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Cenozoic evolution of mobile shales and fluid migration to seafloor: 3D seismic evidence from the offshore western Niger Delta

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Abstract :

The offshore Niger Delta provides a spectacular example of gravity collapse tectonics, but the timing of shale mobilisation remains poorly understood. Here we present new information from the western Niger Delta, based on a detailed interpretation of a 3D seismic volume, calibrated with biostratigraphic data from exploration wells. The study area is underlain by mobile shales containing thrust-fold anticlines, overlain by >5 km thick Late Eocene to present succession of folded and faulted sediments with fluid migration features. Sedimentation rates estimated at one deep well increased during two phases, more than doubling during the Late Eocene to Serravallian (39.5–12.5 Ma), and by up to ten times during the Tortonian (9.5 Ma) to present. Thinning and onlapping geometries within the lowermost, Late Eocene-Burdigalian (39.5–18.5 Ma) interval are interpreted to record syn-depositional deformation. This indicates that shale tectonics in the offshore western Niger Delta initiated early in the evolution of the region, supporting previous interpretations that the active compressional zone of the Niger Delta was in the present continental slope before prograding to the outer-fold-thrust belt in the Pliocene. Stratal thinning above the crests of thrust-fold anticlines in the northeast and southwest of the study area suggests that shale tectonics persisted throughout the Neogene and Quaternary. A chaotic column that rises to seafloor from the crest of thrust-fold anticline, interfingering with the stratified succession is interpreted as a mud volcano edifice that has been active since at least the Burdigalian. This supports early shale mobilisation in response to generation of overpressure and also the fact that mud volcano system once formed, may act as conduits for pressure release throughout the history of a gravity-driven collapse system. The spatial association of seafloor mud volcanoes and pockmarks with deeper thrust-fold anticlines and normal faults suggests fluid migration from depth. In contrast, pockmarks overlying mass-transport deposits and submarine channels suggest fluid-flow from dewatering of more recent sediments. Our findings provide new insights into the Cenozoic tectono-stratigraphic evolution of the offshore western Niger Delta and the relation of shale mobility to fluid migration and escape during continental margin collapse.

Highlights

► Shale tectonics in the offshore Niger Delta initiated early in the evolution of the system in the Late Eocene/Early Miocene ► Buckle folds within the Late Eocene-Burdigalian interval record the onset of shortening and gravity-driven deformation ► Mud volcano systems once formed may act as conduits for pressure release throughout the history of a gravity collapse system ► Increased sedimentation during the Late Eocene-Burdigalian facilitated overpressure development and shale mobilisation ► Mud volcanoes and pockmarks above thrust-fold anticlines and deep faults record deep fluid-flow. Pockmarks above MTDs and submarine channels record shallow fluid-flow

Keywords : Niger Delta, 3D seismic, Shale tectonics, Mud volcano, Syn-depositional deformation, Pockmarks, Fluid migration

1. INTRODUCTION

Mobile shales may be defined as any manifestation of mud-rich sediments (indurated or not) that show evidence of microscopic-scale fluid or plastic movement (Wood, 2010). Provinces of mobile shales are well documented on both passive and active margins including the Niger Delta (e.g., Morley and Guerin, 1996; Graue, 2000; Wiener *et al.* 2010), the Baram Delta (e.g., Van Rensbergen *et al.*, 1999), the Alboran Sea (e.g., Soto *et al.*, 2010), the Trinidad Basin (e.g., De Landro Clarke, 2010; Henry *et al.*, 2010), the Krishna-Godavari Basin (Choudhuri *et al.*, 2010), the Southeast Caribbean (e.g., Deville *et al.*, 2010). Shale mobility involves the deformation of overpressured, undercompacted, mud-rich sediments, which may result in their upwelling and withdrawal (Andrews, 1967; Brauntein and O'Brien, 1968; Mascle, 1979), and the formation of a variety of fault-bounded structures commonly described as shale tectonics (Wood 2010; Deville *et al.*, 2010). Mobile shales were initially thought to give rise to structures comparable to salt diapirs that pierced overlying strata (e.g., Guliev, 1992; Van Rensbergen *et al.*, 2003). However, subsequent studies have recognised that shale mobilisation takes place preferentially at depth, and results in compressional and extensional systems rooted on deep detachment surfaces (Soto *et al.*, 2010; Choudhuri *et al.*, 2010; Wiener *et al.*, 2010; Devile *et al.*, 2010; Peel, 2014; Restrepo-Pache, 2018; Souza *et al.*, 2020). On passive margins, high rates of sedimentation and differential loading of mechanically under-compacted mud-rich sediments typically trigger shale tectonics (see review in Morley *et al.*, 2011). Mobile shales are typically characterised by low densities, velocities and chaotic facies on seismic reflection data (e.g., Graue, 2000; Corredor *et al.*, 2005; Deville *et al.*, 2010; Wiener *et al.*, 2010).

Mobile shale systems are commonly associated with the occurrence at seafloor of fluid escape features such as pockmarks and mud volcanoes, which are indirect evidence of fluid overpressures at depth (see review in Morley *et al.*, 2011). Mud volcanoes are deeply-rooted structures that connect to zones of overpressure at depths of kilometres (e.g., Guliev, 1992; Graue, 2000). Rising fluids from mud volcanoes may mobilise sediments at multiple stratigraphic levels to extrude at surface mixtures of solids, fluids and gas, including hydrocarbons (e.g., Deville *et al.*, 2010; Mazzini and Etiope 2017). On seismic imagery, mud volcanoes may be underlain by columnar edifice, up to kilometres high and wide, interpreted to record the formation and burial of sediment build-ups, collapse calderas and conduits (Graue 2000; Kopf, 2002; Stewart and Davies, 2006; Praeg *et al.*, 2009; Deville *et al.*, 2010; Dupuis *et al.*, 2019). Pockmarks are generally smaller, crater-like depressions that document fluid escape on the seafloor from shallower subsurface depths (King and Maclean, 1970; Hovland and Judd, 1988; Judd and Hovland, 2007; Riboulot *et al.*, 2011; Sultan *et al.*, 2014; Bayon *et al.*, 2015; Wei *et al.*, 2015; de Prunelé *et al.*, 2017; Marsset *et al.*, 2018). On seismic imagery, pockmarks are commonly underlain by pipes, seal bypass systems (Cartwright *et al.*, 2007), recognised as columnar zones of disrupted reflections (Heggland and Nyggard, 1998; Løseth *et al.*, 2011; Hustoft *et al.*, 2007; Moss and Cartwright, 2010; Ho *et al.*, 2012; 2018). Pipes display circular to elliptical geometries, with amplitude anomalies that may be due to the presence of either gas pockets (negative amplitude anomalies, NAAs), or carbonate cement (positive amplitude

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anomalies, PAAs) (Løseth *et al.*, 2001; Hustoft *et al.,* 2007; Gay *et al.,* 2007; Sultan *et al.,* 2014; Bayon *et al.,* 2015; Wei *et al.,* 2015; de Prunelé *et al.,* 2017; Marsset *et al.,* 2018).

The Niger Delta is a mud-rich sedimentary wedge on the West African continental margin, characterised by large-scale shale tectonic structures rooted on deep shale detachments, and a variety of seafloor fluid escape features (e.g., Cobbold *et al.,* 2009; Wiener *et al.,* 2010; Chima *et al.,* 2022; Fig. 1A). The gravitational collapse of the Niger Delta reflects the development of overpressure at depth in response to rapid sediment loading and disequilibrium compaction (see review in Morley *et al.,* 2011). Analogue modelling suggests that the localisation of overpressure within thrust planes facilitates shale deformation and pressure escape as the Niger Delta advance basinward through time (Cobbold *et al.,* 2009; Mourgues *et al.,* 2009; Sapin *et al.,* 2012). The mobile shale systems of the offshore Niger Delta have been examined in a number of studies, based on widely spaced 2D seismic data that generally lack detailed age calibration (e.g., Ajakaiye and Bally, 2000; Kopf, 2002; Corredor *et al.,* 2005; Wiener *et al.,* 2010; Maloney *et al.,* 2010). However, the timing of shale mobilisation remains poorly understood. Hence, the objective of this study is to present new information on the evolution of shale tectonics and fluid migration throughout the Cenozoic in the offshore western Niger Delta. The study is based on interpretation of a commercial 3D seismic volume, calibrated using biostratigraphic data from exploration wells (Fig. 1A, B), building on previous work by Chima *et al.* (2019, 2020). The results allow us to investigate the kinematics of shale mobility from the Late Eocene to present, and to examine the activity of mud volcanoes and pockmarks over the same timescale. Our findings provide new insights into long-term controls on the tectono-stratigraphic evolution of the offshore western Niger Delta and the relation of shale mobility to fluid escape during the collapse of continental margin depocenters.

2. GEOLOGICAL BACKGROUND AND PREVIOUS WORK

The Niger Delta lies in the Gulf of Guinea on the passive continental margin of west Africa (Fig. 1A), which developed by rifting and opening of the South Atlantic Ocean in the Middle Cretaceous (Short and Stauble, 1967; Evamy *et al.,* 1978). The delta is a Cenozoic siliciclastic wedge up to 12 km thick that prograded basinward from the Late Eocene in response to sediment supply from the Niger/Benue River (Reijers, 2011; Fig. 1A). Growth of the Niger Delta led to its gravity collapse above shale detachments up to 4 km below seafloor, and development of three structural zones (Fig. 1A): an extensional zone, dominated by normal faults, a translational zone of mobile shales and mud volcanoes, and a compressional zone of imbricated fold-thrust faults (e.g., Doust and Omatsola, 1990; Bilotti *et al.,* 2005).

The offshore portion of the Niger Delta extends over an area of 75,000 km^2, from the coast to water depths of over 3000 metres below sea-level (Short and Stauble, 1967). It is sub-divided into eastern and western lobes by a basin and swell topography that coincides with the relict Charcot Fracture Zone (e.g., Corredor *et al.,* 2005; Chima *et al.,* 2022; Fig. 1A). The sedimentary wedge of the Niger Delta is composed of three main lithostratigraphic units, the Akata, Agbada and the Benin Formations, which are strongly diachronous (Fig. 2). The Akata Formation (Paleocene-Recent) varies from 3-4 km in thickness, and is dominated by marine facies (Fig. 2), which act as a petroleum source rock and the root of overpressure (Doust and Omtasola, 1990). The Agbada Formation (Eocene-Recent) varies from 2-9 km in thickness, and is dominated by deltaic facies (Fig. 2), which act as a hydrocarbon reservoir or seal (Doust and Omtasola, 1990), and in places host fluid escape pipes (Løseth *et al*., 2011). The Benin

Formation (Miocene-Recent), is up to 2 km thick, and is dominated by coarser-grained alluvial facies (Avbovbo, 1987; Fig. 2).

The study area lies 120 km from the present coastline, on the western Niger Delta continental slope in water depths of 950-1,150 metres (Fig. 1A, B). It corresponds to a 3D seismic survey, covering an area of 638 km^2 (Fig. 1A, B). Part of this 3D survey has previously been used to study reservoir architecture over the Miocene interval (Chapin *et al.,* 2002), seafloor mounds (Benjamin and Huuse, 2015), and canyon-confined pockmarks (Benjamin and Huuse *et al*., 2017). Recent studies of the entire 3D seismic survey identified seven Neogene seismic units capped by regional sequence boundaries (Fig. 3), dated by correlation to Miocene calcareous nannofossils and planktonic foraminifera (see Figs. 7, 8 in Chima *et al.* 2019), and by cyclostratigraphic analysis of the Pliocene and the Pleistocene interval (Chima *et al.,* 2020). In addition, a deeper surface marking the base of the stratified succession overlying mobile shales was assigned to the Late Eocene based on a seismic profile published by Bellingham *et al.* (2014), located a few kilometres from the study area (see Chima *et al.,* 2022).

