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Major modification of sediment routing by a large Mass Transport Deposit in the Gulf of Lions (Western Mediterranean)

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Keywords

Gulf of Lions, Ebro margin, Sediment routing, Rhone deep-sea fan, Canyon, Mass transport deposit, Turbidite

Highlights

- Submarine Mass Transport Deposits can radically modify sediment routing pathways on the continental slope and rise.
- Large Mass Transport Deposits (160 km^3) can be obscured on the seabed where sedimentation rate is high.

Abstract

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In the Gulf of Lions (Western Mediterranean), the emplacement of a large (160 km^3) Mass Transport Deposit, the Rhone Western Mass Transport Deposit (RWMTD), at the base of slope, aside the Rhone deep-sea fan between 1800 and 2700 m water depth, resulted in a major modification of the sediment routing by clogging a drainage network and blocking at the base of slope sediments that were previously routed into the Valencia channel and the Balearic abyssal plain. The RWMTD was sourced from sediments of the western flank of the Rhone upper fan and the adjacent base of slope. The mass transport deposit is characterized by a transparent seismic facies and sediment cores show that it is composed of a stiff laminated muddy lithofacies characteristic of the Rhone fan turbidites with marked contorted beds indicative of remoulding. AMS radiocarbon dating shows that the RWMTD was emplaced between 19.9-21.5 ka cal. BP. It is coeval, within dating uncertainties, with the emplacement of a megaturbidite in the Balearic Abyssal Plain and immediately predates a major avulsion of the Rhone turbidite channel that led to the emplacement of an avulsion lobe (the neofan) on top of the RWMTD. It is not possible to affirm a genetic link between these three major gravity events but one can argue that they share a common forcing in relation with massive turbiditic accumulation during the last sea-level lowstand at the end of the Last Glacial Maximum. This study outlines the importance of mass transport deposits in the building of turbidite systems and, more generally, the major control of mass wasting on the routing and dispersal of sediments across continental margins.

1. Introduction

Besides geohazard and societal issues, slope failures and mass transport deposits play a significant role in the long-term evolution of continental margins because they involve the displacement of very important volumes of sediments and significantly modify the margins morphology and the submarine sediment dispersal pattern (Huppertz et al., 2010; Joanne et al., 2010; Kawamura et al., 2010; Mulder, 2011; Shipp et al., 2011). Furthermore, mass transport deposits may represent up to 10-20% of stratigraphic sequences on continental margins (McHugh et al., 1996; Mulder, 2011; Weimer, 1989). They can play a significant role in the movement and transfer of sediment at river mouth deltas or canyon heads at hourly or yearly time scales (Biscara et al., 2012; Clare et al., 2016 ; Kelner et al., 2014; Mazières et al., 2014; Obelcz et al., 2017; Smith et al., 2007), but also at geologic time scales on canyons and whole margin development (Micallef et al., 2012; Sultan et al., 2007). This is particularly the case for large mass transport deposits that instantaneously redistribute huge volumes of sediment, in the order of several km^3. These are dominantly emplaced on slopes receiving massive sediment input such as glaciated margins (Bryn et al., 2005; Gales et al., 2014; Imbo et al., 2003; Jansen et al., 1987; Lee, 2009; Piper et al., 2003) or deltaic margins during periods of low sea level (Droz and Bellaiche, 1985; Garziglia et al., 2008; Nelson et al., 2011; Piper et al., 1997; Weimer, 1989). They also represent a significant sediment input into abyssal plains in the form of megabeds, particularly in the Mediterranean Sea (Cita and Aloisi, 2000; Reeder et al., 2000; Rothwell et al., 1998; San Pedro et al., 2017)}.

In the Gulf of Lions (GoL) (Western Mediterranean) (Fig. 1), the Rhone deep-sea fan developed since the Pliocene in a complex geologic setting characterized by a continental slope dissected by several shifting canyons (Berné et al., 1999; Bourcart, 1960; Torres et al., 1995), salt tectonics (dos Reis et al., 2005; Droz, 1983; Gaullier, 1993; Le Cann, 1987) and canyon and open slope mass wasting (Sultan et al., 2007). Mass transport deposits on the Rhone fan have long been recognized as major features with high impact on the Late Quaternary fan growth (Droz and Bellaiche, 1985; Gaullier et al., 1998). We present a new detailed mapping of the superficial Rhone Western mass transport deposit (RWMTD) based on a synthesis and reinterpretation of bathymetric and seismic data acquired during several oceanographic campaigns since 1997, and new litho-facies and chronological data from three sediment cores that penetrated the deposits. In addition to considerations on the sedimentary source and trigger mechanisms, the aim of this study is to outline the role played by the emplacement of the RWMTD at the base of slope in the evolution of sediment routing patterns in the western part of the GoL from the upper slope to the Balearic Abyssal Plain within the context of sea-level fluctuations since the Last Glacial Maximum (LGM).

2. Geological background

2.1. Sedimentary setting

Following the reflooding of the basin, after a major sea level drop of the Mediterranean Sea during the Messinian (1500 m according to Hsü et al. (1973)), 3 km of prograding and aggrading sediments were deposited throughout the Plio-Quaternary to reach the present day margin morphology (Leroux et al., 2014; Lofi et al., 2003). Following the Mid-Pleistocene transition (1,250- 700 ka BP; (Clark et al., 2006)), sediment accumulation on the GoL margin increased by two-fold as a result of the increased magnitude of global sea-level changes (Leroux et al., 2017). During the Late Pleistocene, the evolution of the margin and canyons was driven by sea-level fluctuations and thermal subsidence, in the order of 250 $m.Ma^{-1}$, creating accommodation prone to the deposition of sediments (Rabineau et al., 2006; Rabineau et al., 2014). During sea-level falls thick forced-regressive sequences developed (Bassetti et al., 2008; Rabineau et al., 2005; Rabineau et al., 1998; Tesson and Gensous, 1998; Torres et al., 1995) bounded on the slope by condensed intervals, deposited during highstands (Sierro et al., 2009).

During this period of time the evolution of the deep GoL was also controlled by syn-sedimentary salt tectonics. Gravitational gliding and spreading over the Messinian detachment salt level (dos Reis et al., 2005) developed at the mid to lower slope with basinward-dipping active and buried listric faults parallel to sub-parallel to the shelf break (dos Reis et al., 2005) (Fig. 2).

2.2. Sediment routing

In the GoL the main source of sediment is the Rhône River (Pont et al., 2002). Through geological times, sediment dispersal at the mouth of rivers was controlled by sea level fluctuations and the synchronous migration of the shoreline. During periods of low sea level (glacials), the seaward migration of the shoreline moved the sediment depocenters onto to the outer shelf and a significant amount of sediment was routed into the canyons, as evidenced by preserved marked sinuous incisions at some canyons (Baztan et al., 2005; Mauffrey et al., 2015). Numerous canyons dissect the shelf break. In the western part of the GoL, eight canyons, Cap de Creus to Marti canyons, coalesce down slope but do not show a connection with the Valencia channel (Amblas et al., 2006; Baztan et al., 2005; Berné et al., 2004). In the central adjacent part the Petit-Rhone canyon shows a sinuous pattern and is prolonged by the Rhone turbidite system (Droz et al., 2006) (Fig. 1). The developed sinuous channel network of the Rhone turbidite system (Droz et al., 2006) shows that during lowstands a large amount of sediment was efficiently exported as deep as 2800 m water depth and possibly into the Balearic Abyssal Plain. To the west, the sediments were likely funneled into the Sète canyon network and deposited at the base of slope where the canyons morphology abruptly smoothens (Fig. 1). The same configuration applies for La Fonera and Clots del Puget canyons. In comparison, to the southwest, on the south Catalan margin canyons coalesce and extend beyond the base of slope to finally vanish into the Valencia Fan at the northernmost part of the Algerian–Balearic Abyssal plain (Amblas et al., 2011; Maldonado et al., 1985) (Fig. 1). One particularly noteworthy event during the last sea-level rise on the Ebro margin was the emplacement of the Big'95 mass transport deposit that caused a sudden change in sedimentation style in the upper segment of the Valencia drainage network, with a significant decrease in sediment transport and incision capacity (Amblas et al., 2011).

2.3. Turbidite systems

Two thick turbidite systems lie at the base of slope in the GoL, the Rhone turbidite system in the central part of the GoL and the Pyreneo-Languedocian Sedimentary Ridge to the west as shown on the Quaternary isopach map (dos Reis et al., 2005). Smaller turbiditic sedimentary ridges lie at the right hand side of the La Fonera and Clots del Puget canyons (Fig. 1). All these turbidite systems consist of terrigenous sediment, starved during the Holocene highstand, and displaying high sedimentation rates during the LGM lowstand (Beaudouin et al., 2004; Jallet and Giresse, 2005; Lombo Tombo et al., 2015; Melki et al., 2009). The Rhone turbidite system, the largest turbidite system in terms of thickness and area in the GoL and in the western Mediterranean Sea, lies in the prolongation of the Petit-Rhône canyon that seems to have been the main feeder throughout the Quaternary (Droz and Bellaiche, 1985). It represents an accumulation of ca. 3,600 m of turbidites and mass-transport deposits. On the the upper fan, between 1,350 m and 2,000 m water depths, a perched valley, 12 to 4 km wide and 500 to 200 m deep, is cut by a narrow, 1,000 to 600 m wide and 150 to 100 m deep, axial meandering channel (Lombo Tombo et al., 2015; O'Connell et al., 1991; Torres et al., 1997) (Fig. 1). The last channel avulsion most likely occurred during the LGM (Bonnel et al., 2005) and led to the emplacement of a lobe-shaped fan, called neofan (Bonnel et al., 2005; Droz and Bellaiche, 1985; Jégou, 2008; Torres et al., 1997)}. (Fig. 1).

2.4 Slope instabilities

At the base of slope numerous headwall scars are indicative of slope failures (Berné et al., 2004; Droz and Bellaiche, 1985; Gaullier et al., 1998; Sultan et al., 2007; Torres et al., 1995). Scars are superimposed on a network of buried and active listric faults parallel to the margin (dos Reis et al., 2005; Torres et al., 1995) (Figs. 2). Although movements of these faults driven by halokinesis may be a pre-conditioning factor or even a trigger mechanism for sliding (Bellaiche et al., 1986; Droz, 1983) a causal link between these features has not yet been shown. Two large mass transport deposits are lying on the subsurface of the eastern and western sides of the fan and were named the Eastern and Western (superficial) Transparent Series (Bellaiche et al., 1986; Droz and Bellaiche, 1985), Intermediate Unit (Gaullier et al., 1998), Middle Unit (Méar and Gensous, 1993), Eastern and Western Debris Flow (Bonnel et al., 2005; Droz et al., 2001; Lastras et al., 2007a) and more recently Western and Eastern Mass Transport Deposits (WMTD and EMTD) (Droz et al., 2006). In this paper we will adopt the Rhone Western and Eastern Mass Transport Deposits (RWMTD and REMTD) nomenclature. These mass transport deposits are characterized by transparent seismic facies with no apparent internal structures apart from some undisturbed tilted block in the proximal area (Droz and Bellaiche, 1985). Concave and undulated features on top of both deposits, at the contact with adjacent undisturbed strata were interpreted as compression ridges formed by displaced material at the toe of the slope (Droz and Bellaiche, 1985). Scars surrounding both deposits are visible on the fan levees and on the adjacent base of slope suggesting that sliding has affected the whole base of slope and upfan area (Gaullier et al., 1998).

The age of these mass transport deposits remains speculative due to the lack of direct dating. Seismic stratigraphy and coring showed that both are covered by a metric pelagic drape and that the RWMTD is overlapped by the neofan deposits (Bonnel et al., 2005; Droz and Bellaiche, 1985; Gaullier et al., 1998; Torres et al., 1997; Torres et al., 1995) showing that turbiditic activity persisted after its emplacement, This suggests that both deposits probably emplaced during the Last Glacial Maximum, but close to the post-glacial sediment starvation of the Rhone fan dated at ca. 18.5 ka cal BP (Beaudouin et al., 2004; Dennielou et al., 2006; Lombo Tombo et al., 2015).

3. Data and methods

This study is based on a variety of bathymetry and seismic data collected since 1997 during several oceanographic campaigns (Fig. 3; Tab. 1) as well as on three piston cores (Tab. 2).

Two bathymetric Digital Terrain Models (DTMs) were used: a 500 m resolution DTM (IFREMER/CIESM, 2011) and unpublished 50 m and 100 m resolution DTMs based on Simrad EM12 and EM300 multibeam surveys during oceanic campaigns listed (Tab. 1).

Detailed mapping of the RWMTD is based on various seismic data including single and multi-channel GI and mini-GI (vertical resolution in the order of 30 and 10 m, respectively) High Resolution (HR) sparker lines as well as Very High Resolution (VHR) Sub-Bottom Profiler (SBP) lines (vertical resolution ca. 1 m) (Figs. 2, 3 and 4A; Tab. 1). This dense and multi-resolution seismic database allowed a detailed new mapping and characterization of the RWMTD and to produce isochore and isochron maps.

Two sediment cores were collected with the giant Calypso piston corer aboard R/V Marion Dufresne on the northern and southern extremities of the RWMTD. Another core was collected in the central part of the RWMTD with a Kullenberg piston corer aboard

R/V Le Suroit (Figs. 2, 3 and 4A; Tabs. 1 and 2). Identification of lithofacies and grain size is based on visual description and physical properties logging with a Geotek Multi-Sensor Core Logger. AMS radiocarbon dating was conducted on monospecific planktonic foraminifera (*Globigerina bulloides*). Age calibration into calendar scales was calculated by Calib 7.1 software (Stuiver et al., 2018) with the marine13 calibration curve (Reimer et al., 2013).

