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Sedimentary markers in the Provençal Basin (western Mediterranean): a window into deep geodynamic processes

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Abstract :

Deep Earth dynamics impact so strongly on surface geological processes that we can use sediment palaeo-markers as a window into the deeper Earth. Derived from climatic and tectonic erosive actions on the continents, and related to eustasy, subsidence and isostasy, the sediment in a deep basin is the main recorder of these processes. Nevertheless, defining and quantifying the relative roles of parameters that interact to give the final sedimentary architecture is not a simple task. Using a 3D-grid of seismic and wide-angle data, boreholes and numerical stratigraphic modelling, we propose here a quantification of post-rift vertical movements in the Provençal Basin (West Mediterranean) involving three domains of subsidence: seaward tilting on the platform and the slope and purely vertical subsidence in the deep basin. These domains fit the deeper crustal domains highlighted by previous geophysical data. Post-break-up sedimentary markers may therefore be used to identify the initial hinge lines of the rifting phase and the subsidence laws.

INTRODUCTION

Whilst the link between deep Earth dynamics and surface geologic processes appears more and more as a key parameter, deep Earth research, encompassing fields such as seismology and mantle geodynamics, has traditionally operated distinctly from fields focusing on surface dynamics, such as sedimentology and geomorphology [Cloetingh *et al.,* 2013]. Nevertheless, the formation of passive continental margins -namely the process by which the continental lithosphere thins and subsides that remains one of the main challenges in Earth Science-, allows recording in its sedimentary layers the main steps of the Earth dynamic processes (subsidence, uplift, erosion, paleoclimate…). Passive margins represent a sink for sediments resulting from climate and tectonic erosive actions on the continents. Sedimentary layers also record the effects of eustasy, subsidence and isostasy, so that sediment appears as a storyteller of the Earth.

We present here a quantification of the post-rift vertical movements of the Provence Basin (West Mediterranean) based on the interpretation of sedimentary paleomarkers using a large 3D grid of seismic data, correlations with existing drillings, refraction data and validation by numerical stratigraphic modelling with Dionisos [Granjeon & Joseph, 1999]. The results of this 3D analysis emphasize the strong link between deep Earth dynamic processes and surface geologic processes.

Geological Setting

The Provence Basin reveals a structure and evolution corresponding to a young pair of rifted margins formed by the counter-clockwise rotation of the Corso–Sardinian micro-blocks with respect to the Ibero–European plate from the Late Eocene (Priabonian, 33.7 Ma), in a general context of collision between Africa and Europe (Figure 1-A). The opening took place at the southern end of the intra-European rift system, in a back-arc situation, in response to SE rollback of the slab of the African plate subducting beneath the European plate during an extensional phase. This Corso–Sardinian micro-continent rotation resulted in the emplacement of oceanic crust, starting in the Late Aquitanian (23 Ma to 19 Ma) and ending in the Langhian (about 15 Ma) [Olivet, 1996].

Thanks to its recent history, the subsidence in the Provence Basin is still underway at present and continually creates a large amount of space which favours a progressive filling that preserves the record of both the comings and goings of shorelines associated with the rise and fall of sea levels as well as the vertical movements of the margin [Rabineau *et al.,* 2005]. This fact, together with the substantial seismic database available on the Provence margin, including conventional standard seismic lines, high-resolution multi-channel data, very high-resolution profiles and industrial drillings make this basin ideal for constraining evolutionary and subsidence models of rifted continental margins using the sedimentary record.

DATA AND METHODS

Many global, regional and local factors have long been recognised to control the overall geometry and deposition of sediments but defining and quantifying the relative part of parameters interacting to produce the final sedimentary architecture of basins (subsidence, eustasy, sediment supply) is not a simple task. This has been one of the main goals of Seismic and Sequence Stratigraphy, as developed in the late 70's [Mitchum and Vail, 1977; Posamentier, 1988a]. At the same time, the development of quantitative techniques for geological analysis of sedimentary basins (geohistory analysis) were developed [Van Hinte, 1978; Jervey, 1988 ; Allen and Allen, 1990 ; Robin *et al.,* 1996]. They aim to produce a curve for subsidence and sediment accumulation rates through time. This is reached after a number of corrections (decompaction, paleobathymetry and absolute sea-level fluctuations) based on available datasets. The total subsidence is therefore partitioned into contributions from tectonic driving forces, thermal evolution, sediment loading and sea-level fluctuations [Steckler and Watts, 1978 ; Allen & Allen, 2005]. This backstripping depends on strong assumptions: the isostatic response of the lithosphere (e.g. Airy *vs* regional flexure), theoretical law for porosity, paleobathymetries, sea-level changes, densities of mantle and crust and thermal subsidence. Moreover, lateral and longitudinal variations along a margin are important and 1D modeling cannot be applied to the entire margin.

