show alternations of phases of aggradation and erosion (Figs. 7a, 8a). This can be explained as the result of higher frequency sea-level variations, or climatic changes affecting sediment supply and/or storm strength. The storm-induced sediment-gravity flows were not capable to transfer sand beyond the shelf-edge, as shown by the silty heterolithics interlayered with muddy units of core INV05 in the shelf-edge foresets (Figs 5e, 6e, 9). As a consequence, an extensive mudbelt formed in the slope in a setting similar to that of the Karoo Basin as described by Poyatos-Moré *et al.*, (2016). Our research thus shows that, when sediment bypass and erosion prevail in the shelf, conspicuous slope progradation can occur even when the shoreline is relatively far from the shelf edge.

The shift from a compound clinoforms, composed of a shoreline and a shelf-edge clinoform, to a “hybrid shelf-edge clinoform” takes place when the shoreline is located at the shelf-edge (Pratson *et al.*, 2007). It can occur if the shoreline clinoform progrades faster than the shelf-edge one, or following a rapid sea level drop that brings the coast close to the position of the former shelf-edge. The latter process, shown by an abrupt fall of the shoreline break between unit A5a and A5b (Figs. 4b, 7b, 8b) is preferred to explain the establishment of the “hybrid” clinoform in the study area. Successively during the deposition of the lower part of unit C1 a setting consisting of a compound clinoform was re-established. This change corresponds with a decrease in sediment input at the onset of unit C1 (Pellegrini *et al.*, 2018) and is here interpreted as showing that sediment supply was insufficient to counterbalance the increased rate of sea-level rise, ensuing in shoreline landward retreat till its disconnection from the shelf edge.

**Lowstand compound clinoforms, shelf-break trajectory and deep deep-sea deposition**

The resolution of many datasets used in the reconstruction of shelf margin stratigraphy prevents the evaluation of the contribution of compound clinoforms to margin growth (Glørstad-Clark *et al.*, 2011). The resulting inadequate understanding of the location of the shoreline with respect to the shelf-break can lead to the underestimation of the role of compound clinoforms in margin growth (Glørstad-Clark *et al.*, 2011). Through the interpretation of high-resolution seismic and bathymetric data, compound clinoforms are being increasingly recognized as important components of modern continental margins (e.g. Patruno *et al.*, 2015a) and of past successions developed during high stands of sealevel (Glørstad-Clark *et al.*, 2011; Jones *et al.*, 2015; Klausen *et al.*, 2015; Poyatos-Morè *et al.*, 2016). Pellegrini *et al.*, (2015) shown that the conditions necessary for compound progradation can be satisfied even during transgressive phases. Depositional settings, including compound clinoforms, are seldom contemplated in the reconstructions of lowstand shelf margin depositional systems, for which it is often implicit that coastal systems developed at the shelf edge (Porębski & Steel, 2003; Steel *et al.*, 2008; Neal & Abreau, 2009; Glørstad-Clark *et al.*, 2011; Neal *et al.*, 2016). The resultant shelf-edge deltas would be equivalent to the “hybrid” clinoform in the nomenclature of Patruno & Helland-Hansen, 2018). Our study amply documents that compound clinoform development and shoreline- and shelf-break disconnection can be an important attribute of lowstand margin progradation, suggesting that care must be taken in interpreting the location of shoreline position, on the basis of the seismic shelf-break.

In studies dealing with continental margin growth, the shelf-break trajectory has often been taken as an indication of sealevel variations (Helland-Hansen & Hampson, 2009). Rising trajectories are often linked with rises of sealevel, whereas flat and falling trajectories are related respectively to sea-level stillstands and falls (Helland-Hansen & Hampson, 2009). In the study area, a flat shelf-break trajectory develops during the rise of sea level of the late lowstand period (clinothem C1 and C2) as part of a compound clinoform (Figs. 4b, 7b and 8b). Thus, the MAD example indicates that the evolutionary trend of the shelf-break rollover can sometimes be merely indicative of erosion and sediment redistribution along and across the shelf due to oceanographic processes. Our study shows therefore that the sole use of the shelf-break trajectory as an indicator of eustatic changes can lead to wrong interpretation, when the development of compound clinoforms is not recognized, due to poor data resolution.

The trajectory of the shelf-break is also often used to predict the timing of deep-sea deposition of sand; in particular, flat to falling trajectories are taken as indicators of shelf edge bypass and deep sea sand deposition (Bullimore *et al.*, 2005; Johannessen & Steel, 2005). During deposition of clinothem C1 and C2, locally and in the proximity of the barrier, the shelf-break had a flat to slightly falling trajectory but the prevalence of packages of low amplitude continuous reflectors suggests there was

little occurrence of sand bypass to deeper water (Figs. 4b, 7b and 8b). Our data shows therefore that during lowstand development of compound clinoforms the shelf-break trajectory needs to be used with caution as an indicator of bypass of sand grade sediment to the deep-water.