All data were integrated into the IHS Kingdom suite seismic interpretation software. For the interpolation of isochrone and isochore grid, we used the Flex Gridding algorithms, defining a cell size of 50 m. Conversion of seismic two-way travel times into meters in the sedimentary column was made with a sound velocity of 1600 m.s^{-1}, which may represent the minimum sound velocity according to wave velocities measured in sediment cores.

4. Results

4.1 Seabed morphology

The RWTMD has a faint expression on the seabed (Fig. 1) because it is partly overlain by more recent deposits that are the Rhone Neofan, the Pyreneo-Langudocian Sedimentary Ridge (Berné et al., 1999) and some deposits at the outlet of La Fonera canyon (Droz et al., 2001). The seabed morphology is also imprinted by erosional scours developed during the lowstand functioning of the Neofan (Bonnel et al., 2005) and of Cap de Creus canyon (Lastras et al., 2007b) which are still likely active due to deep water active hydro-sedimentary processes related to open-ocean convection (Stabholz et al., 2013).

The most obvious morphological evidence of mass wasting lies in the occurrence of slide scars in the proximal area of the RWMTD at the base of slope and on the side of the Rhone fan (Fig. 4B). All scars show a NE-SW orientation. The orientation of the biggest scar, 30 km long, 10-100 m high headwall, running along slope and gradually becoming perpendicular to the slope on the side of Rhone fan between 2,000-1,900 m water depth, suggests a relation with the RWMTD (Fig. 4B). To the SW the headwall is nearly parallel to the slope at 2,100-2,200 m water depth, while to the NE it gradually becomes perpendicular to the slope between 2,000-1,900 m water depth, on the side of Rhone fan (Fig. 4B). Similar parallel headwalls, also facing to the SE, but shorter and discontinuous and less high are visible about 4 km upslope to the north (Fig. 4B). About 4 km to the south, on the side of the Rhone fan, a 15 km long headwall facing to the NW is perpendicular to the slope (Fig. 4B). The configuration of headwalls across the side of the Rhone fan forms a 7 km wide, 40 m deep along slope corridor that can be interpreted as a pathway for the RWMTD. Noteworthy, the scars are superimposed to the active and buried listric faults network developed by syn-sedimentary salt tectonics (dos Reis et al., 2005) (Fig. 4B).

To the south, the only obvious morphological expression of the RWMTD is a faint NE-SW lineation at the foot of a Rhone fan channel-levee and corresponding to a compression bulge at the lateral toe contact between the RWMTD and the Rhone fan (Fig. 4C).

4.2 Seismic structure of the RWMTD and of adjacent and underlying sediments

The RWMTD appears as a body with a transparent acoustic facies on the VHR, low penetration, SBP lines and on the HR single channel seismic lines (Figs. 5 to 9). However, on the 24-channel HR seismic it shows sub-continuous internal reflections roughly parallel to the seabed that onlap on the sedimentary basement (Fig. 5B). This is evidence that the infill occurred on an inherited morphology. In some areas the top reflector, close to the seabed, shows incisions and roughness, but in relation to more recent superficial deposits or hydro-sedimentary processes such as the neofan channels and scours (Figs 6B, 7 and 8). Truncation of the Rhone fan strata (Fig. 5C) indicates that the RWMTD is related to the failure of the fan levee as also suggested by the collapsed western levee of the Rhone fan. (Fig. 4B).

The top of the RWMTD is rather smooth and shows a slope towards the SW and towards the south that roughly follows the overall trend of the underlying substratum (Fig. 10). To the north and to the south, the RWMTD outcrops, at least at the seismic vertical resolution, while in its central area it is overlapped to the east by the neofan deposits (Figs. 5D and 10A) and to the west by a thin veneer of Pyreneo-Langudocian Sedimentary Ridge deposits and of La Fonera canyon deposits (Fig. 5D, 7 and 8A). The compression bulge to the SE in the distal area is clearly visible and clearly shows that the RWMTD has overlapped the Rhone fan (Fig. 9).

On the VHR SBP lines the structure of the basement of the RWMTD is not visible because of the low seismic penetration. On VHR seismic, in the proximal (north) area the basement corresponds to stratified folded and/or faulted sediments characteristics of the base of slope deposits to the north (Fig. 5D) and Rhone fan stratified Pleistocene deposits to the east (Fig. 5). In the central area the RWMTD is confined between the Rhone fan deposits, to the east, where it pinches out, and the stratified deposits of the Pyreneo-Langudocian Sedimentary Ridge to the west (Figs. 6, 7, 8B and 9). From north to south the RWMTD width is ca. 40 km in the proximal area, 50 km in the central area and gradually narrows to 5 km in the most distal area. The horizontal run-out distance (L) is 180 km (Fig. 10), the height fall (H), i-e the height between the head scar and the most distal deposits is ca. 740 m and the H/L ratio is 0.004.

4.3 Extension, thickness and morphology at the base of the RWMTD

The RWMTD extends from 1,900 to 2,700 m water depth and covers a surface of 6800 km^2. The isochrones map of the basement shows that the RWMTD is emplaced in the large depression between the Rhone fan and the Catalan margin (Fig. 10B). The thickness of the RWMTD (Fig. 10C) is largely between 10 and 50 m thick, with the thickest deposits (67 m) located along a large valley against the Rhone fan (Fig. 10C). Otherwise, downslope, the thickness is rather constant and the volume of the RWMTD is estimated at 160 km^3. By comparison earlier mapping with low resolution seismic gave a surface of ca. 7500 km^2 with a thickness up to 120 mstwtt (96 m) and commonly around 50 mstwtt (40 m) for an estimated volume of 230 km^3 (calculation after Gaullier et al. (1998) with the same velocities as this study). For further comparison, the REMTD covers an area of 7800 km^2 with a thickness up to 160 mstwtt (128 m) and commonly around 50-100 mstwtt (40-80 m) for an estimated volume of 170 km^3 (Coutellier, 1985; Droz and Bellaiche, 1985)

The morphology at the base of the RWMTD is very different from the present-day seabed. Besides an overall slope gradient to the SW and south, it shows a complex morphology characterized by highs and lows. To the north the most proximal deposits lie on stair-like morphologies corresponding to the tip of listric faults (Fig. 5D). To the east, the contact with the adjacent Rhone fan is characterized by truncations of the fan levees indicative of failure and collapse of the levee (Fig. 5C). To the south the RWMTD fills several depressions that build a 12 to 18 km wide and 30 m deep valley against the Rhone fan (Figs 5C, 7 and 9) in the continuation of the present Sète canyon outlet, widening downslope and that connects to the Valencia valley. The RWMTD shows a bifurcation to the SW where it becomes narrower (5 km) and connects to the Clots del Puget and Valencia valleys (Figs. 8C and 8D). A parallel but fainter valley also runs along the Pyreneo-Langudocian Sedimentary Ridge (Fig. 10B). This buried valley to the east shows a concave-up longitudinal profile that fits with the concave-up longitudinal shape of the Sète canyon and Valencia channel suggesting that the three valleys were a continuum before the emplacement of the RWMTD (Fig. 10D).

4.4 Lithofacies and chronology of the RWMTD

Three sediment cores were collected in areas where the RWMTD outcrops at the seabed at the seismic resolution. Core MD01-2435 was collected at a RWMTD proximal location where the WMTD lies on the Rhone fan deposits (Fig. 6A), core KSGC-10 was collected at a RWMTD central location on the neofan area where scours have eroded into the RWMTD and open-ocean convection has prevented the deposition of sediment since beginning of the Holocene (Dennielou et al., 2009; Stabholz et al., 2013), core MD01-2438 was collected at a RWMTD distal location (Figs. 2, 3 and 6B). Sediment in MD01 cores show disturbance related to non-stationary behaviour of the piston, which led to oversampling during coring (Bourillet et al., 2007; Skinner and McCave, 2003), thus preventing straightforward correlation between cores and seismic data. However, the identification of lithofacies was still possible, and sharp contrasts between pelagic, turbiditic and mass transport deposits make straightforward the analogy between lithofacies and well-contrasted seismic facies.

Three sedimentary units were identified (Fig. 11). Unit 1 is composed of foraminifera and calcareous nannoplankton oozes that correspond to ambient pelagic sedimentation. Unit 2 is composed of laminated mud with frequent silt to very fine sand laminae. This facies is interpreted as turbidites deposited by turbidity current spillover from the adjacent perched valley. They are similar to those already described in the Rhone fan valley or on the neofan levees (Bonnel et al., 2005; Dennielou et al., 2006; Lombo Tombo et al., 2015). Unit 3 is composed of stiff mud with colour banding corresponding to sulphide rich laminae and few silt layers characteristics of lithofacies in the Rhone fan (Lombo Tombo et al., 2015). Laminae are either horizontal, oblique or show tight folding. In core MD01-2438 a layer of coarse material in the form of fine to very coarse sand bioclasts and lithoclasts have been involved in the sediment deformation but no evidence of matrix supported clasts or blocks was found. This lithofacies is much denser (>2 $g.cm^{-3}$) and stiffer than the units above with similar (muddy) grain sizes (Fig. 11) suggesting that it is over-consolidated and was therefore either previously buried deeper than its present stratigraphic depth or has gained strength after remoulding. The unit is interpreted as the RWMTD deposits. The plastic deformation and contortion are indicative of shearing and the lack of faulting and blocks show that the sediment remained a coherent mass, at least for the upper sampled part, so that the RWMTD can be classified as a slide or slump because of evidence of plastic deformation (cf. Mulder and Cochonat (1996); Piper et al. (1997); Tripsanas et al. (2008); Nelson et al. (2011); Shanmugam (2015)). The transparent echo-facies that characterizes the RWMTD is commonly interpreted as indicative of disintegration as a result of break up of blocks in the downslope evolution of a slide into a debris flow (Piper et al. 1997). The absence of blocks in the retrieved sediment cores may be due to the low penetration. However, the sediment contortion is also a factor of strata disorganisation consistent with the transparent echo-facies.

In core MD01-2435 (Fig. 11) Unit 1 is described from top to 0.25 m and Unit 2 from 0.25 to 8.90 m. The contact between the units is oblique and erosional. Unit 3 is described from 8.90 to 15,50 m, colour banding is horizontal to sub-horizontal (up to 15° inclination) but inclination varies down core. From 15.50 m to the base of core, the sediment is fully disturbed because it was sucked up during coring, however, despite disturbance the collected sediment is very similar to Unit 3.

In core KSGC-10 (Fig. 11), only Unit 3 is present showing that no sediments were deposited during the Holocene (Dennielou et al., 2009; Stabholz et al., 2013).

In core MD01-2438 (Fig. 11) Unit 1 is described from 0 to 1.00 m. Two layers of coarse sand (2 and 16 cm thick) are intercalated in the unit and correspond to post-glacial and Holocene turbidites already described at the base of slope of the study area (Dennielou et al., 2009). Unit 2 is not present and Unit 1 rests on Unit 3. Unit 3 is described from 1.00 m to the base of core (8.00 m), the contact between Unit 1 and 3 is sharp and horizontal. Colour banding is contorted from 1.00 m to 5.00 m and becomes gradually horizontal to sub-horizontal downcore. From 8.00 m to the base of core the sediment is also fully disturbed and the collected sediment is very similar to Unit 3.

Radiocarbon dating (Tab. 3 and Fig. 11) shows that the hemipelagic Unit 1 was deposited during the deglacial sea level rise and during the Holocene highstand and that turbiditic Unit 2 was deposited at the end of the LGM during and shortly after the onset of the sea level rise (20.7-14.7 ka cal BP). These ages are consistent with those obtained for the same units on the Rhone fan and adjacent areas (Beaudouin et al., 2004; Bonnel et al., 2005; Dennielou et al., 2006; Dennielou et al., 2009; Lombo Tombo et al., 2015). Ages obtained at the top of the RWMTD (Unit 3) and at the base of overlapping units (turbiditic Unit 2 in the proximal position and Unit 1 in the distal position) are similar and show that emplacement of the RWMTD occurred between 19.9 and 21.5 ka cal BP (2 sigma) with an average median age of 21.0 ka cal BP (Fig. 12). However, this does not discard a possibility of several stages of sliding in this age bracket.

5. Discussion

5.1. The Rhone WMTD: a hidden landslide

Unlike several recent mass transport deposits around the world (e.g. Storegga (Bugge et al., 1988), BIG'95 (Lastras et al., 2002), Ruatoria (Collot et al., 2001), among the largest), the RWMTD has a faint seabed morphological expression and could be easily overlooked if no seismic data was available. The lack of morphologic expression is a consequence of two factors : (1) the fact that displaced and deposited sediment infilled the topographic low between the Rhone fan and Pyreneo-Languedocian Sedimentary Ridge and adjacent slope to the west (Fig. 1) and did not created any distal positive relief, (2) seabed rejuvenation by rapid burying related the high sedimentation rates that persisted at the base of slope until 18.5 ka BP (Bonnel et al., 2005; Lombo Tombo et al., 2015), i-e during ca. 1.5 to 3.5 ka after the emplacement of the RWMTDT, and by the development of the neofan avulsion lobe and channel-levee on top of it.

