Revisited Play Concept for Distally-Steepened Carbonate Ramps: The Relevance of Sediment Density Flows in the Stratigraphic Record*

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Introduction

Since the pioneering facies model proposed in the late 60s by W. F. Bishop for the extensive Jurassic Smackover Formation (Bishop, 1968) crossing the southern region of the United States, the definition and classification of carbonate ramps has been the topic of a vast and rich scientific debate. Detailed outcrop research coupled recently with analysis of seismic data led to proposing models based on depositional profile (shelf vs ramp), distribution of facies, and genetic approach in response of interaction between hydrodynamics, sea-level changes, ecology, etc.

The widely-accepted model proposed for ramp settings (Pomar and Tropeano, 2001; Pomar et al., 2004; Pomar et al., 2012) establishes a logical relationship from proximal to distal facies where the assemblage between sedimentary structures and biotic assemblages allow the separation and distinction between inner and middle ramp, ramp slope, and outer ramp. Gentle dips mark the inner and middle ramp environments, which are thought to be comparable to the shore face in siliciclastic systems (cf. Pomar and Tropeano, 2001). A steeper ramp slope develops at the intersection of the sea floor with the wave base. This pass basin wards into the outer ramp (offshore) zone. The distally steepened carbonate ramp can be compared to the storm wedge slope described by Hernandez-Molina et al. (2000) where the infra-littoral prograding wedge advances by coalescent deposits genetically associated with storm-generated currents. In this context, the storm wedge slope (Hernandez-Molina et al., 2000) would be comparable to the ramp slope of cool-water carbonate ramps (Pomar et al., 2012). The carbonate platform edge need not correspond to the shelf edge. The progradation of numerous cool-water carbonate platforms yielded shelf-perched clinoformed prisms (Hansen, 1999; Pedley and Grasso, 2002; Pedley and Grasso, 2006; Massari and Chiocci, 2006; Puga-Bernabéu et al., 2010; Massari and d'Alessandro, 2012; Meloni et al., 2013). In terms of processes, such carbonate wedges are genetically comparable to the siliciclastic infralittoral prograding wedge of Hernández-Molina et al. (2000).

Alternative facies models to the classic ones and widely referred to described before, highlight the occurrence, within the transitional zone from shallow platform to deeper water environment, of prograding fan-shaped deposits consisting of rudstone/grainstones bundles of relatively thin sigmoidal beds with foresets up to 25°dip (Vecsei, 1991, 1998). Interaction between slope gravity processes, off-bank sediment export, and reworking processes by longitudinal currents have also been documented adding to the complexity of erosional and sedimentary processes in intrashelfal settings (Tournadour et al., 2015). Most recently the concept of 'delta drift' was introduced (Lüdmann et al., 2018) to describe a new channel related drift type attached to a carbonate platform slope formed by continuous supply of calcarenites debris deposited at the exit of gateways connecting the carbonate platform with the open ocean.

In this paper, we describe an example from the Mediterranean Sea and one from the Gulf of Venezuela, both illustrating the relevance of sediment density flows in the stratigraphic record of carbonate ramps setting.

The Favignana Calcarenite

Recent detailed work on Lower Pleistocene distally-steepened heterozoan carbonate ramp deposits of Favignana Island (Figure 1), Italy (Kill 2010; Kil and Moscariello, 2012; Slootman et al., 2016; Slootman, 2016), indicates the occurrence of large amount (e.g. up to 60 m thick deposits over an area of ca. 10 km^2) of coarse-grained skeletal remains transported downramp by bimodal energy flows representing either 1) water flows generating sub-critical subaqueous dune deposits or 2) high-energy, upper flow regime, density flows generating thick beds consisting of antidunes, chute-and-pools, and cyclic steps sedimentary structures.

The low energy deposits consist of tabular tangential high to low-angle cross bedded grainstones, alternated with horizontally laminated and bioturbated grainstones, and packstones (Figure 2). The high-energy intervals (Figure 3), forming individual beds reaching up to 6-metres in thickness, are made of highly-irregularly shaped grains with high intragranular porosity caused by frequent interlocking of skeletal grains. These are formed by coralline red algae, bryozoans, molluscs, echinoderms, and benthic foraminifera resedimented on ramp slope and toe position in an intrashelf basin.

The overall architecture of these deposits can be described both at large outcrops scale thanks to the extensive cliffs partly surrounding the eastern side of the Favignana Island and few 2D seismic lines acquired in the 70s and 80s for hydrocarbon exploration in the offshore area.

The striking occurrence of 2 to 10 m deep and narrow (3 to 30 m) incisions (Figure 2 and Figure 3), often with regular semicircular shape, filled with poorly sorted and stratified coarse-grained calcarenites (rudstones/grainstone) with largest clasts consisting of abundant rhodolites and disassembled shells, often displaying a clear fining upward grain-size distribution makes this succession very different from the ones described in 'conventional' ramp settings (i.e. Pomar et al., 2004).

As described in previous works (Kil and Moscariello, 2012; Slootman et al., 2016; Slootman, 2016), these large and deep often narrow incisions pass down-current to typical facies assemblages consisting of parallel horizontal lamination, convex up undulated lamination, scours with backsets infill (Figure 4) which are organized in a series of thinner (2-4 m) but wider lenticular bodies formed under super-critical conditions where sheet flooding antidunes chute-and-pools and cyclic steps developed.

These sedimentary bodies show lateral stacking patterns indicating the overall autogenic lateral migration of the depositional system. Overall the lenticular geometries forming these distal facies seem to be organized in coalescent fan shapes, opening toward the offshore direction. Palaeo-current data (Kil, 2010; Slootman, 2016) indicate a dominant paleo-flow direction to the S-SE where the influence of possible opposite currents (tidal?) in the very distal section of the deposits has been observed (Figure 5).

The detailed analysis of the seismic data cannot resolve the lenticular sedimentary bodies observed in outcrop. However, lateral stacking patterns of large lenticular bodies (ranging in with between 400 m and 1 km, Figure 6) are visible in seismic (line 1) acquired offshore following a direction perpendicular to the palaeoflow direction. These lenticular bodies display reciprocal erosional relationship, suggesting unequivocally the lateral migration of the feeding scours leading to the sediment dispersion and consequent accretion and progradation of the sedimentary system.

The examination of seismic lines located in a distal position (line 2) with respect the overall sedimentary system (Figure 7), highlights the presence of convex-up and sigmoidal lenticular bodies which display lateral stacking and topographic compensation geometries. These are interpreted as the distal apron generated by (catastrophic ?) supercritical flows on distal ramp settings.