During the early lowstand (units A5b and B5), the shoreline- and the shelf-break coincided and a flat to falling shelf-break trajectory developed (Figs. 4b, 7b, 8b). This is the time of the highest input of sandy sediment to the basin as shown by the high amplitude seismic facies of the slope foresets. This observation supports the association of flat or falling shelf-break trajectory with sand bypass across the shelf edge towards the slope (Johannessen & Steel, 2005; Helland-Hansen & Hampson, 2009). However, locally and in proximity of the barrier, high-amplitude reflectors in the slope are also associated with the steeply rising trajectory of the shelf-break associated with clinothem A6, developed during the late lowstand, early rise of sea level. The PRLW is thus a further example showing that a complex relationship between shelf-edge trajectory and basinal deposits exists, and that locally deep-sea sand deposition can be associated with rising shelf-edge trajectory, as shown by Carvajal & Steel, (2006), Steel *et al.*, (2008), Jones *et al.*, (2015), Hodgson *et al.*, (2018). The interval of rising shelf-break trajectory coincides with the development of an “hybrid” shelf-edge clinoform and indicates that the shoreline remained fixed in the same position despite the early sea-level rise. This implies that sediment supply was high enough to counterbalance the early rise of sea level, and to prevent auto-retreat of the coastal system (Muto & Steel 2002; Carvajal & Steel, 2006). The barrier and back-barrier environment was supplied with sediment by long-shore currents that redistributed the sediment introduced in the basin by the major feeding system of the western area. We therefore suggest that the presence of a direct sediment source is not necessary for the shoreline to keep pace with sea-level rise when oceanographic processes re-distribute sediment along the margin. In general, our study reinforces the notion that trajectory analysis alone, can lead to misleading interpretations, if other factors, and specifically sediment supply and oceanographic regime, are not taken into account.

## **Conclusions**

The abundance of compound clinoforms, consisting of shoreline and shelf-edge clinoforms in the MAD, shows that such a type of stratigraphic configuration can be common also during lowstand periods. Moreover, it implies that during part of the lowstand of sea level, due to the separation between the shoreline area and the shelf-edge, relatively coarse-grained deposits do not reach the slope and basin areas, but remains in the outer shelf. Sandy deposits are fed to the slope when the shoreline- and the shelf-break coincide during lowstand periods, when high sediment input promotes the development of shoreline depositional systems at the shelf-break resulting in a “hybrid” clinoform, in spite of the rising sea level. The high sediment influx keeps the shoreline close to the

shelf-break also away from the main river mouth, provided along-shore sediment re-distribution is enough to feed an aggradational coastal barrier system. Compound clinoform development is brought about by the action of powerful processes in the shelf and the shoreline. Their varying efficiency in time and space controls the character of the shelf that accordingly can be depositional or erosional. When the shelf is depositional, the distance from a river sediment source is central in controlling the lithology and facies of the aggradational shelf deposits consisting of a lobe of thick massive sand. Slope progradation occurs during the late lowstand, when the shoreline is far from the shelf edge and results in muddy subaqueous clinothem forming an extensive slope mud-belt. In general, our study shows that oceanographic processes and their intensity are very important in controlling the stratigraphic architecture and sediment partitioning of continental margins.

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Fig. 1. A) Sketch (not to scale) of a progradational continental margin showing some of the different possible clinoform assemblages (modified from Patruno & Helland-Hansen, 2018) A) Different kinds, scales and locations of elemental clinoform systems. B) Compound clinoform with a shoreline and a shelf-edge clinoform. C) “Hybrid” shelf-edge clinoform with shoreline and shelf-break coinciding.

Fig. 2. Relationships between the clinothems of the PRLW (subdivision from Pellegrini *et al.*, 2018) and the sea-level curve by Lambeck *et al.* 2014. The bars that separates the clinothems mark the age of the surfaces used in their subdivision and are coloured accordingly to the seismic lines of the following figures.

Fig. 3. The Mid-Adriatic Deep (MAD) straddles, with NE-SW direction, the central part of the Adriatic Sea. The external contractional structures (black lines in the inset) of the Apennine chain are present in the western side of the Adriatic Sea. The seismic grid used in this study consists of both CHIRP and high resolution seismic lines. The lines shown in this paper, representative of the eastern, central and western area of the lowstand progradational suite of the MAD are highlighted in red.

Fig. 4. Seismic transect showing the architecture of the lowstand progradational suite in the western MAD (location in Fig. 1). A) High resolution CHIRP profile. The three cores, LSD27 (Figs. 5a and 6a), LSD28 (Figs. 5b and 6b), LSD29 (Figs. 5c and 6c) have been used to substantiate the interpretation of the shelf topset of clinothem 2 as part of a compound clinoform. B) Sparker lines showing the various clinothem (surfaces and clinothems correspond with those in Pellegrini *et al.*, 2018). The boxes correspond with the shoreline-break; the circles correspond with the shelf-break; the triangles indicate the roll-over of the “hybrid” clinoform. The yellow line corresponds with the shoreline-break trajectory; the green line corresponds with the shelf-break trajectory.