Rabineau *et al.* [2014] presented a new method to quantify the post-rift subsidence by the direct use of sedimentary geometries. In this paper, we apply this method in a 3D analysis of sedimentary geometries. In a first step, seismic stratigraphy and borehole data have been used to interpret and date the paleosurfaces on all profiles. Those have been correlated at a regional scale and converted in depth using ESP and sonic data from wells to generate isobath and isopach maps and to quantify sediment fluxes through time [Leroux, 2012]. In a second step, 10 fictitious regional lines were extracted from this set of isobath maps (Figure 1-B). We then built vertical dip and strike sections in order to quantify the 3D vertical evolution and potential tectonic deformation of the margin. On each profile, we adjusted paleosurfaces to straight lines, to mesure their subsidence rates (Figure 1-C). This method highlights not only the evolution of subsidence through time but also its spatial segmentation along the margin.

QUANTIFICATION OF SUBSIDENCE

For each profile, three domains of different subsidence were identified by dips and slope-breaks of each horizon[1] (Figure 1-C). Subsidence on the shelf is characterised by a Plio-Quaternary tilt of 0.16°/Myr about a rotational axis located 15 km landward of the present-day coastline (Hinge Line 1, HL1). This Plio-Quaternary subsidence is constant through time [Leroux *et al.,* 2014]. During the Miocene, this rate varies spatially: 0,12°/Myr on the western sections and 0.06°/Myr on the eastern sections, using the same hinge line 1.

Seawards of the hinge line 3 (HL3), in the distal part of the margin, Miocene and Plio-Quaternary reflectors are flat and parallel to the substratum, indicating a purely vertical subsidence. The strong early erosion at the top of the synrift deposits or directly on the substratum suggests a subaerial position of the substratum before the first post-rift deposit [Bache *et al.,* 2010]. This erosional surface is observed on the entire margin and allows us to consider a high position of the entire margin (with a paleobathymetry above sea-level) at the end of rifting. Considering an age of 20 Ma for the end of rifting [Séranne, 1999], we can then calculate the mean post-rift vertical subsidence rate in the deep basin of 500 m/Myr.

Between these two domains, the slope accommodates vertical movements of either side. Whilst the slope break between the slope and the deep basin (hinge line 3) is fixed in space through time, the hinge line 2 (HL2) between the shelf and the slope varies during the Pliocene within an area of less than 20 km, which mainly reflects the prograding-aggrading

[1] Plio-Quaternary key reflectors labelled MES (Margin Erosional Surface in pink), P11 (yellow), PXX (turquoise-blue), Q10 (red), Q5 (purple) and seafloor (marine-blue) are respectively dated at 5.33 Ma, 2.6 Ma, 1.6 Ma, 0.9 Ma, 0.5 Ma and 0 Ma [Leroux *et al.,* 2014]. The substratum (brown) and Miocene markers such as the base of the MSC (Messinian Salinity Crisis in red), the base of Mb -interpretated as an evaporitic unit- (orange), the base and top of salt (green and light green) and the top of UU (Upper Unit in grey) are from [Bache *et al.,* 2009].

sedimentary system on the shelf [Rabineau *et al.,* 2014] rebuilding the margin after the Messinian erosional event [Lofi *et al.,* 2003].

This 3D quantification of subsidence in three domains was then tested with Dionisos [Granjeon and Joseph, 1999] using the quantitative constraints on sediment supply inferred from a 3D stratigraphic analysis (Leroux, 2012, Leroux *et al.,* 2014, Fig S1. in Supplementary Material) and the eustatic curve of Haq *et al.,* (1987), modified by a 1500 m drawdown during the MSC [Clauzon *et al.,* 1982] (Fig S1. in Suppl. Material).

Figure 2 demonstrates that the 3D modelling successfully restores the stratigraphic record with the sedimentary geometries and thicknesses observed from seismic data. This modelling is coherent with micropaleontological data from Miocene borehole samples on the shelf [Cravatte *et al*., 1974] that reveals a deepening of the depositional environment at this time (see Figures S1, S2, S3 and movies S4, S5, S6 in Suppl. Material). The aggrading shelf-slope geometries during the Early to Middle Miocene indicate that the morphology of the margin and the subsidence pattern changed after this early erosion and led to the creation of accommodation. After rifting, the entire Gulf of Lions margin was thus affected by strong post-rift subsidence leading to thick post-rift (Miocene to Quaternary) sedimentary accumulations. After the MSC we can observe a Pliocene progradation trend followed by a Pleistocene progradation-aggradation trend (after 2.6 Ma). All these elements are well reproduced by our simulation.