3. DATA AND METHODS

3.1 Seismic and well datasets

The 3D seismic survey used in this study (Fig.1A, B) was acquired for hydrocarbon exploration using survey techniques standard for exploration data. The data was processed as a zero-phase source wavelet in the American reverse standard polarity. Consequently, an increase in acoustic impedance corresponds to a trough (blue loop) in the wavelet, while a decrease in acoustic impedance corresponds to a peak (red loop) in the wavelet (Fig. 1C). The 3D volume is characterised by a spatial resolution of 25 x 25 metres (bin spacing) and a vertical sampling interval of 4 milliseconds two-way travel time (TWTT). Peak frequency content of 30 Hz corresponds to a vertical resolution of 13.7 metres near the seafloor, decreasing to 25-30 metres at depths > 3000 metres below the seafloor.

Petrophysical data were available from five exploration wells within the study area labelled FM 1 to FM 5 (Fig. 1B). Petrophysical data include gamma ray, resistivity, neutron, density and sonic logs, available for all wells (e.g., Fig. 3B). In addition, Neogene biostratigraphic information was available for four wells, FM 1 to FM 4, although not from the Late Eocene nor the Pliocene to Pleistocene intervals (Fig. 3B). All wells included check-shot (time-depth) data to allow correlation to seismic surfaces.

3.2 Interpretive methods

The seismic and well data were interpreted using sequence stratigraphic methods as outlined by Mitchum and Vail (1977), resulting in the identification of regional stratigraphic surfaces (Fig. 3); for a detailed explanation, see Chima *et al*. (2019, 2020). This study, builds on previous works analysing the stratigraphic surfaces in greater detail. We used an auto-tracking algorithm in Petrel (TM) software to map seismic surfaces that display good reflection continuity, whereas manual picking was used in areas of poor reflection continuity, mainly corresponding to mobile shales and sub-marine channels (Fig. 1B, C). We also carried out 3D seismic geomorphological analysis of time slices and root mean square (RMS) attribute maps (e.g., Figs. 1B, 5). This allowed us to map the geometry and distribution of mobile shales and fluid escape features within the 3D volume.

The 3D grids obtained from mapping of seismic stratigraphic surfaces were converted to time structure (isochron) maps. Time structure maps were in turn, converted to depth maps using velocities from the check-shot data of the deepest well, FM 1. All data were normalised to the seafloor (mud line). We used a 'layer cake' velocity analysis in which we generated linear velocity functions V=KZ+Vo, for multiple intervals (Fig. 4), and used them in Petrel for depth conversion. For strata below the deepest well, FM 1, we extrapolated the linear function V=KZ+Vo using published velocity-depth information from a seismic profile located a few kilometres from our 3D seismic volume (see Bellingham *et al.*, 2014). This allowed us to obtain a consistent linear function down to the Late Eocene surface, which was not penetrated by the deepest well, FM 1 (Fig. 4).

Solid sedimentation rates (Table 1, Fig. 6) were estimated for the deep well, FM 1 with reference to the neutron porosity log, which measures hydrogen index, i.e., the volume of pores saturated with water or hydrocarbons compared to the total volume of the rock (in m^3/m^3). We assumed that 1-neutron porosity unit corresponds to the grain proportion. Consequently, we multiplied the grain proportion by the difference in depth between the top and base of each stratigraphic unit; this yields solid a sediment thickness, which takes into account the progressive increase in sediment loading and compaction with depth. The solid thickness (m) for each stratigraphic unit was divided by the duration of deposition (Ma) to obtain sedimentation rates (m/My; Table 1, Fig. 6).

Uncertainties in the seismic interpretation are mainly due to poor reflectivity associated with thrust-fold structures and an overall decrease in signal quality below 3 s TWT. To address this, we used the ghost method in Petrel to compare, contrast and manually match reflectors across thrust-fold structures to enhance reflection continuity and consistency of seismic interpretation. In addition, we used signal processing algorithms (median filter and structural smoothing) to improve the overall signal-to-noise ratio. Another uncertainty lies in the velocity analysis, which was based on time-depth conversion of only one deep well, FM 1 (Figs. 3B, 4), and directly affects the estimate of solid sedimentation rates. However, the rates we obtained are similar to those in published studies (e.g., Grimaud *et al.,* 2017).

4. RESULTS

The 3D study area on the western Niger Delta slope contains a stratigraphic succession comprising a lowermost seismically chaotic mobile shale unit, overlain by a stratified interval divided by Neogene sequence boundaries (Figs. 3, 7, 8), previously defined and dated by Chima *et al.* (2019, 2020, 2022). For the purpose of this study, six regional stratigraphic surfaces within the study area are referred to by their estimated ages as the Late Eocene (39.5 Ma), Burdigalian (18.5 Ma), Serravallian (12.5 Ma), Tortonian (9.5 Ma), Early Pliocene (4.9-5 Ma) and Middle Pleistocene (0.8-1 Ma) (Figs 3, 7, 8). These surfaces are referred to below in presenting evidence of tectonic structures within and above the mobile shales, sedimentation rates, stratigraphic thickness variations, and fluid escape features within the post-Late Eocene sedimentary succession.

4.1 Shale tectonic structures

The lowermost seismic unit (highlighted in grey in Figs. 7A, 8A) pre-dates the Late Eocene reflector at the base of the stratified succession and is interpreted as part of the overpressured, mud-rich Akata Formation (Cobbold *et al.,* 2009; Wiener *et al.,* 2010;

Bellingham *et al.,* 2014), and may date back to the Paleocene (Doust and Omatsola, 1990). The unit generally displays seismically chaotic internal reflections, as well as mounded surface relief that locally domes overlying stratified units in the northeast and southern part of the study area (Figs. 5, 7A, 8A). Its internal reflection character may in part reflect seismic frequency attenuation at depths below 5 seconds (> 5 km). A deep well that penetrated the top of the unit in the deep-water western Niger Delta encountered overpressured shales at 5.8 km below seafloor (see Cobbold *et al.*, 2009; Fig. 1A for location). A recently published 2D seismic profile that crosses the 3D survey of this study (Fig. 1A, B) shows the lower seismic unit to act as detachment, linking listric normal faults with thrust faults downslope of the study area (see Fig. 4 in Chima *et al.,* 2022).

The mounds at the top of the lower seismic unit display elongate geometries in map view, with orientations that vary from northwest-southeast to northeast-southwest (Figs. 8B, 9A-F). They are underlain by planar discontinuities with subtle reverse stratal offsets (dashed black lines in Figs. 7A, 8A), consistent with thrust fold anticlines. Above the anticlines, the lower part of the stratified succession is offset in places by normal faults that show synthetic and antithetic geometries (Figs. 7A, 8A). Elsewhere, in the upper part of the stratified succession, normal faults with a few tens of meters of offset extend up to 2000 metres below seafloor (Figs. 7A, 10), and display radial patterns in plan view (see pink arrows in Fig. 10D). These normal faults generally extend to near the seafloor in the northern part of the study area (e.g., Figs. 7A, 10A), but are buried in the southern part (e.g., Fig. 7A).

4.2 Neogene sedimentation rates

Solid sedimentation rates estimated from the thicknesses of six stratigraphic units at the site of the deep well, FM 1 (Table 1, Fig. 6), increased from ca. 43 m/Myr during the Late Eocene-Burdigalian to ca. 67 m/Myr during the Burdigalian-Serravallian and to ca. 100 m/Myr during the Serravallian-Tortonian. Sedimentation rates decreased to ca. 60 m/Myr during the Tortonian-Early Pliocene, and to ca. 33 m/Myr during the Early Pliocene-Middle Pleistocene, but increased dramatically to ca. 570 m/Myr from the Middle Pleistocene to present (Table 1, Fig. 6). These values show that sedimentation rates (m/Myr) on the offshore western Niger Delta slope more than doubled from the Late Eocene to the Tortonian, decreased over the Tortonian-Middle Pleistocene and increased by an order of magnitude from the Middle Pleistocene.

4.3 Lateral variations in stratigraphic thicknesses

The stratigraphic architecture of the studied portion of the offshore western Niger Delta is illustrated on interpreted seismic profiles oriented both oblique and perpendicular to the present continental slope (Figs. 7 and 8).

The stratigraphic interval between the Late Eocene and the Burdigalian surfaces displays modest lateral variations in thickness on both down-and along slope seismic sections (Figs. 7A, 8A). Seismic reflections within the unit typically thin and onlap the mounded topographies at the top of the lower seismically chaotic mobile shale unit (see yellow ellipses in Fig. 8A, B). An isopach map between the Late Eocene-Burdigalian strata shows maximum sediment thickness in the southwest of the study area (Fig. 9A).

The six stratigraphic units between the Burdigalian surface and the seafloor reflector all display lateral variations in thickness (Figs. 7A, 8A). In general, the units thin in the northeast (Fig. 7A) and the southwest (Fig. 8A), above mounded topographies at the top of the lowermost mobile shale unit. Isopach maps of the Burdigalian-Serravallian, Serravallian-Tortonian, Tortonian-Early Pliocene, Early Pliocene-Middle Pleistocene, and Middle Pleistocene-present units all show an overall thinning above mounded topography in the northeast and southern part of the study area (see red arrows in Fig. 9B-E).

4.4 Fluid escape features

In the northeast of the study area, a seismically chaotic column rises up to 3 km from the crest of thrust-fold anticline through the Neogene succession to reach the seafloor (Figs 5, 7A). The column varies in width from 2-2.5 km and interfingers with the stratified Neogene succession at stratigraphic levels older than the Burdigalian (see area within dashed white lines in Fig. 7A, E). The seafloor above the column is elevated in the northeast (red box in Fig. 7B) relative to the surrounding areas. The seafloor also displays sub-circular mounds and depressions 50-100 metres high and 2-3 km wide (Figs. 5, 7), interpreted as seafloor mud volcanoes and pockmarks.

Adjacent to mud volcanoes in the northeast (Fig. 11A), a variance attribute map extracted at ~1.3 km below the seafloor reveals lineaments in two areas that extend ~10 km downslope. The 3D seismic data show that the lineaments display moderately erosive base, overlain by moderately continuous-chaotic seismic facies, which are laterally confined adjacent to mud volcanoes (e.g., Fig. 11B). The lineaments have previously been interpreted as scars associated with mobile shale-derived mass-transport deposits (MTDs) (Chima *et al.,* 2019), here re-interpreted as mud volcano outflows. Within the areas of the lineaments are 0.2-1 km wide sub-circular features with high variance (Fig. 11A). On seismic sections, these sub-circular features are underlain by vertical zones of relatively low reflectivity 200-800 metres deep (Fig. 11B, C).

Reflections within these low-reflectivity vertical zones generally display convex-upward geometries and locally dome the seafloor (Fig. 11B, C).

The seafloor in the northeast of the study area displays crater-like depressions of circular to elongate geometry (Fig. 1B, 5, 7B, C, 10D, 11A-C). These features are typically U-shaped on seismic sections and measure 2-50 deep and 1-1000 metres wide (e.g., Fig. 7A, D). The crater-like depressions are underlain by narrower vertical to sub-vertical zones of low reflectivity, up to 500 m wide, which extend 100-800 m below seafloor (Figs. 7A-D, 11C). The low-reflectivity zones increase upward in diameter towards the seafloor depressions (Fig. 11C) and show clear anomaly with background reflections as well as chaotic internal architecture, marked by local occurrences of negative amplitude anomalies (NAAs) (Fig. 7A, D).