Fig. 5. Skematic sedimentologic log of the cores described in this paper. The boxes correspond with the areas shown in the pictures of figure 6. A) Core LSD15-27: shelf-edge topset on the western transect. B) Core LSD15-28: shelf-edge topset on the western transect. C) Core LSD15-29: shelf-edge foreset on the western transect. D) Core LSD15-09: shelf-edge topset on central transect. E) Core INV12-05: shelf-edge foreset on central transect. F) Core LSD15-37: shoreline topset on the eastern transect. G) Core LSD15-35: shoreline foreset on the eastern transect. H) Core LSD15-36: shoreline topset on the eastern transect.

Fig. 6. Pictures of the more characteristic lithologies representative of the different physiographic and depositional environments in the study area. The facies code corresponds with that of Figure 5. A) Core LSD15-27: shelf-edge topset on the western transect. B) Core LSD15-28: shelf-edge topset on

the western transect. C) Core LSD15-29: shelf-edge foreset on the western transect. D) Core LSD15-09: shelf-edge topset on the central transect. E) Core INV12-05: shelf-edge foreset on central transect. F) Core LSD15-37: shoreline topset on the eastern transect. G) Core LSD15-35: shoreline foreset on the eastern transect. H) Core LSD15-36: shoreline topset on the eastern transect.

Fig. 7. Seismic transect showing the architecture of the lowstand progradational suite in the central MAD (location in Fig. 3). A) High resolution chirp subbottom profile, covering the area corresponding with the box in B. The two cores, LSD09 (Figs. 5d and 6d) and INV05 (Figs. 5e and 6e) have been used to substantiate the interpretation of the shelf topset as part of a compound clinoform. B) Sparker lines showing the various clinothems (surfaces and clinothems correspond with those in Pellegrini *et al.*, 2018). The boxes correspond with the shoreline-break; the circles correspond with the shelf-break; the triangles indicate the roll-over of the “hybrid” clinoform. The yellow line corresponds with the shoreline-break trajectory; the green line corresponds with the shelf-break trajectory. C) Enlargement of part of the C1 clinothem, showing that the shelf-edge topset consist of both aggradational packages (green lines) and erosional surfaces (red lines) that cut the upper part of top-truncated shelf-edge forest (purple lines).

Fig. 8. Seismic transect showing the architecture of the lowstand progradational suite in the eastern MAD (location in Fig. 3). A) High resolution CHIRP profile, covering the area corresponding with the box in B. The three cores, LSD37 (Figs. 5f and 6f), LSD 35 (Figs. 5g and 6g) and LSD36 (Figs. 5h and 6h) have been used to substantiate the stratigraphic interpretation from the seismic character. B) Sparker lines showing the various clinothem (surfaces and clinothems correspond with those in Pellegrini *et al.*, 2018). The boxes correspond with the shoreline-break; the circles correspond with the shelf-break; the triangles indicate the roll-over of the “hybrid” clinoform. The yellow line corresponds with the shoreline-break trajectory; the green line corresponds with the shelf-break trajectory.

Fig. 9 Sketch map of the environmental setting and inferred processes in the study area during the deposition of clinothems C1 and C2. The shoreline was located landward from the shelf-break and a compound clinoform formed. A main river entered the MAD to the west, where a wave dominated delta developed. Storm-aided hyperpycnal flows were responsible for sand deposition in the shelf-edge topsets. They were also responsible for the formation of a sandy apron in the upper slope. In the central and western area, away from the main sediment input, a coastal barrier formed in the shoreline area. Here, the shelf-edge topset, corresponding with the shelf, was characterized by sandy heterolithics and an extensive mud-belt formed in the slope.