Western Mediterranean basins and margins have undergone a transition into Late Neogene basin inversion (e.g. Roure *et al*., 2013). Increase in the level of intraplate compression in the Northern Atlantic region could explain the observed rapid phases of Plio-Quaternary subsidence after a phase of quiescence [Cloetingh & Kooi, 1992]. Moreover, in the Gulf of Lion, sediment flux during Pliocene (after 5.33 Ma) is 3 times higher than the flux in the Miocene (Figure S1 in Suppl. Material). This increasing sediment load, driven by climate or tectonic, may therefore play an important role in the increasing subsidence. However, since 2004, many studies on passive margins, which are not in back-arc setting nor in inversion, have shown delayed subsidence which increases long after the breakup, as on Spitzberg Margin [Ritzmann, *et al.,* 2004], on Iberia-Newfoundland Margins [Peron-Pinvidic & Manatschal, 2008], on Morocco Margin [Labails *et al.,* 2009], on Brazilian margins [Aslanian *et al.,* 2009), on Angola margin [Moulin *et al*., 2005] or on the Gulf of Lion margin [Bache *et al.,* 2010; Aslanian *et al.,* 2012; Moulin *et al.,* in press]. In some margins, the presence of carbonates overlying the salt layer shows that a shallow environment lasted after the break-up. The subsidence rate then seems to increase rapidly. The general character of the delayed subsidence followed by an increased subsidence rate implies probably a deep contribution like a lithosphere driven process (as proposed by Aslanian *et al.,* 2009; Huismans & Beaumont, 2011, 2014; Aslanian *et al.,* 2012), whithout excluding basin inversion process and/or sediment overloading".

CORRELATION WITH THE UNDERLYING CRUSTAL DOMAINS

Four structural domains extending from the coast to the oceanic crust have been highlighted on the basis of gravity, magnetic, reflection and wide-angle seismic data (Figure 3) [Pascal *et al.,* 1993, Gailler *et al.,* 2009, Aslanian *et al.,* 2012, Moulin *et al.,* in press; Afilhado *et al*., in press]: a) a 20 km thick continental crust (thinned crust), b) a highly thinned continental zone (the continental necking zone as described by Kooi *et al.,* 1992 ; Cloetingh *et al.,* 1995), which is marked by a prominent reflector (T) easily recognised at depth [De Voogd *et al.,* 1991 ; Moulin *et al.*, in press], c) a 5 km thin domain of unknown crust and complex nature (called a transitional domain), and last d) a thin oceanic crust. The limit between the necking and the transitional domains corresponds to the French-side limit of the pre-rift paleogeography [Olivet, 1996]. The base of the necking and transitional domains presents a 4 km thick layer with anomalous seismic velocities (6.8 – 7.5 km/s) which are neither typical of continental crust nor oceanic crust [Pascal *et al.,* 1993, Gailler *et al.,* 2009 ; Moulin *et al,* in press, Afilhado *et al.,* in press.]. The nature of the transitional domain was a matter of debate [De Voogd *et al.,* 1991; Pascal *et al.,* 1993 ; Séranne, 1999 ; Gailler *et al.,* 2009 ; Bache *et al.,* 2010 ; Aslanian *et al.,* 2012] but the recent results of wide-angle seismic analysis seem in favour of an exhumed lower continental crust nature [Moulin *et al.*, in press; Afilhado *et al.,* in press]. This is beyond the scope of this paper, but a consensus does exist on the very different nature of this crust compared to the crustal domains observed on both sides, and the transitional crust may have different physical behaviour.

Figure 3 presents our reconstructed 3D subsidence map and the striking correlation between the three differential subsidence domains described using paleo-markers and the underlying crustal domains highlighted by geophysical data. Up to present day, the crustal limits defined by the passive margin genesis still control, at the very first order, the vertical movements recorded by sedimentary sequences.

Not all passive margins exhibit a sag basin, with a « pure » vertical subsidence. Therefore, the use of depositional architecture can give a first approximation for the partitioning of the subsidence (with or without a sag basin) and the basement surface geometry.

In the GOL, the sag basin is described to be allochthonous, with exhumed lower crust near the necking and anomalous thinned oceanic crust in the middle of the basin [Aslanian *et al.,* 2012; Moulin *et al.,* in press; Afilhado *et al.,* in press]. This partitioning, with different magnetic and gravity patterns, fits the palaeogeographic reconstructions and is also observed in the salt geometry (connected /separated domes).

Using wide-angle and reflection seismic data, a similar observation was made for the Angola Margin, where the sag basin exhibits a similar mainly vertical, pre-breakup and post-breakup subsidence [Moulin *et al.*, 2005; Aslanian *et al.,* 2009]. As shown in the Gulf of Lion, the post-break-up subsidence of the Angolan basin uses the same hinge lines that have built and segmented the passive margin [Moulin *et al.,* 2005]. However, the nature of its basement is different from the GOL, with an autochthonous upper continental crust (just after the necking) and an allochthonous crust that can be exhumed or intruded [Moulin *et al.,* 2005; Aslanian *et al.,* 2009]. This partitioning is also observed in the salt geometry (connected/separated domes), and fits the initial palaeogeographic reconstruction [Moulin *et al.,* 2010; Aslanian & Moulin, 2010; 2012].

