Advancements in Understanding Deep-Sea Clastic Sedimentation Processes: a preface

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The aim of the Special Issue is to focus current research on processes that lead to widespread sedimentary deposits in the deep sea. Most of our knowledge of the ocean lies in shallower waters, whereas deep waters largely remain a mystery, even though there is increasing reliance on these areas for food, energy and minerals amongst other resources. The deep sea is in fact increasingly targeted by exploration for economic resources (especially hydrocarbons and precious metals) and for infrastructure installations (e.g. pipelines, telecominciation cables, production platforms). It is also the ultimate sink for elements such as carbon that associate with sediments, so it is important to understand residence and recycle times that these processes entail.

Sedimentary deposits of the deep sea are dominated by three principal processes: mass-failures, turbidity currents, and contour currents. These processes are often interdependent; one beginning after another or providing material that is eventually acted upon by a subsequent process. Submarine mass failures **(Fig. 1)** transport sediment from the shelf or upper slope to the deep ocean resulting in mass-transport deposits (MTDs). A mass failure is initiated when the downward driving stress (gravity) exceeds the resisting stress of the seafloor slope material, causing movements along one or more décollement surfaces. Submarine MTDs are generally orders of magnitude larger than their subaerial counterparts, sometimes including 1000's of km^3 of sediment. Turbidites **(Fig. 1)** are the geologic deposits of turbidity currents, which are sediment density flows responsible for distributing vast amounts of clastic sediment into the deep ocean. Turbidites may result from confined or unconfined density flows and form the vast majority of sediment of abyssal plains of the deep sea. Countourites **(Fig. 1)** are produced by thermohaline-induced deepwater bottom currents and may be influenced by wind, tidal and Coriolis forces. The structure and geomorphology of contourite deposits is mainly influenced by the deepwater bottom-current velocity, sediment supply, and seafloor morphology. Single contourites deposits may be in excess of 100,000 km^2 in area, reflecting the importance of this process in the deep sea.

Deep sea survey technologies such as multibeam sonar, improved seismic reflection, 3D seismic reflection and autonomous underwater vehicles in addition to improved numerical simulations have done much to improve our understanding of these processes within the past decade. Scientific study of these processes have flourished to the point that they have become singularly focussed as separate sub-disciplines (e.g. IGCP 640 S4SLIDE on sediment mass failure, IGCP 619 on contourites, and the turbidite research groups at Aberdeen University and University of Leeds, for example).

It is the objective of this special issue to present a number of modern studies of these dominant deep sea sedimentation processes and to specifically highlight the interconnectivity of the processes, exemplifying that in many cases they are coupled and mutually dependent. The Special Issue is constituted mainly from three sources: eleven papers following two conferences held at the end of 2015 (AGU in San Francisco and the 7th

International Symposium on Submarine Mass Movements and Their Consequences in Wellington, NZ) and four papers initially submitted to Marine Geology regular issues and subsequently invited to join the Special Issue.

Covault et al. review the morphodynamic evolution and stratigraphic products of bedforms (10-100 m wavelength) bounded by internal hydraulic jumps ("cyclic steps") in turbidity currents on the western North American margin. The study is integrated with short-term direct monitoring, numerical modeling, and physical experiments. The investigated bedforms are fundamentally important building blocks of the morphodynamic evolution of architectural elements of deep-water depositional systems. They are important features of channel initiation and maintenance.

Puig et al. analysed the morphology of canyon-heads in the Alías-Almanzora canyon system (SW Mediterranean), stressing on the importance of the canyon head location with respect to the principal sedimentary source, which ultimately determined their main geomorphological traits. They generally show an onshore continuation with rivers or intermittent creeks, but some resulted from the formation and merging of linear gullies and are disconnected from any river source. Presumably related to hyperpycnal flows during flash flood events or storm-induced turbidity flows, canyon-heads are key areas for understanding the shelf-to-canyon sedimentary dynamics and assessing the predominant hydrodynamic processes.

Shumaker et al. studied the evolution of hundreds of meters-thick nested complexes of seafloor gullies over a roughly 2 million year timespan in 3D seismic data of Pliocene-Pleistocene continental slope strata in the Taranaki Basin, New Zealand. Slope gradients on gully axes and interfluves are nearly identical, suggesting that gullies are integral to slope sedimentation processes and that the flows maintaining them are also responsible for continental slope sedimentation. These flows are interpreted to be tens of kilometers wide and up to 40 m thick, dilute, sheet-like turbidity currents (possibly generated by large-scale landslide events), which produce net-aggradational, shallowly incised gullies due to autogenic instabilities that promote regularly spaced variations in erosion and deposition.