5. DISCUSSION

A schematic illustration of the evolution of shale tectonics and fluid escape within the offshore western Niger Delta from the Late Eocene to present is shown in Fig. 12.

5.1 Mobile shale evolution since the Late Eocene

In the southern and eastern part of the study area, the Late Eocene-Burdigalian unit exhibits thinning and onlap of its internal seismic reflections onto elongate thrust-fold anticlines, developed within the lower seismic unit (see yellow ellipses in Fig. 8). This is interpreted as evidence of syn-depositional deformation, related to shale mobilisation. Previous studies of the offshore Niger Delta have suggested that shale mobilisation initiated in the Late Miocene to Pliocene (e.g., Cohen and McClay, 1996; Ajakaiye and Bally, 2000; Kopf, 2002; Hooper *et al.,* 2002), and Oligocene-Early Miocene (Wiener *et al.,* 2010). Our results suggest that shale mobilisation in the offshore western Niger Delta may have initiated a bit earlier i.e., during the Late Eocene to Early Miocene (>18.5 Ma). This is further supported by thickness variations within the Late Eocene-Burdigalian unit, the isopach map of which displays maximum thicknesses in the southwest (Fig. 9A), consistent with a discrete depocentre linked to shale mobility. The overall thinning of stratigraphy above the thrust-fold anticlines in the northeast and southwest from the Burdigalian to the present (Figs. 5, 7A, 9B-F), suggests the continued mobilisation of shales throughout Neogene and the Quaternary.

Our finding of an early onset of shale mobilisation compares with findings from other shale tectonic basins. For example, Choudhuri *et al.* (2010) reported Paleocene-Eocene as the onset of shale mobilisation in the Krishina-Godavari Basin, while Soto *et al.* (2010) reported Early Miocene in the Alboran Sea. However, whereas in these two basins shale tectonics ceased in the Pliocene (e.g., Choudhuri *et al.,* 2010; Soto *et al.*, 2010), our results show that it continued through the Pliocene and the Pleistocene in the offshore Niger Delta (Figs. 5, 7A, 8A, 9F). It may be argued that the location of depocenter in the northwest of the study area over the Burdigalian-Middle Pleistocene (Fig. 9A-E) is unrelated to mobile shales and instead due to pre-existing accommodation that was filled in the Middle Pleistocene. However, the general thinning of stratigraphy above the thrust-fold anticline in the northeast and southwest (Figs. 5, 7A, 9B-F) is a typical syn-depositional geometry, which we link to mobile shales.

At the scale of our 3D seismic survey (Fig. 1A, B), the changes in sedimentation rates from the Late Eocene to the present (Table 1, Fig. 6) are comparable to those observed in the regional study by Grimaud *et al.* (2017). Increased sedimentation rates from the Late Eocene to the Tortonian are inferred to have contributed to the early development of overpressures in the offshore western Niger Delta and could have facilitated differential compaction, favouring shale mobilisation and fluid migration (Cobbold *et al.,* 2009; Sapin *et al.,* 2012). The reduction in sedimentation rates during the Tortonian-Early Pliocene (Table 1, Fig. 6) is inferred to reflect sediment sequestration within the Niger catchment or flux transfer from the western to the eastern Niger Delta lobe (Jermannaud *et al.,* 2010). Interestingly, reduced sedimentation rates during the Late Miocene-Early Pliocene (Table 1, Fig. 6) do not appear to have resulted in a reduction in shale tectonics as evidenced by syn-depositional geometries (Figs. 7A, 8A, 9D). The order of magnitude increase in sedimentation rates from the Middle Pleistocene to present is inferred to have intensified shale tectonics as well as the migration and escape of overpressured fluids. This is supported by the presence of active mud volcanoes and crater-like depressions on the modern seafloor (Figs. 1B, 5A and 7).

5.2 Patterns of gravity-driven deformation

The elongate buckle or thrust-fold anticlines within the lower seismic unit (e.g., Figs. 7A, 8A, C) are interpreted as compressional ridges that accommodated deformation of the offshore western Niger Delta continental shelf in response to an increase in sedimentation rates (Chima *et al.,* 2022). Wiener *et al.* (2010) reported mobile shale-related contractional deformation in the offshore eastern Niger Delta during the Oligocene. However, the observed thrust-fold anticlines within the Late Eocene-Burdigalian interval (Figs. 7, 8), suggests that shale tectonics may have initiated a bit earlier in the offshore western Niger Delta. This supports previous observation that the compressional zone of the Niger Delta was located along the present continental slope during the Oligocene/Late Eocene before prograding to the outer-fold-thrust belt during the Pliocene (e.g., Wiener *et al.,* 2010; Chima *et al.,* 2022; Fig. 1A). The relatively small vertical offsets of normal faults coupled with their synthetic and antithetic geometries (Figs. 7A, 8A, 10), and radial patterns (Figs. 10D, 11A), suggest that they developed in response to upward doming above thrust-fold structures (Graue, 2000; Dupuis *et al.,* 2019).

5.3 Fluid escape over time

Fluid escape features rooted at varying depths in the sediment succession play a critical role in venting overpressure from deep geological compartments. In the northeast of the study area, seafloor mud volcanoes (Fig. 5) are underlain by a seismically chaotic column interpreted as a mud volcano edifice (Fig. 7A, E), which rises from the crest of a large thrust-fold anticline. The contiguity of the edifice with the anticline is consistent with the mud volcano recording the release of overpressured fluids from the underlying mobile shales (Guliev, 1992; Graue, 2000). We infer that hydraulic fracturing of the crest of the anticline (Fig. 7A, E) facilitated upward fluid migration, which drove soft sediment fluidisation and extrusion at the seafloor, at rates that kept pace with deltaic sedimentation (Graue, 2000; Davies, 2003; Stewart and Davies, 2006; Dupuis *et al.,* 2019; Figs. 5, 7B, C). The interfingering of the mud volcano edifice with background sediment at least as old as the Burdigalian (Fig. 7A, E), indicates the structure has acted as a conduit for fluid escape throughout the Neogene history of progradation and gravity-collapse of the offshore Niger Delta. Similar interfingering relationships have been observed in many areas of mud volcanism and interpreted to record the growth and burial of a mud volcano edifice during continued sedimentation (e.g., Brown and Westbrook 1988; Deville *et al.,* 2010; Praeg *et. al.,* 2009). The presence downslope of the mud volcano edifice of buried mass-transport deposits, observed as laterally confined, moderate-chaotic seismic facies with erosional lineaments at its base (Fig. 11A, B), records the recent outflow of mud-rich sediments during active mud volcanism.

Crater-like depressions on the seafloor are interpreted as pockmarks and giant pockmarks (King and Maclean, 1970; Hovland and Judd, 1988; Judd and Hovland, 2007; Figs. 1B, 5, 7, 10, 11B, C). The pockmarks are underlain by wide and narrow, low-reflectivity seismic zones interpreted as narrow and wipe pipes, respectively (Gay *et al.,* 2007; Hustoft *et la.,* 2007; Løseth *et al*., 2001; Marsset *et al.,* 2018; e.g., Figs. 7A, E, 11C). The crater-like nature of the giant pockmarks (e.g., Figs. 5, 7), suggests an erosional action of fluid release, commonly associated with buried, overpressured reservoir of gas, oil or interstitial water, or a combination of the three (Hovland and Jud, 1998). Gay *et al.* (2012, 2017), suggested that fluid pipes cause deformation of surrounding unconsolidated sediment during upward flow, leading to the formation of a V-shaped structure. Calibrated with geochemical data in the offshore eastern Niger Delta, Bayon *et al.* (2007), demonstrated the presence of low methane gas within a giant pockmark similar to those observed in this study (Fig. 7). A recent study of the same area by Marsset *et al.* (2018), demonstrated that the giant pockmarks and their underlying acoustic pipes are remnant features, formed by focused fluid release and sediment collapse. We lack geochemical data for the calibration of the nature of fluid flow through the pipes observed in this study. However, the wide pipes (e.g., Fig. 7A, D) resemble the V-shaped pipes described to have focused a combination of methane and other fluids in the eastern Niger Delta (e.g., Bayon *et al.,* 2007; Marsset *et al.,* 2018). The presence of a negative amplitude anomaly (NAA) at the upper part of the wide pipe (Fig. 7D) further supports gas migration through the structure (Moss and Cartwright, 2010; Riboulot *et al.,* 2011; Cartwright and Santamarina, 2015). Similarly, the concave upward geometry and the overall upward increase in diameter of the narrow pipes displayed in Fig. 11D are similar to those described by Moss and Cartwright (2010), and Cartwright and Santamarina (2015). These authors interpreted narrow pipes as the product of a combination of hydraulic fracturing, erosional fluidisation or collapse due to volume loss. The upward increase in diameter of the pipes results from periodic expulsion of accumulated debris, which partially clog the the pipes (Løseth *et al*., 2011; Moss and Cartwright, 2010; Cartwright and Santamarina, 2015; Ho *et al.,* 2018). The vertical zones of relatively low reflectivity (Fig. 11B, C) observed within lineaments adjacent to the mud volcano edifice (Fig. 11A), are interpreted as fluid escape and entrained sediment expulsion features (Van Rensbergen *et al.,* 2007; Benjamin *et al.,* 2017).

The concentration of pockmarks in the northeast around mud volcanoes and deep faults (e.g., Figs. 1B, 5, 7C, 10A-C), suggests their connection to deeply buried sources e.g., the overpressured, mud-rich, Akata Formation (Cobbold *et al.,* 2009), or deeply buried reservoirs (e.g., Leduc *et al.,* 2013; Marsset *et al.,* 2018). The concentration of pockmarks along shallow sub-marine channels and above mass-transport deposits (e.g., Figs. 1B, 10), suggests the role of post-depositional compaction in shallow fluid migration (Riboulot *et al.,* 2011; Benjamin and Huuse, 2015; Marsset *et al.,* 2018).

6. CONCLUSIONS

An analysis of the spatio-temporal evolution of mobile shales and fluid escape features in the offshore western Niger Delta based on an interpretation of 3D seismic data calibrated by well data provides new insights into the long-term (Late Eocene/Early Miocene) controls on the tectono-stratigraphic evolution of the region. The following conclusions can be drawn:

1. Thinning and onlapping geometries within the Late Eocene-Burdigalian interval indicate that shale tectonics in the offshore western Niger Delta initiated early in the evolution of the system, in the Late Eocene to Early Miocene. The general thinning of stratigraphy from the Burdigalian to the present above the crest of thrust-fold anticlines indicates that shale deformation controlled the Neogene and Quaternary stratigraphic evolution of the offshore Niger Delta.
2. The presence of elongate thrust-fold anticlines corroborates previous observations that the active compressional zone of the offshore Niger Delta lay in the present slope during the Oligocene/Late Eocene, before migrating to the outer fold-thrust belt in the Pliocene.
3. Increased sedimentation rates during the Late Eocene to Burdigalian reflect early progradation of the offshore western Niger Delta siliciclastic wedge, which may have contributed to the generation of fluid overpressures, triggering shale mobilisation and pressure release through mud volcanoes.
4. The presence in the northeast of the study area of an active mud volcano edifice recording extrusive activity older than the Burdigalian (18.5 Ma), is consistent with an early development of overpressures and suggests that once formed, mud volcanoes may continue to act as conduits for pressure release throughout the history of a gravity collapse system.
5. The concentration of mud volcanoes and pockmarks above thrust-cored anticlines and deep-penetrating faults is consistent with a deep origin of migrating fluids, while pockmarks above mass-transport deposits and submarine channels support fluid-flow from dewatering of more recent sediments.

