Multidisciplinary Study of Marine Archives: Reconstruction of Sea-Level, Sediment Yields, Sediment Sources, Paleoclimate, Paleoceanography and Vertical Movement on Margins: Examples from the Western Mediterranean Sea

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Abstract

The numerous processes (superficial and deep) occurring on margins, their origins, consequences, interactions and quantifications are only very partially described and understood. The identification of the relative role of factors is sometimes completely contradictory between authors. Here, we showed the results of a long-term multidecadal and multidisciplinary study (using geophysical, geological, stratigraphic, paleontological, geomorphologic, geochemical, microbiological and numerical models) in the Western Mediterranean Sea that acts as a natural laboratory at many different scales. We showed how sediments efficiently recorded at the same time: variations of glacio-eustatic sea-level changes, variations of sediments yield and sources, and also enabled quantifying vertical movements and geodynamic worldwide events but also detailed regional mass transport, turbidites and contourites deposits. They are also an archive of paleoclimatic, palaeoceanographic and diagenetic processes.

Keywords

Sea-level • Subsidence • Sediment yields • Erosion • Isostasy • Messinian • Pliocene • Quaternary • Mass-transport • Contourites

1 Introduction

The study of margins is stimulated by several economic challenges like that of the oil industry, on the one hand, that of mineral exploitation (extraction of sand, gravel, diamonds,), on the other, and finally that of coastal activities (coastal management, fishing activities, renewable marine energy and human settlement), all in relation to global changes, in particular, the consideration of past, present and future climate change.

However, the mechanisms active on the so-called passive margins are numerous, and their interactions remain poorly understood, especially the link between deep structural processes (rifting, extension, subsidence) and surficial processes (erosion, transfer, deposition processes from the continent to the deep basin, impact of climate, currents, diagenetic processes).

The study of sediments on margins is fundamental for a better understanding of the organization and mechanisms of deposition in four dimensions (in space and time) and their link to deeper processes. It is, in fact, the geological history that needs to be reconstructed while determining, prioritizing and quantifying the relative importance of the various parameters (tectonic, climatic, eustatic and hydrodynamic) that have controlled sedimentation and sediment preservation. These fundamental questions are recurrent at all scales of time and space.

2 Settings and Materials

Here, we showed a long-term multidecadal study in the Western Mediterranean Sea that has been undertaken at different scales. Due to its geographical and political situation, the Western Mediterranean represents a key area whose exploration allows crucial progress on the study of margins. The Mediterranean represents what can be called a natural laboratory, i.e., a small site where hypotheses and models of fundamental interest for Earth Sciences can be tested in a more global way: on the formation and evolution of margins, on sedimentary records, sea-level variations, sediment fluxes, on paleoclimate influence and on the influence of tectonic heritage on vertical movements.

This long-term study took advantage of a large academic and industrial database and effective collaborations during the GDR Marges Gulf of Lions (2000–2007), then the Action Marges Programs (2008–2016) and the Labex Mer (2010–2018) and ISblue (2019–2029) ANR Programs, all with numerous cruises using the French Oceanographic vessels and facilities (http://campagnes.flotteoceanographique.fr). In addition, the EC-funded Eurostrataform, TOPO-EUROPE and PROMESS 1 projects gave access to in situ-monitoring of present-day, deeply rooted processes, and long (100-300 m long) boreholes, respectively.

3 Results and Discussion

3.1 Sediments: An Archive of Glacio-Eustatic Variations and Their Impacts

We showed for the first time through a combination of seismic stratigraphic interpretation, cores and stratigraphic modelling that the sequences preserved on the outer shelf corresponded to 100,000-year climate cycles (Rabineau et al. 2005) resolving a controversy dating back to the 1990s. We then proposed a re-evaluation of sea-level amplitudes at the last five glacial maxima based on direct observation of paleo-shorelines by correcting their present-day depths from post-depositional subsidence (Rabineau et al. 2006, 2014) (Fig. 1).