Maier et al. make use of integrated high-resolution datasets to quantify morphodynamic sensitivity of seafloor gradients acting throughout deep-water depositional systems on the continental slope offshore Los Angeles, California. The active right-lateral Palos Verdes Fault creates and maintains variations in seafloor gradient (also related to landslide headwall scarps) that influence sediment accumulation, depositional environment, grain size of deposits, and seafloor morphology. Deposition of fine-grained sediments is inversely correlated to small changes (~0.5-1.5°) in underlying gradient. These results help to bridge gaps in scale between existing deep-sea and experimental datasets and may provide constraints for future numerical modeling studies of sediment flow dynamics.

Hesse and Khodabakhsh review Labrador Sea Heinrich layers, which are distinct, normally decimetre to centimetre thick layers of ice-rafted debris with low foraminifera contents deposited in the North Atlantic during the Late and middle Pleistocene. They show five distinct depositional facies involving auxiliary processes of particle transport besides ice rafting to explain their anomalous, metre thickness in proximal sites near the iceberg source. The high concentrations of fine-grained detrital carbonate in Heinrich layers is inferred to have been supplied by bottom-following turbidity flows and lofted sediment columns arising from freshwater generated turbidity currents. The level of surface turbidity during Heinrich events though was probably considerably higher than at other times.

Sun et al. dissect three superimposed Quaternary MTDs interbedded with turbidites in the Pearl River Mouth Basin of the northern South China Sea using high-resolution 3D seismic data. Each MTD is characterized by linear grooves at its base, by chaotic seismic reflections and complex internal structures, such as remnant, rafted and faulted blocks. Headscarp locations are controlled by both the underlying structures (such as basement highs and related faults) and the distribution of weak layers that are probably gas-bearing thin turbidite silt beds. Most of the volume of MTDs was derived by local failure of lower continental slope sediments rather than by transport down the sediment pathway for failed sediments and turbidites.

Li et al. studied the Sahara Slide Complex offshore of NW Africa, a giant submarine landslide, with an estimated run-out length of ~900 km, ~35-km wide upper headwall, an evacuated volume exceeding 150 km^3 and associated turbidites. The morphology of the upper headwall is the result of multiple failure events, which probably occurred retrogressively in the form of gravity spreading and translational slides on three different widespread glide planes suggesting failure along pronounced, continuous weak layers. The presence of weak layers is considered as the main preconditioning factor for instability in this landslide. The young age of the failure, dated at ~2 ka BP during a sea-level highstand, calls for a reassessment of slope instability and tsunamigenic potential on continental margins that are considered stable.

Bahk et al. studied three successive Pliocene MTD units interbedded with turbidites in the Ulleung Basin, characterized by continuous strong-amplitude negative basal reflections with transparent to chaotic internal seismic facies. In each MTD unit, bulk density, P-wave velocity, and resistivity values gradually increase in the basal part and abruptly decrease at the lower boundary. Nine sedimentary facies indicate a variety of mass-transport processes such as sliding with brittle to plastic deformation and high-to low-viscosity debris flows. The presence of a sandy MTD accounts for the basal densification and strong-amplitude negative basal reflections. Absence of such sandy basal MTDs elsewhere implies unpredictability of lithologic characteristics in MTDs with similar seismic reflection signatures.

Elger et al. analyzed submarine landslides on the glaciated NW Svalbard continental margin, where the alternation of rapidly deposited glaciogenic and contourite material generates overpressure in the sediment column. The landslides are developed on contourite drifts bounded seaward by ridge-transform junctions. Different slope failure histories are strongly influenced by differences in local controlling factors, including slope gradient, tectonic activity, changes of climate and oceanography, gas hydrates and fluid migration systems,. In particular, toe erosion,which is dependent on the throw of normal faults, and the different thickness and geometry of contourite deposits can result in a critical slope morphology and exert pronounced effects on slope stability.

León et al. presents a combined onshore-offshore morpho-structural characterization of the El Golfo giant landslide, island of El Hierro (Canary Archipelago). The subaerial headscarp shows a discontinuous arcuate profile formed by two nested semi-circular amphitheaters that extend offshore along a smooth chute, suggesting the occurrence of at least two large retrogressive events. Channels/gullies and escarpments developed along the submarine sector of the scar also indicate smaller-scale events and predominance of sediment bypass. In the lower slope, two subunits of submarine mass transport deposits, are identified. The distal deep-water area is characterized by multiple allocthonous blocks up to 1.5 km in diameter and 300 m high, randomly distributed on the seafloor. These blocks run-out on the deep seafloor more than 30 km from the headscarp source area. Each of the MTD's has a volume on the order of 100's km^3.