At river mouth subaqueous deltas or upper slopes under high sedimentation rates sliding seems to be a frequent quasi intrinsic process of sediment movement and transfer but resulting morphologies are quickly buried and obscured, sometimes within days to years (Biscara et al., 2012; Clare et al., 2016 ; Kelner et al., 2014; Mazières et al., 2014; Obelcz et al., 2017; Smith et al., 2007). Our study shows that obscuration may occur on much larger areas at slope bases. Indeed, the RWMTD case may be atypical but it raises the question of the recognition of large mass transport deposits and outlines that bathymetric data alone are not sufficient for their recognition on high sedimentation rate continental margins such as glacigenic and deltaic margins and that inventories (e.g. Urgeles and Camerlenghi, (2013)) may be incomplete at the largest end of the spectrum.

5.2. Source and trigger mechanisms

The recurrence of mass transport deposits in many deep-sea fans on deltaic margins such as the Mississippi (Twichell et al., 1991; Weimer, 1989), Amazon (Piper et al., 1997), Danube (Popescu et al., 2001) or Nile (Garziglia et al., 2008) shows that sediment loading, mostly during lowstands, is a major preconditioning factor for sliding. Sliding can occur when the stress exceeds the sediment strength and no external trigger mechanism is actually needed to explain sliding of high sedimentation rate poorly-consolidated sediment, even with low slopes, (Croguennec et al., 2017; Dennielou et al., 2017). This configuration can be clearly invoked for the Rhone slope and fan where high sedimentation rates, in the order of several meters per thousand years, during the Last Glacial Maximum (Lombo Tombo et al., 2015; Sierro et al., 2009) have shortly preceded the emplacement of the RWMTD. Among preconditioning factors, the occurrence of a presently buried valley adjacent to the Rhone fan, in the continuation of the Sète valley, suggests oversteepening by lateral retrogressive erosion along the Rhone fan. This process has been proposed for explaining the broadening of the Bourcart Canyon (Baztan et al., 2005; Sultan et al., 2007). At some stage, these recurrent failures may have triggered a massive retrogressive failure of the fan levee and adjacent slope. Another preconditioning factor could be local slope oversteepening by vertical movements of listric faults (dos Reis et al., 2005) (Fig. 4B).

External triggers can occur and hasten sliding. In the GoL. earthquake shaking can be discarded as the GoL is a low seismicity area where during the last 50 years most earthquake magnitudes were lower than 4 (Manchuel et al., 2017). Furthermore, a minimum magnitude of 7 is needed to trigger instabilities on high sedimentation rate lowstand sediments in the neighbouring Bourcart Canyon (Sultan et al., 2007).

5.3. Processes for propagation and long runout distance

The RWMTD appears as a seismically homogenous and transparent body with no evidence of particular internal structure. A large part of the body is buried under late and post-glacial turbiditic deposits and erosions that might have obliterated morphological features on top of the RWMTD (Bonnel et al., 2005; Droz and Bellaiche, 1985; Gaullier et al., 1998; Torres et al., 1997). However, seismic data reveal a rather flat morphology on top (Figs. 6 to 10) and do not show evidence of faulting, blocks formation, rafting or retrogression as observed in the neighbouring Big'95 landslide on the Ebro Margin (Lastras et al., 2002; Lastras et al., 2004). On the contrary, the RWMTD shows evidence of widespread ductile-plastic behaviour with folding and contortion in the clay-rich sampled sediment (Fig. 11), and the formation of a compression bulge at the SE limit against the Rhone fan (Figs. 4C, 4D and 9). The ductile-plastic interpretation is reinforced by the fact that the RWMTD has spread onto and filled the pre-existing seabed morphologies (Figs. 5 to 10).

Mass transport deposits can propagate over very long distances, in the order of several hundreds of kilometres for the largests, and the runout distance is roughly proportional to the size of the slide (De Blasio and Elverhøi, 2011; Haflidason et al., 2005). The RWMTD exhibits a H/L ratio in the order of 0.004, which fits within the morphometric characteristics of many mass transport deposits in the world (Issler et al., 2005). In particular, it fits particularly well with the characteristics of the Storegga's 63 slide lobes (Haflidason et al., 2005; Issler et al., 2005) suggesting that they share common mechanical properties and propagation processes. Indeed, like the Storrega slide, the RWMTD involved clay-rich sediments but with drastically different sources because the Norwegian margin is fed by glacial and glacigenic sediments, while the GoL is fed by temperate deltaic sediments. Many studies outline a discrepancy between the mechanical properties (high strength, high density, low porosity) of cohesive sediment in mass transport deposits and their exceptional long runout distances that would necessitate much lower sediment strength (De Blasio et al., 2005). This is also the case for the RWMTD that exhibits clay-rich sediments with exceptional high densities (between 2 and 2.2 g.cm^{-3}) that evidence over-consolidation with regards to the overlying sediment (Fig. 11). Modelling of long runout distance by viscoplastic model requires to introduce very low sediment strength (De Blasio et al., 2005), much lower than that of the slided sediment and of the mass transport deposit. However, remoulding of sediment and adjunction of water (shear wetting) during transport can significantly decrease the sediment strength (De Blasio et al., 2005) and enhance lubrication at the base and front of the mass transport deposit and explain long runout distances (De Blasio and Elverhøi, 2011). In addition, hydroplaning may also increase lubrication (De Blasio et al., 2005; Mohrig et al., 1998). The present high density of the RWMTD suggests a drastic strengthening of sediment during transport or after transport. Sediment densification is a common feature of mass transport deposits that occurs in response of shearing in highly sensitive clays and explaining that they exhibit contrasted impedance with the surrounding sediment and are very well imaged on seismic data (Dugan, 2012). The important folding and contortion in the clay sediment sampled on the top 7 m of the RWMTD at proximal, central and distal locations, is an evidence that shearing occurred during transport and may thus explain the present high density.

5.4. Timing and synchronism with other major sediment gravity deposits in the north-western Mediterranean

The emplacement of the RWMTD is dated during the LGM between 19.9-21.5 ka cal BP (end of the LGM) according to our radiocarbon dating at the base of sediment drape on top of the RWMTD (Fig. 11). In the north-western Mediterranean, this period of time and the ensuing post-glacial sea level rise are characterized by several other major events that are the BIG'95 mass transport deposit (26 km^3) on the Catalan-Ebro margin (Lastras et al. 2002), the Rhone EMTD (150-200 km^3) (Droz and Bellaiche, 1985; Droz et al. 2006) in the GoL, and the megaturbidite in the Balearic Abyssal Plain (ca. 500 km^3) (Rothwell et al., 1998).

The BIG'95, seems to have been emplaced in a different setting than that of the RWMTD. It affected the Ebro fed clay-rich deposits but that, unlike the Rhone fed deposits, are less focused and spread through several canyons and developed at the base-of-slope several channel–levee complexes with an apron-ramp turbidite system (Alonso and Maldonado, 1990; Lastras et al., 2004). Sliding and long runout occurred at shallower water depth from the upper slope at 200 m water depth to 2000 m water depth (and more recently, at the end of the deglacial sea level rise at 11.0-11.5 ka cal BP (Lastras et al., 2002; Lastras et al., 2004). However, like for the RWMTD, high sediment load and over-steepening during lowstand may have been a determinant trigger mechanism (Lastras et al., 2004).

The age of the REMTD is still unknown but like the RWMTD it is very shallow, it also involved adjacent turbidite leveed deposits and it lies at the same water depths (1,900-2,700 m). Although both deposits are clearly separated by the Rhone deep-sea turbiditic valley (Droz and Bellaiche, 1985), it is quite likely that their emplacement is coeval, share common trigger mechanisms and that may even correspond to a single event.

Megaturbidites are interpreted as the possible product of massive slope failures that evolved into turbidity current(s) eventually deposited and trapped in the deepest part of closed oceanic basins like in the Mediterranean (Cita and Aloisi, 2000; Reeder et al., 2000). Exceptional high-impact hazards capable of broadly shaking or reworking sediments on slopes such as volcanic eruptions, earthquakes and tsunamis have been suggested as a trigger mechanism (San Pedro et al., 2017), but environment-climatic driven triggers such as sea-level change or gas hydrate destabilisation are also evoked (Reeder et al., 2000; Rothwell et al., 2000). A 8–10 m thick dominantly muddy megaturbidite fills the whole Balearic Abyssal Plain over 60,000 km^2. In seismic data it appears as a laterally continuous, acoustically transparent layer (Rothwell et al., 1998). The source remains unknown but thickening and coarsening of the basal sand of the megabed towards the north suggests emplacement from that direction (Rothwell et al., 1998). The calibration of the weighted mean radiocarbon age obtained on top of the megabed by Rothwell et al. (1998) gives a 2 sigma age comprised between 20.3 and 20.9 ka cal BP with a median probability of 20.6 ka cal BP (Reimer et al., 2013) but the group of dates obtained is bracketed between 19.5 and 21.7 ka cal BP (Fig. 12). Therefore, ages of both RWMTD and Balearic Abyssal Plain megaturbidite are the same within 2-sigma confidence interval and no chronological order can be given between the two deposits, reinforcing the possibility of a genetic link compatible with the proposed northern source. However, the exceptional volume of the Balearic Abyssal Plain megaturbidite shows that the related mass movement was likely efficiently evacuated from the source failure, which is not the case of the RWMTD and REMTD. Therefore, even though the RWMTD and REMTD may have contributed to feed the megaturbidite, the failure source must be also sought in adjacent areas characterized by recurrent slope failures like the Ligurian margin (Ioualalen et al., 2010; Migeon et al., 2011).

5.5. Consequences on sediment routing in the western Gulf of Lions rise and Rhone fan

Sedimentation and sediment transfer processes in the GoL and Catalan-Ebro margins are characterized by high sediment input from the Rhone and Ebro River and by numerous canyons dissecting the outer shelf and slope efficiently draining sediments towards the base of slope. The transfer was obviously efficient during the LGM lowstand with the growth of the deep-sea fans and sedimentary ridges (Beaudouin et al., 2004; Jallet and Giresse, 2005; Lombo Tombo et al., 2015; Melki et al., 2009). Even during the Holocene highstand, although sediment fluxes at the shelf break are several orders of magnitude lower than during the LGM, canyons remain an efficient pathway as they can focus high amplitude hydro-sedimentary processes with a strong imprint on the sea bed morphology (Canals et al., 2006; Lastras et al., 2007b; Palanques et al., 2006; Payo-Payo et al., 2017) and even deposit sandy turbidites at the base of slope (Dennielou et al., 2009). In the western part of the GoL, the Sète canyon network, the La Fonera canyon and the Clots del Puget canyon presently reach the base of slope and vanish at ca. 2300 m (Fig. 1).

The longitudinal concave-up shape of the buried valley along the western flank of the Rhone fan, in the direct prolongation and in good fit with the concave-up longitudinal shape of the Sète canyon and the Valencia channel (Figs. 10B, C, D and 13A), shows that during the LGM, prior to the emplacement of the RWMTD, the western GoL canyon drainage network and the Ebro-Valence canyon drainage networks were coalescing and that, probably, the Valencia fan was collecting significantly more important volumes of sediment (Fig. 13A). The presence of such an important erosional channel questions about the sediment source and flow capable of developing and maintaining this conduit. The presence of an axial incision in several canyons (Bourcart, Herault and Marti) suggests that these canyons heads were connected with major rivers during the last glaciation and were fed by sustained confined turbidity currents (Baztan et al., 2005).

This is confirmed by the mapping of the LGM paleo-fluvial drainage network on the shelf that shows that the Herault canyon was fed by the Rhone River (Jouet et al., 2006) and may have supplied frequent turbiditic flows to develop the valley.

The burying and clogging of this channel resulted in a major reorganisation of the sediment routing in the north-western Mediterranean. It is not possible to determine the magnitude of the decrease in the quantity of sediment supply into the Valencia channel, but this question could be easily addressed by collecting sediments cores along the Valencia channel, both upstream and downstream of the channels coalescence. The RWMTD was not found inside the Valencia valley, while it is still visible inside the extremity of the Clots del Puget/Entrant de Palamos valley where both valleys coalesced (Fig. 8D). Indeed, the RWMTD may have never been engaged inside the Valencia channel, but it is also possible that deposits have been eroded and removed from the valley. This is also suggested by evidences of upstream erosion in the Valencia channel, in the order of several meters per thousand years since the LGM (Amblas et al., 2011).

A close examination of seabed morphology at the outlet of the Sète canyon network shows large erosive bedforms in the distal reaches, including grooves and crescent scours (Lastras et al., 2007b) and shows that the seabed has a concave-up shape on top of the RWMTD (Fig. 4B and 4D). This is indicative that bed-load sediment transport with dominantly bypassing and erosive processes have persisted down the Sète canyon network during the LGM after the emplacement of the RWMTD and have started the excavation of a new drainage at the same location of the buried one. Shallow, lobe-shaped deposits, such as the Sète lobe (Droz et al., 2001), at the extremity of the canyon are also suspected (Fig. 13B). There are also evidences of currently active hydro-sedimentary processes in the Cap de Creus canyon such as dense water cascading capable of transporting huge quantities of sediment (Canals et al., 2006; Lastras et al., 2007b; Palanques et al., 2009) further suggesting that excavation is still ongoing.

We have shown that several sediment failures that fed the RWMTD have affected the Rhone fan deposits and that headscars have even nearly reached the perched valley (Fig. 4B and 6A). The last, westward, avulsion of the Rhone deep-sea channel occurred shortly after the emplacement of the RWMTD as indicated by the subsequently deposited neofan resting on top of the RWMTD (Figs. 5 to 8) (Droz and Bellaiche, 1985; Torres et al., 1997). Interestingly, the channel avulsion occurred in an area where the RWMTD extends onto the Rhone levee and that can be interpreted as a failure area similar to that further north (Fig. 4B and 5C). Therefore one can argue that channel avulsion may have been triggered after breaching of the levee by the failure of the levee, although downstream clogging of the Rhone channel is also evoked (Droz and Bellaiche, 1985).