A higher-frequency eustatism is also imprinted in sediments at 20 to 40 ka but also at the scale of bond cycles (7 ka) (Bassetti et al. 2006; Jouet et al. 2006; Jouet 2007; Mauffrey et al. 2015). Those glacio-eustatic sea-level changes have a strong impact on canyons functioning

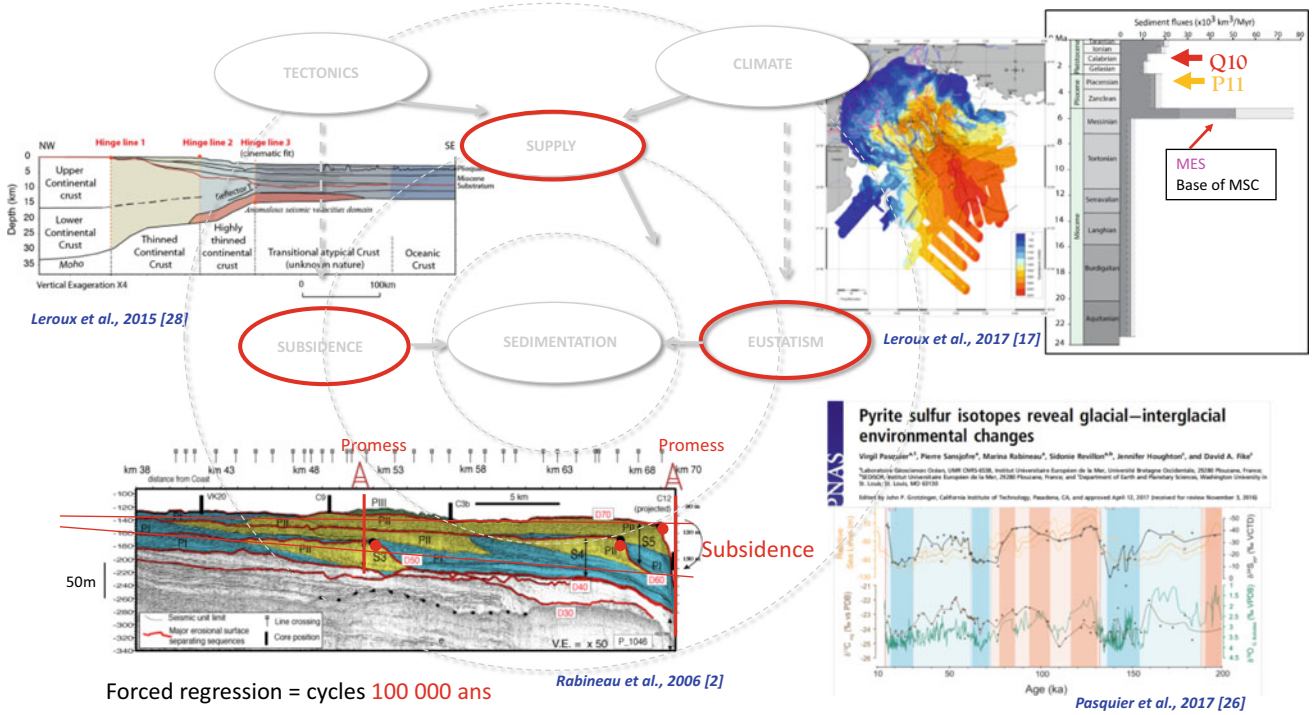

Fig. 1 Quantification of different factors influencing sediment transfer and sediment record (modified from Rabineau et al. (2006), Leroux et al. (2017); Pasquier et al. (2017), Leroux et al. (2015a)

(Baztan et al. 2005; Gaudin et al. 2006) and sediment delivery to the deep-sea through turbidites, mass-transport deposits and contourites (Droz et al. 2006; Lombo Tombo et al. 2015; Miramontes et al. 2016, 2019; Dennielou et al. 2019; Badhani et al. 2019).