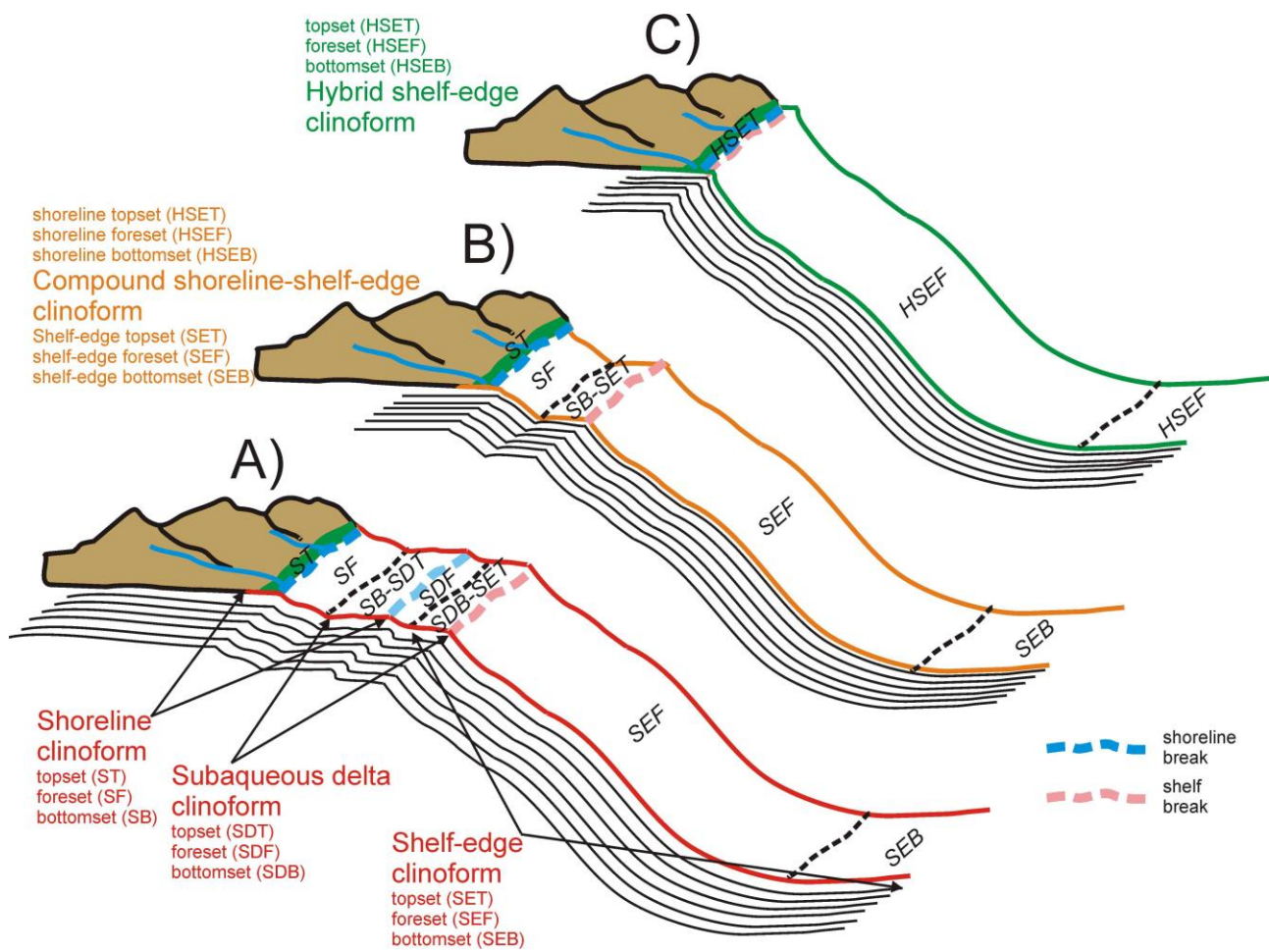


Fig. 1

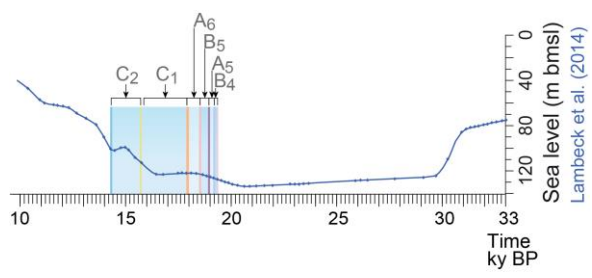