The difference between the two examples shows that a sag basin can occur with different crustal nature as shown by geophysical data. In both cases the exhumed/intruded lower continental crust is involved. The wide angle results in GOL [Afilhado *et al.,* in press] and in the Santos Basin [Klingelhoefer *et al.,* 2015; Evain *et al.,* accepted] show that the transition between exhumed lower crust to oceanic crust is not abrupt and raises the question on the role of the lower continental crust "flow", that can be gradually recrystallized to build the first atypical oceanic crust [Bott, 1971; Aslanian *et al.,* 2009: Sibuet *et al.,* 2012; Evain *et al.,* accepted; Afilhado *et al.,* in press].

Anyway, in both cases, whilst the combination of depositional architecture, surface observations and palaeogeographic reconstructions will not give the exact crustal nature, they can give crucial information such as: basement surface geometry, allochthonous/autochthonous nature, and, thanks to magnetism, oceanic nature.

CONCLUSION

Using the new method of Rabineau *et al.* [2014] to quantify the post-rift subsidence by the direct use of sedimentary geometries on the 3D analysis of tilts of stratigraphic markers in the Gulf of Lions margin, we individualize three domains of subsidence: on the platform and slope, the subsidence takes the form of a seaward tilting with different amplitudes, whereas the deep basin subsides purely vertically, as in the case of a sag basin. These domains fit with the deeper crustal domains highlighted by previous geophysical data implying that the post-break-up subsidence re-uses the initial hinge lines of the rifting phase and that the sedimentary record (even the last 5 Ma) is correlated with the underlying structural domains. This study provides therefore strong evidence for the recognition and importance of the link between deep Earth dynamic processes and surface geological processes [e.g. Braun, 2010, Cloetingh *et al.,* 2013]. The vertical coupling between mantle and surface processes promises new insights into past mantle dynamics through the geological record and the sediments are a precious tool for deciphering the laws of subsidence, even in their recent history, and can be considered as the storyteller of vertical and horizontal movements (Rabineau, 2014) and can be used as a window on deep geodynamic processes.

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Competing financial interests

The authors declare no competing financial interests.

FIGURE CAPTIONS

Fig1. (A) Location of the study area (black box) on a bathymetric map of the Provence Basin. Opening of the basin is illustrated by black arrows. Shaded area corresponds to the oceanic crust domain. (B) Location of all our synthetic vertical sections on our bathymetric map drawn from seismic data (B). This map also shows the extension of our stratigraphic interpretation and the position (red line) of the dip section shown on (C) in which the tilts and the subsidence of stratigraphic paleosurfaces are analysed. Colored circles correspond to slope-breaks for each of these surfaces. Three hinge-lines (grey area) are noted. On the shelf these stratigraphic surfaces allowed us to measure a constant Plio-Quaternary subsidence tilt rate (0.16°/Myr). The tilt rate of the substratum is 0.11°/Myr if we denote the end of rifting at 20 Ma. In the basin, the post-rift subsidence is purely vertical; its mean rate is estimated at around 500 m/Myr (see the text for explanation).

Figure 2. (A) Deposit paleobathymetries and resultant geometries predicted by Dionisos in our 3D stratigraphic modelling of the Gulf of Lion and Provence basin. The sedimentary architecture of the margin and final depths of the stratigraphic markers (relative to the substratum) are well reproduced by the model. We can compare this simulation with the NW-SE seismic profile ECORS 1 on (B): on both we observe the deepening of the Miocene depositional environment, the Messinian trilogy (LU, MU & UU after Lofi et al., 2011) and the prograding trend during the Pliocene followed by a prograding-aggrading trend during the Pleistocene (after 2.6 Ma). Note that the vertical scale units are respectively metres in A and seconds (twtt) in B. This explains the relative differences in unit thicknesses, in particular for

the pre-Messinian Miocene unit. See also seismic lines corresponding to the black boxes S1 & S2 in the supplementary information.

Figure 3. (A) 3D post-rift subsidence map drawn after our seismic interpretation and the analyses of our 10 synthetic vertical sections. The structural domains highlighted by geophysical data [Moulin et al., in press] and the geometries of the post-rift sedimentary pile are reported along a NW-SE dip line-drawing (B). There exists a striking correlation between the sedimentary record of subsidence and the nature of the underlying crust. The continental crust (domains 1 and 2) is tilted whereas the intermediate COT (Continent-Ocean Transition) domain (domain 3) subsides in a purely vertical way, such as in a sag basin. See the text for explanation.

SUPPLEMENTARY MATERIAL

• Figure S1. Major input parameters (evolution of the eustatic curve and sediment supply) for the 3D simulation of post-rift filling of the Provence basin. The simulation was run over the last 20 Ma with a 0.1 Ma time-step. The basin is defined as a rectangular area (250x400 km) and the initial basement at 20 Ma is flat with a paleobathymetry around +100 m (cf text for explanation).

• Figure S2. Interpretated LRM18 seismic reflection profile. The offlap-breaks are represented with white dots; Inset: the overall geometry of Pliocene-Quaternary strata shows prograding clinoforms (or prisms) with a clear geometrical change in the Late Pliocene to Quaternary clinoforms (after yellow horizon p11), from essentially prograding (green) to prograding-aggrading (yellow). Leroux *et al.,* 2014 (in press).