The extensive outcrop examination and interpretation of offshore 2D seismic lines, indicate that the Favignana Calcarenites are originated from the alternation of wide, lobated coalescent fans and tabular and continuous subaqueous dune beds overall forming an extensive sediment apron connecting the shallow carbonate platform (factory) to the deeper basin (Figure 8). In particular, this sedimentary succession is formed by a complex assemblage of 500 m-long and tens of meters thick, S-SE prograding clinoform units, dipping about 5 to 20 degrees (Slootman et al., 2016) suggesting the establishment of phases of relatively steep ramp settings. Based on the large occurrence of re-worked inner platform/ramp coarse-grained material occurring within the Favignana Calcarenite, its overall geometry and areal distribution we suggest the term of re-sedimented Carbonate Ramp Apron (CRA) deposits to describe this succession. Specifically, the depositional processes associated with the CRA environment is characterised by the following sedimentological and geomorphic aspects: a) the sedimentary processes are characterised by bimodal deposition associated with both wave-driven low energy currents which occasionally during exceptional high energy events (storms or ? tsunamis) trigger catastrophic sedimentary density flows passing from confined to unconfined conditions; b) the sediments are supplied by wind-induced currents to the CRA from a wide and open zone (gateway) of few to several km in width; c) the absence of permanent distributary channels providing and dispersing sediment in the accumulation area, as they occur in deltas or subaqueous fans; d) a typical apron shape with a wide upcurrent side widening downcurrent on the ramp slope. For the reasons mentioned above the term apron is preferred over the term delta (Lüdmann et al., 2018) which has instead a well-established meaning in geomorphology and marginal marine clastic sedimentology (i.e. triangular shape with a well-defined apex corresponding to the point source of sediments).

Other Examples of CRA Deposits

The occurrence of similar facies has been identified in outcrops in several locations in the Mediterranean region (Cyprus, Southern Italy, Corsica) although individual cases may not have been interpreted with this new proposed depositional model (e.g. Tropeano and Sabato, 2000; Pomar and Tropeano, 2001). Similarly, resedimented carbonate ramp apron (CRA) deposits in comparable distally-steepened heterozoan or rhodalgal carbonate steepened ramps could be recognized in subsurface reservoirs (i.e. Iran, Philippines, China, etc.) providing new insight on internal architecture, properties and connectivity.

An example of subsurface reservoir where CRA deposits may form a substantial part of the stratigraphy is the Upper Oligocene-Lower Miocene carbonates of the Perla gas field in the Gulf of Venezuela (Caribbean region).

The Perla Carbonates

In the Gulf of Venezuela (Southern Caribbean Sea), the Oligocene-Miocene carbonate forming the main reservoir of the Perla gas field (Figure 9) have been described from core, wireline well and 3D seismic data (Pomar and Pinto, 2013; Pinto et al., 2015). On this basis, the reservoir succession is broadly characterized, from bottom to top (Figure 9), by 1) Unit 1: siliciclastics deposits; 2) Unit 2: carbonates grainstones containing mostly coralline red algae, large benthic foraminifera, rhodalgals, rudstone and floastones and rhodoids and, at the top, by: 3) Unit 3: mixed-, resedimented carbonate-clastics sediments, displaying both structureless and faint undulated lamination. The latter were originally interpreted as the product of density flows (Pinto et al., 2015).

The facies type, internal geometry, and thickness variations of Unit 3, suggest that this could also represent the product of high-energy flow, likely reaching supercritical conditions which would be attained in a distally steepened carbonate ramp environment. In particular, facies variation and biostratigraphic analysis along the E-W transect through 3 wells (P3, P2, and P4; Figure 9), indicate vertical changes in large benthic foraminifera suggesting a continuous relative sea-level rise during a diachronous deposition, resulting in a backstepping succession (Figure10) on a pre-existing topographic high.

Seismic data in fact indicate that the Perla carbonate ramp was attached to a basement high (palaeo-island or isolated platform) than could be part of an archipelago (Pinto et al., 2015) where inner platform environment could be connected to open ocean through relatively steep slopes.

The shallower stratigraphic interval, onlapping on the basement high would therefore correspond to Burdigalian resedimented limestones (Figure 10) which are here interpreted as CRA deposits conveyed from inner platform into the ocean along a steepened carbonate ramp where sedimentary structures, such as those ones described for the Favignana Calcarenite, developed. This genetic model is supported by the sigmoidal architecture observed in 2D and 3D seismic which is consistent with the backstepping facies (Figure 11) recognized from the core-based sedimentological studies (Pinto et al., 2015).

Conclusions

Facies assemblages recognized in the Favignana Calcarenite are formed by bimodal depositional processes resulting in a distinct and alternating sedimentary packages. A low-energy sedimentary assemblage formed by typical subaqueous dunes consisting of tabular cross bedded grainstones and packstones often bioturbated is coupled with a heterogeneous facies assemblage where, coarse-grain filled erosional depressions, largely variable in size, formed by downslope confined flows generating elongated scours are associated with low-angle cross bedded grainstones formed in supercritical conditions (backset bedded, antidunes, etc.).

The geographical distribution of these deposits based on outcrop examination and 2D seismic line interpretation indicate they have a triangular shape which form a series of coalescent fans forming an overall apron connecting the shallow carbonate platform/inner ramp setting (factory) to the deeper basin through a steep ramp.

Cool-water CRA (carbonate ramp aprons) are depositional systems in which skeletal sand and gravel are redistributed basinwards on a ramp, off a shallow carbonate platform by tractive currents as a result of flow funneling in between topographic highs. These deposits are different and should not be confused with the carbonate apron models proposed by of Mullins and Cook (1986) who describe either carbonate deep water turbiditic systems accumulated at the base of the slope or talus cones formed at the margins of carbonate build ups.

Similarly, to what has been described for the Favignana Calcarenite, carbonate ramp aprons (CRA) deposits could represent an important part of ancient sedimentary record of intrashelf carbonate successions such as the Oligocene/Miocene carbonate of the Perla gas field in the Gulf of Venezuela.

Including the presence of this newly identified facies and related architectures in the play concept for distally-steepened carbonate ramps in intrashelf basins, is relevant from an exploration and development perspective in order to assess fully the potential of reservoirs extension and understand fluid flow behavior in carbonate reservoirs.

