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‘’Geological characterization of a potential CO_2 storage play in the Gela offshore (southern Sicily) and the role of a gravitational slide’’

Mariagiada Maiorana [a,*], Attilio Sulli [a], Matteo Marelli [b], Mauro Agate [a]

[a] Department of Earth and Marine Science - University of Palermo, Italy
[b] Halliburton - Via del Marchesato, 25- Ravenna, Italy

A R T I C L E I N F O

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A B S T R A C T

In a context where European policies mandating a 55% reduction in CO2 emissions by 2030, Carbon Capture Storage (CCS) presents a viable solution for achieving substantial emissions cuts. Identifying existing and new potential sites for CCS in offshore southern Sicily is crucial to meeting this goal.

The Gela offshore region is predominantly characterized by the Gela Thrust System (GTS) and its associated Gela Foredeep (GF), a narrow (less than 20 km) and elongated (approximately 100–120 km) depozone that comprises the thicker Plio-Pleistocene sandy sediments of the offshore Sicilian sector. This area is covered by the Gela Slide, a 1500 km^2 gravitational slide.

The potential of Plio-Pleistocene clastic deposits in this regionfor CCS implementation has not been previously explored. In this study, we investigated a potential caprock-reservoir system covering around 840 km^2 in the Gela offshore area. Our analysis involved interpreting key horizons from a dense grid of 2D seismic reflection profiles, conducting well-to-seismic tie analysis and developing a refined velocity model.

The study reveals a promising storage play within the foredeep basin-filling deposits. This potential storage play consists of Lower Pleistocene foredeep turbidite sands of Sabbie di Irene Fm. (reservoir) and of the Middle-Upper Pleistocene pelitic deposits of the Argo Fm. (primary seal). Additionally, the basal shear level of the Gela Slide has been investigated as a potential secondary seal. Analyzing its extent, age, and interaction with the GTS offers valuable insights into the relationships between tectonics and sedimentation, which could lead to the identification of suitable sealing layers for CCS purposes.

This study thus provided new data on the thickness, depth, facies and rock volumes of the main reservoir and seals, highlighting their potential suitability for CCS applications.

1. Introduction

From 1997 to 2017 Carbon Capture and Storage (CCS) initiatives facilitated the storage of a cumulative total of 30.4 milion tonst of CO_2 (Global CCS Institute, 2019; National Academies of Sciences Engineering Medicine, 2019; Kelemen et al., 2019). Given these achievements and the future projections, CCS is poised to play a crucial role in meeting the global Carbon Dioxide Removal (CDR) () of about 10 gigatons per year by 2050(United Nations Environment Program (UNEP), 2017; National Academies of Sciences Engineering Medicine (2019); Kelemen et al., 2019). CCS is particularly important for hard-to-abate industries, aiding in emissions reductions and contributing to European Green Deal’s objectives: reducing net greenhouse gas emissions by at least 55% by 2030 and achieving climate neutrality by 2050.

Currently, most captured CO_2 is injected into depleted hydrocarbon reservoirs, occasionally for CO2-enhanced oil recovery (CO2-EOR) (Global CCS Institute, 2019). However, these reservoirs offer limited capacity compared to saline aquifers, which have the highest geologic storage capacity due to their extensive nature (Hughes, 2009).

Sleipner (offshore Norway) was the world’s first commercial CO_2 storage project in saline aquifers. It involves injecting CO_2 into the Utsira Formation, a vast shallow marine sandstone of Miocene age, with a CO_2 storage capacity ranging from 1 to 60 gigatons at the basin scale (Ringrose et al., 2021).

The Sicily Channel is known for its many geological traps, but most are in a carbonate context (e.g., carbonate builds-up, Frixa et al., 2000), which may offer limited capacity for CCS or CO_2-EOR projects (Civile et al., 2013).

* Corresponding author.
E-mail address: mariagiada.maiorana@unipa.it (M. Maiorana).

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Since the most suitable aquifers are typically found in sedimentary basins (Hughes, 2009), this study focuses on a portion of the largest sedimentary basin in the Sicily Channel, the Gela Foredeep, to assess its potential as a CO_2 storage. The strategic advantage of targeting aquifers for CO_2 injection is their capacity to accommodate larger volumes compared to depleted oil and gas fields (Hughes, 2009). Moreover, given the extent of the Gela Foredeep, it is possible that suitable reservoir identified in this study might also be present in other areas of the foredeep, warranting future exploration.

Since the Gela Foredeep is covered by a 1500 km^2 gravitational slide following the tip of the Gela Thrust System (Trincardi and Argnani, 1990), we examined this feature in order to detect a potential sealing layer. Gravitational complexes can form kilometre-scale deposits resulting from gravity-induced deformation of strata on continental slopes (Mangano et al., 2023). These features typically develop over a long-lasting overpressured basal detachment, often shaly, which acts as a rheologically weak zone (Morley et al., 2011) and thus, potentially serve as a seal (Sun et al., 2021). Given that ongoing fluid can weaken the basal detachment and reduce its friction, fluid seepage and slope instability often occur together. This association has been observed in the central Mediterranean (Crotone Basin) where, slope instability since the Pliocene has coincidedwith the development of gas-bearing traps (Zecchin et al., 2018; Mangano et al., 2023a, 2023b).

The criteria for selecting suitable CO_2 storage sites vary based on the type of storage (EOR, depleted fields or Saline aquifer storage). Most European projects follow the guidelines established by the GeocapacityProject (http://www.cgseurope.net/Sections.aspx?section=491.492.494), which identify key characteristics for reservoirs and seals. An ideal reservoir should exhibit high permeability, porosity and be mainly composed of sandstone. It should be located at a depth between 800 and 2500 m b.s.l. The ideal seal should have low permeability and porosity, preferably composed of mudstone, with a thickness exceeding 50 m. In CCS projects, both primary and secondary seals are critical for preventing CO_2 leakage from underground storage. The so-called "primary seal" is the main geological barrier directly above the CO_2 storage reservoir, preventing the upward migration of injected CO_2. The "secondary seal" is an additional layer of impermeable rock located above the primary seal (not necessary directly), providing extra protection against CO_2 leakage and acting as a backup if the primary seal fails or is compromised. Identifying multiple seals (e.g., primary, secondary, etc.) is essential for maximizing storage efficiency and minimizing risk, especially in large-scale storage operations (Chadwick et al., 2008).

This paper addresses (i) the identification of new storage sites, comparing them to previous regional assessments (Donda et al., 2011; Civile et al., 2013)and (ii) an analysis of interactions between Gravitational Slide and Gela Thrust System to investigate the potential formation of secondary sealing layers.

2. Geological setting

The structural configuration of Sicily Channel (Fig. 1) has been significantly influenced by the Neogene active convergence between European and African plates (Carminati et al., 2012). The Sicily Channel is part of the northern African continental platform and is crossed by three NW-trending, relatively deep troughs: Pantelleria, Malta and Linosa grabens (Civile et al., 2021) (Fig. 1). A passive rifting process is widely accepted to explain these extensional structures accompanied by a local crustal thinning of the Sicily Channel (Finetti, 1984; Civile et al., 2010, 2021; Maiorana et al., 2023). The rifting process, which began in the Early Pliocene, led to the opening of the Pantelleria, Malta and Linosa Grabens and was accompanied by extensive volcaninc activity. This volcanism produced both subaerial and submarine volcanic features, often linked to fluid flow processes (Spatola et al., 2023; Maiorana et al., 2024). The active convergence between European and African plates also resulted in the development of three key regional-scale elements (Roure et al., 1990; Lentini et al., 1996; Catalano et al., 2013; Butler et al., 2019).

a) The Iblean-Pelagian foreland, part of the African plate, which is exposed in the southeastern corner of Sicily (Iblean Plateau) and is

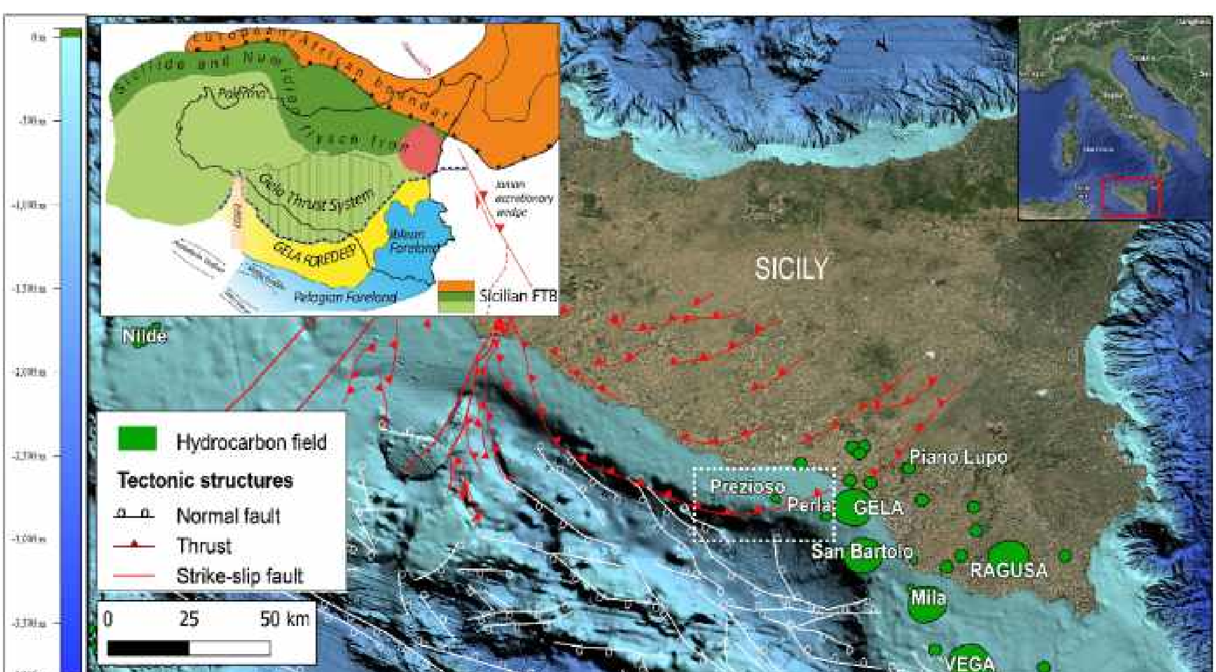

Fig. 1. Map showing the Sicilian onshore and offshore tectonic lineaments (courtesy of Neftex® Halliburton) with in indication of the study area (white dotted square); on the top right the geographic location of the Sicilian area is shown; on the top left the tectonic domains are shown (mod. after Catalano et al., 2013; Civile et al., 2018). Bathymetric base map from GEBCO (https://www.gebco.net/data_and_products/gridded_bathymetry_data/).