• Figure S3. Comparison between (A) a regional seismic profile from (Bache, 2009) and (B) the same seismic profile extracted by Dionisos from our Messinian modelling. On this synthetic seismic line, the impedance constrasts (in red and blue scale) highlight the same discontinuities we have observed on the seismic profile A. The final simulated present-day topography (in blue-scale) is superimposed on the synthetic section.

• Movie S4. 3D stratigraphic model of the Gulf of Lions and Provence basin from 20 to 0 Ma. The movie shows deposit paleobathymetries and resultant geometries predicted by Dionisos.

• Movie S5. Evolutional model of the Gulf of Lions and Provence basin through 3D stratigraphic modelling during the Messinian Salinity Crisis. The movie shows deposit paleobathymetries and resultant geometries predicted by Dionisos.

• Movie S6. Evolutional model of the Gulf of Lions and Provence basin through 3D stratigraphic modelling during the Messinian Salinity Crisis. The movie shows lithologic facies and resultant geometries predicted by Dionisos.

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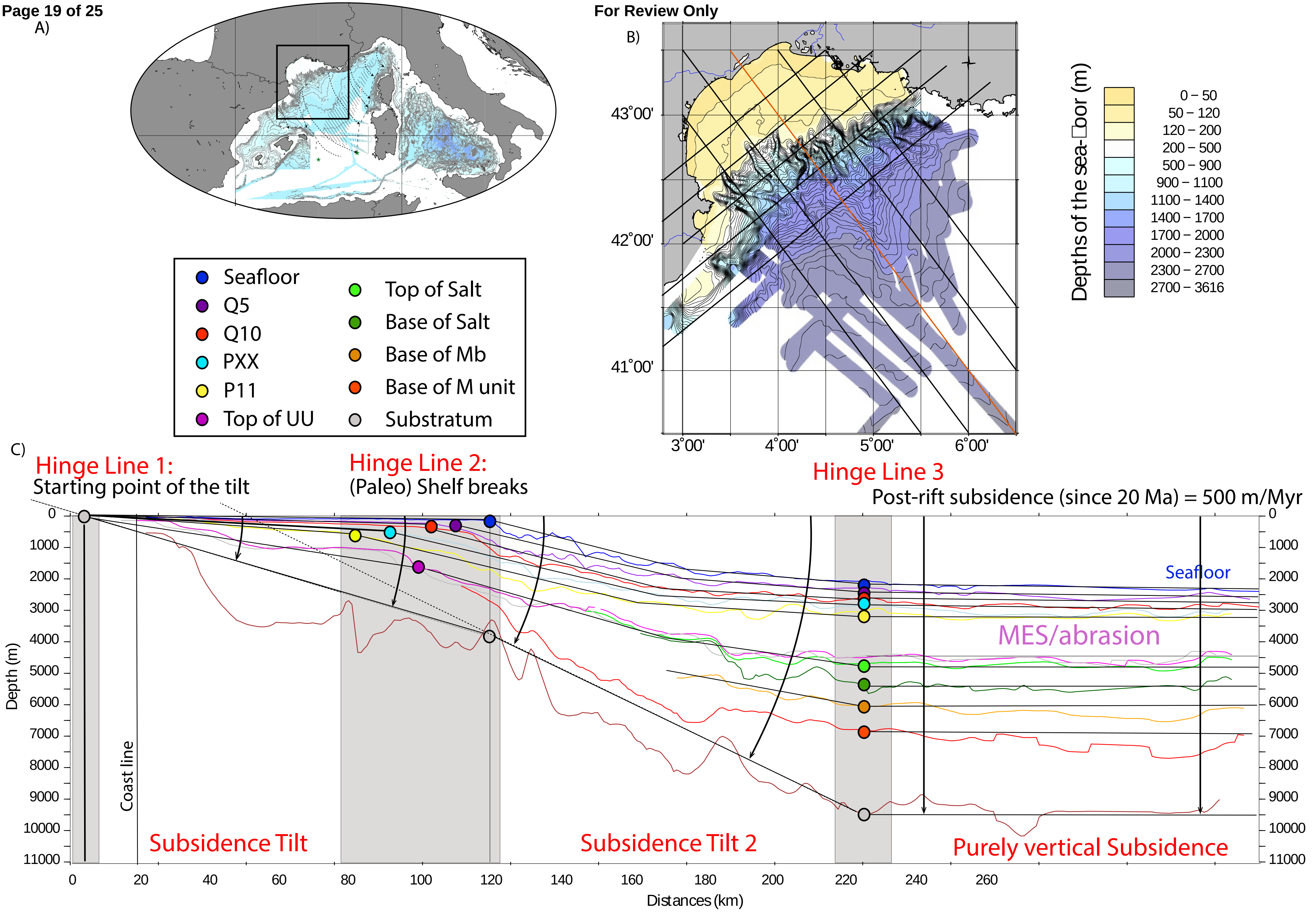
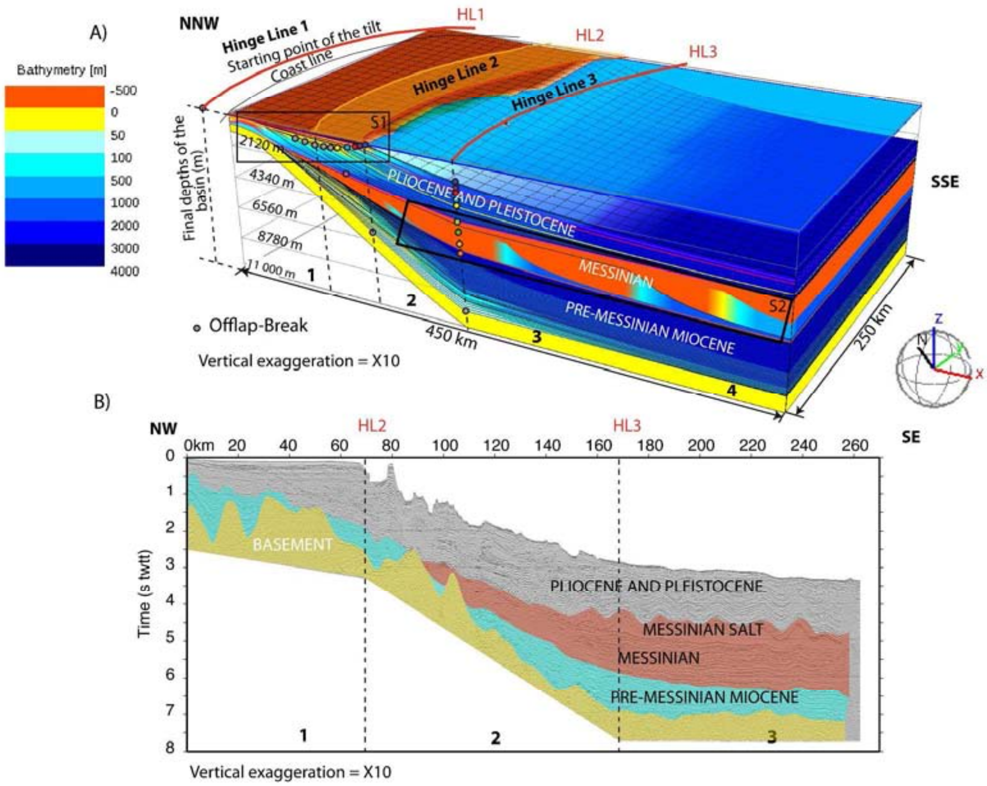