Acknowledgment

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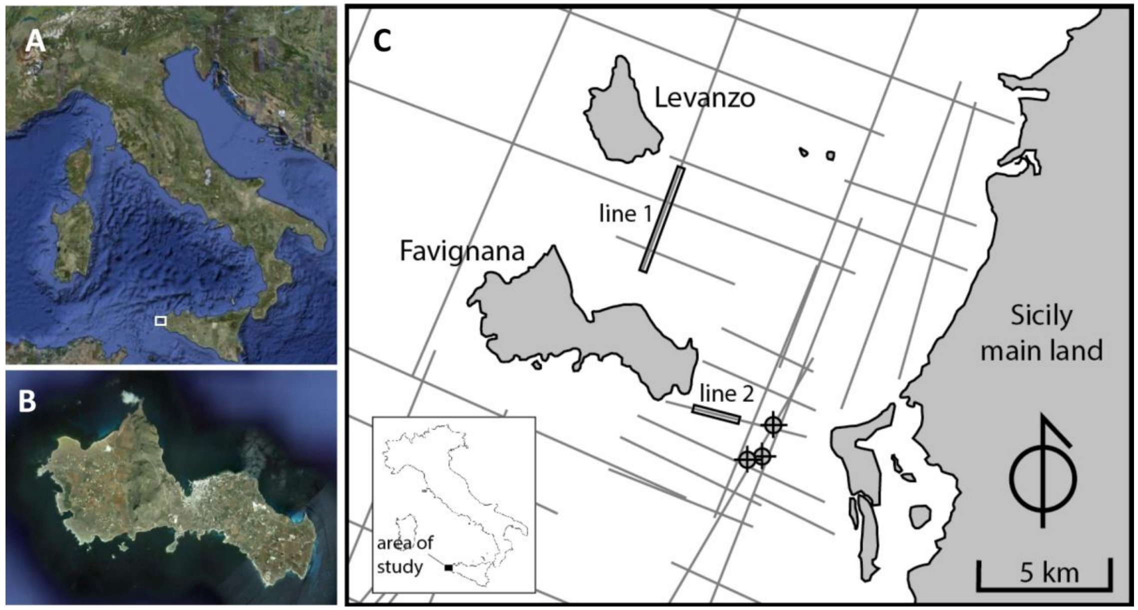

Figure 1. A) Geographical location of the study area (white square) in the southern part of Italy and B) satellite image of the Favignana Island (offshore western Sicily). C) Location map with indication of the 2D seismic lines examined in this study. The highlighted seismic lines are presented in this article (lines 1 and 2).

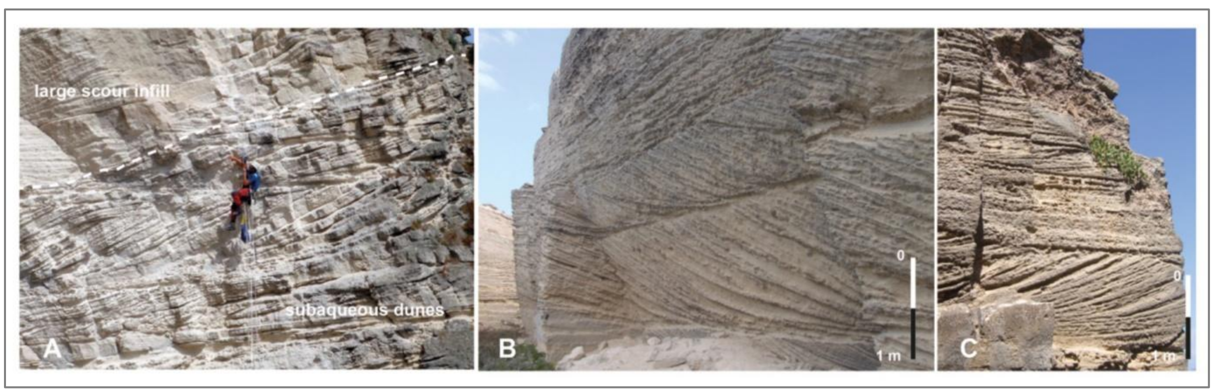

Figure 2. A) Stacked compound subaqueous dunes of different size consisting of tabular and tangential cross bedded grainstones passing to, often bioturbated, packstones at the laminae toe sets. These deposits are cut by a large scour filled by irregularly bedded rudstones and grainstones rich in rhodolites and large shell fragments. B) Thick tabular and tangential high-angle cross bedded grainstones showing several steep reactivation surfaces overlaid by a thick package of small-scale through cross bedded grainstones. This succession indicates a change in flow regime most likely linked to changes in accommodation space due to high sediment supply. C) Tabular and tangential high-angle cross bedded grainstones overlaid by a composite stack of horizontal and low-angle bedded grainstones and bioturbated packstones.

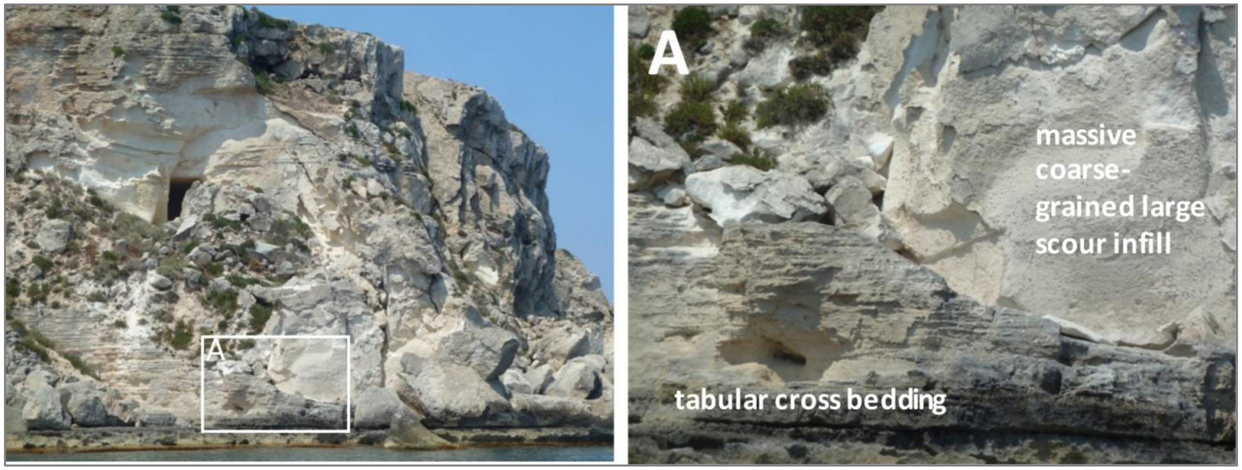

Figure 3. View of the ca. 50 m height northern cliff of the Favignana Island providing a good example of the stratigraphic setting and internal architecture of the calcarenite succession. Large scour filled with massive/structureless rodholite-rich coarse-grained calcarenites, deeply cutting on tabular cross bedded calcarenites showing the typical bimodality of depositional style of the Favignana Calcarenite succession; A) detail of the sharp scour base.