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DATA AVAILABILITY STATEMENT

The dataset that used in this study are highly confidential. They are not publicly available due to the tripartite confidential agreement signed by the first author, Shell Nigeria (the onwer of the data) and Sorbonne Université (Paris), where the research was carried out. Interested researchers can apply directly to Shell Nigeria through the Department of Petroleum Resources, Port Harcourt, Nigeria.

CONFLICT OF INTEREST

I, Kelvin Ikenna Chima, hereby state that I have dully acknowledged the donor of the dataset used in this study (Shell Nigeria) and also the sponsor, Petroleum Technology Development Fund (PTDF) of the Federal Republic Nigeria. I also wish to clearly state that there is no conflict of interest in this study.

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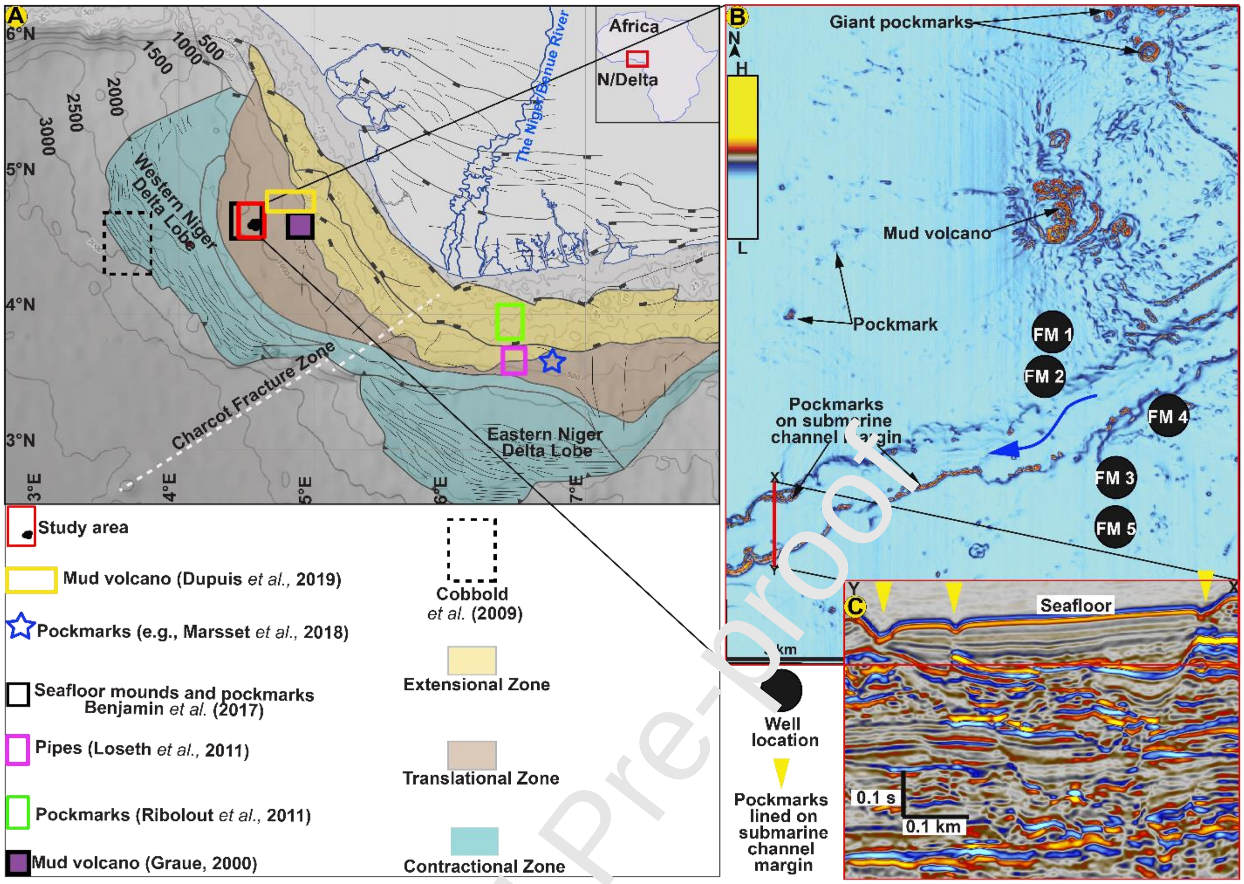


Fig. 1. Location of the study area. A. Bathymetric map of the Niger Delta showing the distribution of its main structural zones, seafloor fluid escape features and the location of 3D seismic study area (red box) (modified after Sapin *et al.*, 2012). B. Attribute map (RMS amplitude) of the seafloor horizon showing the distribution of fluid escape features and location of five exploration wells used in this study (after Chima *et al.*, 2019). C. Seismic section showing pockmarks aligned on a mud-draped submarine channel.

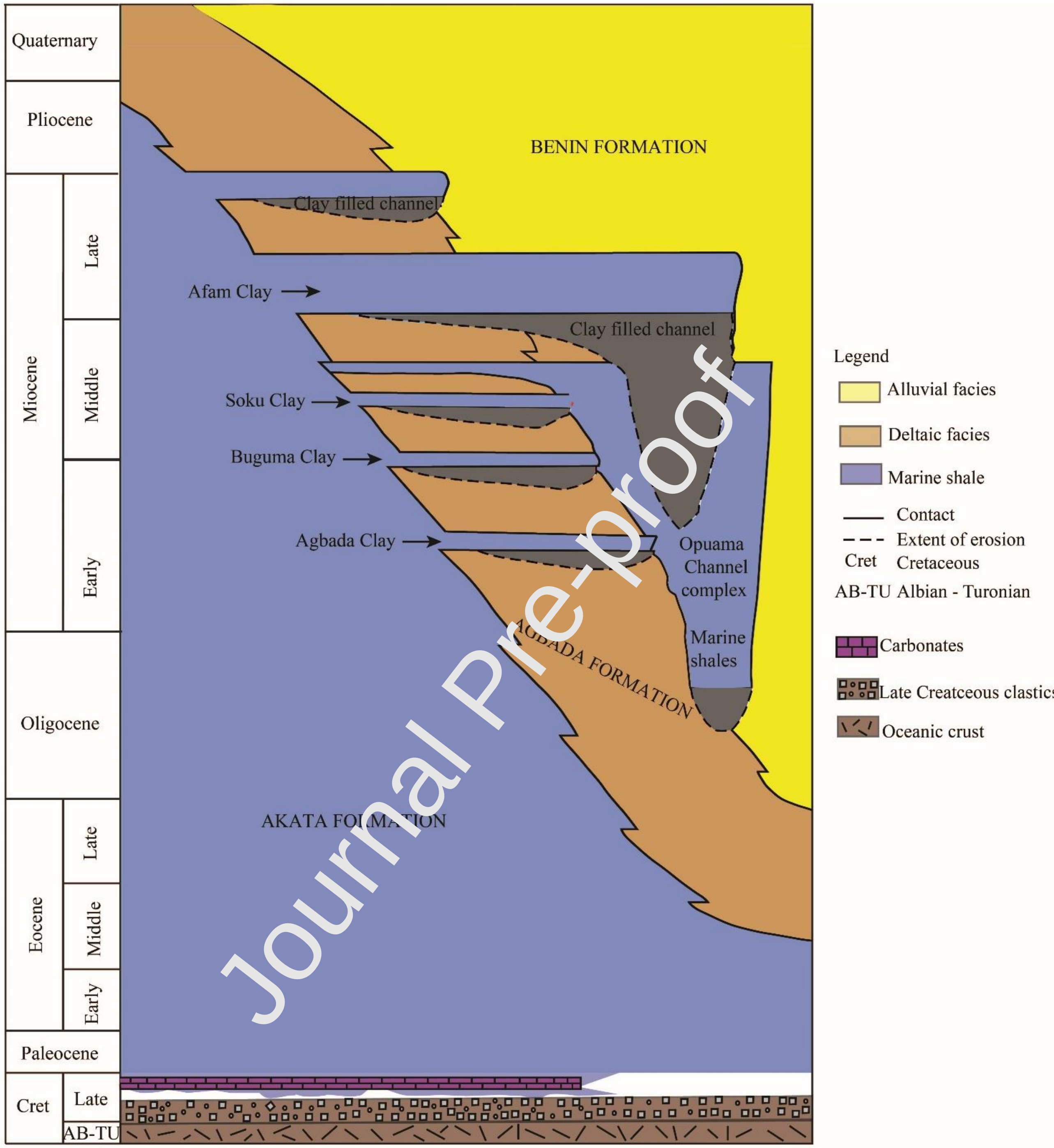


Fig. 2. Schematic illustration of the three main diachronous lithostratigraphic units of the Niger Delta, the Akata, Agbada and the Benin Formations, and the underlying Late Cretaceous units (after Brownfield, 2016).