Fig. 2

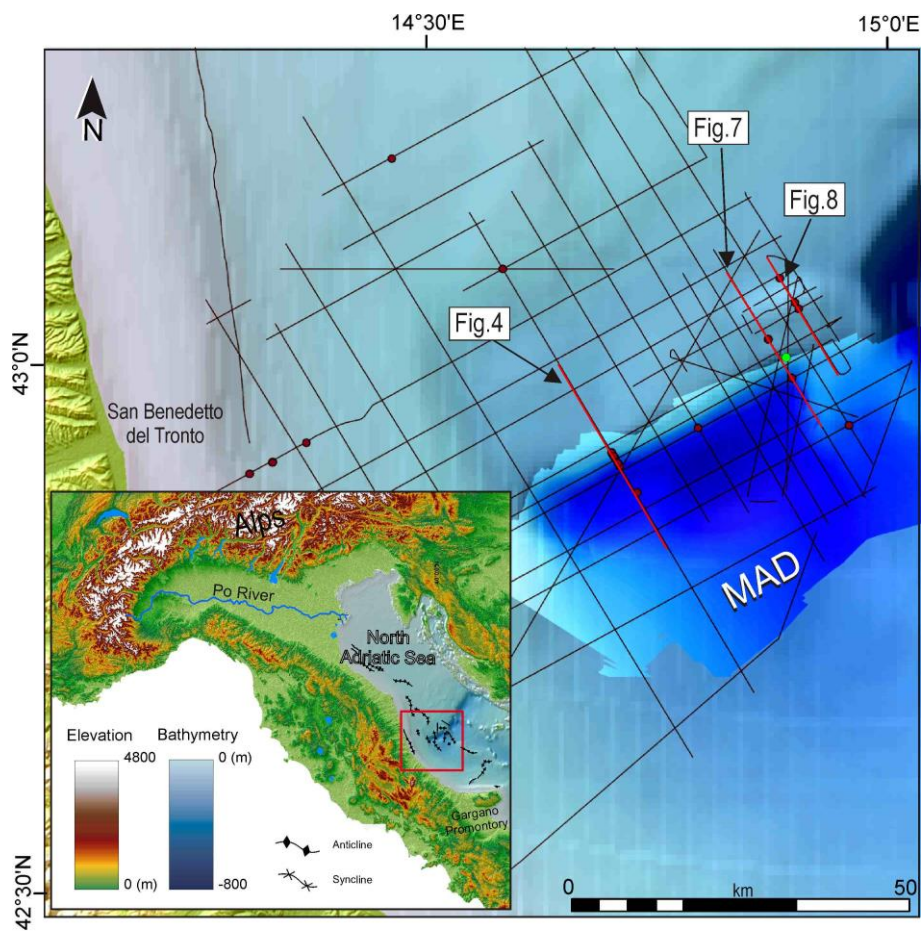


Fig. 3