Gong et al. infer flow processes and sedimentation in mixed contourite-turbidite channels using 3D seismic data from the NW South China Sea margin, coupled with the quantification of oceanographic processes and morphological results. Contour currents resulting from the Northern Pacific Deep Water flowing through the bends of contourite channels around a topographic high lead to an imbalance in the transverse direction, around the bend, between 3 competing forces (i.e., upslope directed Coriolis forces versus downslope directed centrifugal and pressure-gradient forces). The resulting helical flow circulation, which promoted asymmetric intra-channel deposition (i.e., downslope deposition versus upslope erosion), also forces contourite channels to consistently migrate in an upslope direction.

Baldwin et al. describe abyssal sediment waves in seismic profiles from the Caroline Basin, western Pacific Ocean, which indicate bottom currents at this location have shaped the seabed beginning in the early to mid-Miocene. About 135 m thickness of sediment waves with roughly 9–36 m wave heights and 1–2 km wavelengths accumulated, most likely in carbonate-rich sediments (based on DSDP Site 62, 450 km to the south) in response to bottom water flow that was documented at ODP Site 1124 in the SW Pacific. Steady growth and slow NW migration continued for much of the Miocene. About 212 m below the seafloor, lateral migration halted and wave growth slowed. This evolution is inferred to be linked to development of global thermohaline circulation.

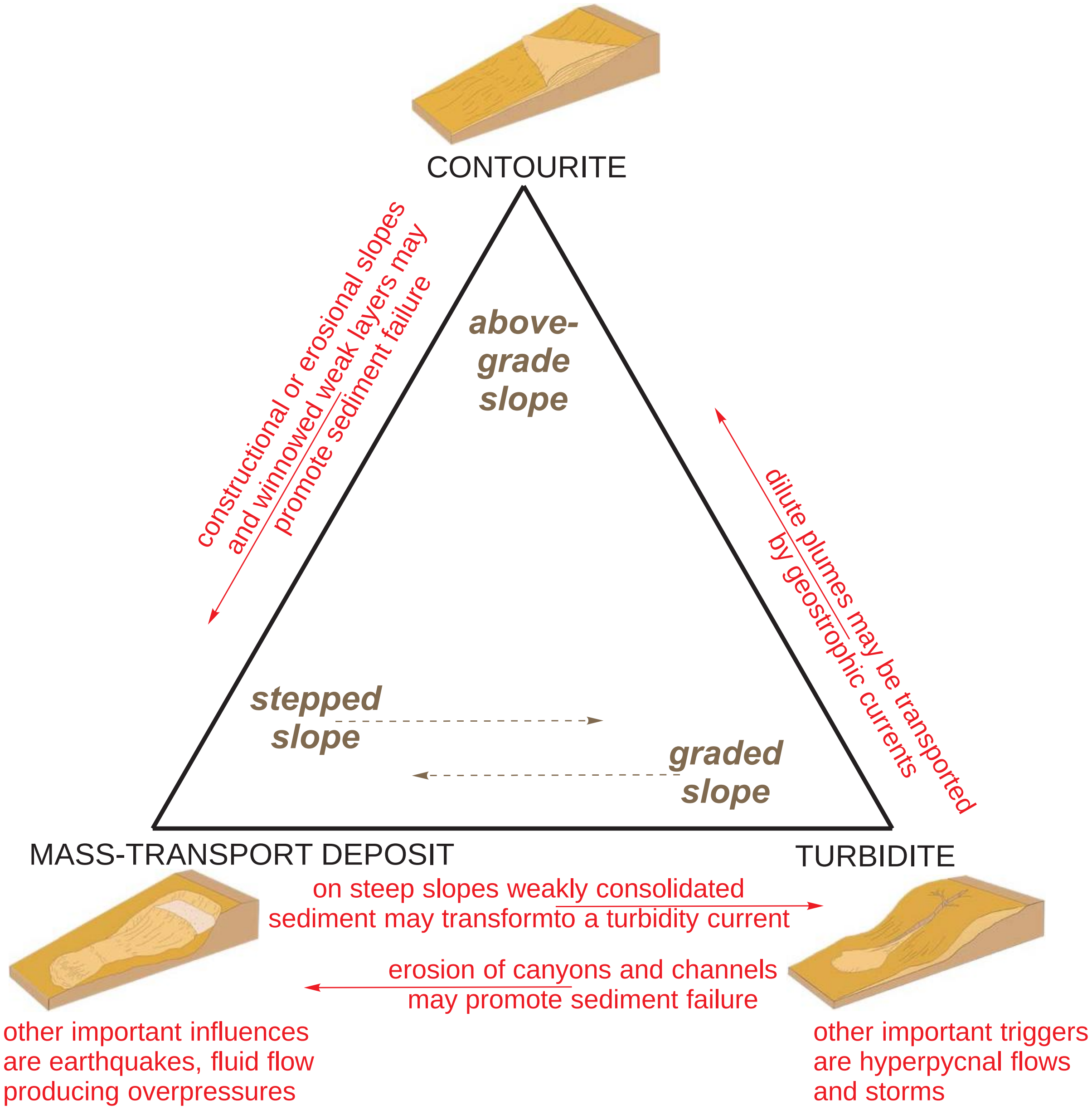
Rashid et al. documents the stratigraphy of the past 48,000 years and the record of sediment failures on a shallow plastered contourite drift swept by the Labrador Current on the SE Grand Banks (eastern Canada). Geotechnical analysis shows that the latest Quaternary sediments are mildly underconsolidated, perhaps due to high sedimentation rates (up to 0.5 m/ka) enhanced by leakage of deep fluids. Atterberg limit measurements of silty sediments indicate susceptibility to liquefaction under cyclic loading. These shallow water contourite deposits have a higher sand and coarse silt content, much less biogenic material, and more rapid variations in sediment and geotechnical properties than those of the deep-water equivalents, all of which make them more susceptible to sediment failure.