The major disruptions in the sediment routing occurred shortly (ca. 3 ky) before the onset of the post-glacial sea level rise at ca. 18.5 cal. ka BP and the sediment starvation of slope and base-of-slope fans consecutive to the backstepping of sediment depocenters onto the shelf (Berné et al., 2007; Lombo Tombo et al., 2015). Therefore the consequences on the sedimentation in the Valencia fan, the final sink, may not be well visible and recorded. It is possible to extrapolate the consequences during a future lowstand. Since there are evidences that the concave-up morphology at the base of slope has already started to recover, one can argue that during a future lowstand the recovery may be complete and that the Valencia channel may collect again the sediments from the Sète canyon network, but, in addition and this is a major contrast with the LGM, the neochannel avulsion will possibly also route the Rhone sediment into the Valencia channel and fan making it the collector from the two major north-western

Mediterranean rivers, the Ebro and the Rhone. However, this would be a temporary situation because the Rhone levees display several collapses prone to trigger breaches and new channel avulsions (Fig. 4B and 6A).

5.6. Significance for sediment routing in the submarine realm

Modification of sediment transport pathways in the terrestrial realm by rerouting of rivers after hillslope landslides or glacier retreat is well documented and major (>10^5 m^3) terrestrial landslides can instantaneously modify river pathways for periods of times relevant to landscape evolution (>10^4 yr) (Ouimet et al., 2007; Shugar et al., 2017). Large landslides can also act as a primary control on channel morphology and longitudinal river profiles, modify the adjustment of rivers to regional tectonic, climatic, and lithologic forcing (Ouimet et al., 2007), and therefore influence the volume and rates of sediment delivered into the oceans. Though marine landslide volumes are up to three order of magnitude larger than their aerial counterparts (Hampton et al., 1996; Urgeles and Camerlenghi, 2013) and are major elements of sedimentary margin development, their contribution to deep-sea sediment routing is not well documented. As a consequence of their widespread occurrence in turbidite systems, landslides, mass transport deposits or mass transport complexes play a significant role in the topography of channels or slopes, affect the resulting accommodation space, the development and bifurcation of deep-sea channel, and *in fine* can control the routing and dispersal of sediment at the fan scale (Armitage et al., 2009; Bernhardt et al., 2012; Corella et al., 2016; Kawamura et al., 2010; Kneller et al., 2016; Ortiz-Karpf et al., 2015). However, a fundamental modification of a deep-sea sediment transport network by a single submarine mass transport deposit at continental margin scale seems unprecedented. Noteworthy, the present case also involves rapid turbidite accumulation showing that rapid changes of sediment routing may occur in areas of massive sediment deposition prone to rapid evolution of submarine morphologies. We suggest that the converging pattern of the canyon network as well as the semi-confined morphology at the base of slope of the western part of the GoL created a receptacle suitable for rapid infill and blocking of canyons.

6. Conclusions

A comprehensive mapping of the Rhone RWMTD was performed, based on seismic data collected during several oceanographic campaigns between 1997 and 2008. The RWMTD emplaced on the western flank of the Rhone fan and involved sediment from the base of slope and from the adjacent Rhone fan levee. The RWMTD covers a surface of 6800 km^2. It represents a volume of 160 km^3 of folded and contorted laminated clayey high-density stiff sediments that have spread over 180 km.

Our results show that :

- Large mass transport deposits can be obscured in settings where sedimentation rates are high. This underlines the importance of integrated (swath bathymetric, seismics, core data) studies, and also suggests that hazard catalogues constructed from seafloor morphology alone may be incomplete.
- Mass wasting is a major process of the margin development in the GoL and more generally in the north-western Mediterranean. Several very large events occurred within a very small time window in the Western Mediterranean (Rhone Western and Eastern mass transport deposits and Balearic Abyssal Plain megaturbidite) and account for a significant proportion of the stratigraphy. Though probably not genetically linked, they occurred in period of time of large sediment transport into the base of slope during the Last Glacial Maximum.

- Large landslide deposits can fundamentally modify sediment routing systems in the marine realm at margin scale. Mass wasting must therefore be considered as a major internal forcing on sediment dispersal. These drastic events can have a major impact on downstream sedimentation at the base of slope and abyssal plains where sedimentation is therefore not only controlled by externally forced fluctuations of sea level and sediment flux.

It can be pointed out that the emplacement of the RWMTD in the lowstand systems tract, shortly (1-2 ky) before the onset of the post-glacial sea level rise and Rhone fan sediment starvation (Lombo Tombo et al., 2015), is conform to the Exxon sequence stratigraphy sea-level based model.

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Sample list

Core MD01-2435: http://igsn.org/BFBGX-88347

Core KSGC-10: http://igsn.org/BFBGX-87938

Core MD01-2438: http://igsn.org/BFBGX-88349

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Figure captions

Figure 1

Bathymetric map of the Gulf of Lions and Catalan margins with indication of main morpho-sedimentary features (white dashed lines: sedimentary deposits; black dashed lines: Mass Transport Deposits; violet dashed lines: main canyons; black solid line: current Petit-Rhone canyon/channel). Gulf of Lions canyons (Berné et al., 2004): CC: Cap de Creus, LD: Lacaze Duthier, P: Pruvost, Bc: Bourcart, He: Herault, S: Sète, CL: Catherine Laurence, M: Marti (whose coalescence forms the Sète canyons network), PR: Petit-Rhone, GR: Grand-Rhone, Ms: Marseille, PL: Planier, C: Cassidaigne. Catalan margin canyons (Canals et al., 1983): LF: La Fonera, CdP: Clots del Puget, B: Blanes. REMTD:

Eastern Mass Transport Deposit, RWMTD: Western Mass Transport Deposit. Limits of sedimentary bodies are from Droz et al. (2006) except Valencia Fan from Maldonado et al. (1985).

Figure 2

Location map of slides headwalls, of buried and active listric faults (dos Reis et al., 2005), of seismic lines shown in Figs 5 to 9 and of sediment cores (white dots). PLSR: Pyreneo-Langudocian Sedimentary Ridge, PRDSF: Petit-Rhone Deep-Sea Fan, PRN: Petit-Rhone Neofan, REMTD: Eastern Mass Transport Deposit, RWMTD: Western Mass Transport Deposit. See Fig. 1 for canyon names.

Figure 3

Location map of used seismic data and sediment cores

Figure 4

A: Seabed morphology of the study area (map of slope) with location seismic lines and sediment cores. B: zoom in on the seabed morphology on the proximal area of the Western Mass Transport Deposit (RWMTD) at the base of slope. See scars headwall superimposed on active listric faults. Thick red arrows indicate possible main sources and pathways of the RWMTD across the western levee of the Rhone fan. C: zoom in on the seabed morphology of the eastern distal area of the RWMTD showing a bulge against the Rhone fan. D: Bathymetric section A-A' and B-B' show the morphologic expression of the compression bulge. C: bathymetric sections across the Sète valley (A-A'), showing the compression bulge at the contact between the RWMTD and the Rhone fan (B-B' and C-C'). See Figs. 2 and 4A for location. PLSR: Pyreneo-Langudocian Sedimentary Ridge.

Figure 5

The Rhone Western Mass Transport Deposit (RWMTD) as seen by several types of seismic: (A and C) single channel mini GI air-gun, (B) 24-channel mini-GI air-gun, (D) 6-channel 50 Hz GI air-gun, in the proximal area at the base of slope; strike lines (A, B, C), dip lines (D). Lines A and B were acquired simultaneously but with two different streamers. See the nearly transparent facies of the RWMTD on the single channel air-gun line (A) while on the 24-channel air-gun line (B) it shows internal reflections. See Figs. 2 and 4A for lines location. The top (red line) and base (blue line) of the RWMTD in D are issued from the interpretation of sub-bottom profiles. PLSR: Pyreneo-Langudocian Sedimentary Ridge.

Figure 6

Sub-Bottom Profiler lines (A) across the Rhone fan valley and proximal area of the Rhone Western Mass Transport Deposit (RWMTD) showing sliding of the turbiditic levee, and (B) along the central and distal area of the RWMTD. See also location and penetration of sediment cores on the RWMTD. See Figs. 2 and 4A for lines location.

Figure 7

Sub-Bottom Profiler (A) and air gun (B) seismic line across the central area of the Rhone Western Mass Transport Deposit (RWMTD). See overlapping more recent deposits and erosional features (Rhone neofan deposits and channels, scours field and deposits from La Fonera canyon). The top (red line) and base (blue line) of the RWMTD are indicated. See Fig. 2 and 4A for lines location.

Figure 8

Sub-Bottom Profiler line across the distal area of the Rhone Western Mass Transport Deposit (RWMTD). See infill of substratum relief (A), overlap of RWMTD on the Rhone fan (B), infill of Palamos valley (C) and confluence of Clots del Puget/Entrant de Palamós and Valencia valleys. The top (red line) and base (blue line) of the RWMTD are indicated. See Figs. 2 and 4A for lines location.

Figure 9

Sub-Bottom Profiler line across the eastern side of the Rhone Western Mass Transport Deposit (RWMTD) showing overlapping and a compression bulge against the Rhone fan. The top (red line) and base (blue line) of the RWMTD are indicated. See Figs. 2 and 4A for lines location.

Figure 10

Set of maps obtained after interpretation of seismic lines. A: isochron map converted into meters below seafloor of the top of the Rhone Western Mass Transport Deposit (RWMTD). White lines outline deposits that overlap the RWMTD, thick lines: Pyreneo-Langudocian Sedimentary Ridge (PLSR) and neofan, thin lines the Sète and La Fonera lobes (Droz et al., 2001). B: isochron map converted into meters below seafloor of the base of the RWMTD. White arrows outline the presently buried valleys in the prolongation of the Sète canyon. Blue dotted line (A-A’) shows the location of depth profiles shown on D. C: isochore map of the RWMTD. D: Depth profiles along the buried valley in the prolongation of the Sète canyon; red: base of the RWMTD; blue: top of the RWMTD; black: present bathymetry. Listric faults (LF) offsets are visible on the bathymetry profile at the base of slope, in the RWMTD proximal area.

Figure 11

Lithofacies of sediment cores collected in the Rhone Western Mass Transport Deposit (RWMTD) at proximal (core MD01-2435), central (core KSGC-10) and distal (core MD01-2438) locations. See Figs 2, 3 and 4A for location of sediment cores.

Figure 12

Graphic presentation of radiocarbon dating at the base of the hemipelagic drape on top of the Rhone Western Mass Transport Deposit (RWMTD) (this paper) and of the Balearic Abyssal Plain Megabed (Rothwell et al., 1998).

Figure 13

Reconstruction maps of canyons and turbidic channels drainage network and sediment routing during the Last Glacial Maximum (LGM), before (A) and after (B) the emplacement of the Rhone Western Mass Transport Deposit (RWMTD). Solid black line indicated location of the buried valley as mapped from seimic lines. Dashed black lines indicate possible location of another parallel valley and areas where the lack of seimic lines do not allow mapping the buried valley. See Fig. 1 for canyon names.

Table captions

Table 1

Oceanographic campaigns and data used in this study. See location in Fig. 3

Table 2

Location and characteristics of sediment cores used in this study. See Figs. 2 and 3 for location.

Table 3

Radiocarbon dating carried out on sediment cores. Calendar ages BP (Before Present) calculated with Calib 7.1 and Marine13 calibration curve (Reimer et al., 2013). $\Delta R = 48$ y ; SD = 101 y was determined after reservoir ages in the Gulf of Lions obtained from Calib 7.1 marine reservoir database.