submerged in the Pelagian Sea with its African basement (i.e. the Pelagian–Iblean foreland) (Catalano et al., 2013).

b) The south to southeast-vergent Sicilian Fold and Thrust Belt (SFTB), which includes: i) a "European" element (Kabilian-Calabrian tectonic units), exposed in north-eastern Sicily and continuing in the southern Tyrrhenian; ii) a "Tethyan" element (Sicilide units); iii) an "African" element, composed of carbonate thrust systems (Sicilian-Maghrebian units), with a frontal thrust wedge called Gela Thrust System (GTS) (Fig. 1) composed of Cenozoic terrigenous, evaporitic and clastic-carbonate deformed rocks (Argnani, 1990; Butler et al., 1992; Catalano et al., 2013; Lickorish et al., 1999; Sulli et al., 2021). In the Early Pleistocene, the last stage of advancement of the GTS is recorded at 0.8 Ma (late Calabrian) (Di Stefano et al., 1993; Cavallaro et al., 2017; Maiorana et al., 2023)

c) The Late Pliocene-Quaternary Gela Foredeep (GF), a narrow and elongated foredeep basin located along the frontal sector of the Sicilian thrust belt in southern Sicily and its offshore region (Sulli et al., 2021) (Fig. 1). This depocenter represents a significant Plio-Quaternary foredeep basin. Since the Early Pliocene a basin wide event, linked to a regional uplift, affected this area, later inducing a gravitational collapse involving the Gela Basin deposits (Trincardi and Argnani, 1990). The head of the produced slide (involving more than 700 m of the GF deposits) follows the tip of the GTS.

3. Stratigraphic setting

The Gela Foredeep (GF) is characterized by a substantial sedimentary sequence composed of Pleistocene turbidite sandstones and mudstones, which contains several multiple depositional sequences (Di Stefano et al., 1993; Catalano et al., 1996; Patacca and Scandone, 2004). In the shelf zone, Pleistocene deposits show well-developed prograding complexes that correlate with the turbidites found in the basin (Di Stefano et al., 1993).

Ghielmi et al. (2012) proposed a lithostratigraphic scheme for the GF, which includes the following informal units (Fig. 2).

- Trubi Formation (Lower Pliocene): This formation consists of upper Zanclean-basal Piacenzian marly limestone. Thin layers (10–20 m) of transgressive grey-whitish fossiliferous marls of Trubi Fm. were deposited only in a relatively limited onshore area.
- Ponte Dirillo Formation (middle Pliocene-to-Holocene): This formation consists of grey and grey-green clays deposited by fall-out with draping geometry on the foreland ramp and foreland of the Gela Basin. The thickness, laterally very variable, usually ranges from 20 to 50 m.
- Argille Basali Formation (Lower Pleistocene): This formation consists of foredeep turbidite sediments, including grey and grey-green clay and silty clay. The maximum thickness reaches approximately 110 m.
- Sabbie di Irene Formation (Lower Pleistocene): Composed of foredeep turbidite sands and clays, the Sabbie di Irene Fm. is characterized by a highly efficient Type I turbidite system (sensu Mutti et al., 1999), featuring a notable basin-scale tabular geometry.
- Argo Formation (Middle-Upper Pleistocene to Holocene): This formation consists of foredeep turbidite sands and clays, with a maximum thickness of around 1300 m. It is frequently intercalated with mass-transport deposits, particularly along the inner foredeep margin. Their size and frequency increase in the middle-upper part of the Argo Formation. Most of the chaotic deposits are represented by slumps produced by submarine failure of slope sediments of the Pleistocene progradation originally deposited on the Gela Nappe. These deposits, developed along the northern margin of the Sicily Channel, were produced by submarine failure of slope and shelf

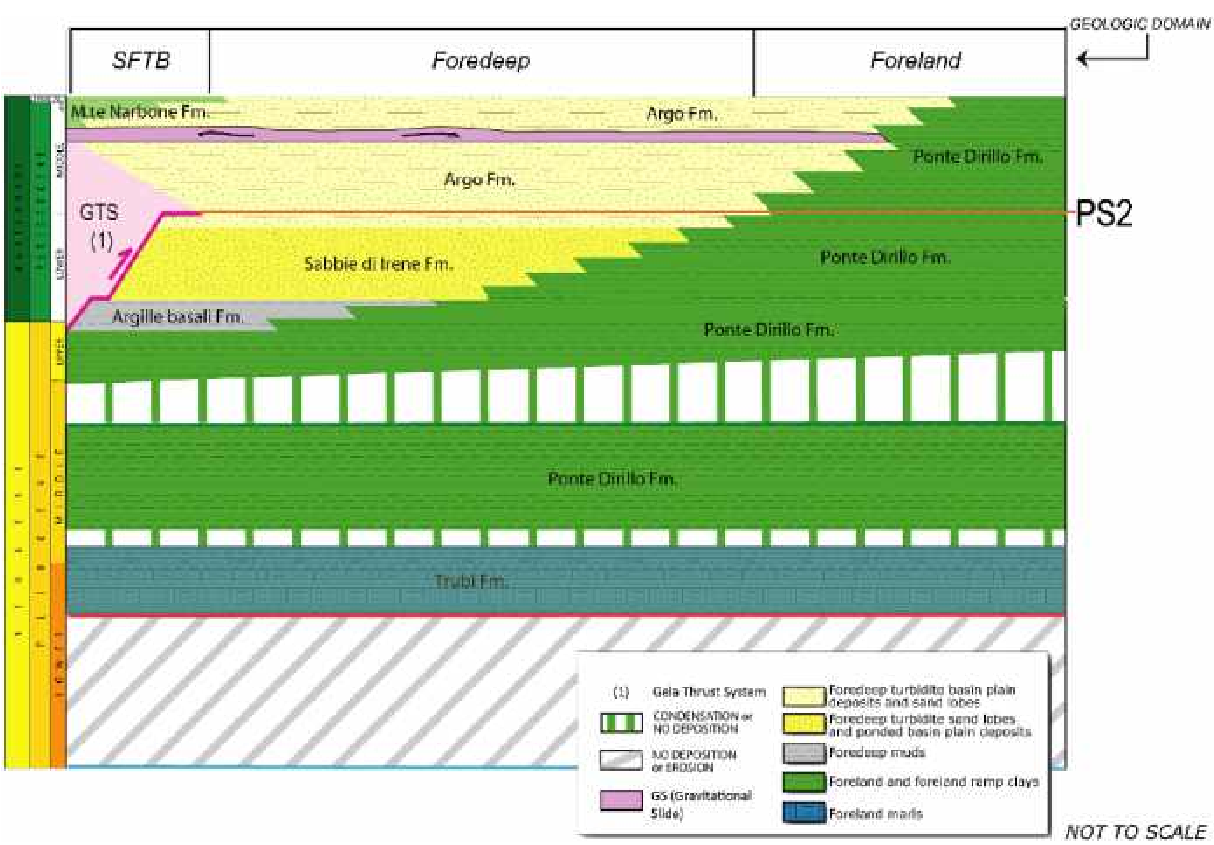

Fig. 2. Stratigraphic scheme of the Plio-Pleistocene Gela Basin succession (mod. after Ghielmi et al., 2012) along the SFTB (Sicilian Fold and Thrust Belt), foredeep and foreland domains. PS2: Pleistocene Sequence 2, a pelitic level from Ghielmi et al. (2012).

deposits of the Pleistocene Prograding Complex, consisting of slope, shelf, and coastal deposits.

In their study, Ghielmi et al. (2012) also identified an interval termed ‘‘PS2″, which corresponds to a clayey layer found in the study area and located at the top of the Sabbie di Irene Fm. The acronym "PS" stands for ‘‘Pleistocene Sequence’’. Ghielmi et al. (2012) distinguished PS1 (older) and PS2 (younger) in the Plio-Pleistocene foredeep succession, noting that these are bounded by tectonic or eustatic-controlled boundaries, generally corresponding to abrupt changes in depositional systems type and distribution. In the foredeep (Gela Basin), PS2 corresponds to turbiditic deposits (pelites) of the Argo Fm., while in the ramp, it aligns to pelites of the Ponte Dirillo Fm. The upper boundary of PS2 is associated with the advancement of the GTS toward the foreland, which led to the deformation of the underlying turbiditic succession.