A)
B)
43˚00'
42˚00'
41˚00'
3˚00'
4˚00'
5˚00'
6˚00'
Depths of the sea-floor (m)
0 – 50
50 – 120
120 – 200
200 – 500
500 – 900
900 – 1100
1100 – 1400
1400 – 1700
1700 – 2000
2000 – 2300
2300 – 2700
2700 – 3616
Seafloor
Q5
Q10
PXX
P11
Top of UU
Top of Salt
Base of Salt
Base of Mb
Base of M unit
Substratum
C)
Hinge Line 1:
Starting point of the tilt
Hinge Line 2:
(Paleo) Shelf breaks
Hinge Line 3
Post-rift subsidence (since 20 Ma) = 500 m/Myr
Seafloor
MES/abrasion
Coast line
Subsidence Tilt
Subsidence Tilt 2
Purely vertical Subsidence
Depth (m)
Distances (km)



Deposit paleobathymetries and resultant geometries predicted by Dionisos in our 3D stratigraphic modelling of the Gulf of Lion and Provence basin (A). The sedimentary architecture of the margin and final depths of the stratigraphic markers (relative to the substratum) are well reproduced by the model. We can compare this simulation with the NW-SE seismic profile ECORS 1 on (B): on both we observe the deepening of the Miocene depositional environment, the Messinian trilogy and the prograding trend during the Pliocene followed by a prograding-aggrading trend during the Pleistocene (after 2.6 Ma). Note that the vertical scale units are respectively metres in A and secondes (twtt) in B. This explains the relative differences in unit thicknesses, in particular for the pre-Messinian Miocene unit. See also seismic lines corresponding to the black boxes S1 & S2 in the supplementary information.