Table 1

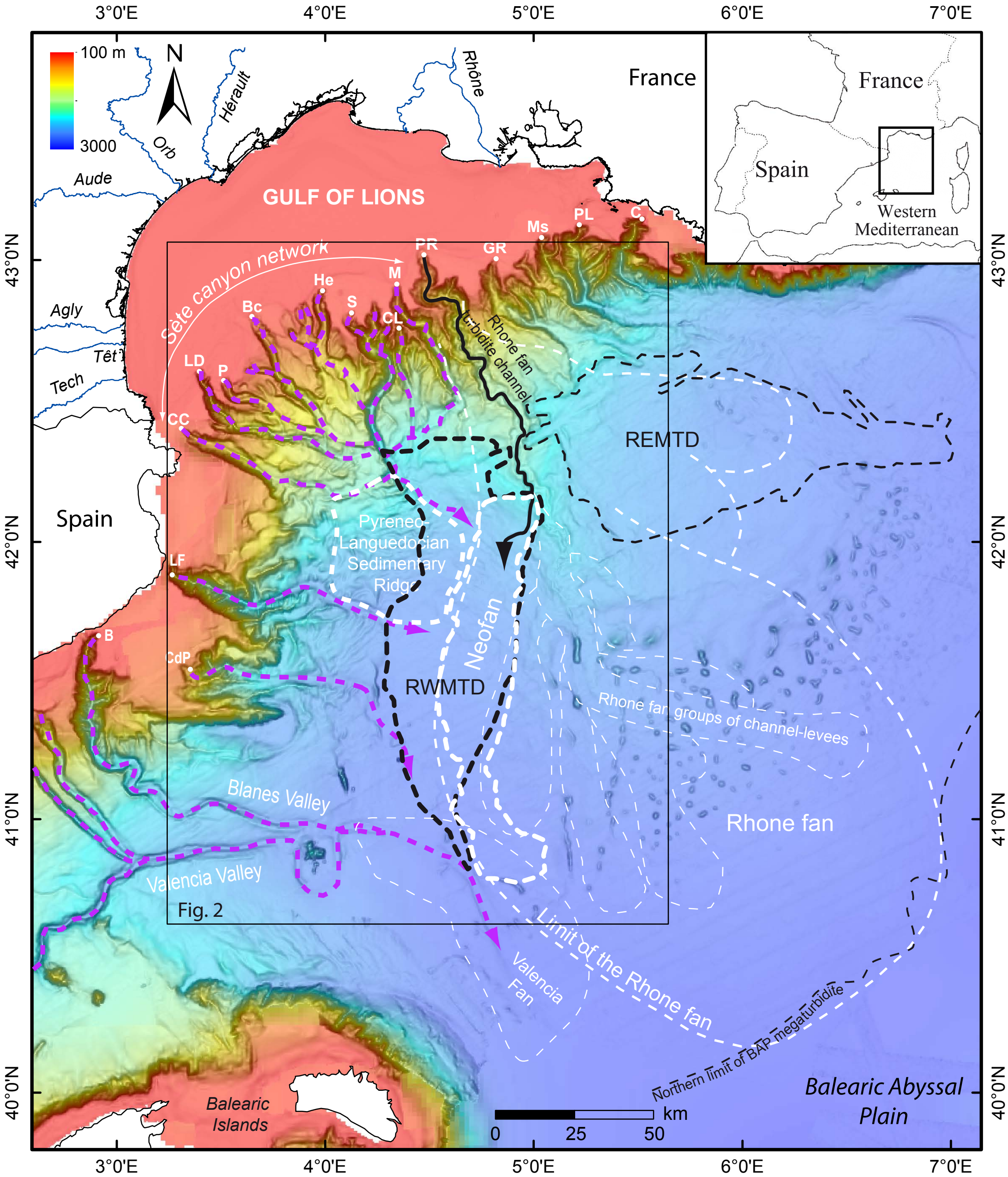
Campaign	Year	Ship	Data	Reference
Calmar97	1997	R/V L'Atalante	EM12, HR 6-channel 50 Hz GI, VHR 3.5 kHz SBP	(Loubrieu, 1997)
Marion	2000	R/V Le Suroît	EM300, HR single channel and 24 channels 130 Hz mini-GI	(Berné, 2000)
Gmo1	2001	R/V Le Suroît	EM300	(Cochonat, 2001)
MD123 / Geoscience1	2001	R/V Marion Dufresne	Calypso cores	(Turon, 2001)
Gmo2-Carnac	2002	R/V Le Suroît	EM300	(Sultan and Voisset, 2002)
Progres	2003	R/V Le Suroît	EM300, HR 6-channel 50 Hz GI, VHR 2-5.2 kHz SBP	(Droz, 2003)
Sardinia	2006	R/V L'Atalante	EM12, VHR 3.5 kHz SBP	(Aslanian et al., 2006)
Melrose Seepgol	2007	R/V Le Suroît	EM300	(Rabineau and Aslanian, 2007)
Rhosos	2008	R/V Le Suroît	EM300, VHR 2-5.2 kHz SBP	(Berné and Dennielou, 2008)

Table 2

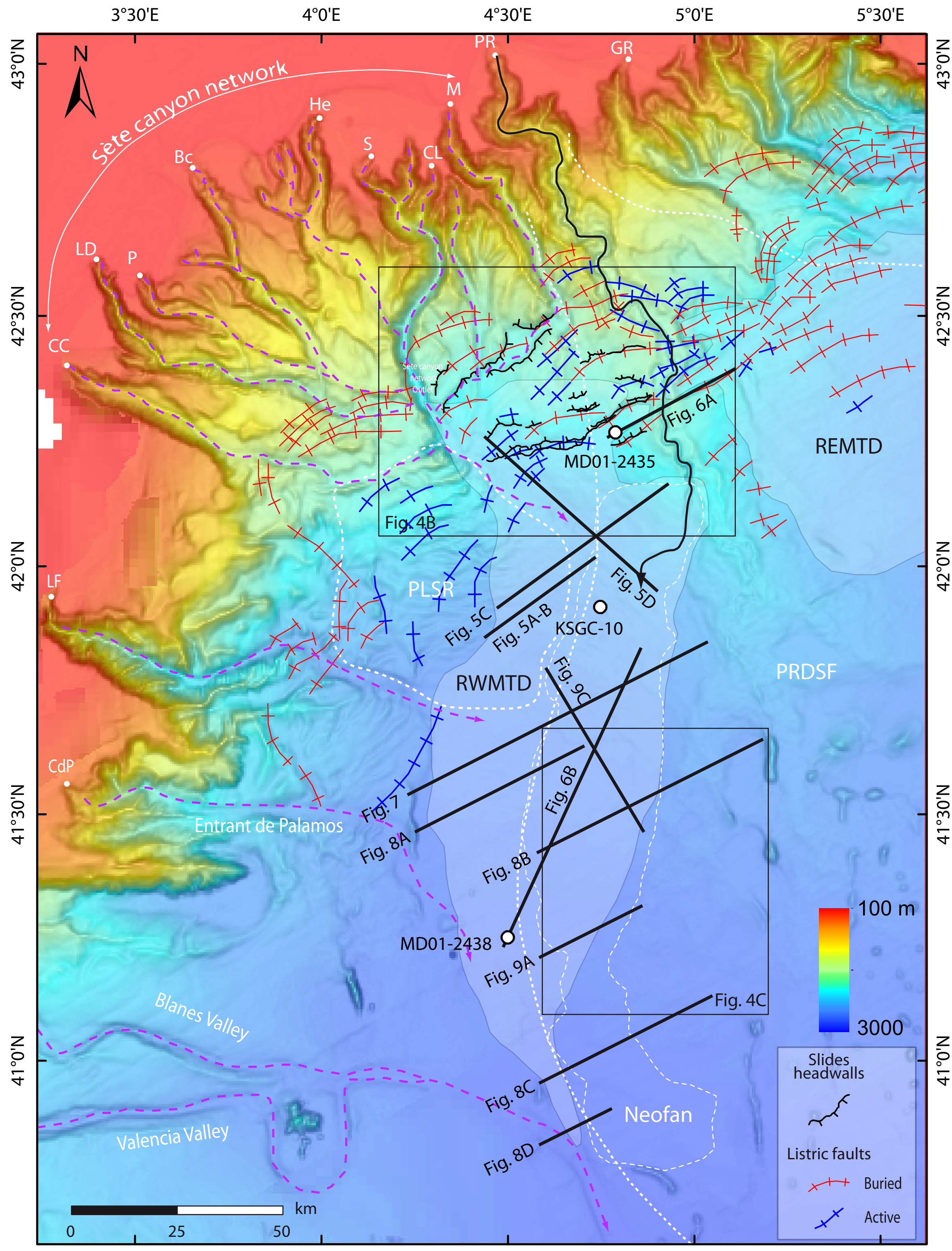
Core	Area	Latitude	Longitude	Water depth (m)	Length (m)	IGSN
MD01-2435	Proximal area	42°15.66’ N	004°47.18’ E	2025	19.23	BFBGX-88347
KSGC-10	Central area	41° 55.277’N	004 44.608’ E	2399	2.03	BFBGX-87938
MD01-2438	Distal area	41°14.91’ N	004°29.97’ E	2628	9.00	BFBGX-88349

Table 3

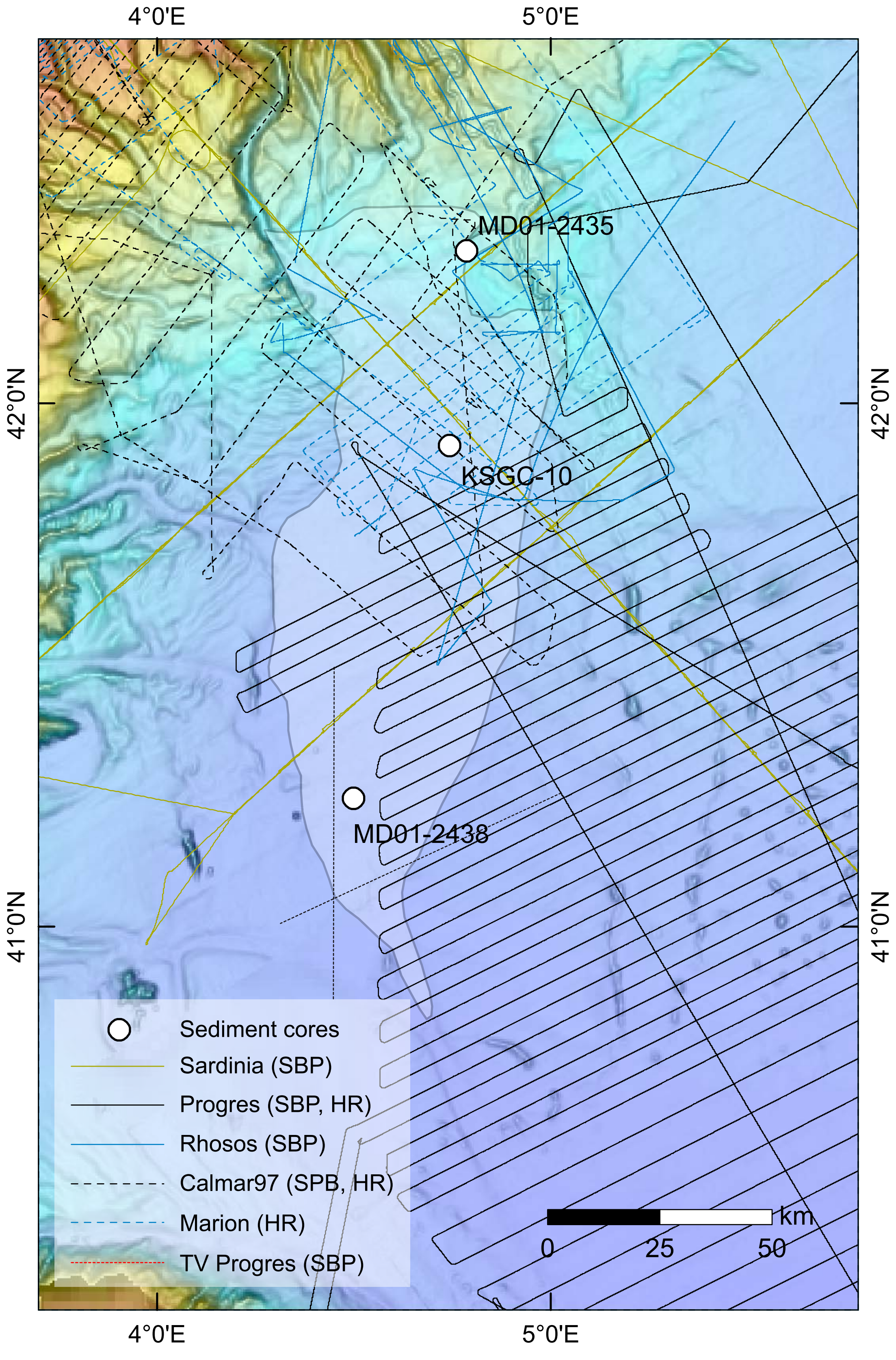
Core	Depth (cm)	Radiocarbon age (y BP)	1σ calendar age (y BP)	2 σ calendar age (y BP)	Median calendar age (y BP)	Dated material	Lab. number
MD01-2435	22-24	12,940±70	14,379-14,980	14,163-15,134	14,666	*G. bulloides*	Poz-14639
MD01-2435	853-858	17,940±90	20,921-21,331	20,726-21,535	21,128	*G. bulloides*	Poz-14641
MD01-2435	917-923	18,310±90	21,450-21,825	21,194-21,981	21,625	*G. bulloides*	Poz-14642
MD01-2438	96-100	17,260±80	20,110-20,446	19,949-20,600	20,276	*G. bulloides*	Poz-14649
KSGC-10	1-2	840±30	318-499	239-621	415	*G. bulloides*	Poz-13817