4. Materials and methods

For this analysis, we utilized a dense grid of 2D seismic reflection profiles along with data from 8 exploration wells (Fig. 3), sourced from the ENI database. Exploration boreholes (Figs. 3 and 4) were employed to calibrate the seismic profiles. The interpretation of key horizons was conducted using the seismo-stratigraphic methods outlined by Vail et al. (1977).

The Landmark DecisionSpace Geosciences package was used to perform the seismic interpretation of key horizons and main faults, well-to-seismic tie, velocity model, depth conversion, to create depth and isopaque maps (in-depth domain) and to generate a 3D view in-depth domain. The well-to seismic tie was necessary to calibrate the well log data response to two-way time seismic generating new time-depth curves in the process and also a single synthetic seismic trace along the well bulk shifting and/or stretching and squeezing the well data. This way the horizons interpreted on the seismic in TWT (Two Way Time) should match the surface picks in TVD (True Vertical Depth). The well to seismic tie was done for 8 wells, on an individual basis, covering the whole study area.

4.1. Well-to seismic tie and velocity model

The velocity model is a crucial step to convert seismic two-way time into depth domain, enabling the calibration of seismic response with well data. This was achieved by integrating well check-shots and logs (sonic and density) and performing well-to seismic tie generating new time-depth curves in the process and a single synthetic seismic trace at each well location.

For each well, the sonic and density logs were multiplied and then convolved with a seismic wavelet (close to a 20 Hz zero phase Ricker, representative of the seismic frequencies) to provide a preliminary synthetic log in the time domain, using the original check-shot curve for the depth to time conversion of well data. The sonic log was also used to integrate the check-shot velocities. All the above steps were performed by the DecisionSpace® Geosciences software.

Subsequently, the synthetic log was shifted and/or stretched to match the seismic responses; this was mainly done manually moving the data points (check-shot stations) interactively. This means modifying the time-depth relationship (i.e. velocity) along the well so a new check-shot was created for each well (example in Fig. 5). Available logs data do not cover the upper part of the well-data.

The well-tie process was guided by geophysical principles to avoid unreasonable interval velocities and ensure that seismic horizons in time matched three key surface picks in the depth domain.

The new time-depth curves from the well-to seismic tie process served as the first type of information for the construction of a preliminary velocity mode, which represents both vertical and lateral variation of velocities. Velocity changes reflect variation in lithology and/or fluid contents, compaction and might also identify, with the correct resolutions, significant faults and fractures.

To take advantage of new calibrated time-depth curve relatively fine resolution, a vertical sampling of 5 m has been chosen with 100 m in X and Y. To ensure uniform velocity distribution along wells located 5 and 50 km apart, 3 significant time surfaces have been selected.

Kriging was used as proved to provide smoother interpolation of velocity values laterally accounting for the different distance of well locations.

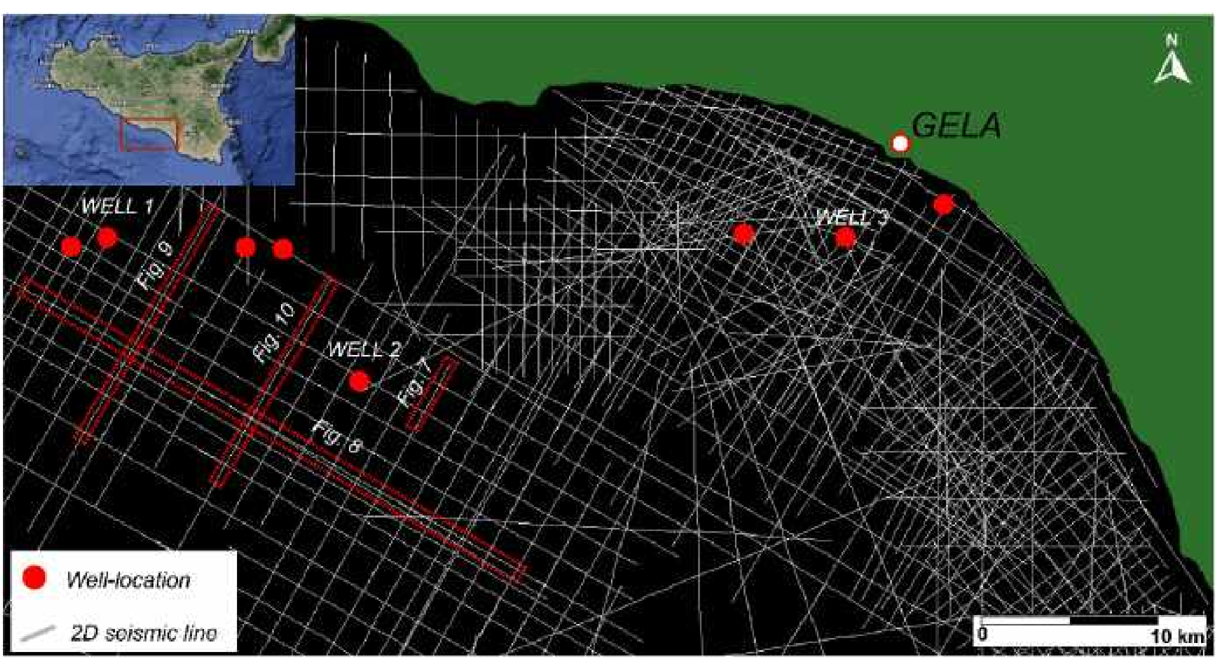

Fig. 3. Dataset location with 2D seismic reflection profiles and wells.

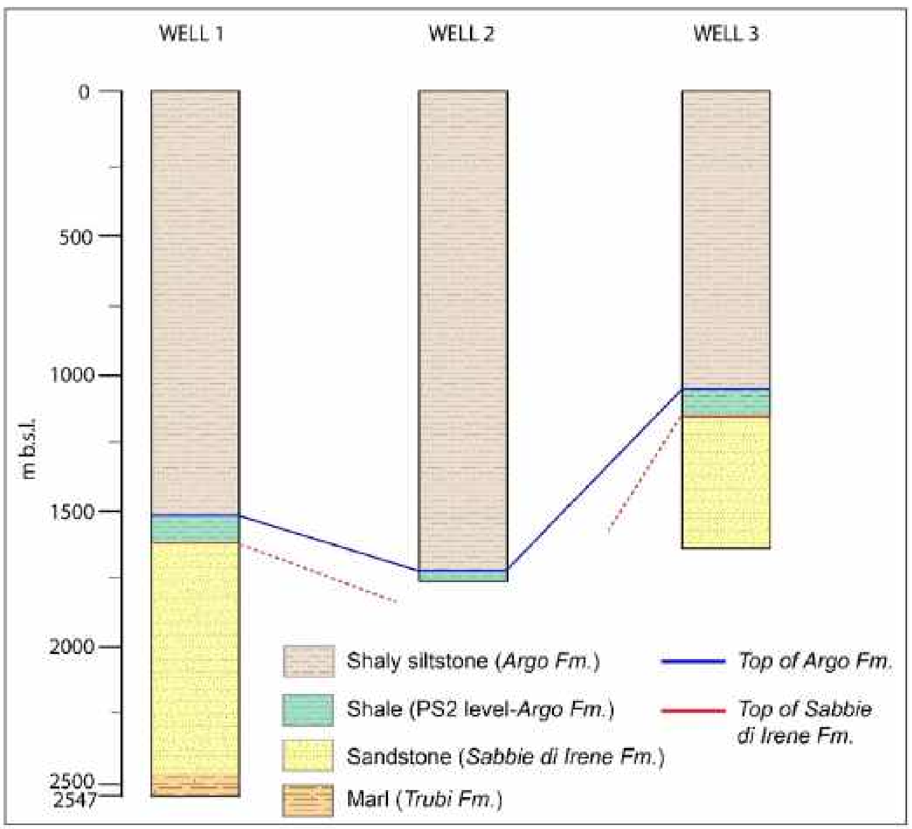

Fig. 4. Simplified stratigraphic columns of the main exploration boreholes used in this study and their stratigraphic correlation (location of boreholes in Fig. 3).