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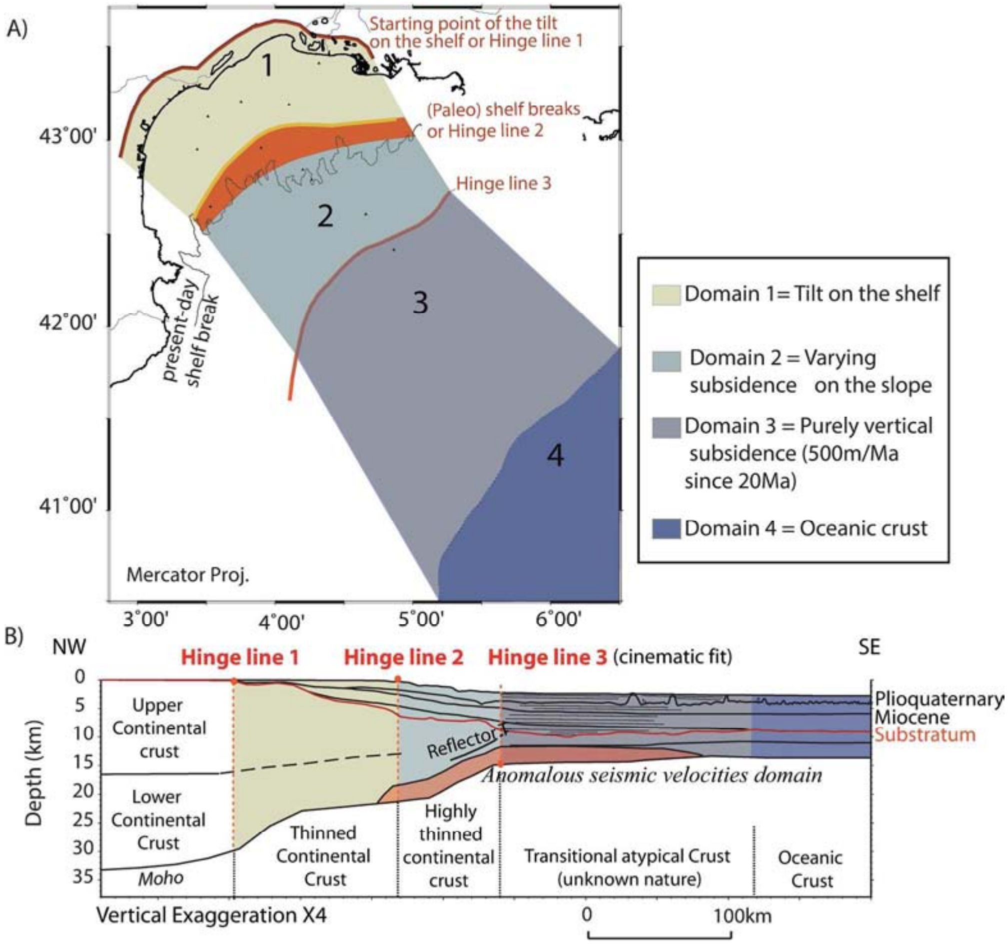

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What follows is supplementary material, which will be made available online but will not appear in the print version.

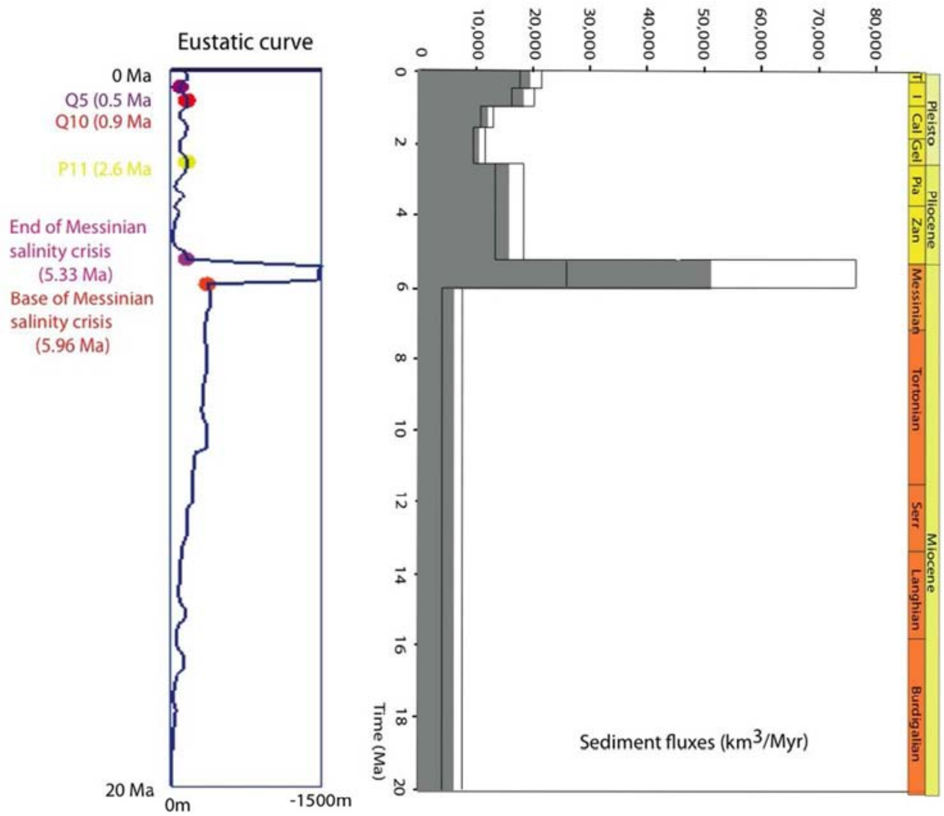

Figure S1 (Supplementary Information). Major input parameters into the model (subsidence excluded): evolution of eustatic curve and sediment supply

Major input parameters (evolution of the eustatic curve and sediment supply) for the 3D simulation of post-rift filling of the Provence basin. The simulation was run over the last 20 Ma with a 0.1 Ma time-step. The basin is defined as a rectangular area (250x400 km) and the initial basement at 20 Ma is flat with a paleobathymetry around +100 m (cf text for explanation).