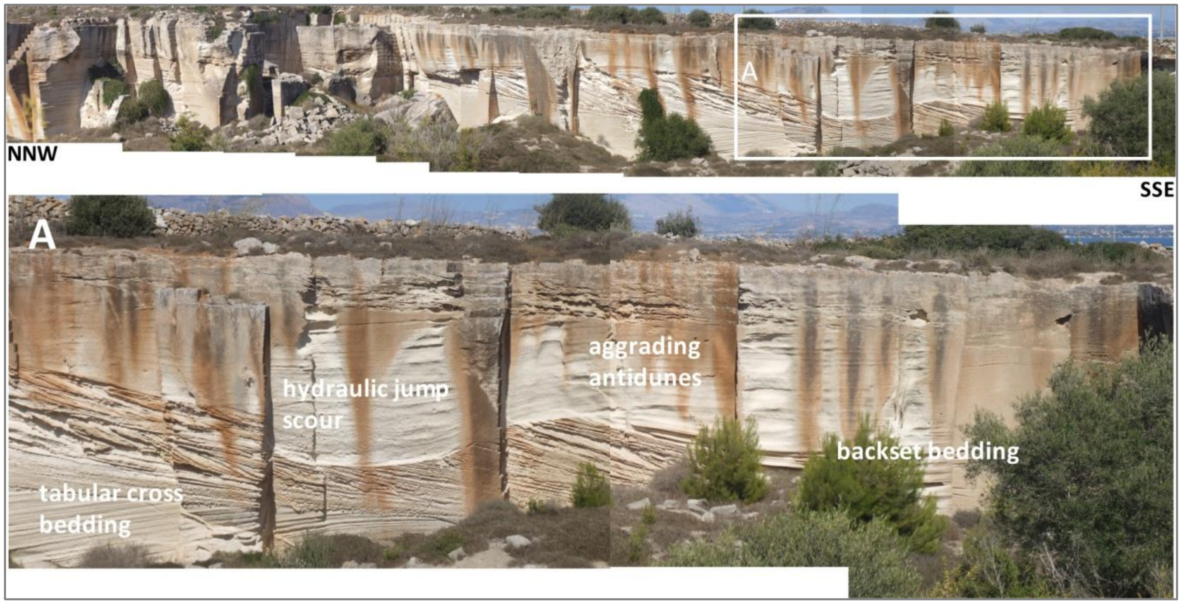

Figure 4. Sedimentary structures forming the Favignana Calcarenite showing the typical bimodal composition consisting of high angle tabular cross laminated sets, alternated with rudstone grainstones scour fills super critical (density) flows deposits.

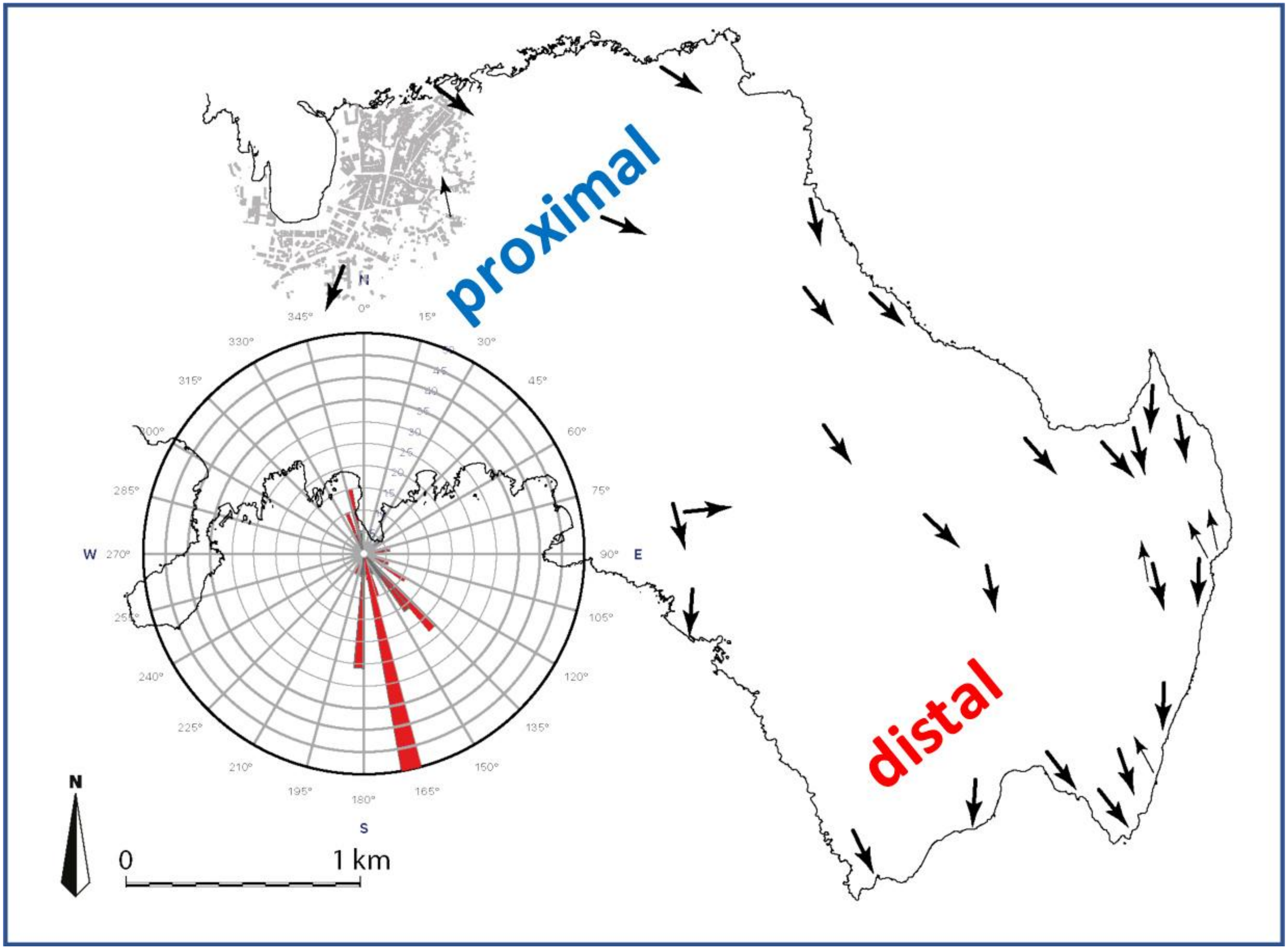

Figure 5. Paleo current direction measured on Favignana Calcarenite outcrops indicating a dominant direction towards the SSE with minor contribution of northerly (tidal?) paeoflows (modified from Kil, 2010 and Slootman, 2016).