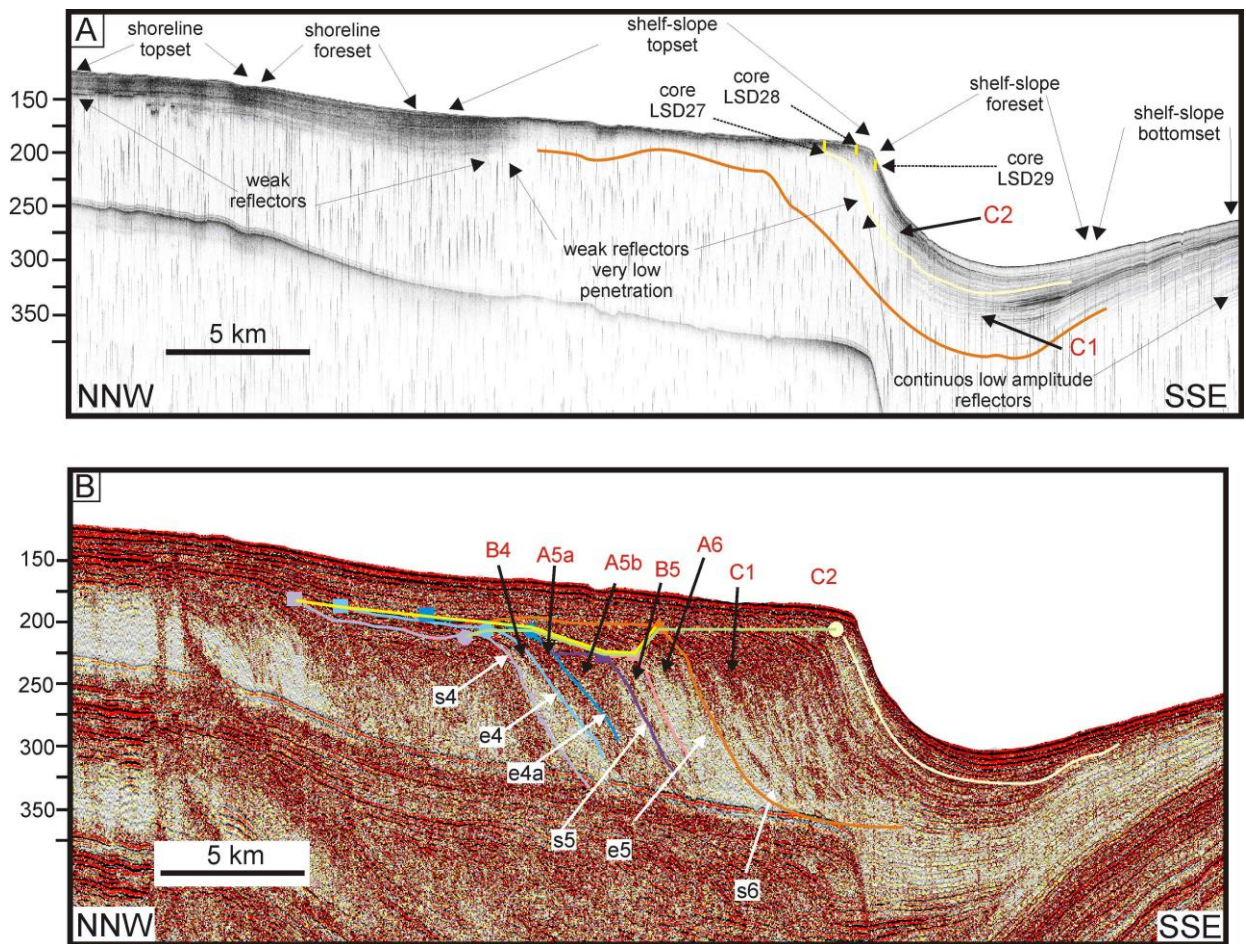
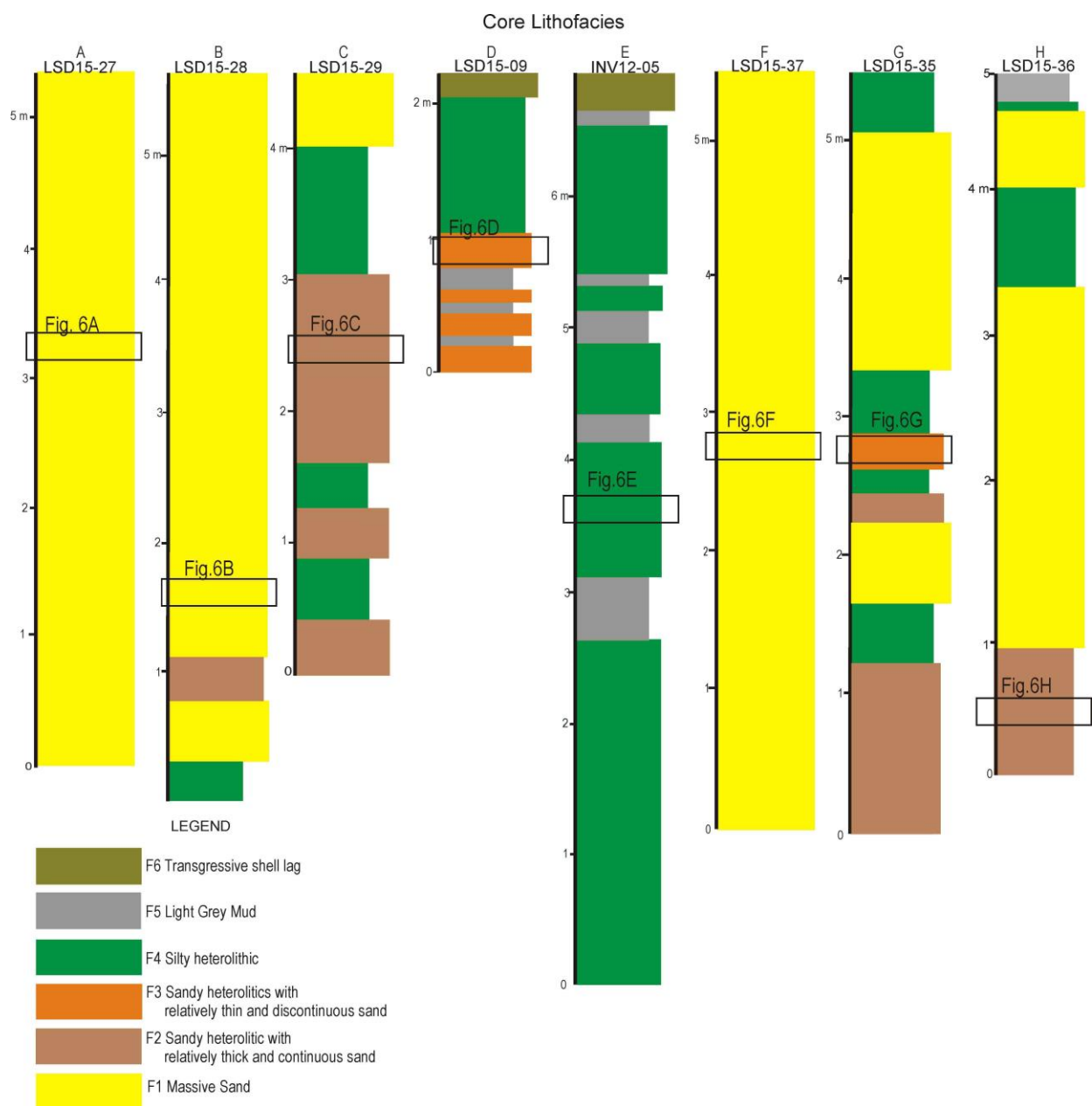