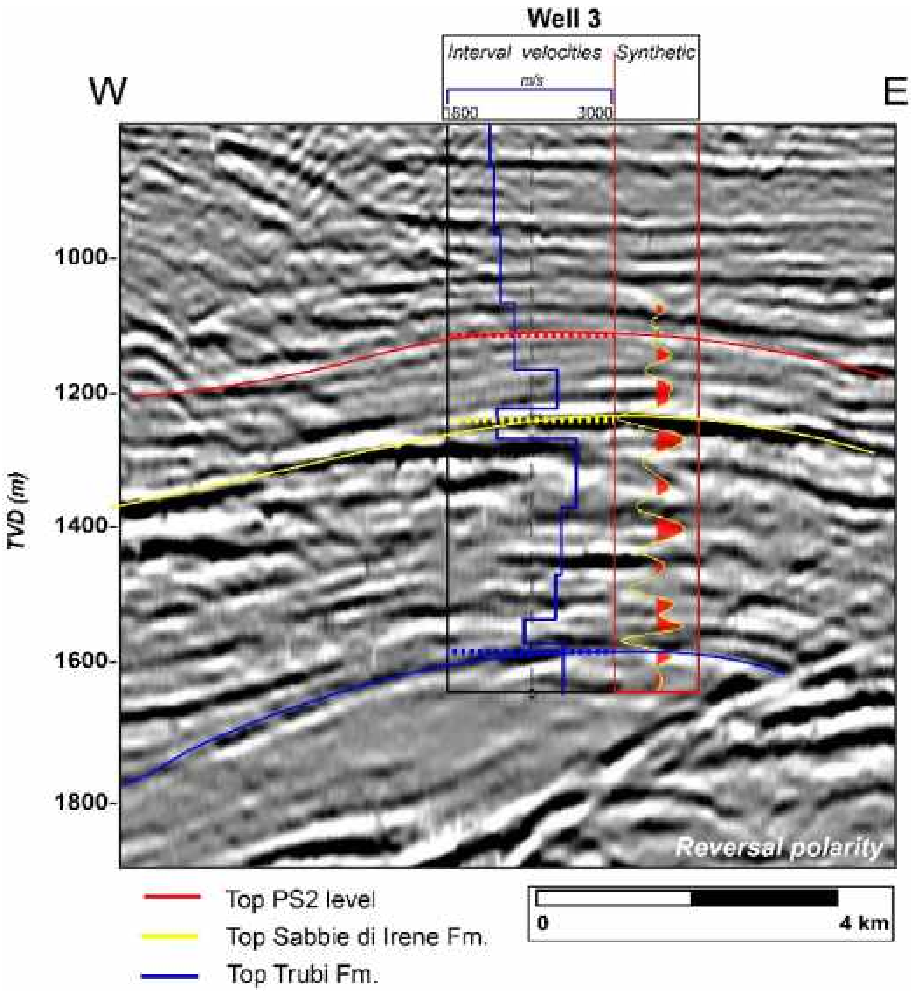

Fig. 5. Example of the computed single synthetic trace and the resulting time-depth curve for Well 3 (see location in Fig. 3). Well surface picks are indicated with dotted line matching the horizons colours (continuous line).

The resulting velocity model (Fig. 6) was used for time-to-depth conversion of the main horizons. These were ultimately gridded with a 250 × 250 m resolution introducing conformance rules so that there would be no overlap between the horizons and flexed to match the well surface picks, marking the top of the main units (residual fit operation).

Additionally, the thickness of reservoir and seal layers were calculated. Using that data, the software DecisionSpace® Geosciences automatically generated the Gross Rock Volume for each layer.

5. Results

5.1. Seismic stratigraphy (time domain)

The interpretation of the TWT seismic reflection profiles was based on the identification of key surfaces limiting the seismic units, identified as follows, bottom to top (Fig. 7):

Unit 1: is represented by a low reflectivity interface showing a high lateral continuity. This unit shows some interruption attributed to normal faults and a thickness increasing towards south. It is limited at the top by a low amplitude reflector and at the bottom by a high amplitude reflector with low lateral continuity (Fig. 7) interpreted as the "Messinian Unconformity"; Unit 2: the reflectors within this unit exhibit good lateral continuity, high frequency, and tabular geometry. The unit shows a decrease in thickness toward the south, where the reflectors onlap with onlap geometries on the Unit 1 (Fig. 7). Toward the north, instead, the reflectors cut-off on the GTS basal thrust; Unit 3: characterized by high amplitude reflectors with medium frequency, good lateral continuity and tabular external shape (Fig. 7). Onlap termination on the Unit 1 are observed to the south and on the GTS to the north (Fig. 7); Unit 4: it exhibits reflectors with amplitudes varying from low to high, all characterized by high lateral continuity and tabular external shape (Fig. 7). Locally onlap terminations are observed on Unit 1; Unit 5: this unit shows a tabular external shape and high frequency reflectors, locally with an intercalation of chaotic levels with low amplitude reflectors marked at the base by a high amplitude reflector. Reflectors show gradual decrease in amplitude upwards (Fig. 7). The top of the unit is a high amplitude reflector corresponding to the seafloor (Fig. 7).

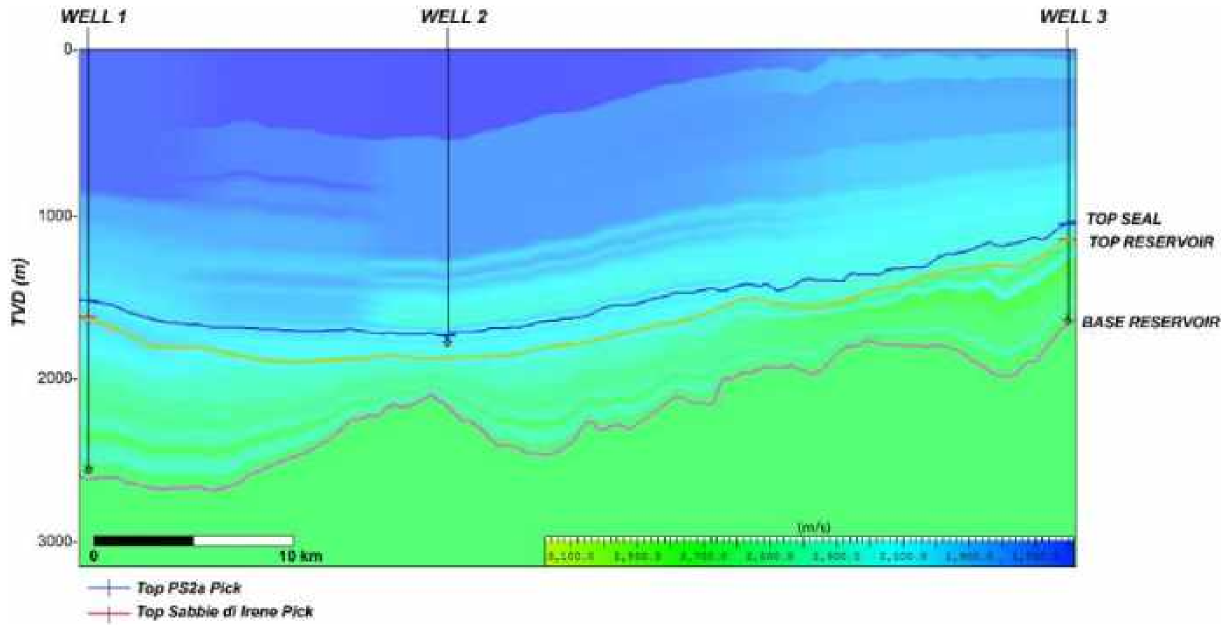

Fig. 6. Velocity model represented along well cross-section between wells 1, 2, 3 (see Fig. 3 for location). See the velocity distribution following the significant interpreted reflectors and the matches with the surface picks.

5.2. Lithological significance of interpreted seismic units

After the well-to-seismic tie process, formation tops indicated in the well-logs data were associated to the corresponding horizons. The correlation between seismic units and formations (for which the top is indicated by well surface picks) is described in Table 1.

The well surface pick marking the top of the Trubi Fm (Figs. 4 and 5). corresponds to the top of the Unit 1 (Fig. 7). The unit consists of marls and turbidite clays of the Early Pliocene (Zanclean) and covers, with variable thickness and lateral pinch-out terminations, the Messinian Unconformity (Todaro et al., 2021; Lofi et al., 2011). The deposition of pelagic marls of Trubi Fm. indicates an aggrading sedimentation controlled by a relative sea level rise; the net reduction of acoustic impedance contrast generates semi-transparent seismic facies that makes this deposit well recognizable, as observed by Civile et al. (2018). The synthetic of the Well 1 in Fig. 5 shows peaks reducing their amplitude at the top of Trubi Fm.; this amplitude reducing is similar to the one observed in the southern Pyrenees turbidite system at the transition between mud-dominated to sandstone-dominated unit (Falivene et al., 2010). The well surface pick marking the top of the Sabbie di Irene Fm (Figs. 4 and 5). corresponds to the top of the Unit 2 (Fig. 7). The unit consists of Lower Pleistocene thick-bedded coarse-to fine-grained sands of proximal and distal sand lobes facies association. Well bottom cores analyzed in Ghielmi et al. (2012) show a number of turbidite typical sedimentological features, such as: (1) unusual thick clay layers associated to the thicker sand layers; (2) uncommon thick laminated sand intervals; (3) presence in the same sand layer of current ripples with opposite directions. Sabbie di Irene Fm. turbidites have been attributed to a highly efficient Type I turbidite system (sensu Mutti et al., 1999) characterized by remarkable basin-scale tabular geometry. The strong reflections imaged in the synthetic of the Well 1 in in Fig. 5, could be related to the turbidite typical sedimentological features mentioned above, which reflects in acoustic impedance variations as also shown by Falivene et al. (2010). Well surface pick at the top of the PS2 level (Figs. 4 and 5), located at the base of the Argo Fm., corresponds to the top of the Unit 3 (Fig. 7). The PS2 mainly consists of fine-grained basin-plain turbidite deposits of the Early Pleistocene (about 0.9 Ma). With a remarkable basin-scale tabular geometry, the PS2 turbidites have also been attributed to Type I highly efficient turbidite systems sensu Mutti et al. (1999). The largest acoustic impedance in the synthetic of the Well 1 in Fig. 5 is located between sandstones and mudstones, so at the base of the PS2 level; the top of PS2 is instead marked by a weak transition to a lower amplitude peak. Above the PS2 level, the Argo Fm., composed of foredeep turbidite sands and clays of Middle-Late Pleistocene (Ghielmi et al., 2009), has been attributed to Unit 4 (Fig. 7) given the alternation of levels with different reflection coefficients which generate variable amplitudes reflectors.