Dennielou et al. RWMTD - Figure 1

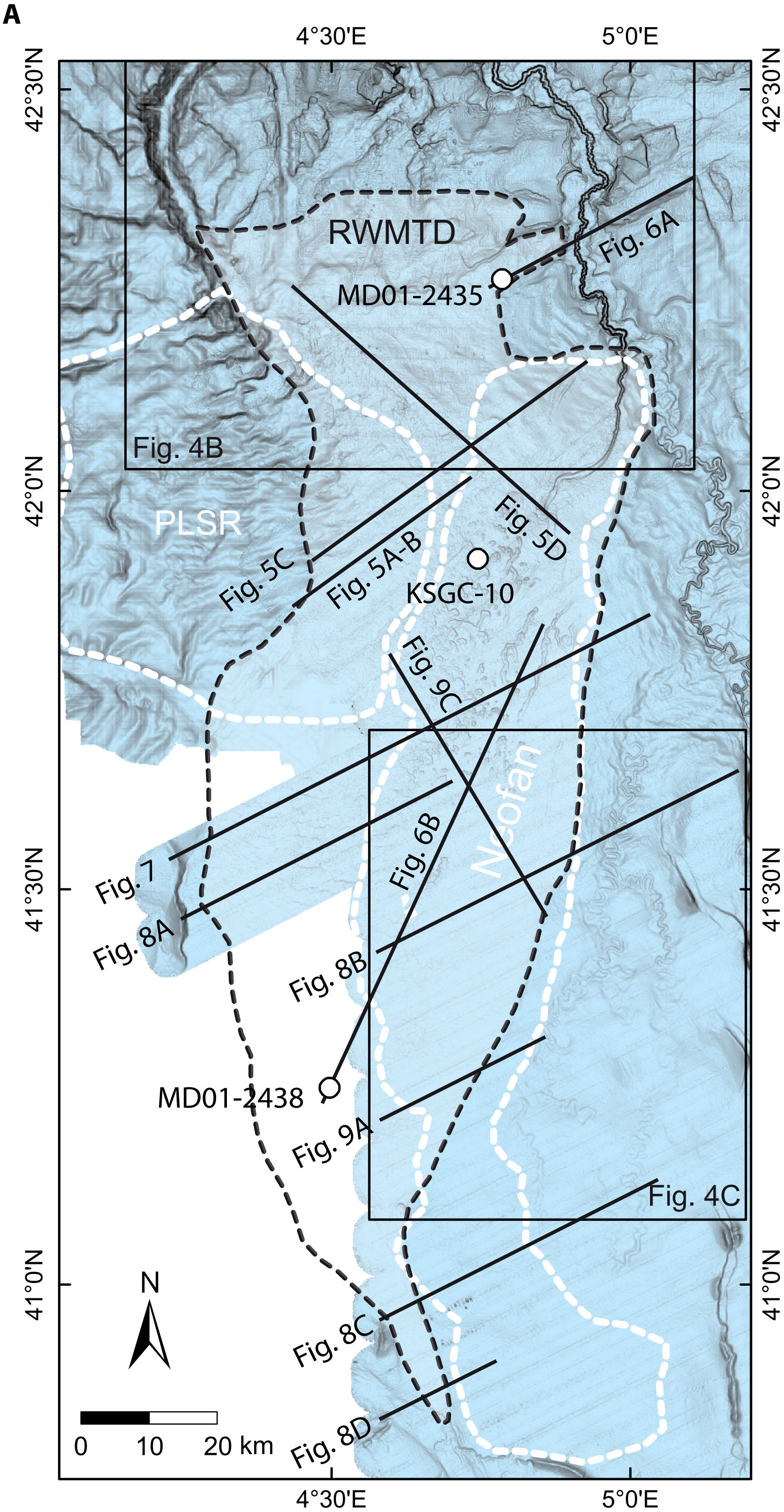


Dennielou et al. RWMTD - Figure 2

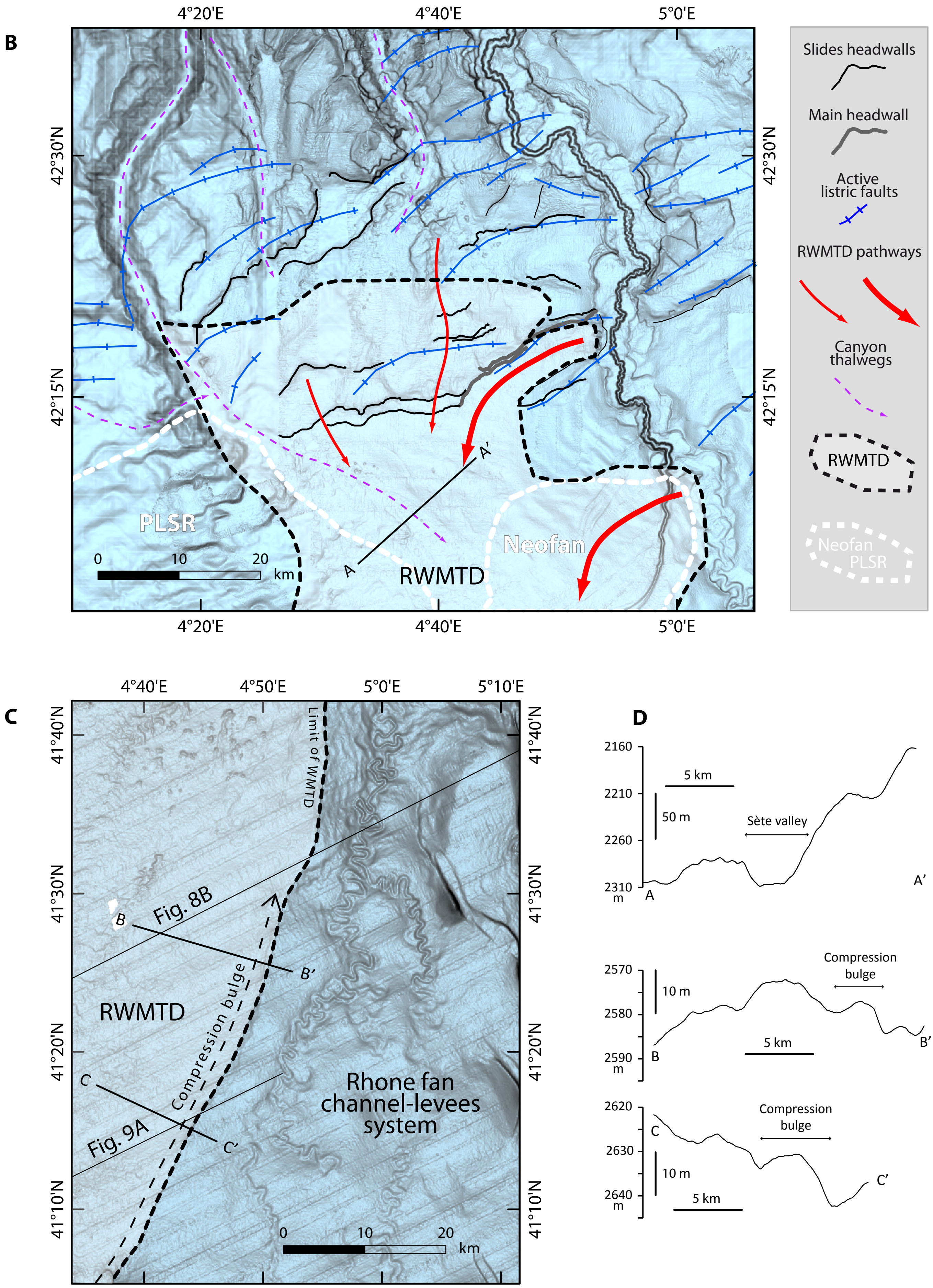


Dennielou et al. RWMTD - Figure 3

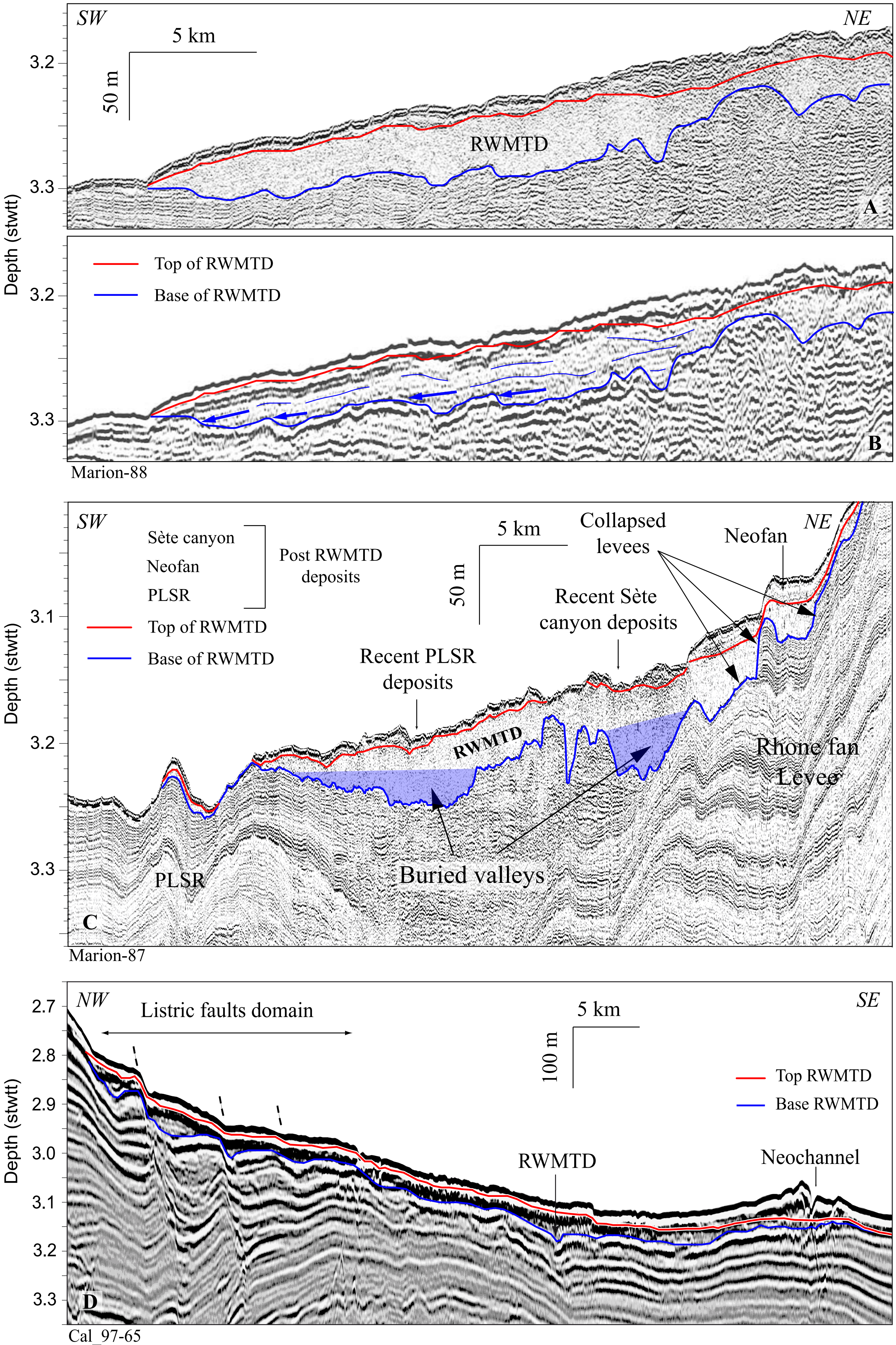
A



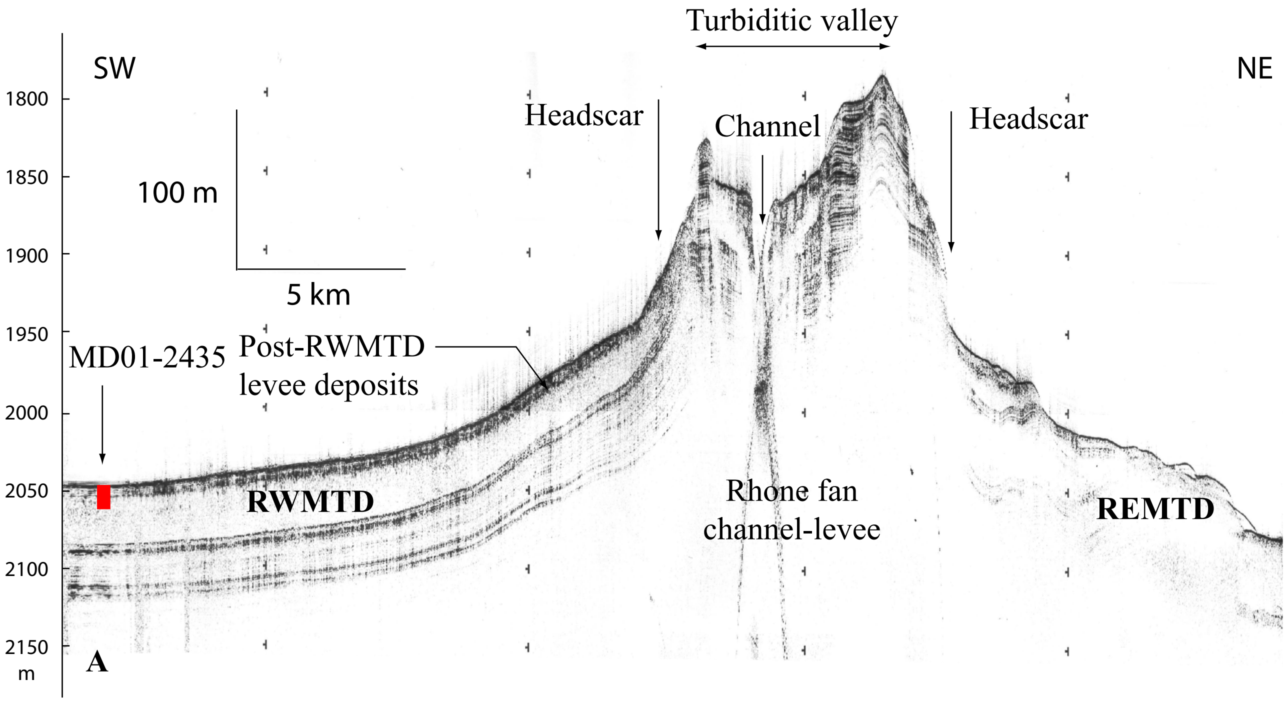
Dennielou et al. RWMTD - Figure 4

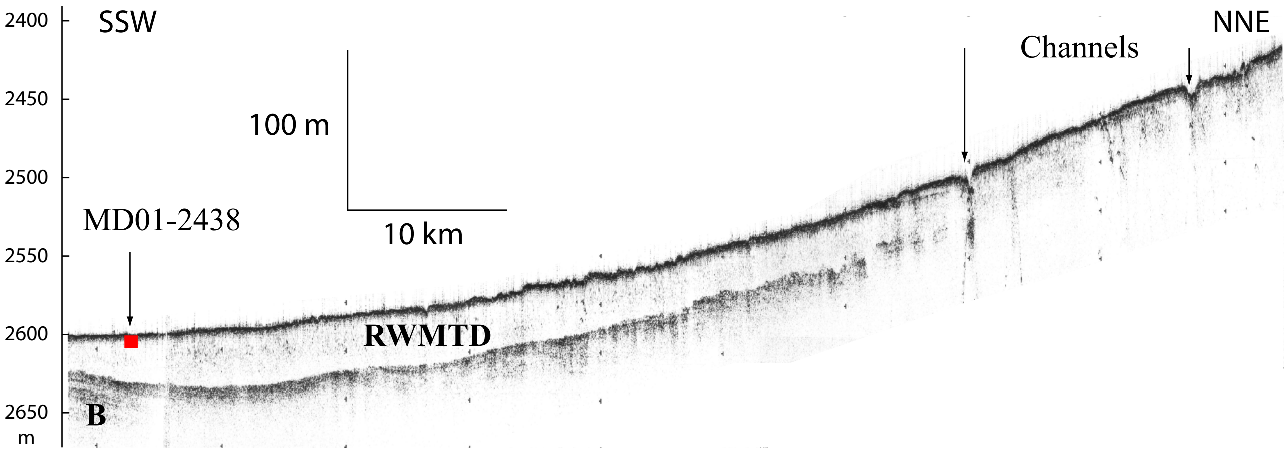