On larger scale, two erosional surfaces D1 and D0 have been interpreted as corresponding to two major paleoclimatic stages over the entire Plio-Quaternary period: the establishment of 100,000-year cyclicities around 0.9 Ma and the establishment of glaciations in the Northern Hemisphere around 2.6 Ma (Leroux et al. 2014).

3.2 Sediments: An Archive of Sediment Fluxes

Leroux established for the first time and with an unprecedented resolution on a global scale, the sedimentary volumes and erosion/deposit balances over the last 6 Ma in the Liguro-Provencal Basin (Leroux et al. 2017, 2018) (Fig. 1). This study describes a very strong increase (×2) in detrital flows around 1 Ma in relation to the climate changes of the Mid-Pleistocene Revolution. The global acceleration (×3) of terrigenous flows over the last 5 Ma, defended by many authors and correlated with an uplift of the great orogens (here in connection with the Alps), is also observed in the Liguro-Provencal basin, even if the famous Messinian Salinity Crisis tends to disturb the signal (Leroux et al. 2017). These results are confirmed by onshore multi-approach quantification of denudation rates using cosmologic and geomorphologic methods (Molliex et al. 2016). A similar study has been performed in the Valencia Basin (Pellen et al. 2016). Pellen et al. (Pellen et al. 2019) also addressed the apparent paradox concerning the Ebro and Rhône basins, i.e., the fact that the current drainage areas of the two rivers are equivalent (85,835 km^2 and 98,800 km^2, respectively) while the Messinian river networks identified so far were very different (<100 km for the Ebro and >400 km for the Rhône). Pellen et al. (2019) solve this paradox by showing an incision length of the Ebro that extends well beyond the edge of the Miocene platform into the Valencia Basin and actually reaches 270 km-long. Pellen et al. (2019), also show that at the outlet of this river network, the product of Messinian erosion is preserved in the form of a forced regression prism identified in the Minorca Sub-basin.

3.3 Sediments: An Archive of Onshore Sources

Can we read in the offshore sediments the relative impact of the differentially eroded zones and therefore quantify the relative influence of onshore sources of sediments? This topic was studied using radiogenic isotopes Nd and Sr. This work has revealed unexpected variations in isotopic

compositions of Gulf of Lion sediments between periods of low sea levels and periods of high sea levels. Thus, during the glacial periods, sediments from the catchment basins draining the Languedoc-Roussillon, Lower Rhône and the Pyrenees dominate. Conversely, during interglacial periods, sediments from the Rhône catchment area (especially the upper Rhône) are predominant in the sediment mixture (Révillon et al. 2011).

Finally, the question of the relative part of terrigenous inputs compared to that of biogenic (in situ) inputs is critical for sediment flux studies and difficult to understand; it is therefore a strong uncertainty factor for quantification. This question is particularly true with regard to carbonate inputs, which occurs in different forms (terrigenous, biogenic, dissolved). In the "classical" studies, the authors focus mainly on the terrigenous fraction, i.e., the sedimentary fraction resulting from continental erosion transported to the sea by the action of rivers, winds, etc., as opposed to the carbonate fraction of biogenic origin, resulting mainly from biological production (organisms synthesizing carbonate exoskeletons such as foraminifera, nannofossils, bivalve shells, etc.). As a result, the authors equate the non-carbonated flux with the terrigenous flux.

The original use of elemental and isotopic geochemistry (87Sr/86Sr) on the carbonate fraction alone demonstrated that the sediments of the Aude-Hérault interfluvial (Promess drilling) correspond to a mixture between current and recent biogenic carbonates but also to much older carbonates (Jurassic, Cretaceous, Miocene) directly exported from the onshore watersheds (Pasquier et al. 2019a).