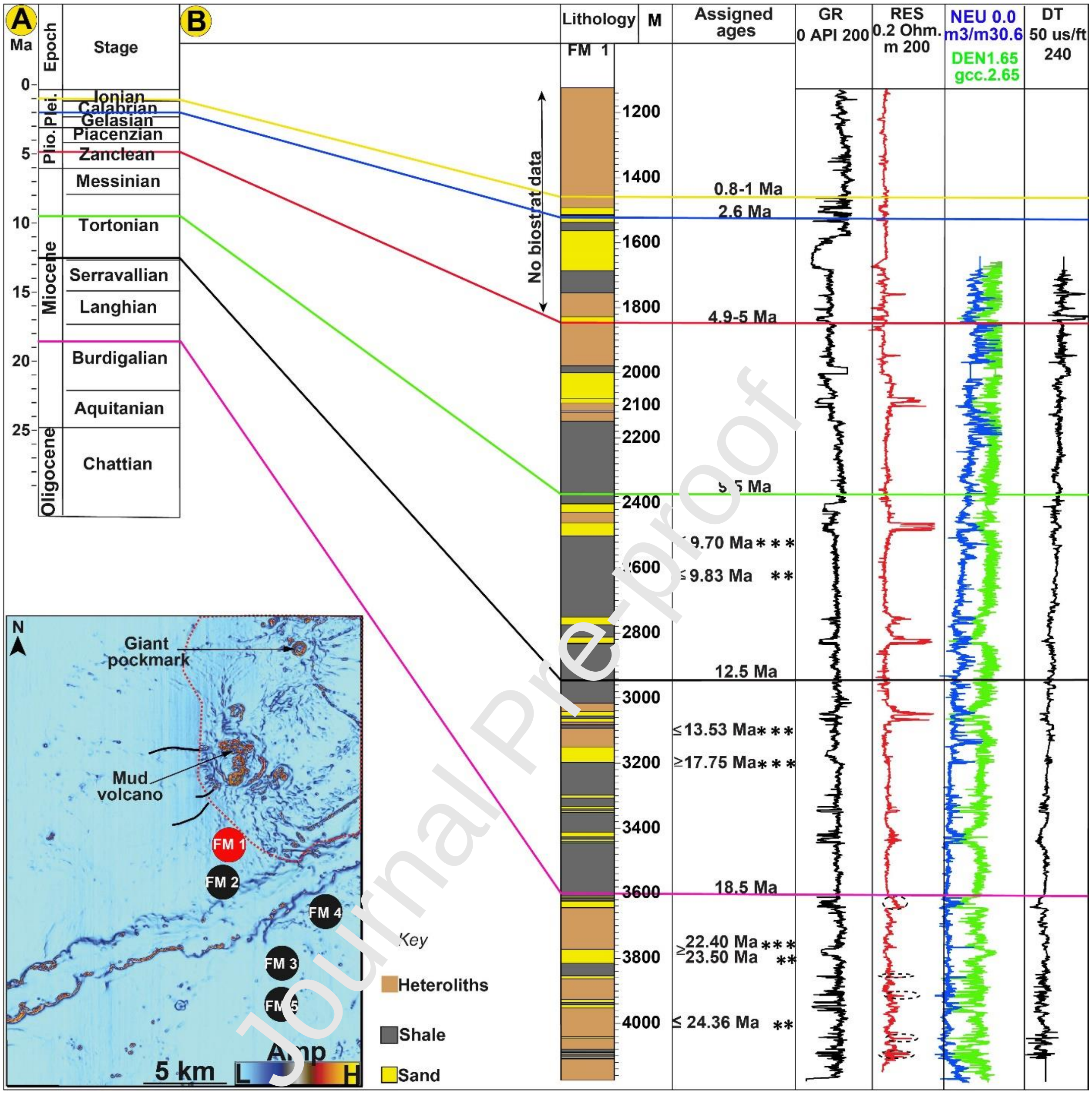


Fig. 3. Neogene stratigraphic succession of the offshore western Niger Delta; insert at lower left shows the locations of the wells used (see also Fig. 1). A. Geologic time scale (after Agnini *et al.*, 2016; Raffi *et al.*, 2016; Backman *et al.*, 2012; Anthonissen and Ogg, 2012), coloured lines show Neogene sequence stratigraphic surfaces identified and dated by Chima *et al.* (2019; 2020). B representative deep well, FM 1, with petrophysical logs (GR=gamma ray, RES=resistivity, NEU=neutron, DEN=density, DT=sonic), biostratigraphic ages (24.36-9.7 Ma), and

cyclostratigraphically assigned ages (4.9-1 Ma) used to estimate the ages of the seismically-defined surfaces presented in this study (modified after Chima *et al.*, 2019).

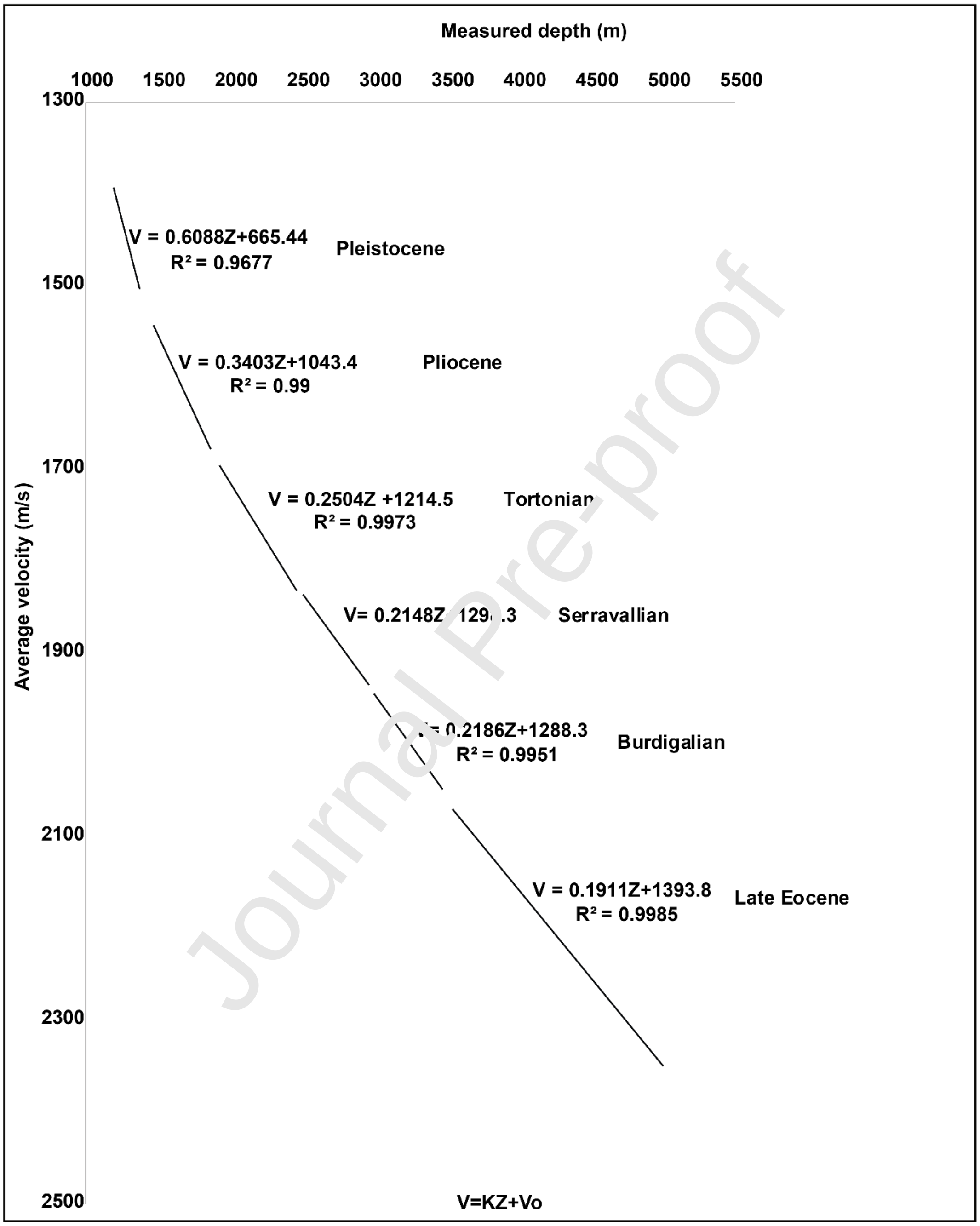


Fig. 4. A plot of average velocity ($V_{avg.}$) from checkshot data versus measured depth (m) in the deep FM 1 well (location in Figs. 1, 2), used in time-depth conversion of the seismically-defined surfaces (modified from Chima *et al.* 2022).

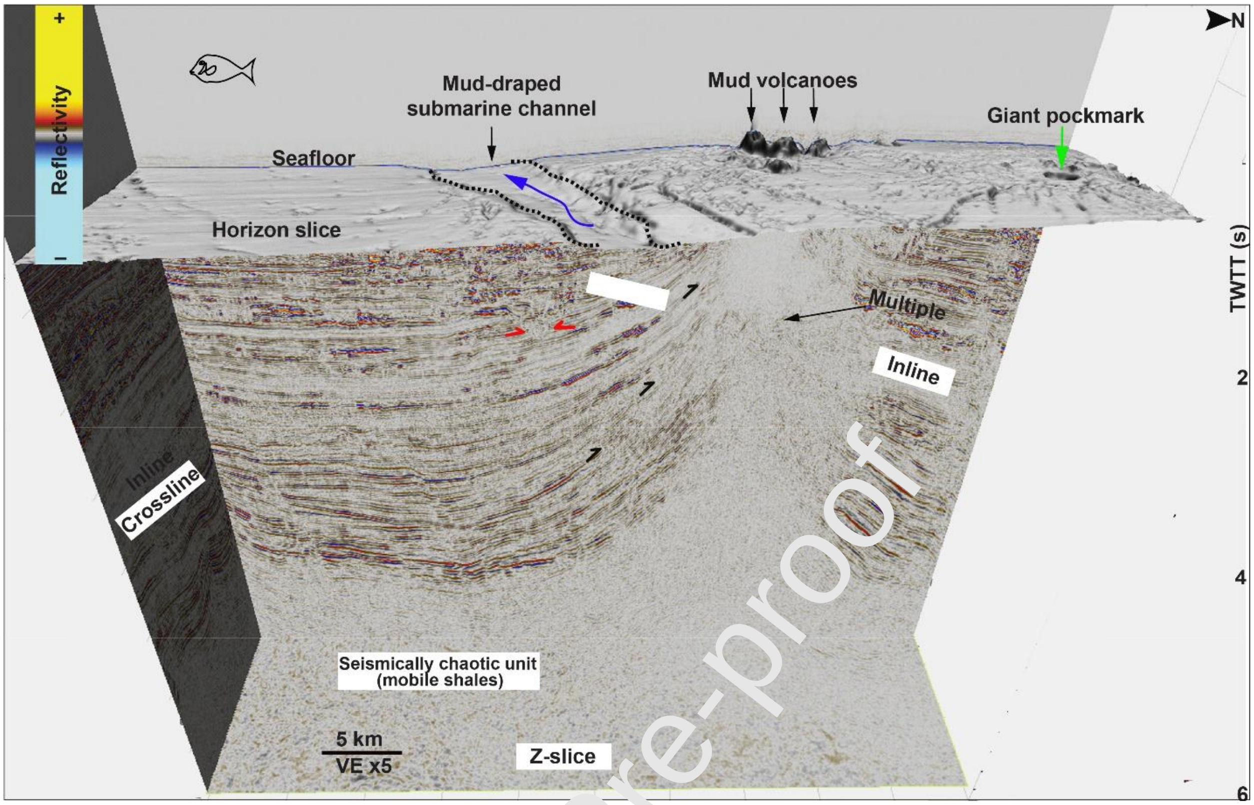


Fig. 5. Perspective view of the 3D seismic data cube, showing the use of in-lines, cross-lines, time-slices (Z) and variance attribute of the seafloor horizon to analyse stratigraphic relationships and geomorphological features on the offshore western Niger Delta slope. Note the presence in the northeast of a seismically chaotic zone of varying width, associted at seafloor with elevated reliefs (interpreted as mud volcanoes), and fluid escape features. See text for more detailed exlanation.

Table 1. Sedimentation rates estimated from the deep well, FM 1.

