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Reply to the comment on “A new classification system for mixed (turbidite-contourite) depositional systems: Examples, conceptual models and diagnostic criteria for modern and ancient records” by Sara Rodrigues, F. Javier Hernández-Molina, Marco Fonnesu, Elda Miramontes, Michele Rebesco, D. Calvin Campbell [Earth-Science Reviews (2022), 104030]

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1. Introduction

We appreciate the comments by G. Shanmugam on the paper “**A new classification system for mixed (turbidite-contourite) depositional systems: Examples, conceptual models and diagnostic criteria for modern and ancient records**” **by S. Rodrigues, F.J. Hernández-Molina, M. Fonnesu, E. Miramontes, M. Rebesco, D. C. Campbell [Earth-Science Reviews (2022), 104,030]**”. Most of the comments from G. Shanmugam refer to the sedimentary facies scale, with special emphasis on the distinct types of deposits and their definitions. It was quite a surprise that G. Shanmugam’s comments did not include any remarks about the descriptions or discussions elaborated in Rodrigues et al. (2022a), such as the large-scale morphological features recognized in mixed (turbidite-contourite) depositional systems through bathymetric or seismic data or the newly proposed classification scheme. Rodrigues et al. (2022a) has a very brief sub-section on the sedimentary facies recognized in mixed systems (e.g., Section *5.4 Sedimentary facies and deposits of mixed systems*, page 22), which is based on a few key contributions from past literature (such as Mutti and Carminatti, 2012; Fonnesu et al., 2020; Rodrigues et al., 2022b). His comments appear to be a compilation of his own assertions and do not provide a clear link to the contribution of Rodrigues et al. (2022a) or to the study of mixed depositional systems.

Initially, G. Shanmugam focuses his comments on the multitude of turbidite and bottom current processes that occur in contourite and turbidite settings, as well as their definitions and models. He states that Rodrigues et al., (2022a) proposed a new classification for mixed depositional systems “*based on their notion that there is only one type of turbidite and that there is only one type of contourite in deep-marine systems*”, but the authors have never made such a statement in their manuscript. He also reports that Rodrigues et al. (2022a) “*failed to provide a clear and precise definition of the terms turbidite, contourite, and*

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bottom current", but nevertheless the authors have provided definitions and references for those terms. Accordingly, G. Shanmugam outlined four distinct problems in Rodrigues et al. (2022a) review paper, namely (1) the turbidite problem, (2) the contourite problem, (3) the bottom-current problem, and (4) the seismic geometry vs. sedimentology problem.

As indicated above, G. Shanmugam's criticism is focused on turbidite and bottom current processes in non-mixed settings, while very few points are made about these processes in mixed depositional systems. As clearly stated in the Introduction of Rodrigues et al. (2022a), the aim of this review paper was to "*compile all currently known cases*", "*present new undocumented examples*" and "*compare their lateral migration, stratigraphic stacking patterns and seismic facies*". In addition, "*a new classification system is proposed, along with clear diagnostic criteria, to address some of the previous inconsistencies and to characterize the spatial and temporal variability of mixed systems*". Therefore, we believe G. Shanmugam has misinterpreted the aims of this review paper and raised issues unrelated to or not covered in this study. He uses this comment to highlight points that are controversial in literature or that follow opinions different from his own publications, in order to open a discussion that is not fully relevant to the identification or recognition of mixed systems. In fact, the problems raised in Shanmugam's comments have been a recurrent point of debate for several years now. Deep-water processes, their definitions and models have been profusely discussed by him and other authors since the 50s (Kuenen and Migliorini, 1950; Bouma, 1962; Middleton and Hampton, 1973; Lowe, 1982; Cullis et al., 2018). We do agree that there is a high degree of variability in deep-water turbidite and bottom current processes, both in contourite and turbidite settings, as well as in mixed depositional settings. However, the paper by Rodrigues et al. (2022a) focuses solely on reviewing the interactions between turbidite and bottom currents in mixed depositional systems to improve their recognition and classification and, therefore, does not approach these processes separately in other depositional environments (e.g., in pure contourite or turbidite settings). The authors will therefore not partake in the debate surrounding the definitions and models of these processes in non-mixed depositional environments. However, the authors will reply to the points raised about these processes in mixed depositional systems, specifically points 1–4 in problem 1, points 1–2 in problem 2, points 7–9 in problem 3 and point 12 in problem 4.

2. Problem 1: The turbidite problem

G. Shanmugam indicates that Rodrigues et al. (2022a) lacks sufficient cover on turbidite papers and should include further references for their facies, models and types. Considering that Rodrigues et al. (2022a) is focused solely on the interactions between turbidites and bottom currents in mixed systems, it cannot cover a full review of turbidite facies or models in dominant turbidite settings, which do not take into consideration the potential interactions that may occur between turbidity and bottom currents. Furthermore, Rodrigues et al. (2022a) cannot refer to turbidite deposits or types that have yet to be observed in mixed systems due to the lack of evidence or case studies. The study of mixed systems is considered relatively "new" with only ~47 currently known cases in existence (see **Fig. 1** and **Table S1**). Nevertheless, Rodrigues et al. (2022a) has included several references to extensive reviews of turbidite models and deposits, such as Haughton et al. (2009), Meiburg and Kneller (2010), Covault et al. (2012), Cullis et al. (2018) and Hubbard et al. (2020), among others (see pages 1, 6, 7 and 10). These contributions have mentioned the references requested by G. Shanmugam, along with other pioneering works (such as Lowe 1982; Mutti and Normark 1987; Pickering et al. 1995, among others) and have furthermore discussed the points raised in Problem 1.