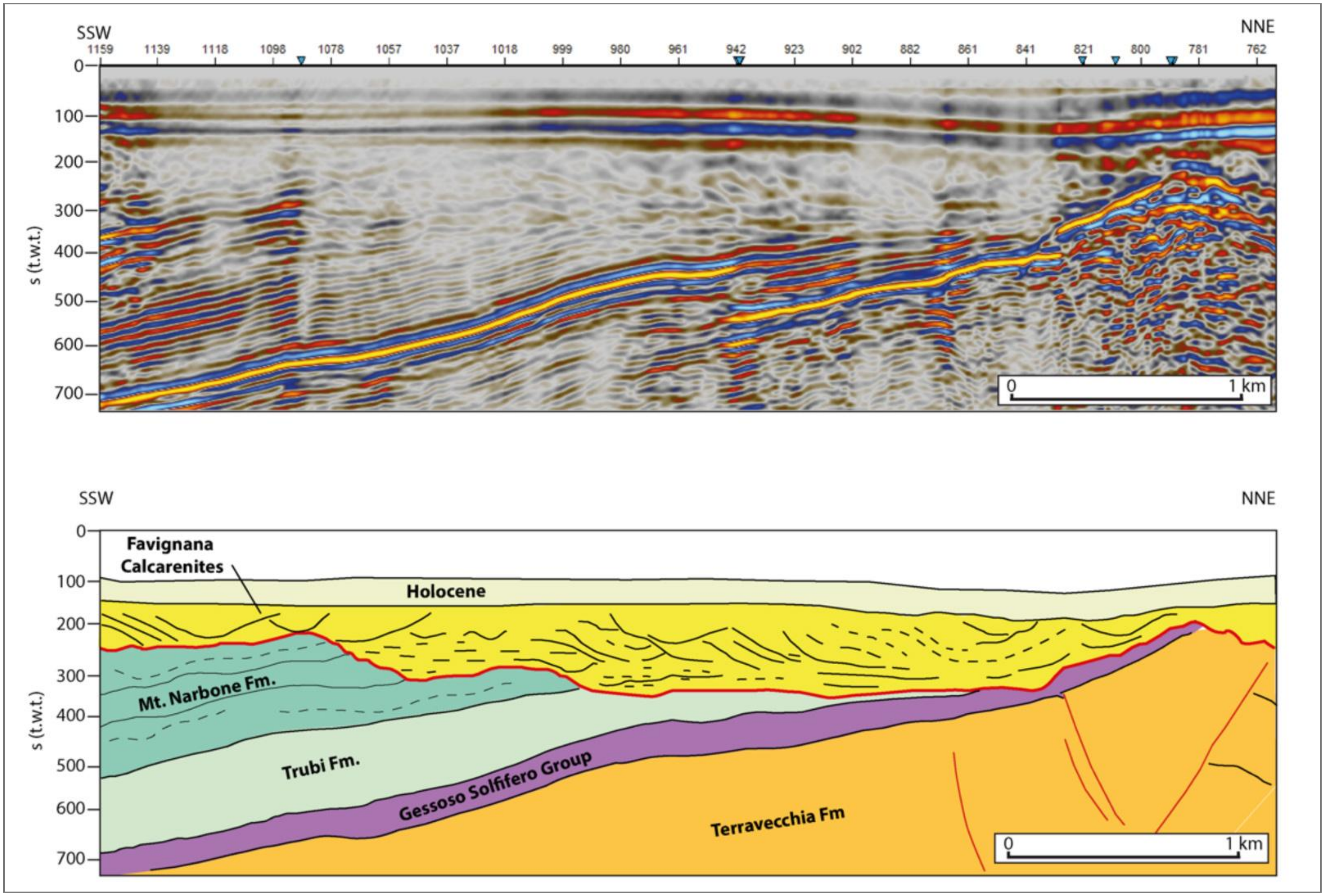

Figure 6. 2D seismic line oriented N-S located at the North of the Favignana Island (see Figure 1 for location) showing the Favignana Calcarenites that unconformably overlays a Meso-Cenozoic deformed substrate belonging to the Sicilian Fold and Thrust Belt. In the Favignana Calcarenites deposits, sedimentary bodies with concave base migrate laterally to the North displaying overall down-cutting geometries. These are interpreted as the product of large incisions generated by (catastrophic ?) gravity or storm inducing supercritical flows on proximal ramp settings.