Age (Ma)	**Solid Sedimentation rates (m/Myr)**
1.0-0	570
4.9-1.0	33
9.5-4.9	60
12.5-9.5	100
18.5-12.5	67
39.5-18.5	43

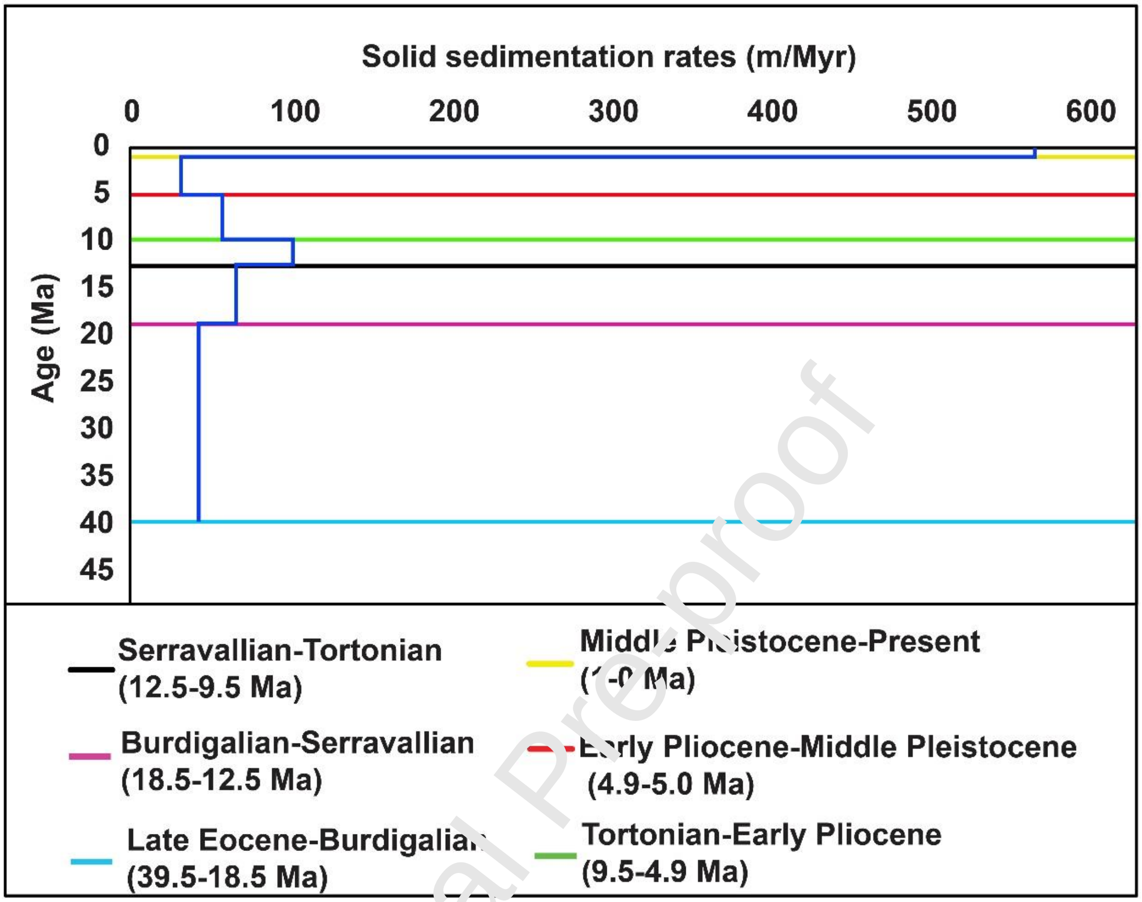
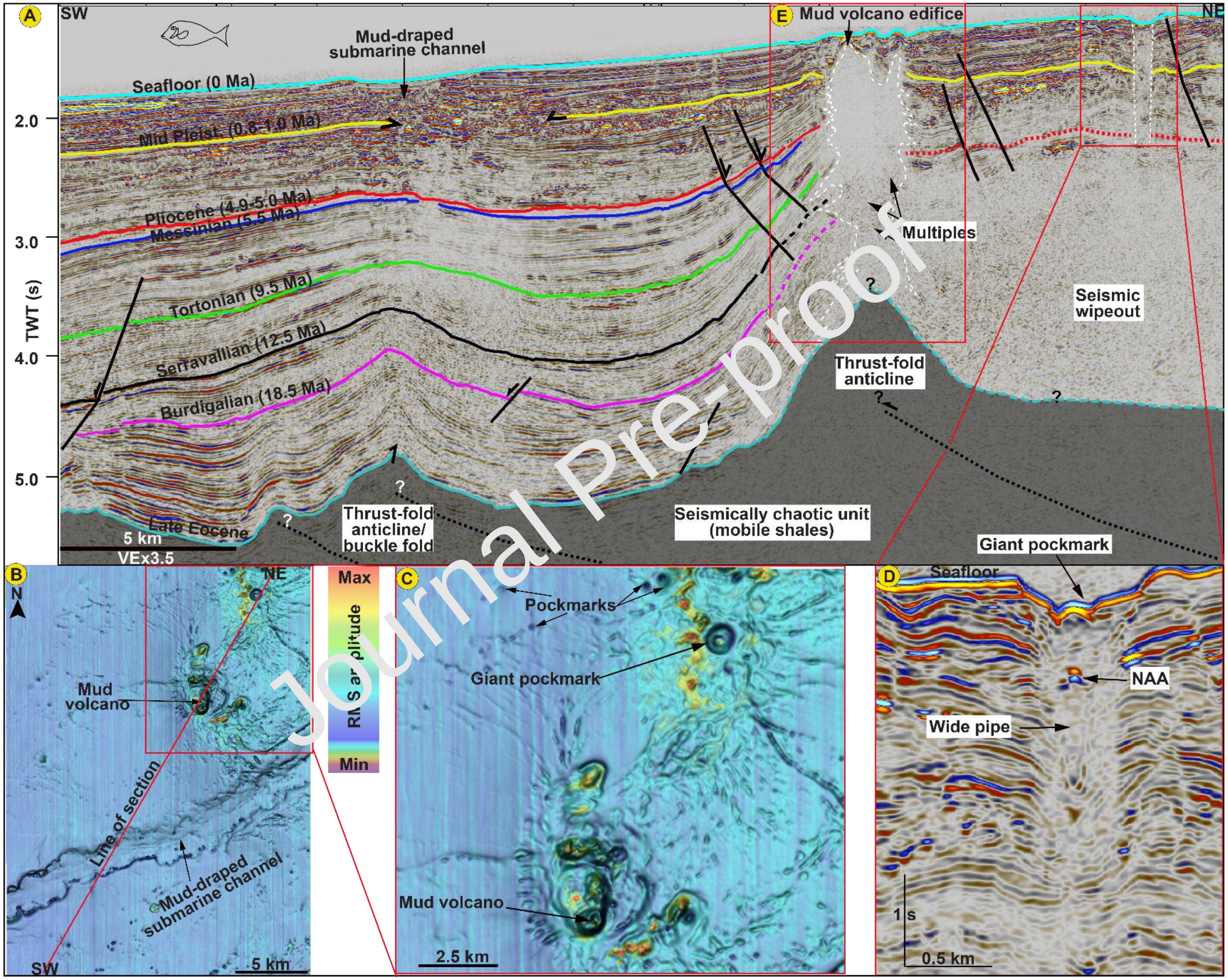


Fig. 6. Sedimentation rates in the offshore western Niger Delta estimated from deep well, FM 1 (location in Fig. 1).


A
SW
NE
Mud-draped submarine channel
Seafloor (0 Ma)
Mid Pleist. (0.8-1.0 Ma)
Pliocene (4.9-5.0 Ma)
Messinian (5.5 Ma)
Tortonian (9.5 Ma)
Serravallian (12.5 Ma)
Burdigalian (18.5 Ma)
Late Eocene
TWT (s)
2.0
3.0
4.0
5.0
5 km
VEx3.5
Thrust-fold anticline/ buckle fold
Seismically chaotic unit (mobile shales)
E
Mud volcano edifice
Multiples
Thrust-fold anticline
Seismic wipeout
Giant pockmark
B
N
Mud volcano
Line of section
Mud-draped submarine channel
5 km
Max
RMS amplitude
Min
C
Pockmarks
Giant pockmark
Mud volcano
2.5 km
D
Seafloor
NAA
Wide pipe
1 s
0.5 km

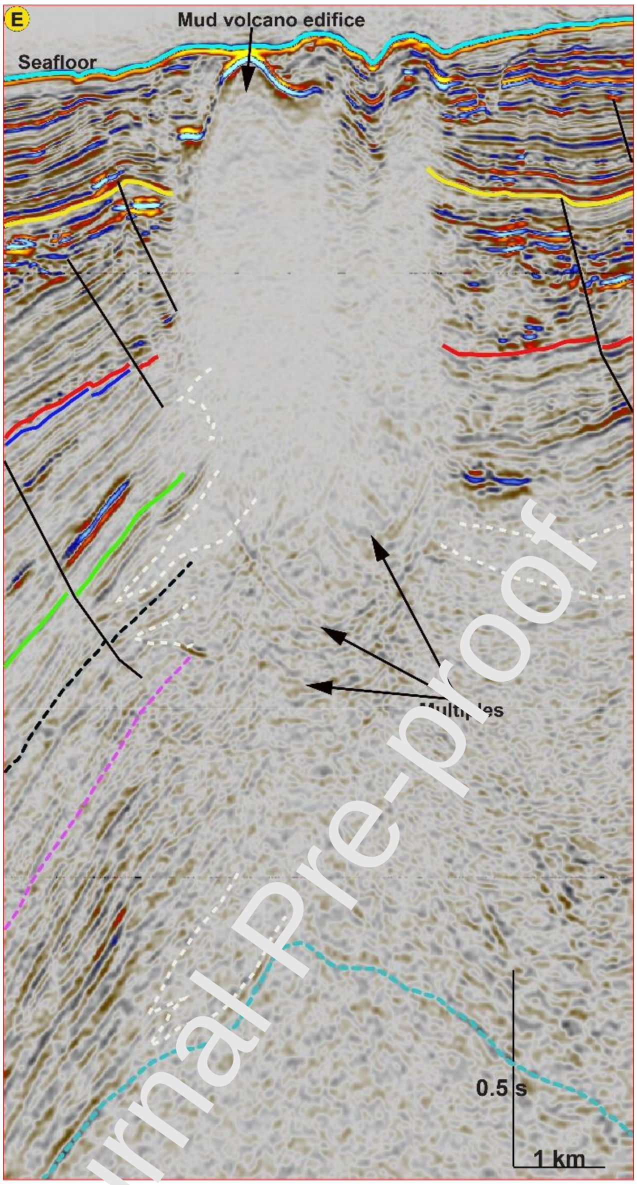


Fig. 7. Stratigraphic architecture of the offshore western Niger Delta slope. A. An interpreted NW-SE seismic profile, oblique to paleo-flow direction, showing the overall thinning of stratigraphy from the Burdigalian to the present above the seismically chaotic zone, interpreted as thrust-fold anticline in the NE. This feature is overlain by a seismically chaotic column, which interfingers with background sediment (hashed white areas in Fig. 7A, E), and elevated seafloor reliefs. B. RMS amplitude map of the seafloor superimposed on variance attribute map, showing the elevated seafloor and fluid escape features. C, D: Detailed view of seafloor fluid escape features.