G. Shanmugam also suggests that the authors should clarify which definitions did they adopt for the identification of turbidites. In Section *3.3 Nomenclature*, Rodrigues et al. (2022a) clearly outlined that they have taken into consideration the studies of Macauley and Hubbard (2013), Hubbard et al. (2014, 2020) and Cullis et al. (2018), which have studied the hierarchical classifications and definitions of turbidites and their depositional systems. In addition, our review paper also refers to the pioneering works of Bouma (1972), Middleton and Hampton (1973), Mutti et al. (1980), Postma (1986) and Mutti (1992), among others. Rodrigues et al. (2022a) also considers the recent studies by Azpiroz-Zabala et al. (2017a, 2017b), de Castro et al. (2020), Fonnesu et al. (2020), Fuhrmann et al. (2020), Miramontes et al. (2020) and Rodrigues et al. (2022b) dealing with facies analysis, grain-size and empirical field data (along with several others in pages 4–6, 18–22 and 23–24), as they have investigated turbidites in mixed systems through sediment cores, well data, moorings and flume tank experiments. The authors therefore disagree with the problem raised by G. Shanmugam, as they have provided extensive references for turbidite processes and their deposits.

3. Problem 2: The contourite problem

Regarding contourites, G. Shanmugam states that Rodrigues et al. (2022a) needs to define the term "contourite" and that the authors basically follow the definition of Hollister (1967). In Section *3.3 Nomenclature*, the authors clearly outline that they followed the definitions presented in Faugères et al. (1999) and Rebesco et al. (2014), which consider that contourites and their features are defined as "*formed or substantially reworked by the persistent action of along-slope bottom currents*" (see page 4 of Rodrigues et al. 2022a). These works made a comprehensive review on contourites and bottom-current processes and take into consideration all of the previously proposed definitions (including Heezen and Hollister 1964; Hollister 1967; Lovell and Stow 1981; and Faugères et al. 1999, among others). In addition, G. Shanmugam asserts that if Rodrigues et al. (2022a) adopted the broader definition of Lovell and Stow (1981), the authors must explain why they consider tidalites as contourites. This is a gross assumption as Lovell and Stow (1981) is cited only in **Fig. 2** of Rodrigues et al. (2022a), which shows all of the previous studies that have mentioned or investigated mixed depositional systems since the 70s. Moreover, Lovell and Stow (1981) focused primarily on the identification of ancient sandy contourites in various depositional settings, all in "*relatively deep water, certainly below wave base*" (quoted from page 3 of Lovell and Stow 1981) and therefore do not consider contourites to be sediments deposited by tidal currents.

4. Problem 3: The bottom-current problem

Rebesco et al. (2014), Hernández-Molina et al. (2016) and Yin et al. (2019) have clarified that water masses are a consequence of the thermohaline circulation and normally represent geostrophic flow (Wunsch 2002; Rahmstorf 2006; Kuhlbrodt et al. 2007; Cochran et al. 2019). But there are a number of hydrographic processes that modulate water mass circulation, such as benthic storms, overflows, interfaces between water masses, vertical eddies, horizontal vortices, tides and internal tides, internal waves and solitons and tsunami related traction currents. Water masses move continuously through the oceans' basins (Rahmstorf 2006; Kuhlbrodt et al. 2007) and any persistent current near the seafloor can be considered a bottom current (Rebesco et al. 2008). Bottom currents are therefore defined as semi-permanent water-mass flows, capable of eroding, transporting and depositing up to gravel-sized sediment in seafloor environments (Rebesco et al. 2008; Rebesco et al. 2014). Rodrigues et al. (2022a) clearly delineates this definition in the Introduction (see page 1) and furthermore supports it with relevant, key references (such as Rebesco et al. (2014), Shanmugam (2008), etc.).