Fig. 4





**Fig. 5**

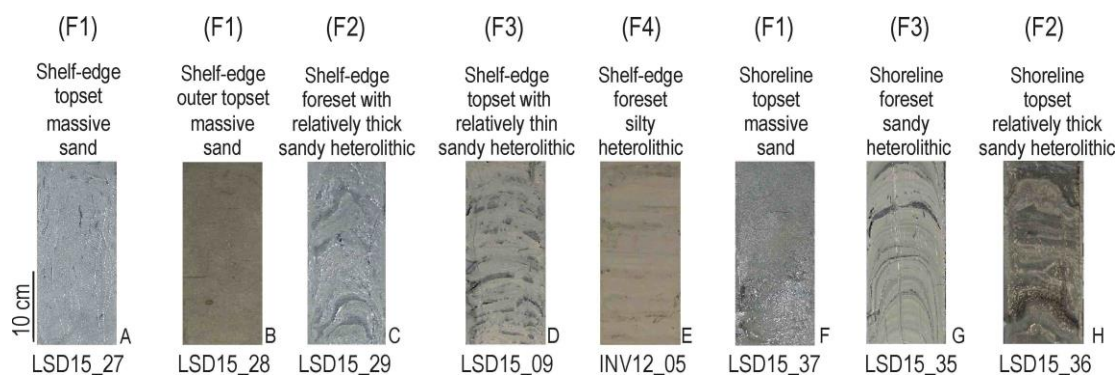


Fig. 6

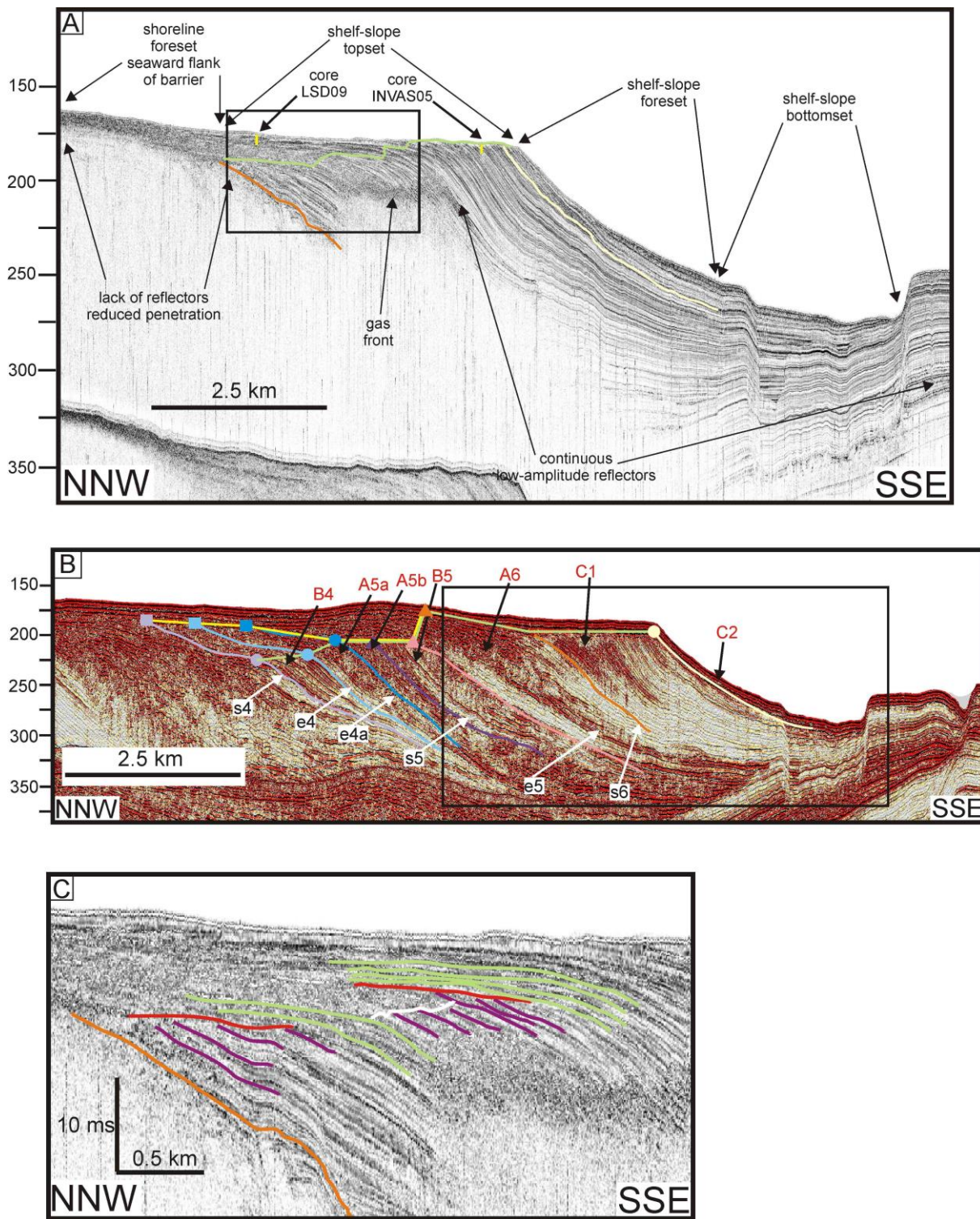