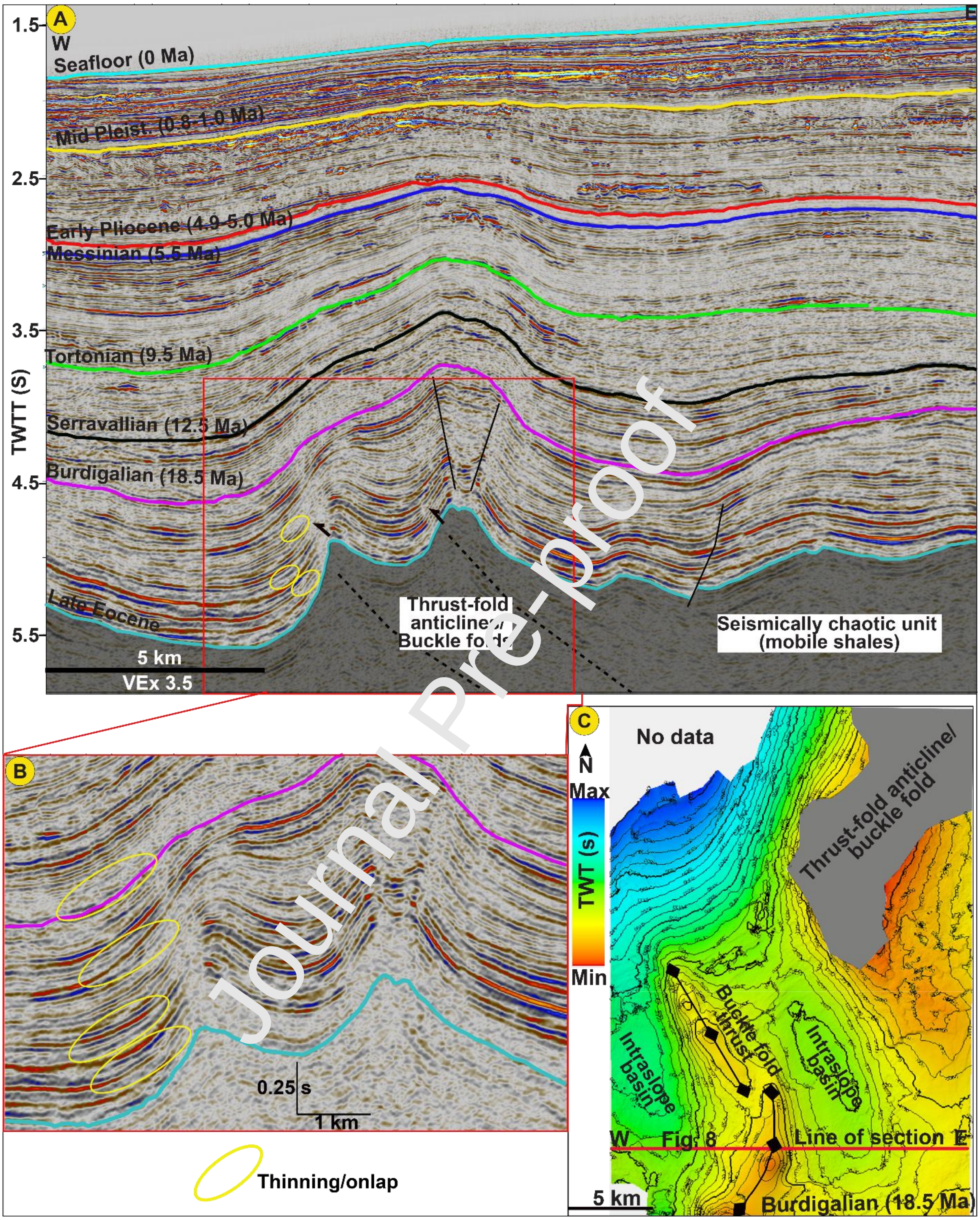


Fig. 8. Stratigraphic architecture of the offshore western Niger Delta slope along strike. A. An interpreted E-W seismic profile, showing a general thinning of stratigraphy from the Burdigalian to Present, above buckle folds (detailed view in panel B). C: Time structure map of the Burdigalian surface, showing the geometry of the interpreted thrust-fold anticlines or

buckle folds. Note the thinning and/or onlapping of reflections (yellow ellipses) within the Late Eocene-Serravallian interval.

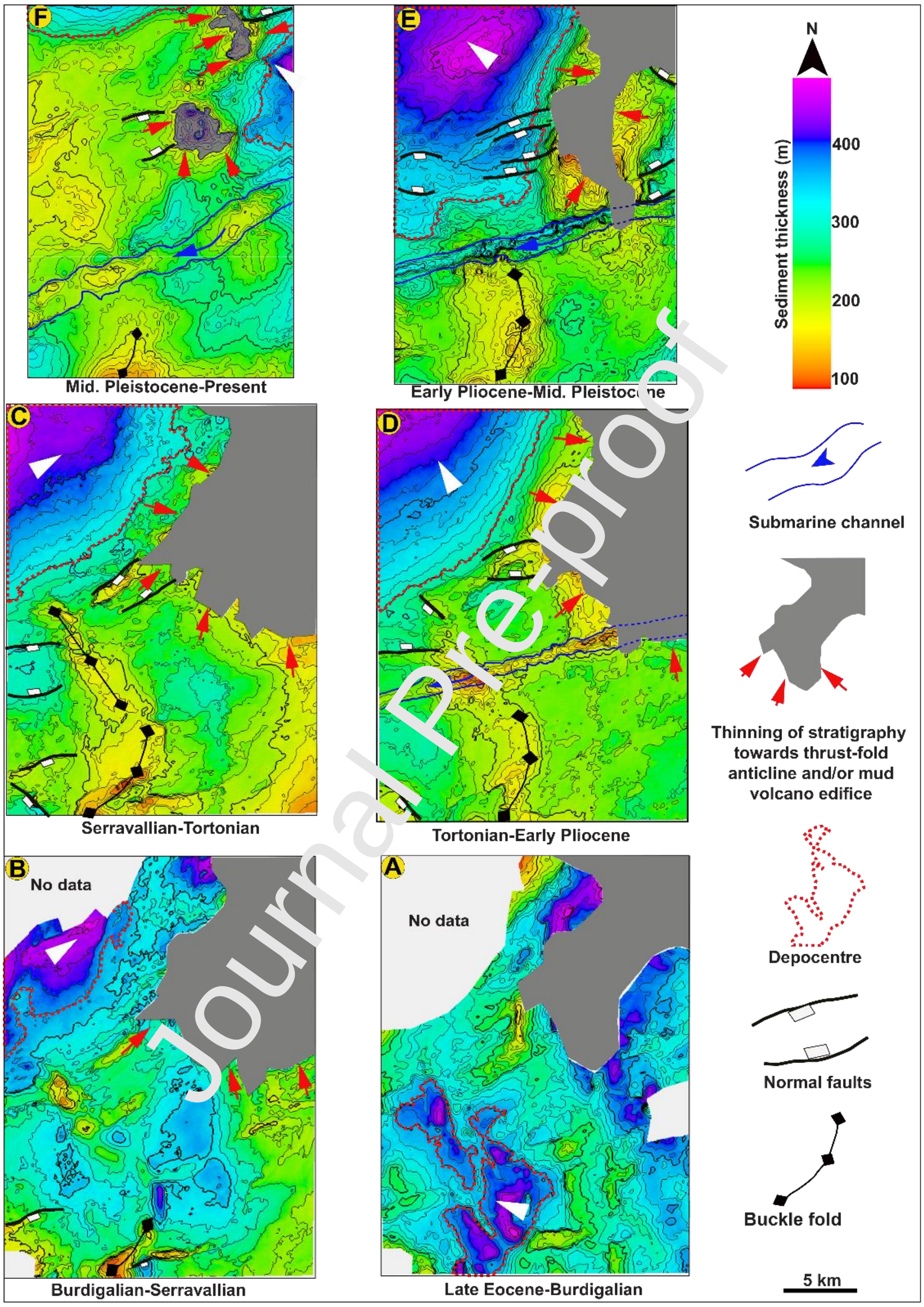


Fig. 9 A-F. Isopach maps showing the spatio-temporal shifts in depositional patterns from the Late Eocene to the present. Note the general thinning of stratigraphy towards the thrust-fold anticline and/or mud volcano edifice in the northeast (red arrows) in panels B-F, and the presence of discrete depocentre (white arrow) within the Late Eocene-Burdigalian interval.

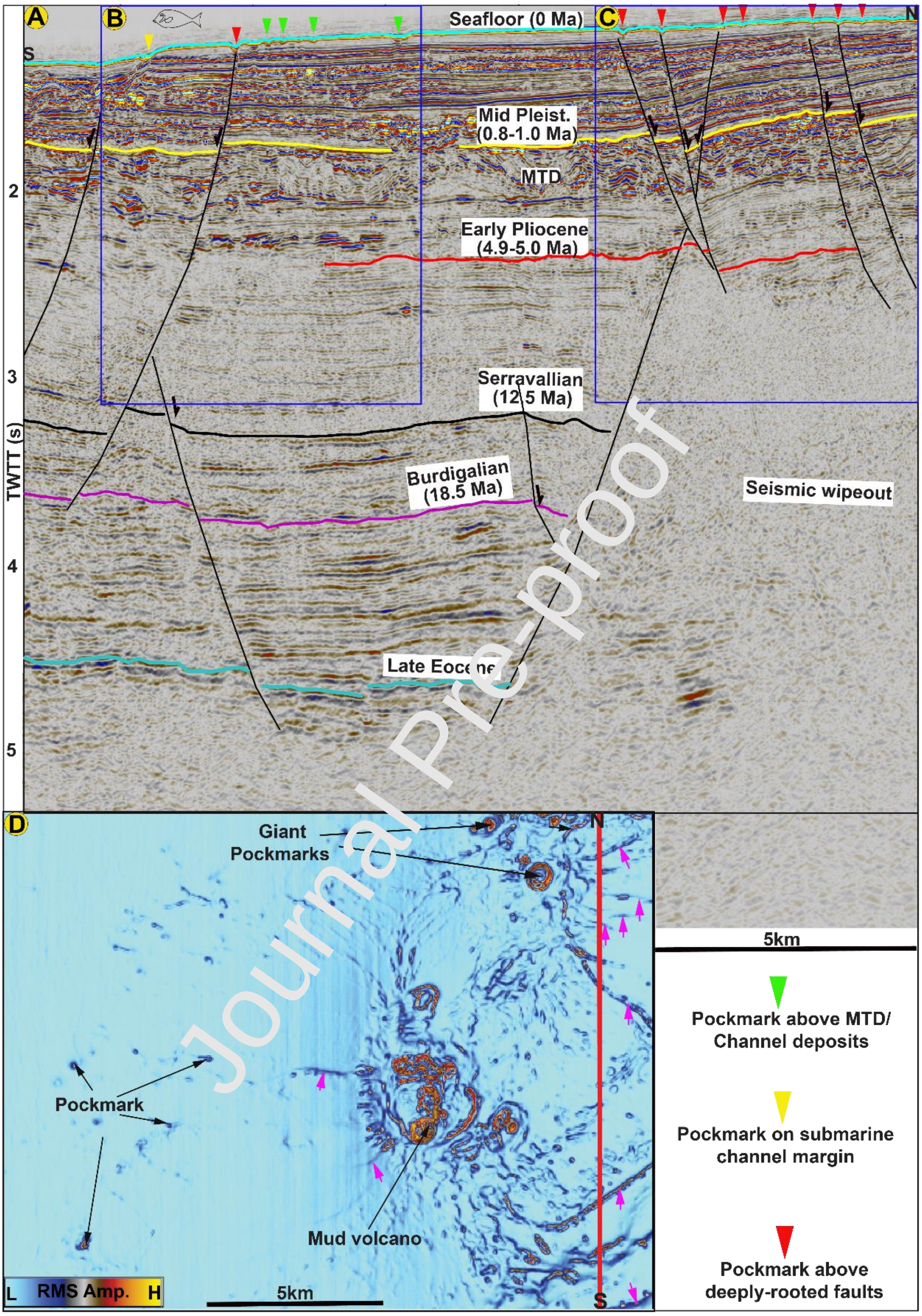
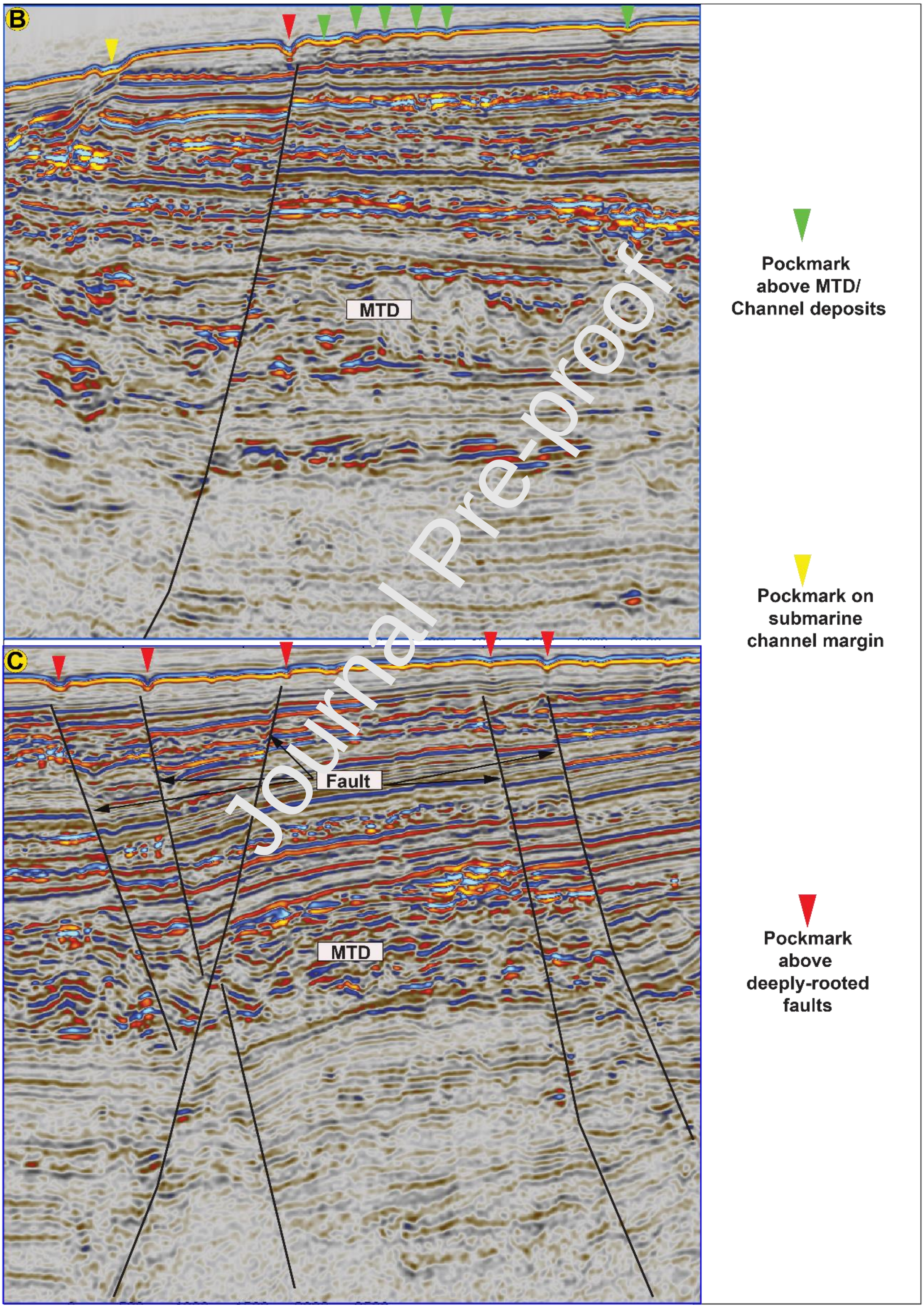