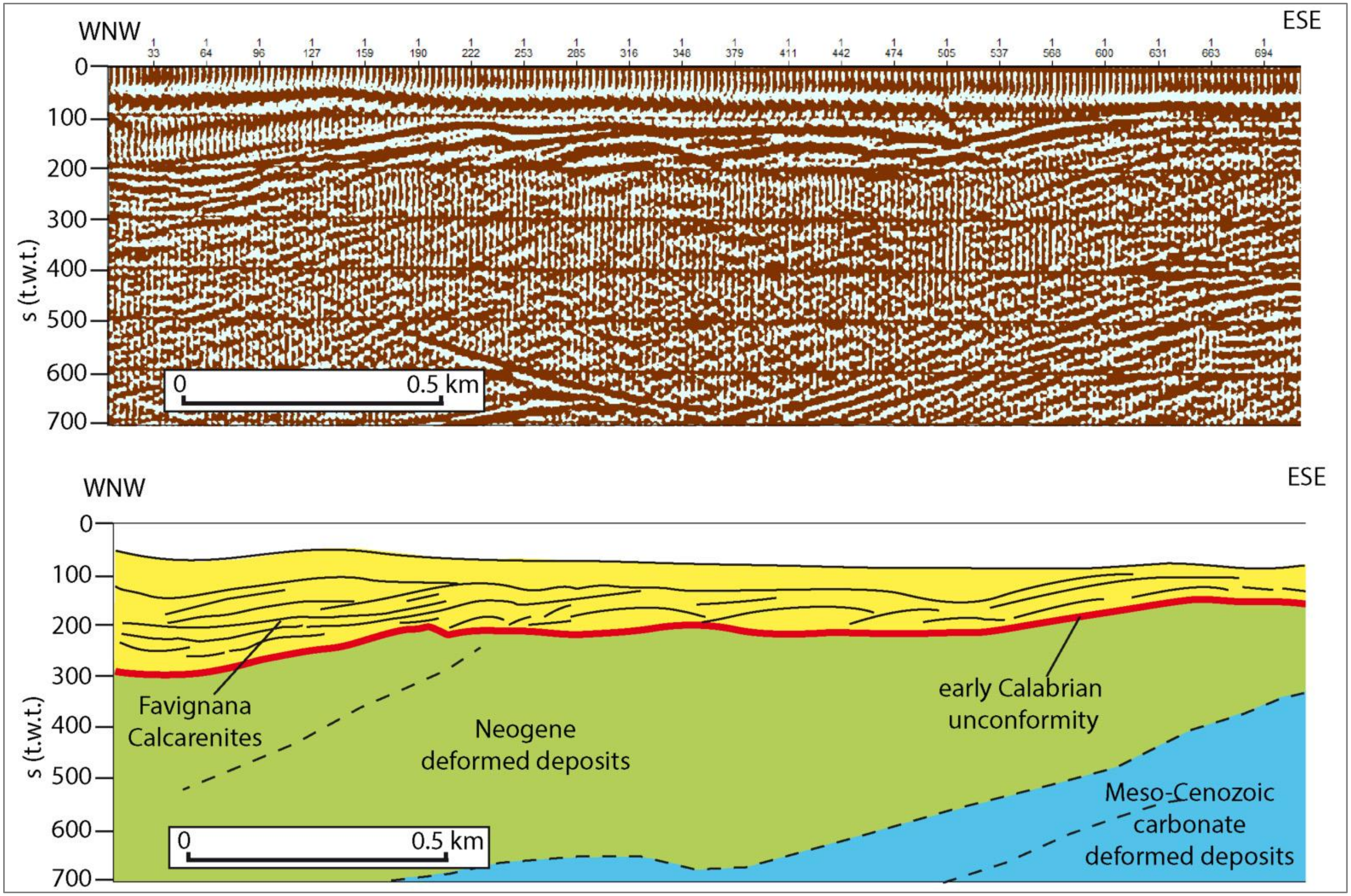

Figure 7. 2D seismic line oriented E-W located at the East of the Favignana Island (see Figure 1 for location). Convex up sedimentary bodies migrating laterally displaying topographic compensation geometries. These are interpreted as the product of originally supercritical flows in steep ramp setting which turned into waning flow in distal ramp settings as the current and sediment move downslope. This geometry characterizes the distal part of the carbonate ramp aprons.

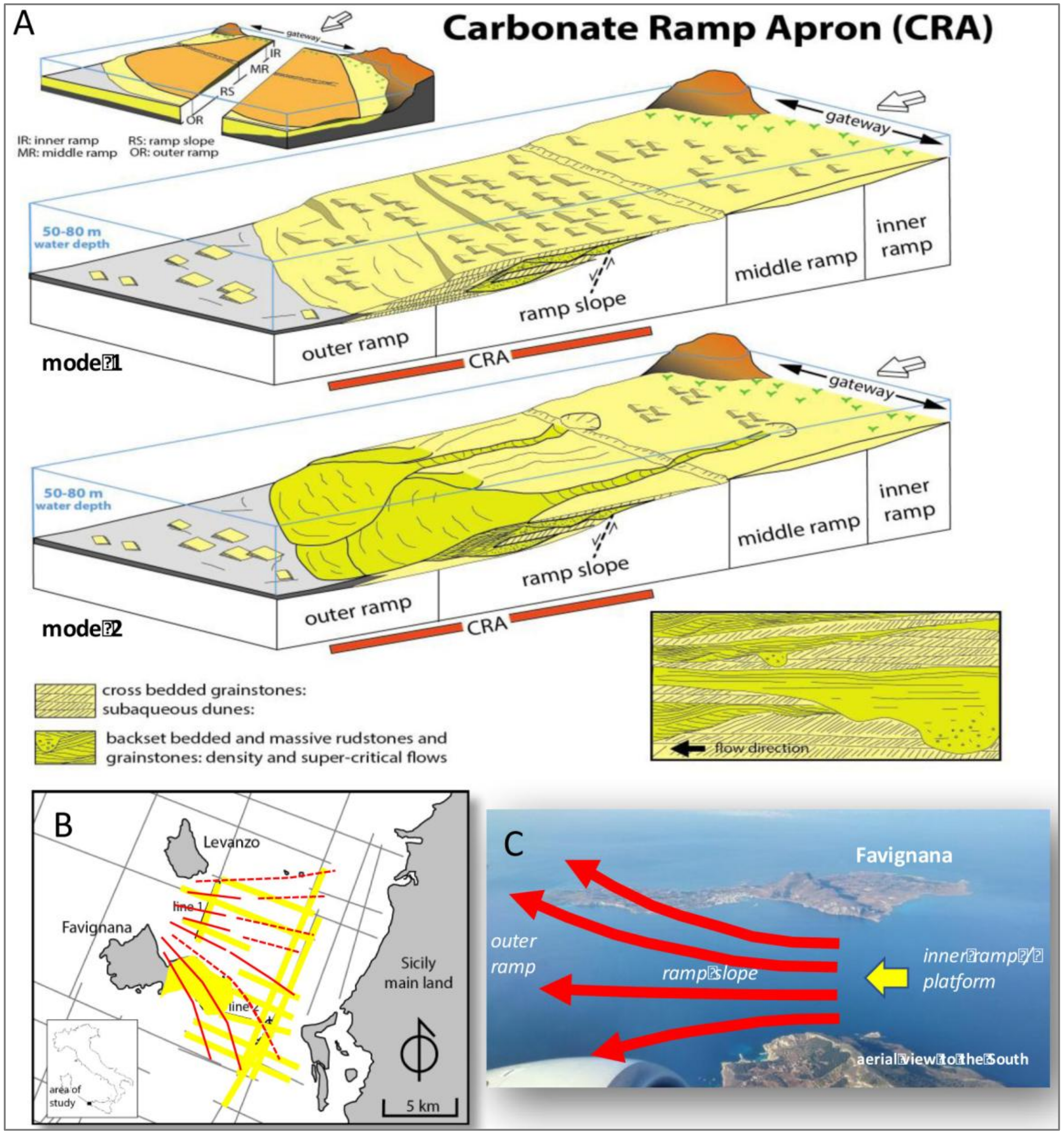

Figure 8. A) Proposed depositional model for high-energy dominated steep ramp settings based on the data from the Favignana Calcarenite where CRA deposits form an important part of the sedimentary record. Large sediment erosions/collapse-induced bottom currents resulting in large sediment transfer from carbonate factory to ramp slope/outer ramp primarily by density and super-critical flows. B) Geographical distribution of the Favignana Calcarenite based on outcrop and 2D seismic line (yellow) and reconstruction of CRA deposits (red lines). C) Oblique aerial photograph showing the reconstructed settings of the Favignana Calcarenite ramp.