In Rodrigues et al. (2022a), mixed systems are usually depicted as a result of distinct interactions between along-slope bottom currents (marked by blue arrows) and down-slope gravity currents (drawn as red arrows), as shown in **Fig. 18** and also in **Figs. 15–17**. Nearly 30 years ago, Shanmugam et al. (1993) also proposed a conceptual model for the formation of mixed systems through the interaction of bottom and turbidity currents. But the problem with the model portrayed in Shanmugam et al. (1993) is that it considers mixed systems to be a result of bottom current reworking only. Furthermore, G. Shanmugam defines hybrid flows and their deposits as “hybridites” (Shanmugam 2021). However, the term “hybridite” has not been adopted by other authors and could create more confusion due to the more famous definition of “hybrid events beds”, which characterize gravity flows generated beds that incur a flow transformation from frictional to mostly cohesive flows (Haughton et al. 2009; Fonnesu et al. 2015, 2018). Most continental margins host complex interactions between along- and down-slope processes, which create numerous features and deposits across deep-marine settings. Frequent interactions may form mixed depositional systems composed of bottom current reworked sands (BCRS), pure turbidites and contourites or other deep-water deposits (Viana et al. 1998; Mulder et al. 2008; de Castro et al. 2020; Rodrigues et al. 2022b). Some studies have drawn a distinction between mixed and hybrid systems (Sansom 2018; Fonnesu et al. 2020; Fuhrmann et al. 2020). These studies tend to assert that mixed systems deal with a wider spectrum of features and deposits formed under synchronous and asynchronous interactions (Mulder et al. 2008; Rodrigues et al. 2022a), whereas hybrid systems only form under synchronous interactions (Sansom 2018; Fonnesu et al. 2020; Fuhrmann et al. 2020). Key examples of mixed depositional systems have been identified offshore Argentina (Rodrigues et al. 2021), Uruguay (Creaser et al. 2017), Mozambique (Fonnesu et al. 2020; Miramontes et al. 2021), Tanzania (Sansom 2018; Fuhrmann et al. 2020), Antarctic Peninsula (Rebesco et al. 1998, 2002; Hernández-Molina et al. 2017; Rodrigues et al. 2022b, 2022c), Southeast Greenland (Rasmussen et al. 2003) and Canada (Deptuck and Kendell 2020; Rodrigues et al. 2022d), as well as along the Southwest Iberian margin (Mencaroni et al. 2021) and in the South China Sea (Gong et al. 2013). Innovative experiments by Miramontes et al. (2020) have furthermore demonstrated how mixed systems form in response to down- and along-slope sedimentary processes and that when along- and down-slope currents are contemporaneous, their channels migrate in an up-current direction. Rodrigues et al. (2022a) has therefore taken into consideration the complexity surrounding mixed systems (based on recent and ancient examples) and proposed a three-part classification scheme for mixed systems based on their location, elongation, dimensions, lateral migration, spatial and temporal variability: 1) contourite-dominated mixed systems, 2) synchronous systems, and 3) turbidite-dominated mixed systems. Diverse interactions between along- and down-slope processes appear to occur across these systems, from synchronous (where the bottom and turbidity currents occur coevally in time and space) to asynchronous and passive interactions (where the bottom and turbidity currents do not interact in time and more rarely, in space). These interactions are responsible for building a myriad of deposits across proximal to distal depositional settings, such as mixed / hybrid sedimentary facies, interfingering sequences of contourites and turbidites or reworked turbidite deposits. This new classification scheme can thus be used in ongoing studies or future research to better understand the interactions between down- and along-slope processes as well as their resulting products.

As reported above, Rodrigues et al. (2022a) does not follow the concept of Lovell and Stow (1981). We are therefore surprised that G. Shanmugam still assumes that tidal currents correspond to up- and down-flows along submarine canyons or channels. Tides are omnipresent in the global ocean (Dykstra 2012), with varying degrees of influence, and are capable of controlling water mass circulation along the slope, as previously reported by oceanographers (e.g., Jonkers et al. 2010; Zhang et al. 2016), marine sedimentologists (e.g., Rebesco et al. 2014; Hernández-Molina et al. 2016; Yin et al. 2019; de Weger et al. 2021) and numerical simulations (e.g., Chen et al. 2016).

5. Problem 4: The seismic geometry vs. process sedimentology problem

G. Shanmugam’s comments about depositional processes being interpreted solely from seismic facies of ancient strata is also out of the scope of Rodrigues et al. (2022a). There are many types of seismic data (2D vs. 3D), which have significantly different resolutions. This problem therefore revolves around the scale of the work and depends strongly on the seismic resolution of the available seismic dataset. Seismic analysis and seismic facies are essential to identify and recognize distinct sedimentary environments and their evolution through time on ancient strata in marine basins. Seismic data allows to decode the sedimentary processes and products at a long-term spatial scale, however it is limited by the vertical and horizontal resolution of the seismic dataset and, therefore, its resolution cannot always be compared to the sedimentary facies or facies associations identified in outcrops or exploration wells. Nevertheless, there are some case studies in past literature that were able to calibrate seismic to well data in mixed systems and which were cited in Rodrigues et al. (2022a). For example, Fonnesu et al. (2020) calibrated the seismic and core facies of the Mozambican Eocene mixed systems; Fuhrmann et al. (2020) and Sansom (2018) focused on the Tanzanian Cretaceous to Paleogene hybrid systems; Mencaroni et al. (2021) studied the modern mixed drift developed offshore SW Iberia; Mutti et al. (2014) calibrated the Brazilian Eocene-Oligocene mixed systems; de Castro et al. (2020) studied the Gulf of Cadiz’s BCRS and Rodrigues et al. (2022b) investigated the modern Antarctica Peninsula mixed systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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