Fig. 7

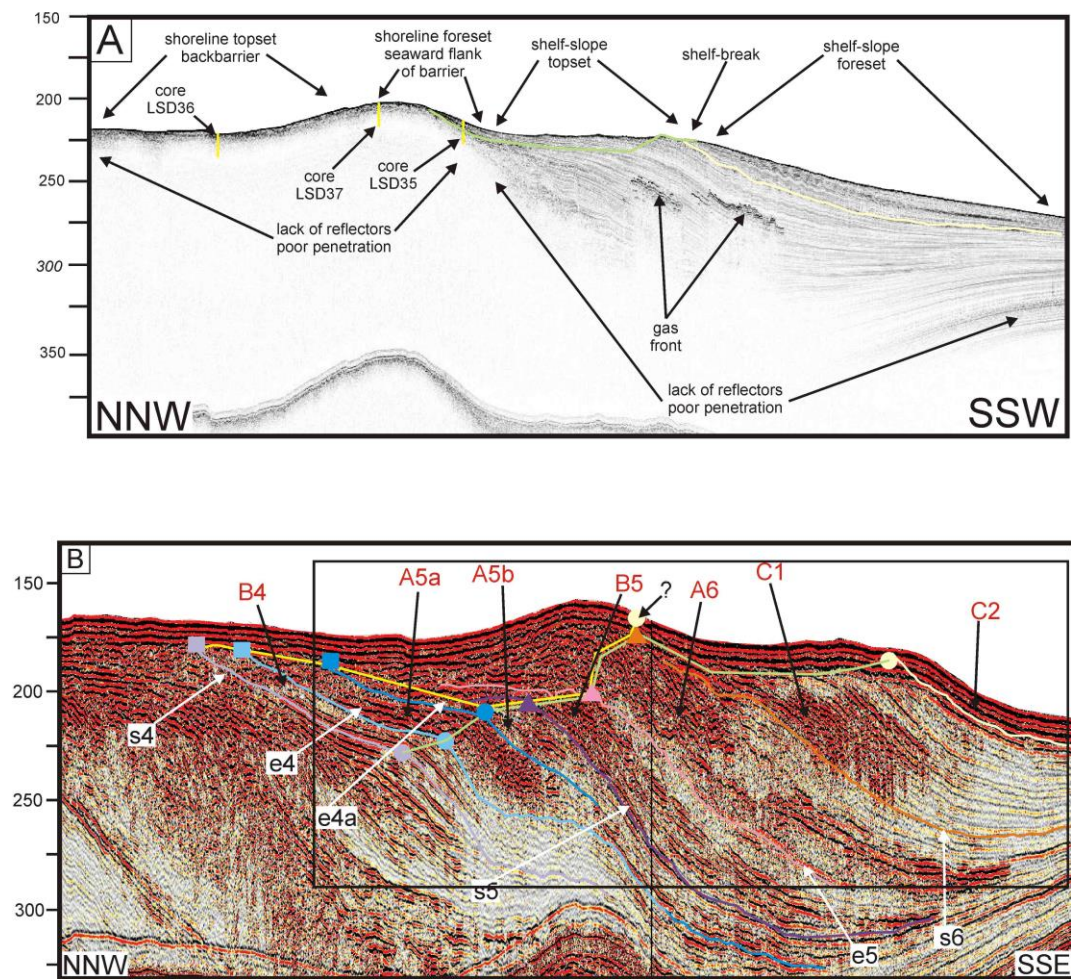


Fig. 8



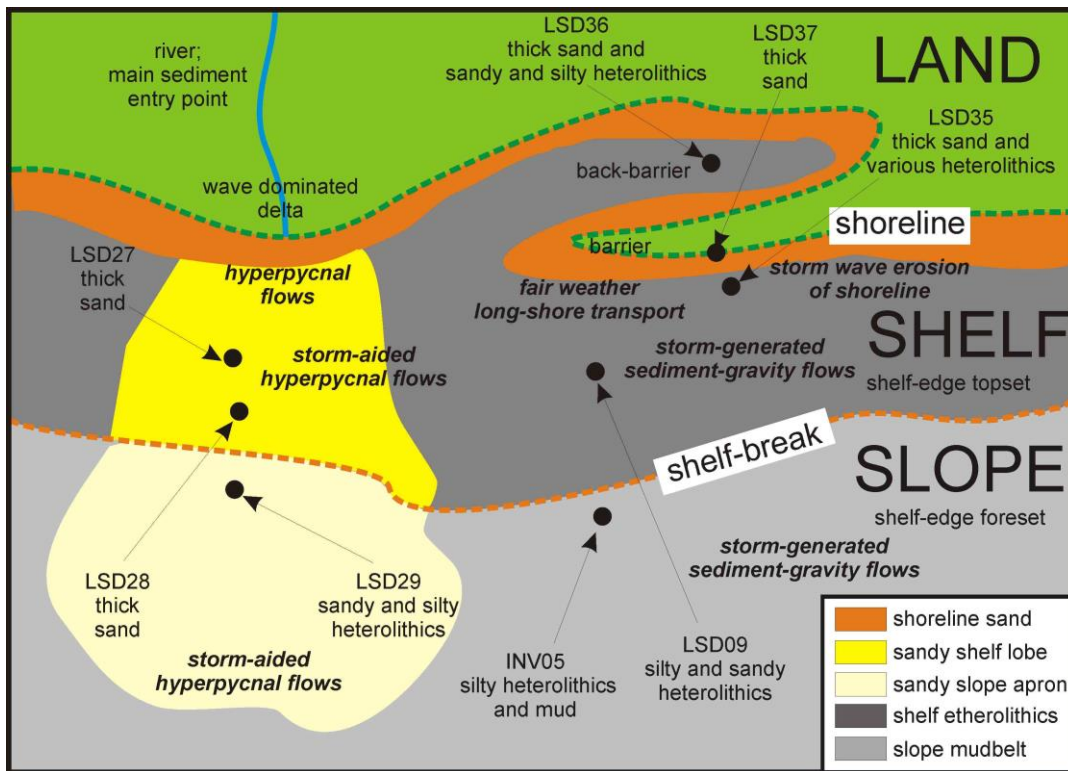


Fig. 9