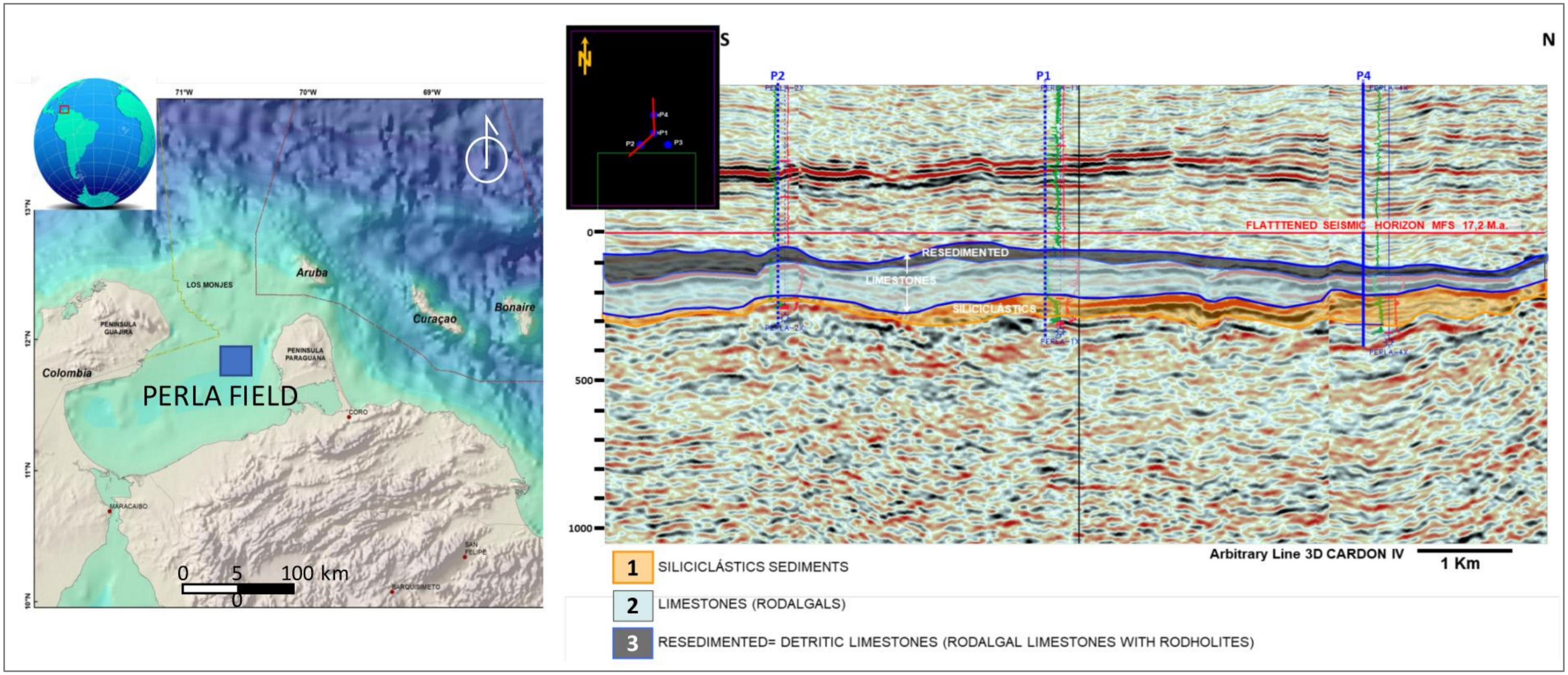

Figure 9. A) The Gulf of Venezuela map with indication of the Perla gas field location. B) Arbitrary seismic line, selected from 3D cube CARDON IV, flattened on an intra-Early Miocene horizon showing the vertical distribution of main lithofacies drilled in the Perla gas field (wells P2, P1, and P4) where the N-S thickness variation is visible.