The variable amplitude reflectors with chaotic configuration highlighted in the Unit 5 is typically indicative of presence of a disturbed material (Lee et al., 2004). This level, located in the middle-upper part of the Argo Fm., has been so attributed to a Gravitational Slide (GS) as reported by Trincardi and Argnani (1990) and Ghielmi et al. (2012), since its typical chaotic feature due to sediment mixing and deformation (Fig. 7). Trincardi and Argnani (1990) and Ghielmi et al. (2012) correlate these signals to slumps produced by submarine failure of slope sediments of the Pleistocene prograding deposits originally covering the GTS. However, the available data did not cover the top of Argo Fm. and it is therefore not possible to describe the trend of the synthetic signal.

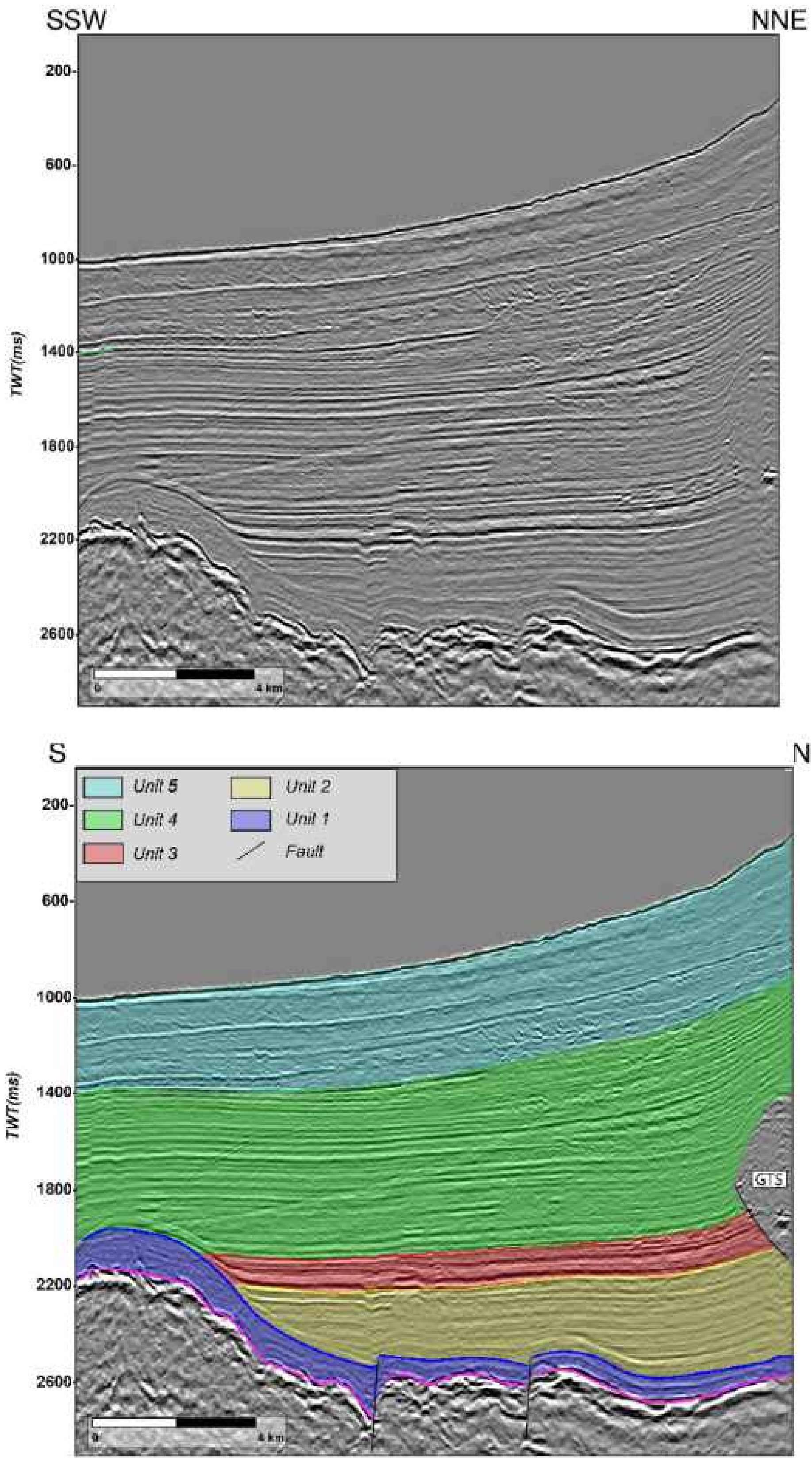

Fig. 7. (a) Uninterpreted (above) and (b) interpreted (below) seismic reflection profile showing the main seismic units from 1 to 5 for of the study area. GTS: Gela Thrust System. See location in Fig. 3.

Table 1
Interpretation of the main seismic units on the basis of well analysis. The age refers to the surface that marks the base of the unit.

Seismic Unit	Formation	Facies	Age (Ma)
Unit 5	Argo Fm.	Foredeep turbidite sands and clays with GS intercalation	0.6
Unit 4	Argo Fm.	Foredeep turbidite sands and clays	0.3
Unit 3	PS2a- Lower Argo Fm.	Turbidites pelites	0.8
Unit 2	Sabbie di Irene Fm.	Turbidite sands and clays (Type I) Average porosity 33.9 %	0.98
Unit 1	Argille Basali Fm.	Turbidite clays	1.79
	Trubi Fm.	Marls and turbidite clays	5.33

5.3. Seismic interpretation of Gela offshore (depth domain)

The interpreted 2D seismic reflection profiles (Figs. 8 and 9) are distinguished by a wide depocenter (16 km long, filled by at least 2 km of deposits) limited at its northern part by a tectonic wedge well defined by the presence of a basal thrust that tips out towards SSW (Maiorana et al., 2023) and in its southern part by a regional monocline (Figs. 8 and 9). The basin filling host at its base a high-amplitude reflection associated with the M-reflector, which corresponds to a widespread irregular erosional surface (Figs. 8 and 9). This surface cuts through the underlying units and is interpreted as the top of the Messinian evaporitic sequence. Over the M reflector, the Trubi Fm. is observed, highlighted by its typical semi-transparent acoustic facies associated to the marly deposits; its deposition records the onset of the deep basinal conditions following Catalano et al. (1996), Lofi et al. (2011) and Ghielmi et al. (2012). The Trubi Fm. is covered by a ~700 m thick level of variable amplitude reflectors, related to the Sabbie di Irene Fm. deposits consisting of a Lower Pleistocene sandy turbidites with basin-scale tabular geometry (Figs. 8 and 9). Laterally, onlap terminations of the deposits are observed to the north towards the GTS and to the south towards the regional monocline covered by the Trubi Fm. A ~200 m thick level of turbidite pelites interpreted as PS2 level overlies the Sabbie di Irene Fm. with a tabular geometry (Figs. 8 and 9). It is marked at the top by a high amplitude reflector and show internally, onlap termination on the GTS to the north and to the regional monocline to the south. The PS2 level is covered by a ~600 m thick unit attributed to the foredeep turbidite sand and clays of the Argo Fm., showing variable amplitude reflectors (due to its variable lithofacies) with a tabular geometry (Figs. 8 and 9). Figs. 8 and 9 highlight the presence of a chaotic signal in the lower part of this unit. A high amplitude reflector is found at the top of this, marking a shear surface indicating the passage to the GS unit. Fig. 9 shows the chaotic signal of this unit, ~800 m thick, while Fig. 9 shows the same unit with semi-transparent facies, a difference attributed to the high lithological variability of the sediments involved in deformation.

5.4. Gela Gravitational Slide (Gela GS)

Unit 5, comprising the Argo Fm. deposits, host a wide body, at least 800 m thick, delimited at the base by a high amplitude reflector. This body has been firstly identified in 2D seismic reflection profiles by Trincardi and Argnani (1990), who called it ‘‘Gela Gravitational Slide-Gela GS’’. The analysis of a 3D seismic reflection profile derived from Ghielmi et al. (2012) (Fig. 10) allowed us to obtain a better characterization on the Gela GS geometry and configuration.

Following Lewis (1971) the conceptual model for units resulting from slope failure, a systematic distribution of strain is exhibited in Gela GS with extensional structures in the upslope region, and compressional structures in the downslope region. The Gela GS exhibits a typical