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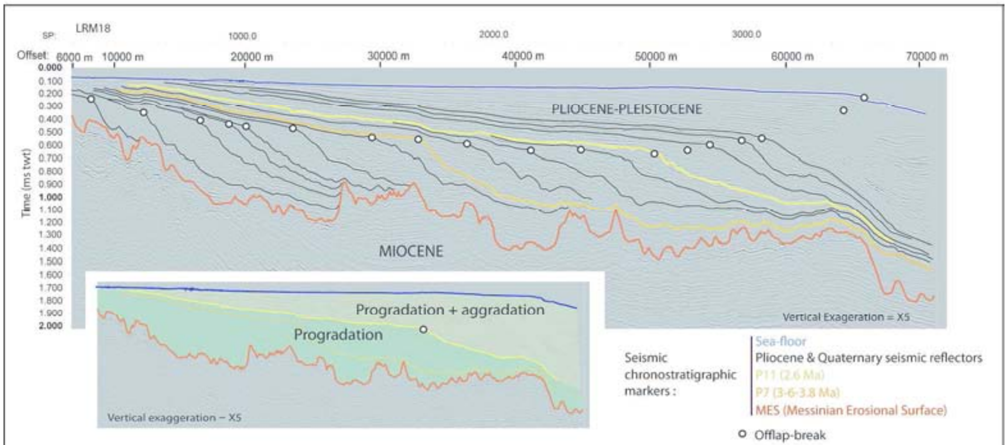

Figure S2 (Supplementary Information). The overall geometry of Pliocene-Quaternary strata on the shelf shows prograding clinoforms (from 5.3 Ma to 2.6 Ma) followed by prograding-aggrading prisms (from 2.6 Ma to present-day). Our 3D stratigraphic modeling successfully restitutes these geometries (Figure 2).

Interpretated LRM18 seismic reflection profile. The offlap-breaks are represented with white dots; Inset: the overall geometry of Pliocene-Quaternary strata shows prograding clinoforms (or prisms) with a clear geometrical change in the Late Pliocene to Quaternary clinoforms (after yellow horizon p11), from essentially prograding (green) to prograding-aggrading (yellow). Leroux et al., 2014.

1080x565mm (72 x 72 DPI)

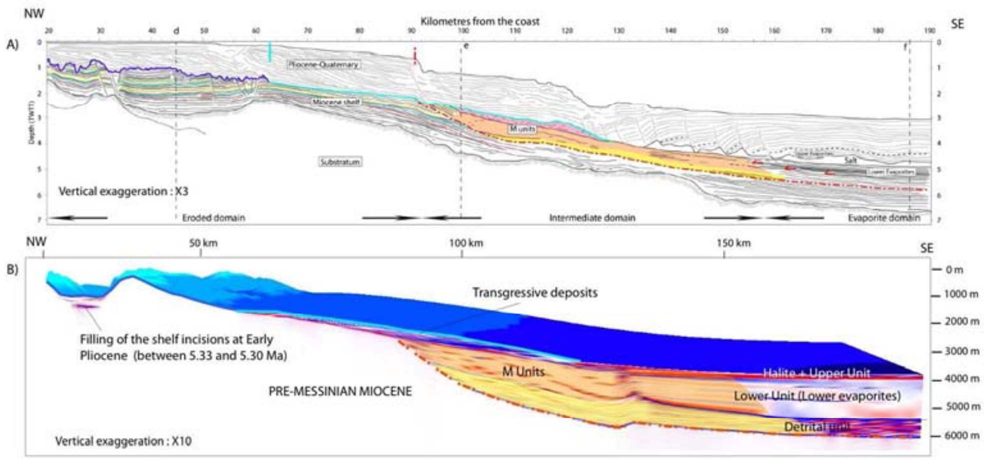

Figure S3 (Supplementary Information). Comparison between (A) a regional seismic profile and (B) the same seismic profile extracted by Dionisos from our Messinian modelling. Our 3D modelling successfully restitutes the sediment geometries during the Messinian Salinity Crisis.

Comparison between (A) a regional seismic profile from (Bache, 2009) and (B) the same seismic profile extracted by Dionisos from our Messinian modelling. On this synthetic seismic line, the impedance constrasts (in red and blue scale) highlight the same discontinuities we have observed on the seismic profile A. The final simulated present-day topography (in blue-scale as function of the depth) is surimposed on the synthetic section.

259x135mm (150 x 150 DPI)