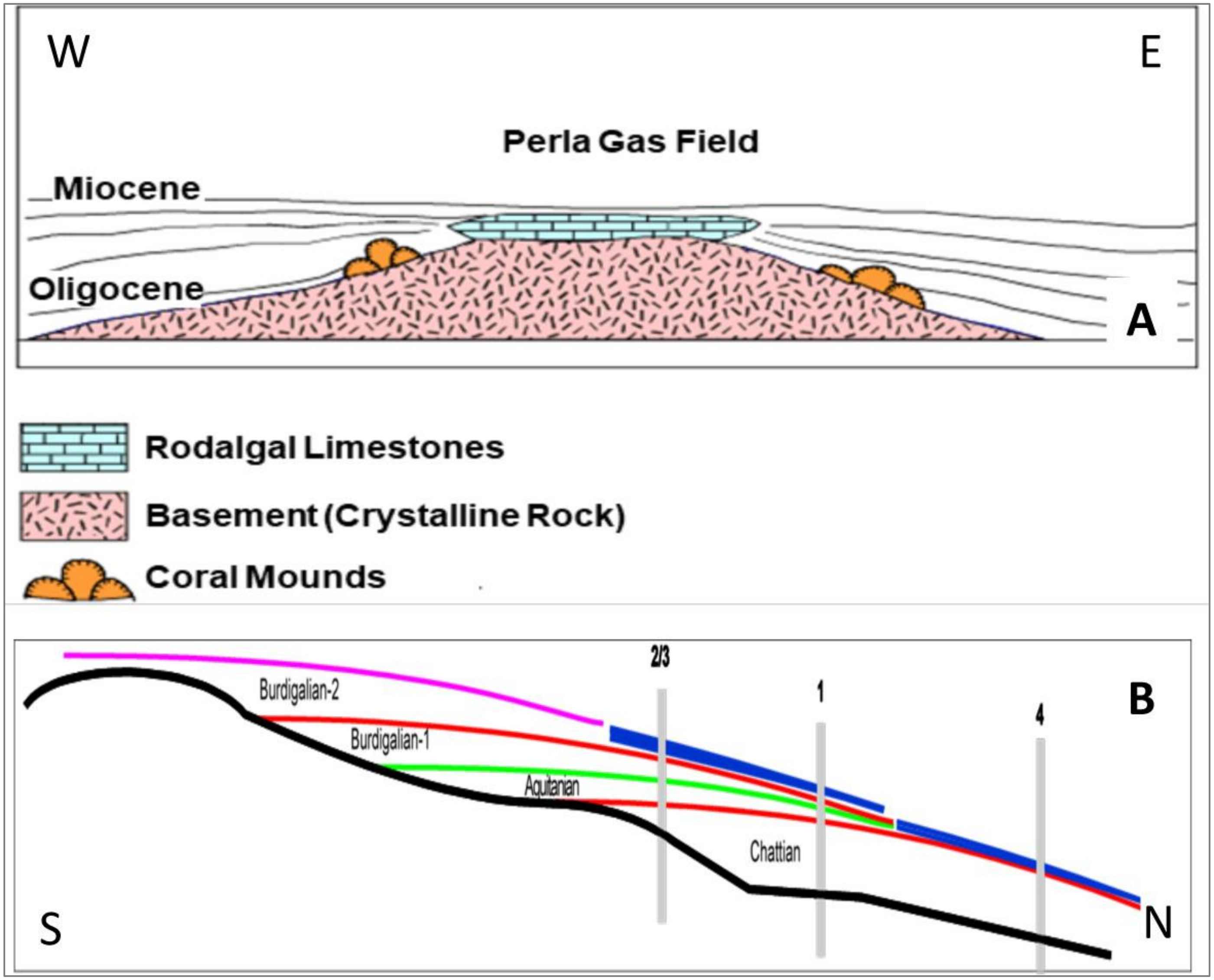

Figure 10. A) Sketch of the Perla field carbonate ramp with the palaeo-island and B) sketch illustrating the backstepping geometry of the Perla carbonate ramp sedimentation on the northern sector of the Perla palaeo-island. (from Pomar and Pinto, 2013).

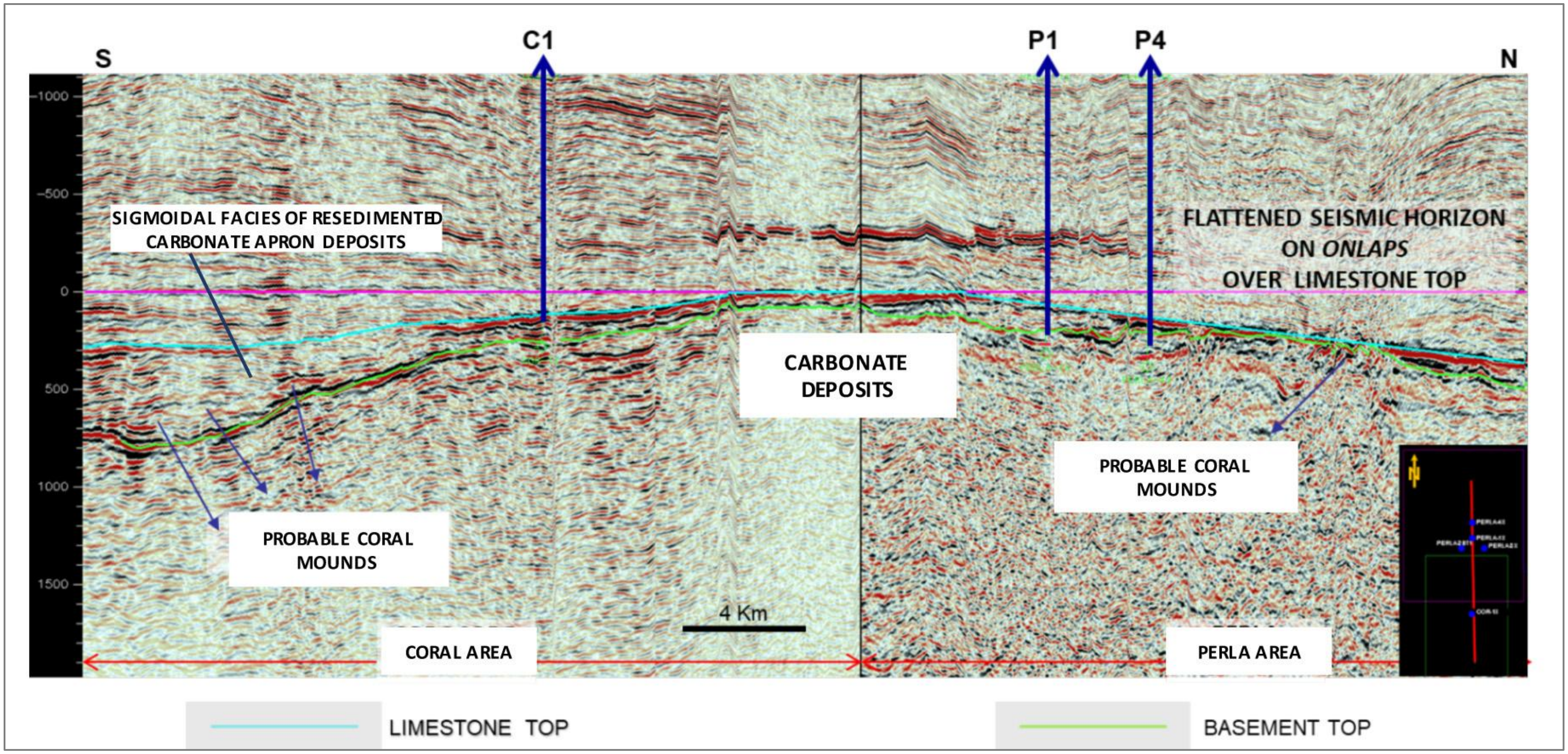

Figure 11. Flattened seismic line across the Perla area on a Burdigalian shale units. On the southern side, the seismic facies of the wedging out interval of the carbonate succession is interpreted here as possible expression of CRA deposits generated from the inner shallower ramp located at center of the image and deposited in steeply dipping ramp setting.