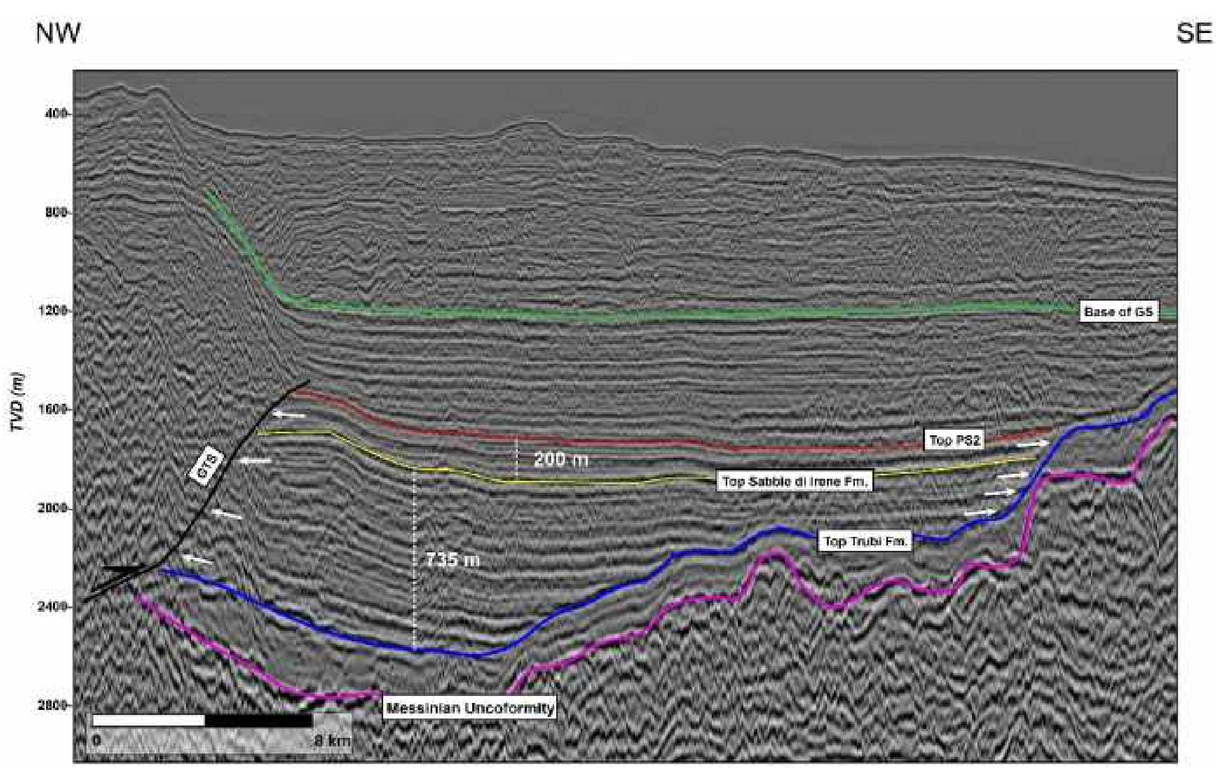

Fig. 8. Interpretation of the seismic reflection profile A converted in depth domain (see Fig. 3 for location). White arrows indicate the main onlap terminations.

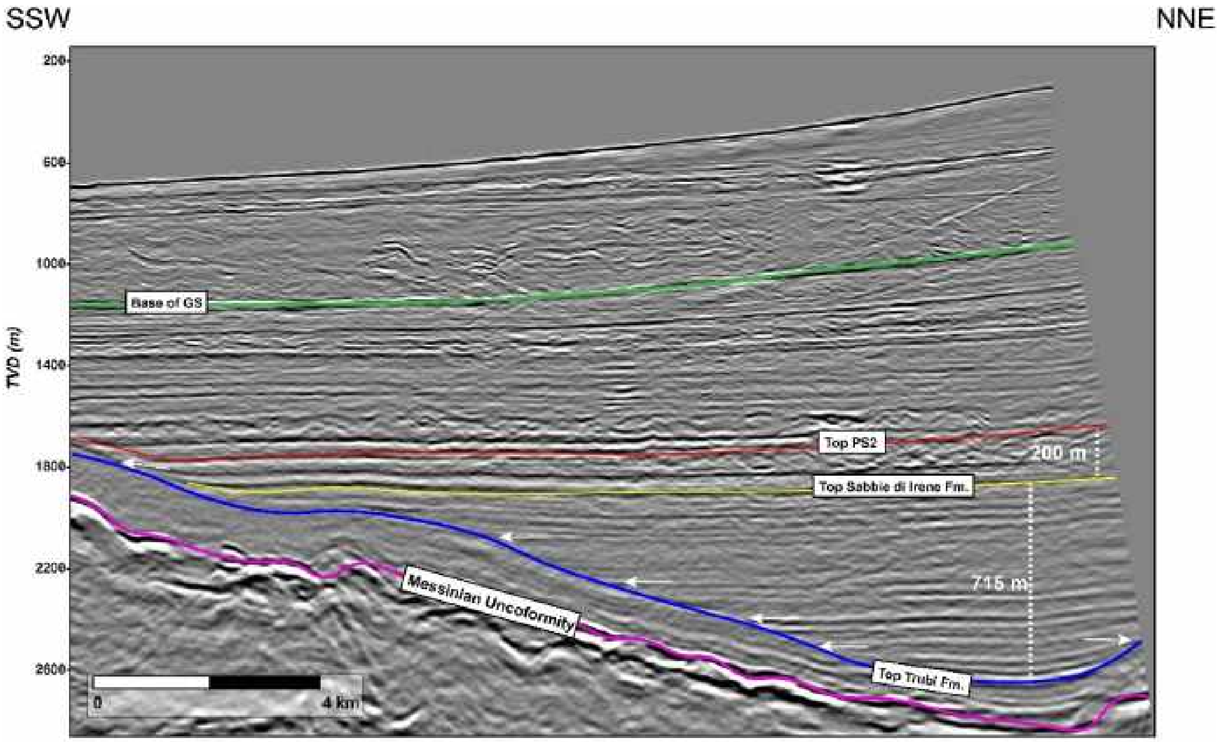

Fig. 9. Interpretation of the seismic reflection profile B in depth domain (see Fig. 3 for location). White arrows indicate the main onlap terminations.

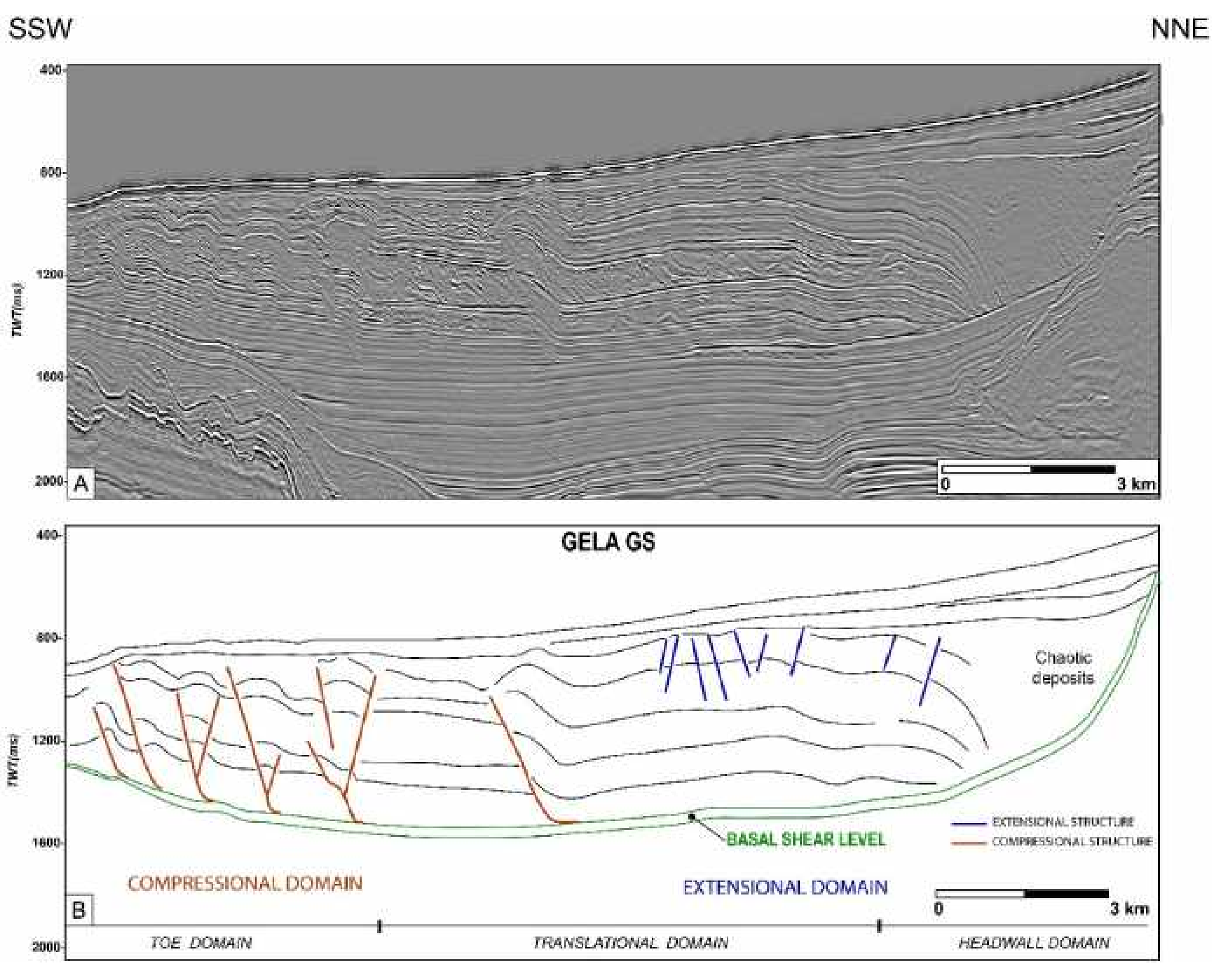

Fig. 10. (A) 3D seismic reflection profile along the Gela GS (Gela Gravitational Slide) after Ghielmi et al. (2012); (B) line drawing showing the internal geometry (see Fig. 3 for location).