Dennielou et al. RWMTD - Figures 4A, 4B, 4C

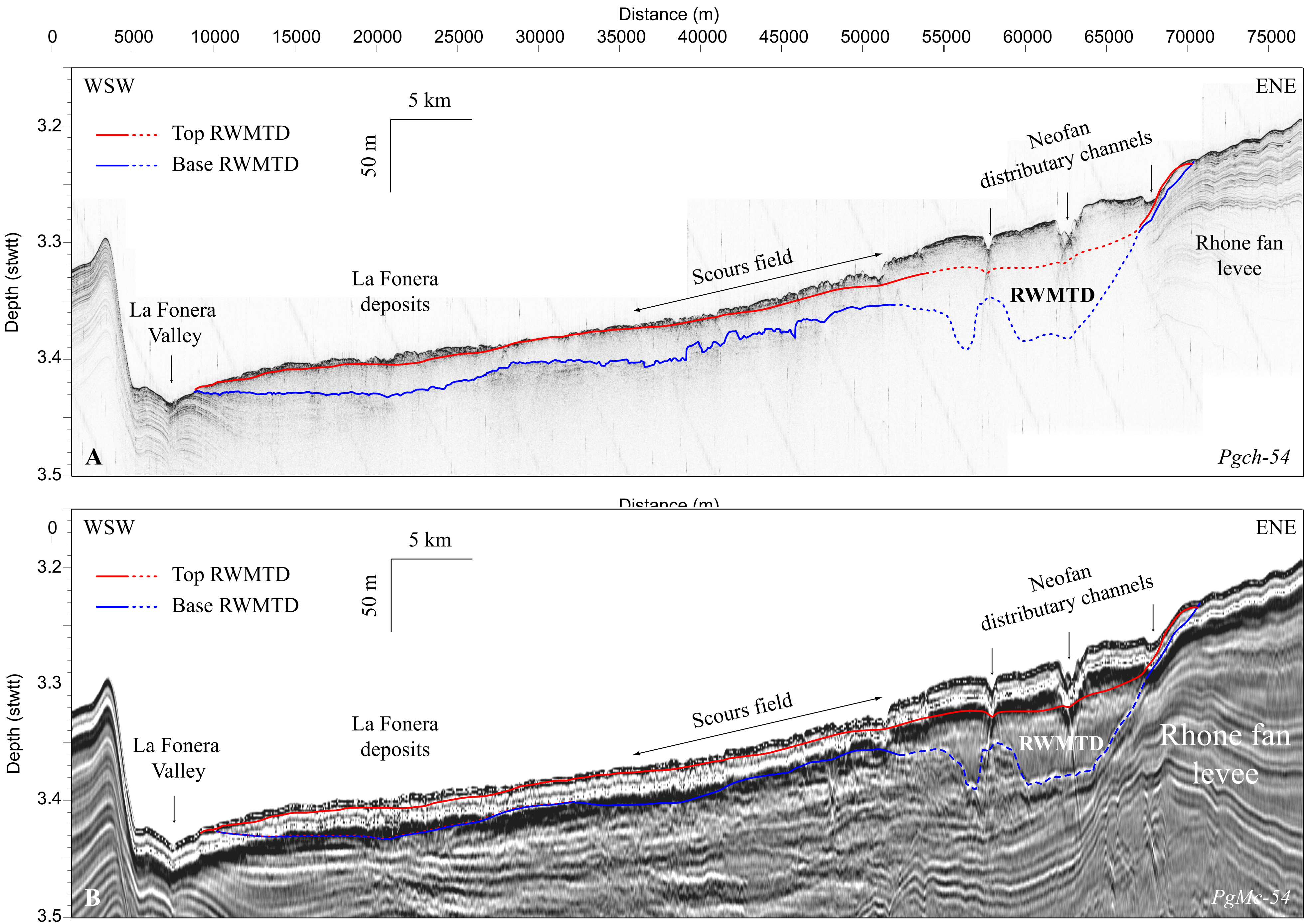


Dennielou et al. RWMTD - Figure 5

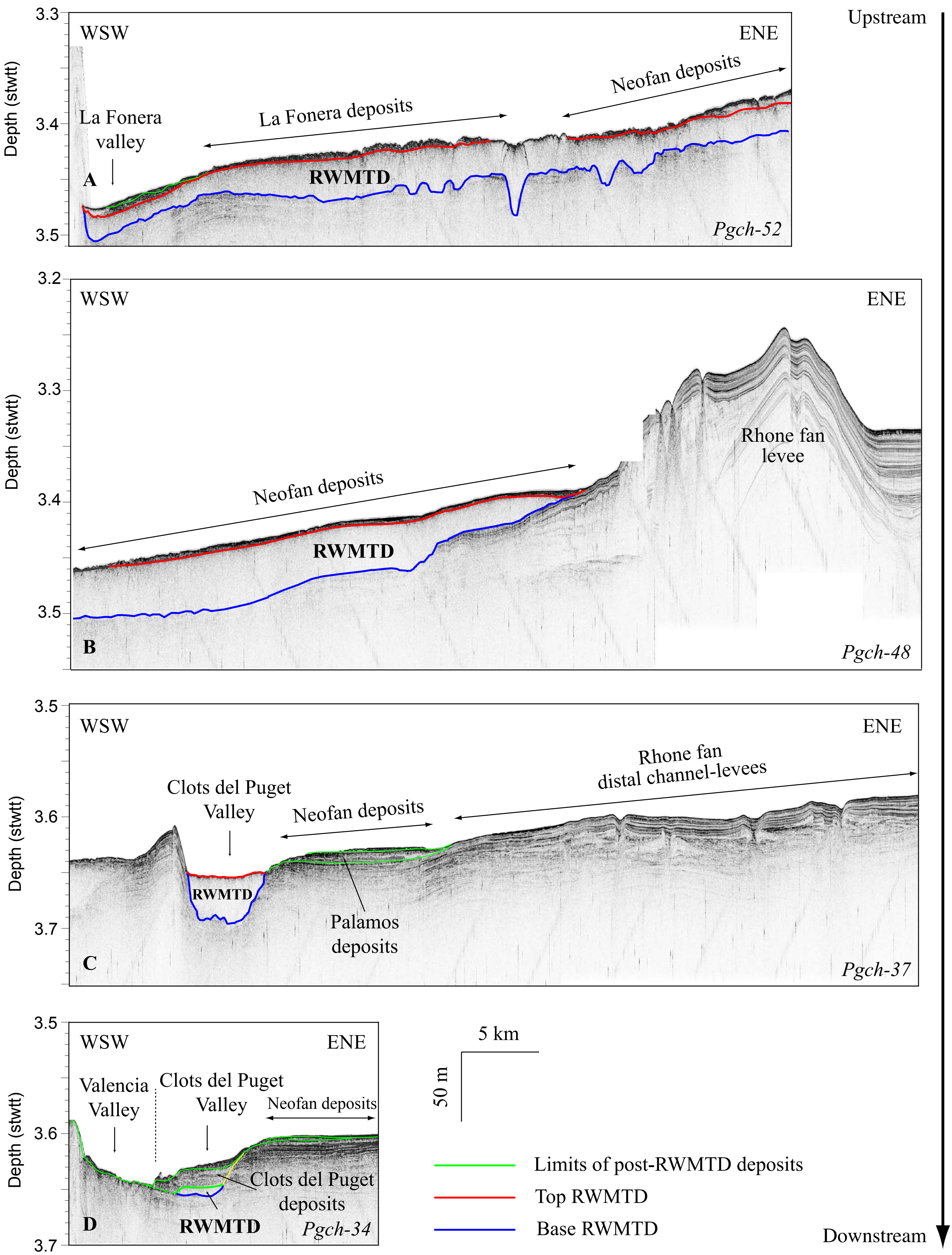




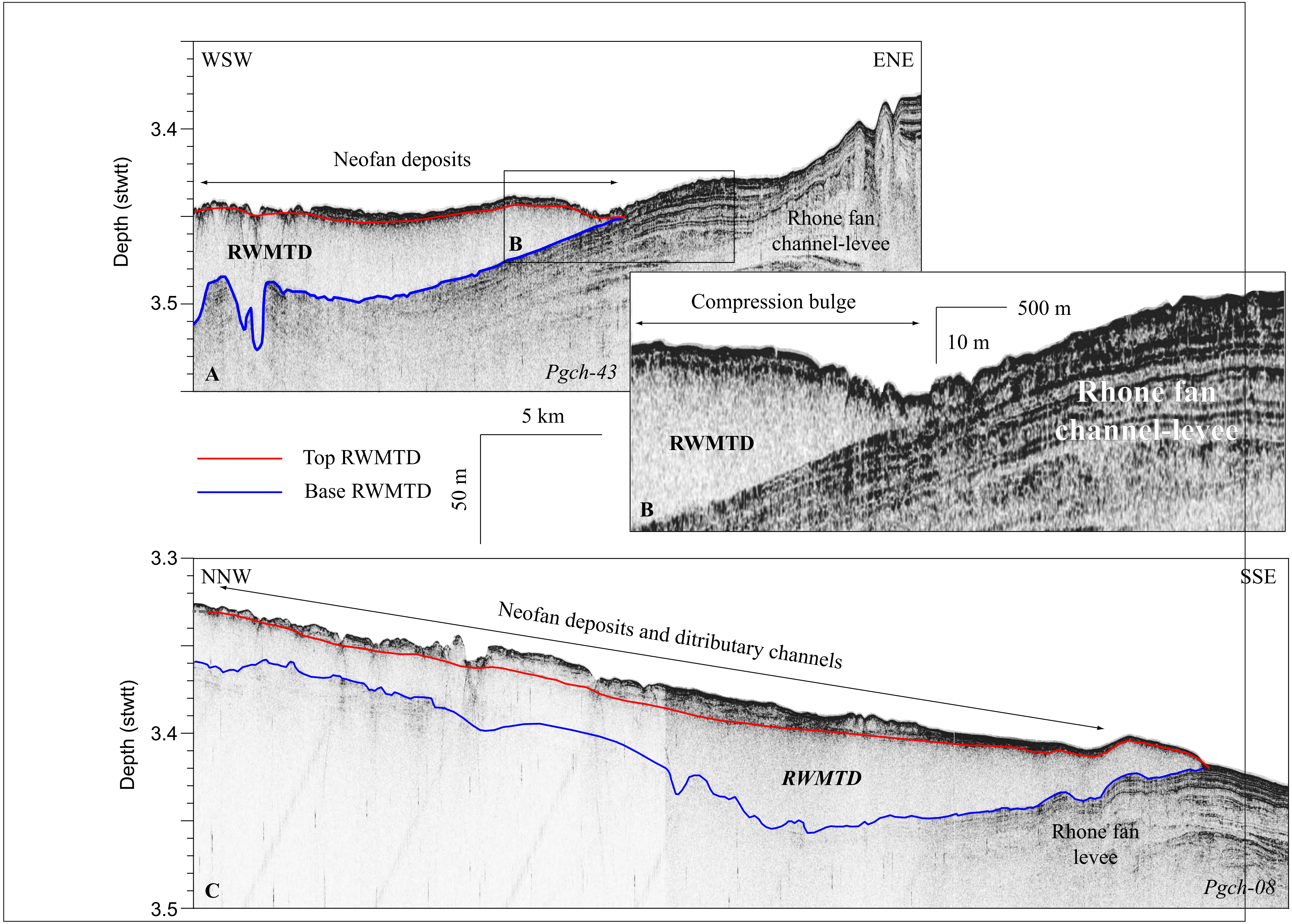
Dennielou et al. RWMTD - Figure 6



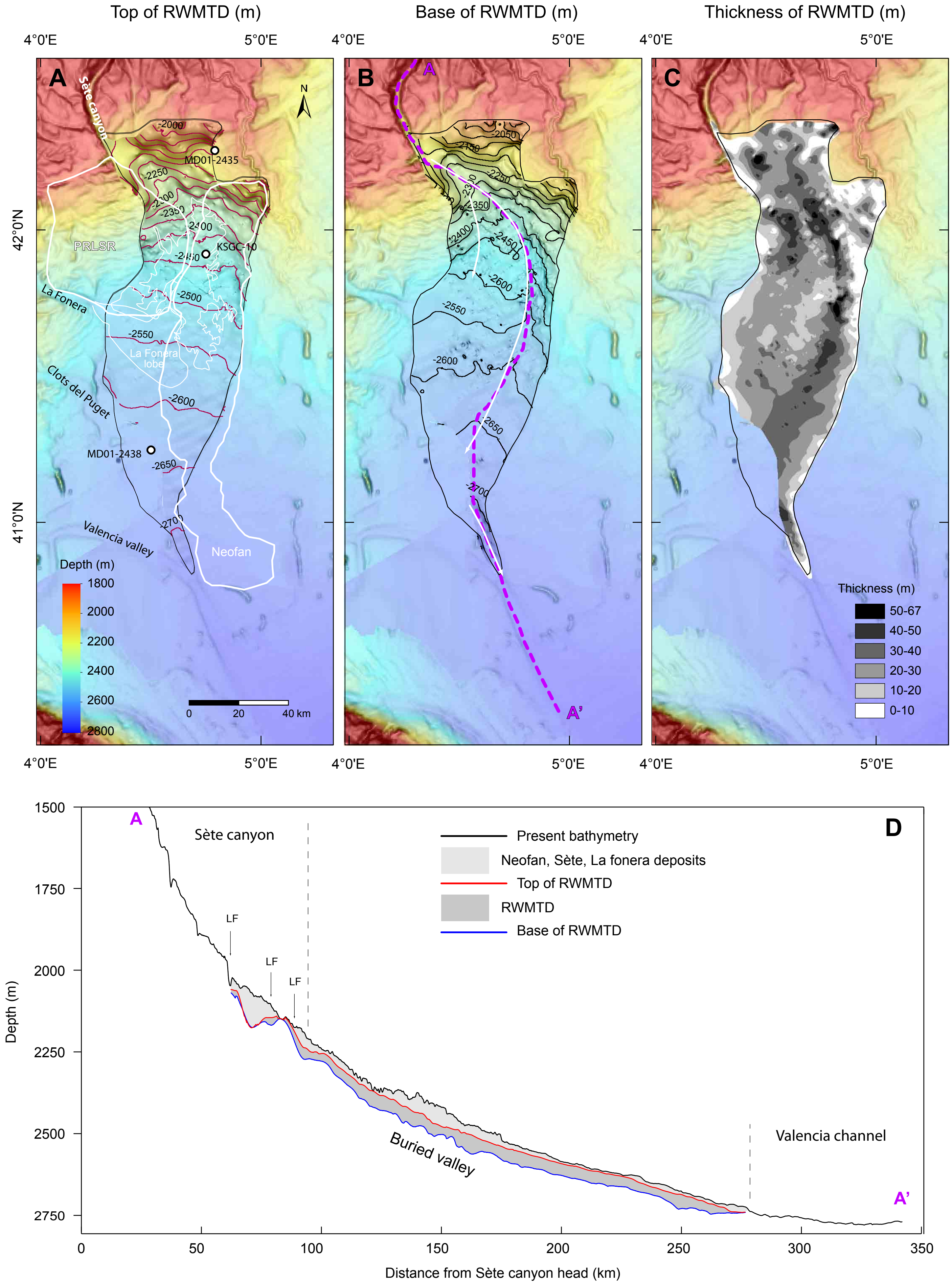
Dennielou et al. RWMTD - Figure 7



Dennielou et al. RWMTD - Figure 8