Fig. 10. A. An interpreted N-S seismic profile (location shown by red line in panel D). B, C. Zoomed seismic sections, showing pockmark distribution above normal faults (red arrows),

thick mass-transport deposits (green arrows) and a submarine channel deposits (yellow arrows).



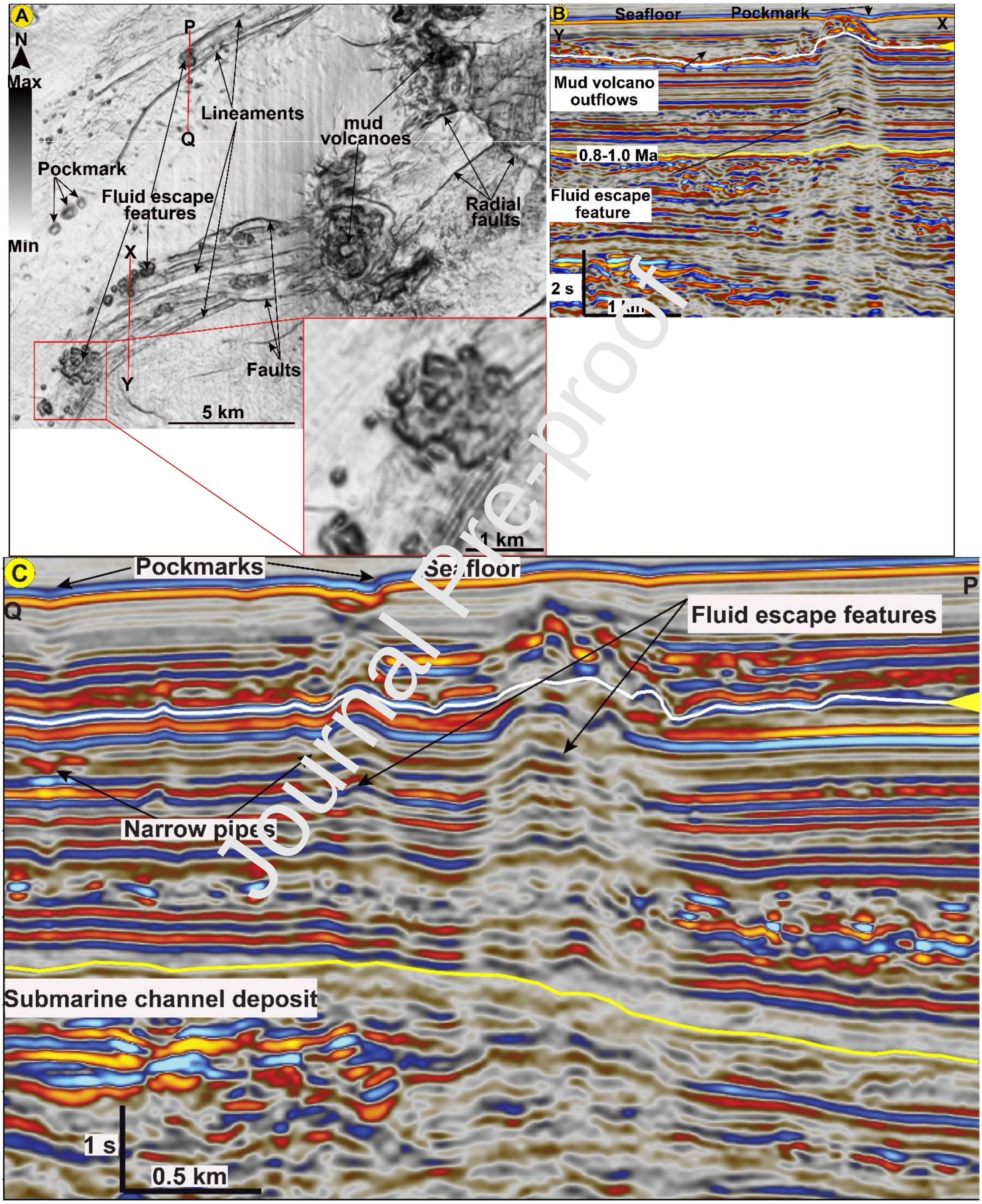

A
N
Max
Min
P
Q
Lineaments
mud volcanoes
Pockmark
Fluid escape features
Radial faults
X
Y
Faults
5 km
1 km
B
Seafloor
Pockmark
Y
X
Mud volcano outflows
0.8-1.0 Ma
Fluid escape feature
2 s
1 km
C
Pockmarks
Seafloor
Q
P
Fluid escape features
Narrow pipes
Submarine channel deposit
1 s
0.5 km

Fig. 11. A. Variance attribute map (stratigratigraphic level indicated by yellow arrow in panels B, C), showing mud volcanoes and associated sediment outflows as well as fluid escape features.

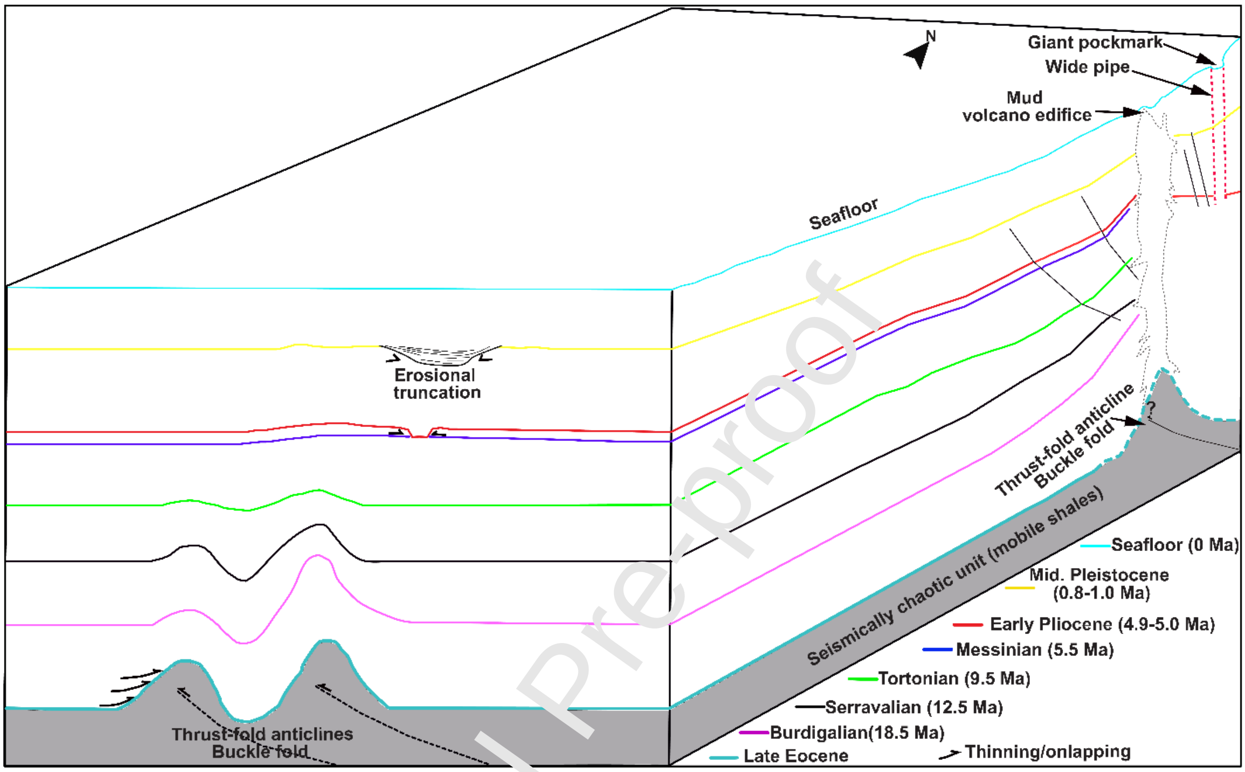


Fig. 12. Schematic illustration of shale evolution and fluid escape features on the offshore western Niger Delta from the Late Eocene to present (not to scale). See text for more detailed explanation.

Highlights

- Shale tectonics in the offshore Niger Delta initiated early in the evolution of the system in the Late Eocene/Early Miocene
- Presence of buckle folds within the Late Eocene-Burdigalian interval record the onset of contractional toe thrusting and gravity-driven deformation
- Mud volcano systems once formed may act as conduits for pressure release throughout the history of a gravity collapse system
- Increased sedimentation during the Late Eocene-Burdigalian facilitated overpressure development and shale mobilisation
- Mud volcanoes and pockmarks above thrust-fold anticlines and deep faults record deep fluid-flow, while pockmarks above MTDs and submarine channels record shallow fluid-flow