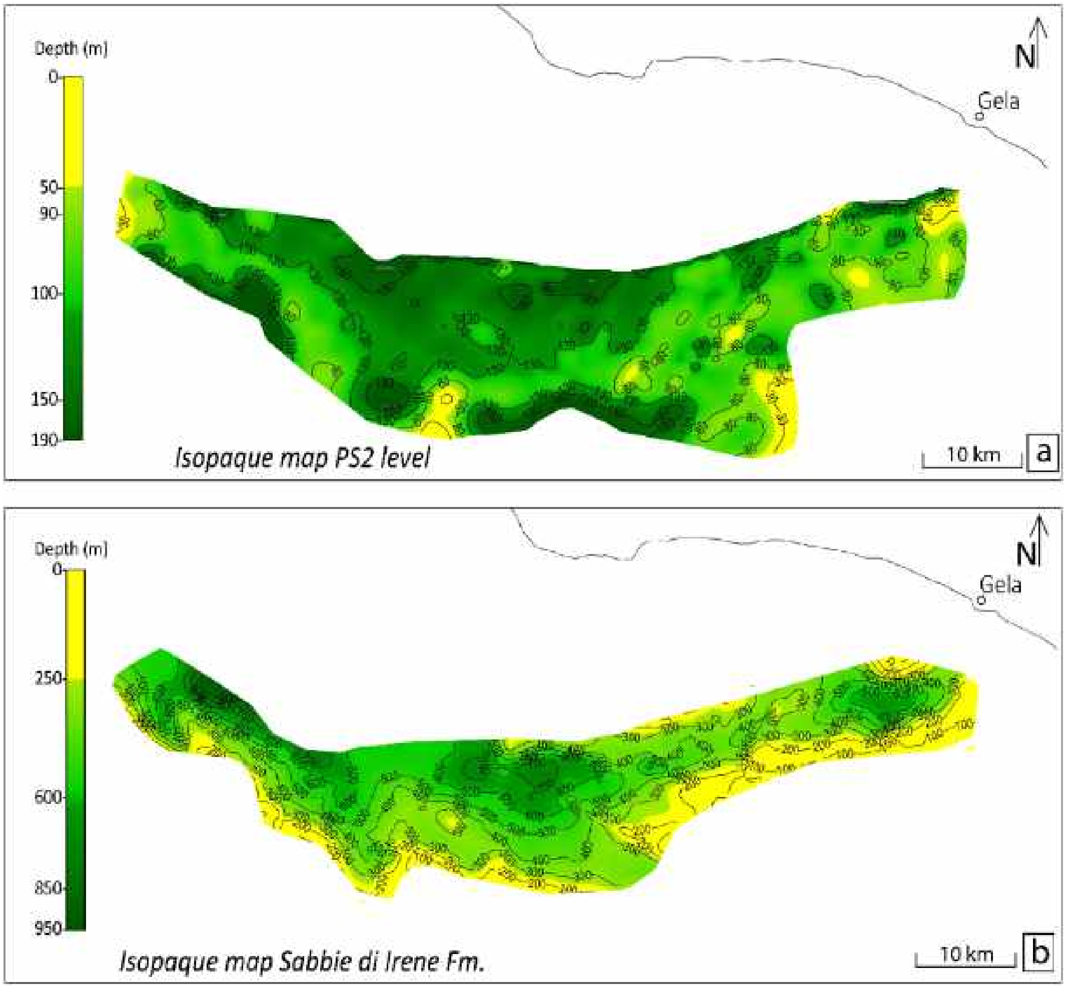

Fig. 11. Isopaque maps of (a) PS2 level and (b) Sabbie di Irene Formation.

'tripartite' anatomy (Martinsen, 1994; Lastras et al., 2002): the headwall domain, the translational domain and the toe domain (Trincardi and Argnani, 1990; Bull et al., 2009).

The Gela GS basal shear surface, highlighted by a high amplitude reflector, suggests an abrupt change in acoustic impedance (Fig. 10). This surface forms a laterally continuous, bed-parallel undeformed reflection occurring beneath the disrupted Gela GS.

The headwall domain exhibits a chaotic unit, which occupies the space left by the rollover within the slide head (Fig. 10). Over the choaotic unit, prograding reflectors including the post-LGM deposits are observed, as the ones described by Trincardi & Argnani (1990). A headwall scarp defines the boundary of the upslope margin of the Gela GS. The headwall scarp is steeply dipping, showing an inclination of ~35° and is about 700 m high (Fig. 8); the sense of slip is predominantly dip-slip, the material is transported directly downslope and away from the scarp itself (Fig. 10).

The translational domain comprises the main south-oriented translated body of the Gela GS. Is noted that the movement of the failed material downslope across the basal shear surface can lead to intense deformation (Martinsen,1994). In fact, internally within the body, a series of extensional and contractional structures interfere in the mid-slope area (Fig. 10), as typically observed in similar translational systems (Ge et al., 2019); an upslope migration of the extensional domain and downslope migration of the contractional deformed the domain interrupts the continuous seismic reflections and generates a series of convex upward, SW-oriented folds affected by brittle deformations (Fig. 10).

The toe domain represents the downslope region of the Gela GS. This sector is characterized by the development of large-scale ''thrust and fold system'' frontally confined. Thrusts affect the entire thickness of the Gela GS body in the vicinity of the ramp above the basal shear surface, into which they detach (Fig. 10). The thrust faults occur in pairs of opposite verging, dip up to 40° and define regularly spaced (average 1 km) pop-up structures with maximum displacements of up to 300 m (Fig. 10).

5.5. *Thickness and distribution of the Gela offshore units*

In order to estimate the Gross Rock Volumes in place, surfaces indicating the depth and thickness of the main levels were constructed as in Figs. 11–13.

The PS2 level (Fig. 11a) isopaque map shows a major thickness in the central sector of the study area, where it reaches an average thickness of 180 m; the lower values in thickness (~30 m) are reached in the north-eastern sector of the study area. No major faults were interpreted within these sequences. The isopaque map of the Sabbie di Irene Fm (Fig. 11b). indicates values from ~800 m decreasing to ~100 m towards south (foreland).

Unfortunately, it was not possible to generate an isopach map for the GS due to the limitations of the 2D data resolution, which does not permit the detailed identification of features comparable to those observed in the high-resolution 3D section provided by Ghielmi et al. (2012).

For the bottom of Gela GS, a depth map has been computed

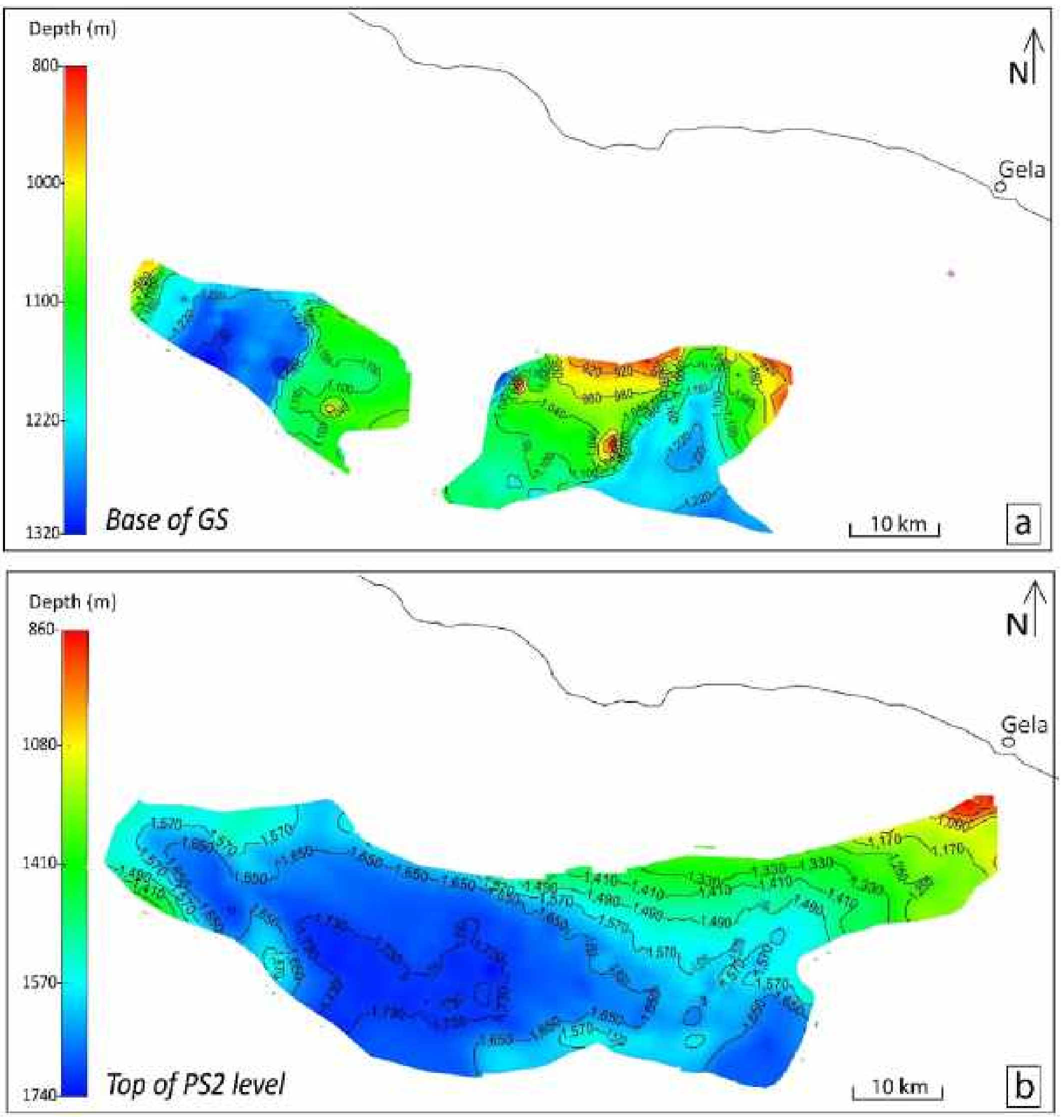

Fig. 12. Depth maps of (a) Base of Gela GS and (b) PS2 level.