3.4 Sediments: An Archive of Paleoclimate and Microbial Activities

Can we use isotopic studies to decipher the relative role of sea-level and climate (hydrologic) changes? The variations in isotopic carbon (∂13C) and nitrogen (∂15 N) compositions of organic matter preserved in Gulf of Lion sediments shows a correlation of variations with sea level for the last G/IG cycle (MIS4 to MIS2). At the lowest sea level, the borehole is in a prodeltaic position with more negative (lighter) isotopic values. On the other hand, for the previous glacial (MIS6) and last interglacial (MIS5) it is the climate that predominates with strong periods of river discharges. We proposed that the latter results from the intensification of North Atlantic disturbances and precipitation in the Mediterranean (Pasquier et al. 2019b). On a smaller time-scale (Holocene), the influence of both melt-water pulses and hydrological changes were also found (Bassetti et al. 2016).

In addition to the analyses of organic carbon and nitrogen, a characterization of sulfur isotopes preserved in sedimentary pyrite was also carried out (Pasquier et al. 2017). Pasquier shows that the sediments deposited in the Gulf of Lions over the past 500,000 years have one of the highest isotopic variations reported to date (Fig. 1). In addition, the cyclicity observed suggests that strong climate control is at play, which calls into question the overall aspect of this geochemical tool. Two important mechanisms are proposed to explain this isotopic fractionation: (i) a modulation of bacterial activity by climate, and/or (ii) a local modulation related to the nature of the sediments involved in the formation of pyrite in relation to eustatic variations (Pasquier et al. 2017).

3.5 Sediments: An Archive of Vertical Movements and Geodynamic

The precise and detailed reading of sediment markers makes it possible to quantify vertical movements over the entire margin (Rabineau et al., 2006, 2014) and to show that sediments reflect, until very recent periods, the crustal structure of the margin and thus represent a window into the Earth's deep processes (Bache et al. 2010; Leroux et al. 2015a; Afilhado et al. 2015; Moulin et al. 2015; Arab et al. 2016; Do Couto et al. 2016) (Fig. 1).

Using a 3D-grid of seismic and wide-angle data, drillings and numerical stratigraphic modelling, a quantification of the post-rift vertical movements of the Provence Basin can be described with three domains of subsidence: seaward tilting on the platform and slope and purely vertical in the deep basin. These domains fit with the deeper crustal domains highlighted by wide-angle seismic data. The post-break-up sedimentary markers may therefore be used to identify the initial hinge lines of the rifting phase and the subsidence laws (Leroux et al. 2015b; Rabineau et al. 2015) (Fig. 1).

Using markers related to the Messinian salinity crisis (MSC, e.g., Clauzon et al. 2015), we were also able to propose a novel estimate of the isostatic rebound associated with this erosional and salinity crisis which reached 1.3 km of uplift at the edge of the platform in less than 700,000 years (maximum duration estimated for the crisis) (Rabineau et al. 2014).

Do Couto et al. (2016) also used stratigraphic markers on high-resolution 2D seismic profiles located in the Alboran Sea to propose that the pull of the dipping subducting lithosphere controlled the subsidence of the thickest depocenter during the Miocene.

Very recently, new heatflow measurments have been undertaken in the Western Mediterranéean Sea (Poort et al. 2020), Leroux and co-authors also showed that the MSC event was, in fact, linked to a world-wide geodynamic revolution (Leroux et al. 2018).

4 Conclusions

Our results obtained on the continental margins from oceanographic campaigns, deep boreholes or land-based studies, do shed new light on the understanding of the dynamics of the mantle, the lithosphere and their interactions with the hydrosphere and the biosphere and challenge certain concepts considered as established, thus demonstrating the importance of deeply holistic and integrated studies.

However, further studies are needed to better understand and quantify (1) the sediment origin and explanation of the variability of initial (upstream) erosion and the transfer time of those sediments to the deep-sea (2) the origin, importance and consequences of major oceanographic currents and their influence on the sediment record.

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