Newton and Huuse review the extensive geological and geophysical data available from the late Cenozoic Atlantic margin of Norway, where periods of erosion and deposition were controlled by multiple processes (including fluvial, glacial, and oceanographic) acting independently and together. Contourites along the margin provide insight into the connection of the Arctic and Atlantic Oceans from the Miocene onward. Glaciation caused topographic relief changes and generated offshore geohazards such as the Storegga Slide, which mobilised some ~3000 km^3 of sediments during the Holocene. Glaciogenic debris flows have also been observed as a key depositional process at the shelf edge and have contributed to the generation of erosive turbidity currents and canyon formation.

Mosher et al. show the influences of turbidity currents, contour currents and sediment mass failures on the geomorphology of the deep-water NW Atlantic margin. They classify the margin into four categories based on their bathymetric shape: graded, above-grade, stepped and out-of-grade. These shapes were created as a function of the balance between sediment accumulation and removal. This descriptive method of classifying continental margins facilitates interpretation of the dominant sedimentary processes. Turbidity currents developed graded slopes by slope by-pass. Detached drifts formed above-grade slopes whereas plastered drifts formed stepped ones. Large mass-failures created out-of-grade slopes (below grade) while smaller failures created above-grade or stepped slopes.

All of the papers in this Special Issue describe sedimentary processes that, independently or together, account for movement of sediment from shallow to deep water and lead to widespread deposits in the deep sea (**Fig. 1**). In addition to the significance of mass-failures, turbidity currents, and contour currents, the importance of glacial processes in clastic deep-water sedimentation has been highlighted, e.g., for producing glacigenic debris flow deposits, ice-rafted debris, melt-water flows and landslides. Most papers are focused on one of the dominant deep-sea sedimentation processes, but others, like Mosher et al., Newton et al., Rashid et al., and Elger et al. call attention to the relationships among processes, identifying that in a multitude of cases they are inherently coupled. Further research is needed to explore the various interconnections among different processes and a growing number of studies and sessions in scientific congresses are expected to deal with mixed systems.

Figure 1: Ternary diagram signifying the continuum of clastic deep-sea sedimentation processes that exists between sediment mass-failure, turbidity currents, and contour currents.


CONTOURITE
constructional or erosional slopes and winnowed weak layers may promote sediment failure
above-grade slope
dilute plumes may be transported by geostrophic currents
stepped slope
graded slope
MASS-TRANSPORT DEPOSIT
TURBIDITE
on steep slopes weakly consolidated sediment may transformto a turbidity current
erosion of canyons and channels may promote sediment failure
other important influences are earthquakes, fluid flow producing overpressures
other important triggers are hyperpycnal flows and storms