Dennielou et al. RWMTD - Figure 9



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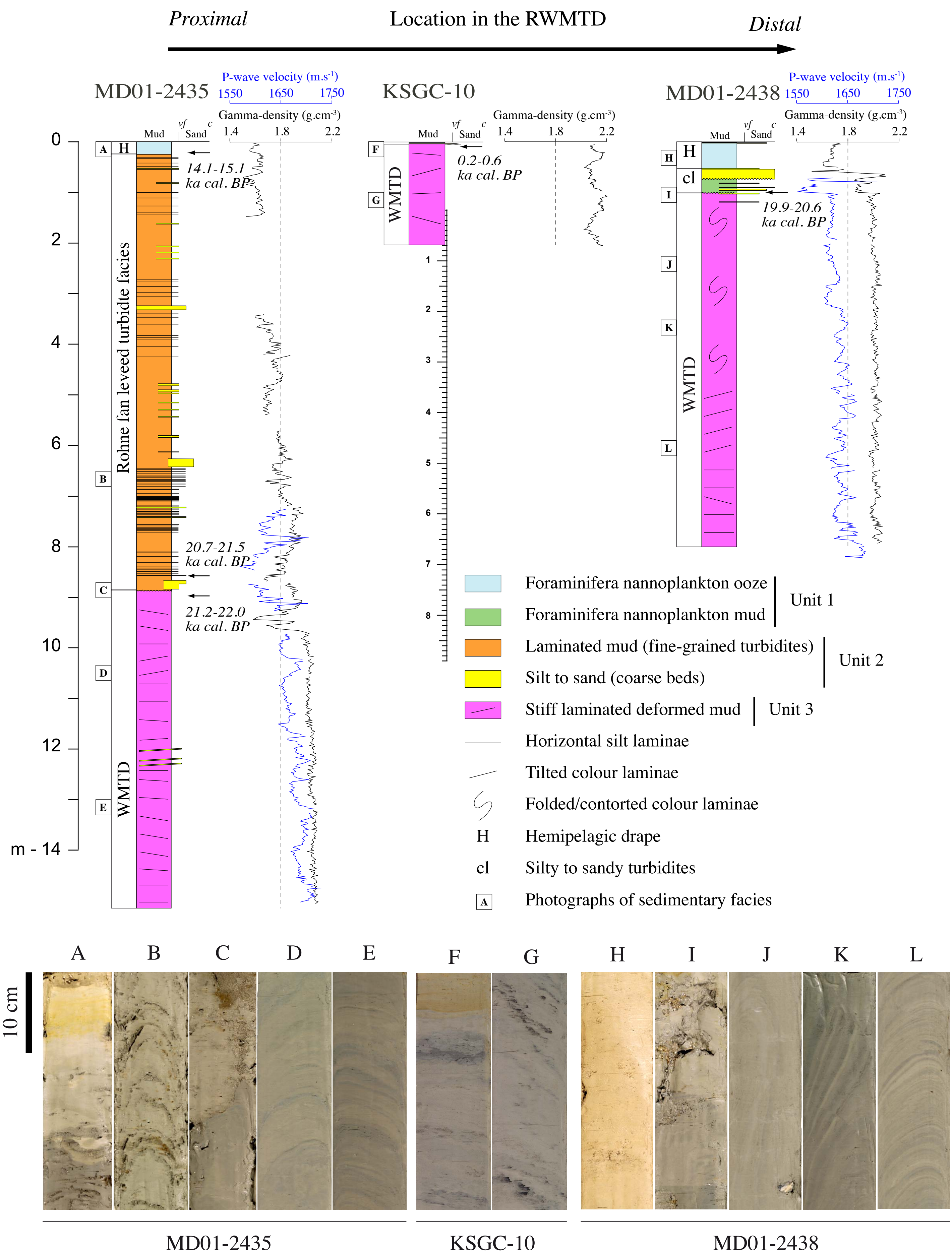

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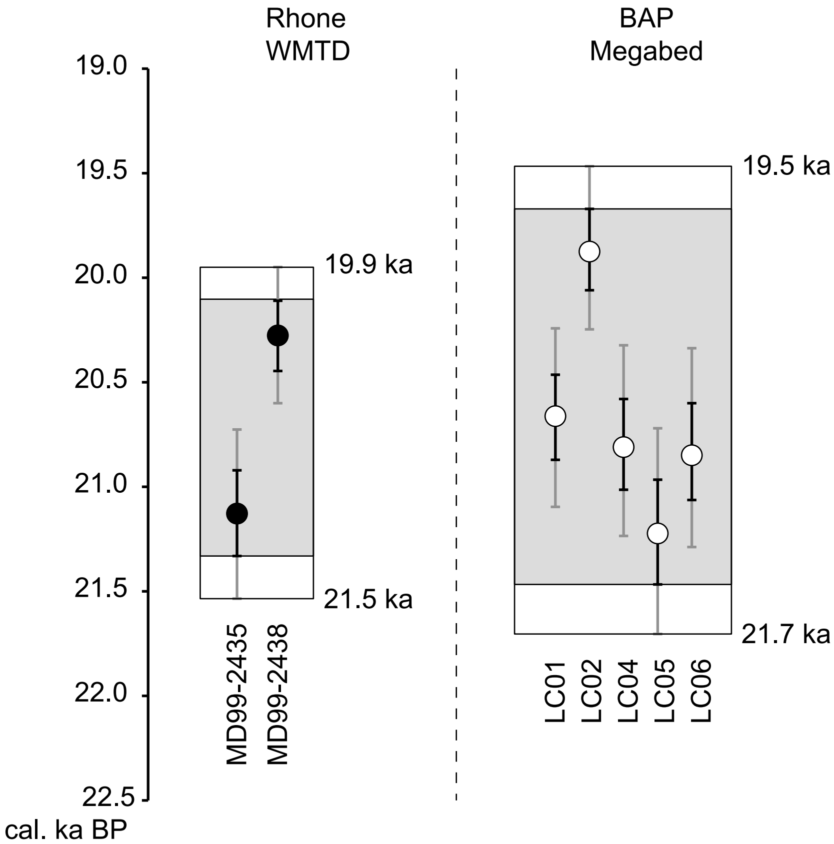

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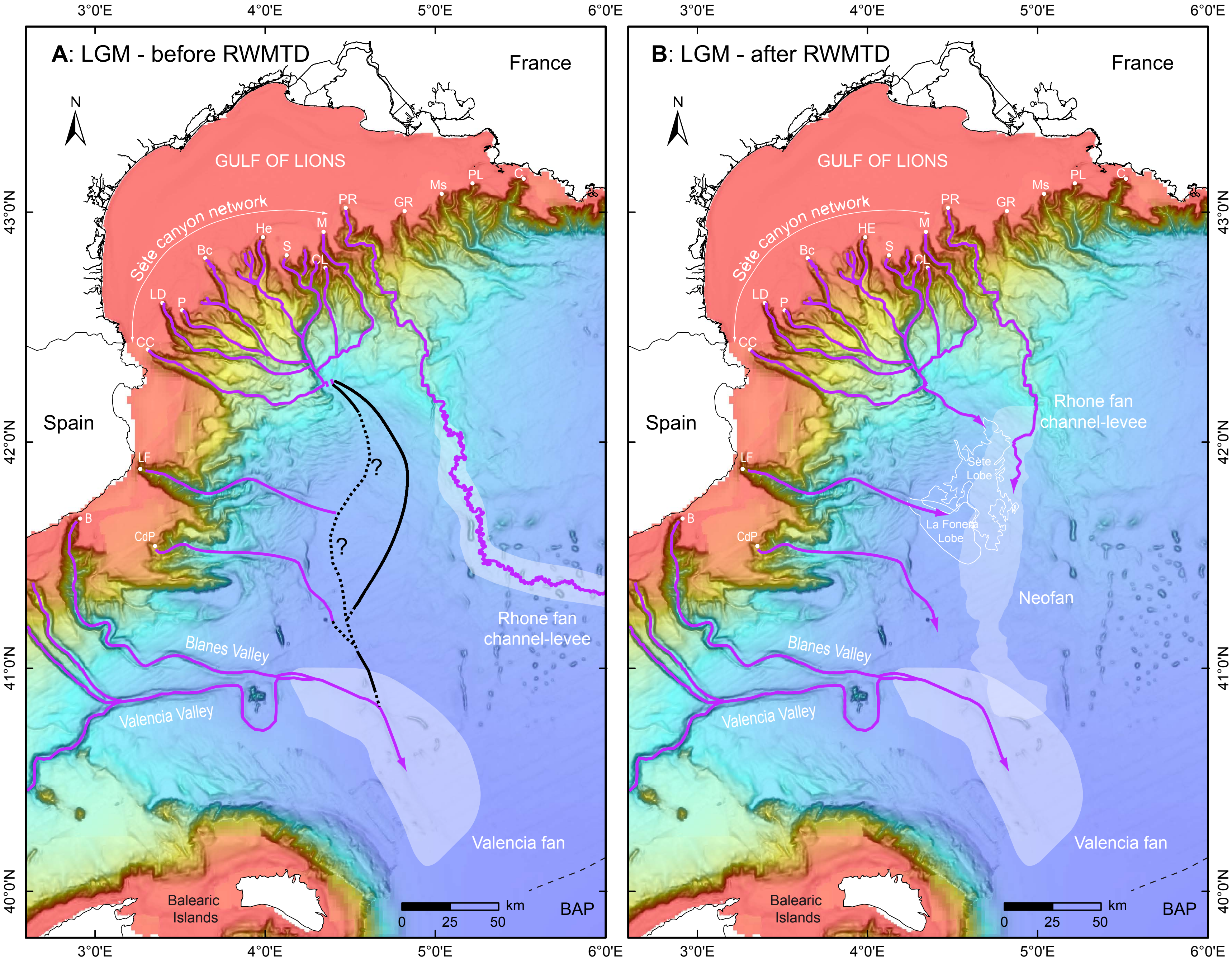

Dennielou et al. RWMTD - Figure 13