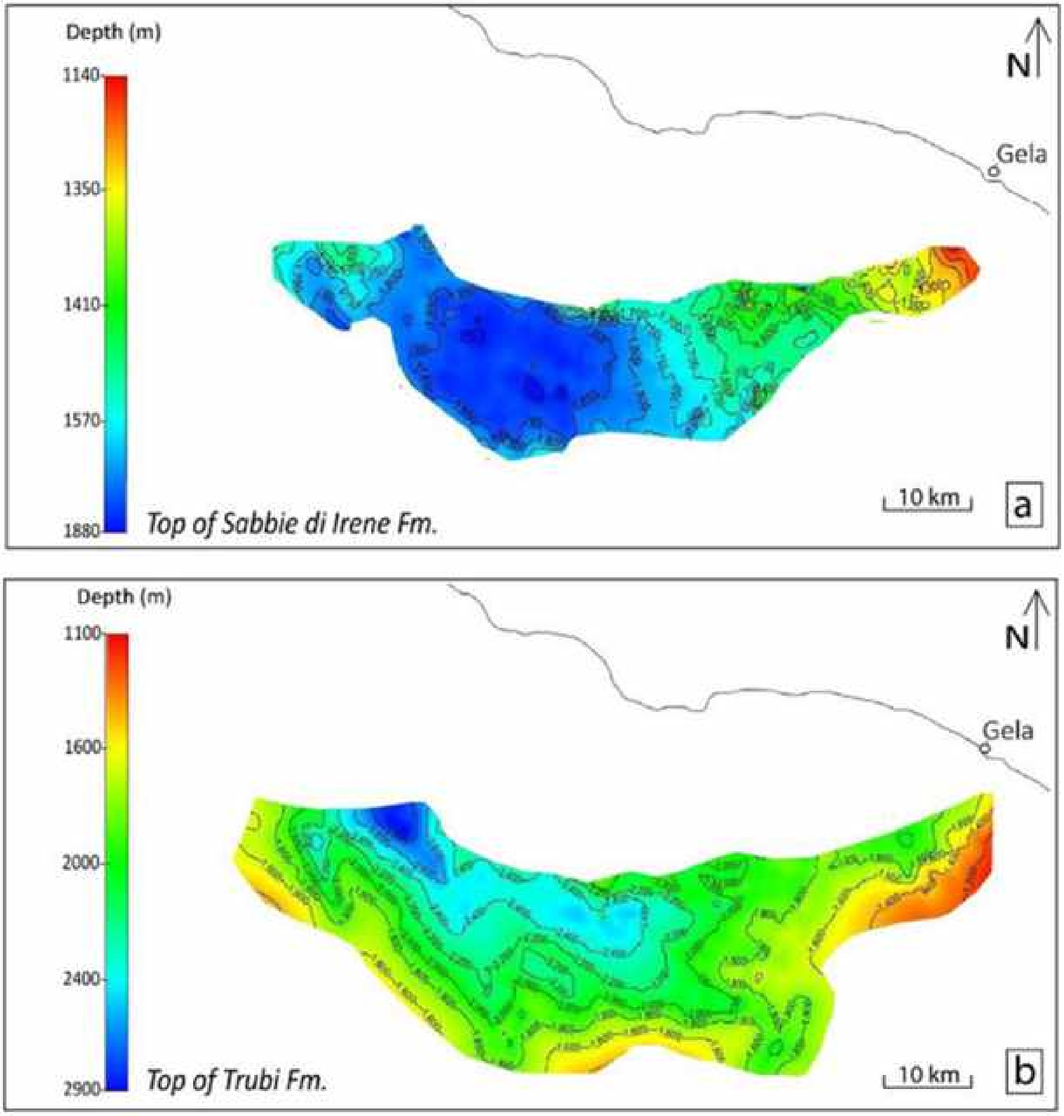

Fig. 13. Depth maps (a) of the top of the Sabbie di Irene Fm. and (b) of the top of Trubi Fm.

(Fig. 12a): the presence of a discontinuity in the surface distribution, localized in the central sector of the study area is highlighted. The depth ranges from 800 to 1320 m. Also, depth maps for the top of PS2 (Fig. 12b) and top Sabbie di Irene Fm (Fig. 13a). confirm that the major depth of the basin is reached in the central part of the study area. Instead, the Trubi Fm (Fig. 13b). shows a minor depth at the southern edges of the study area.

Based on these maps (Figs. 12 and 13), a 3D model of the Gela Foredeep units was reconstructed (Fig. 14). This enabled the estimation of the Gross Rock Volume for the Sabbie di Irene Formation, which extends over approximately 578.4 km^2, amounting to 3.2832E+11 m^3.

6. Discussion

6.1. Tectono-stratigraphic evolution of the Gela offshore

The seismo-stratigraphic interpretation has identified five key geological that shaped the Gela offshore area.

1) The Messinian Salinity Crisis (MSC): Occurring around 5.97 to 5.33 Ma, the MSC was a significant geological event marked by the near-complete desiccation of the Mediterranean Sea and the deposition of extensive evaporites (Selli, 1954; Hsü et al., 1978; Lofi et al., 2011; Haq et al., 2020; Zecchin et al., 2020, among the others). The

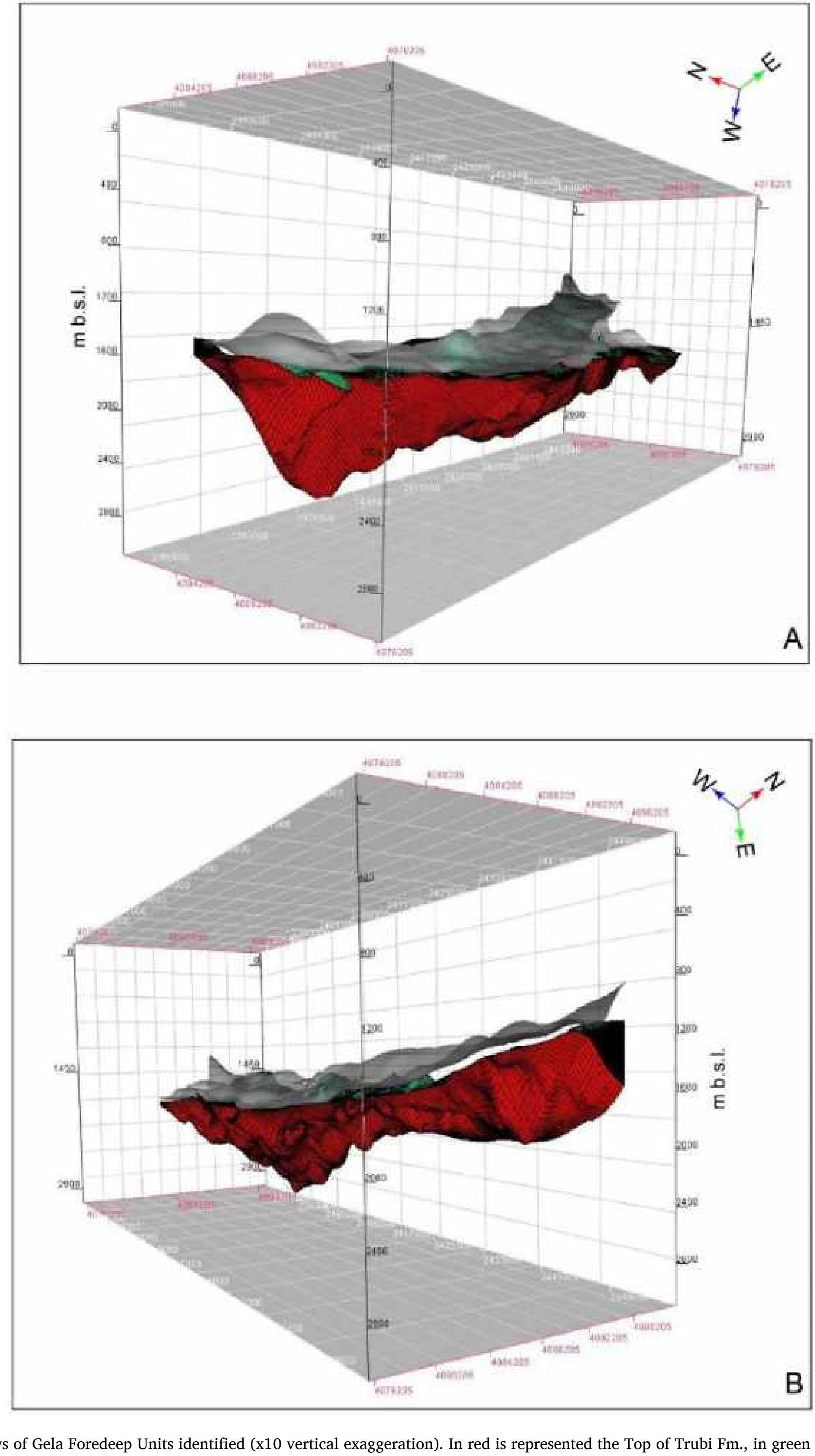

Fig. 14. A, B: 3D views of Gela Foredeep Units identified (x10 vertical exaggeration). In red is represented the Top of Trubi Fm., in green the top of the Sabbie di Irene Fm., and in grey the top of the PS2 level.

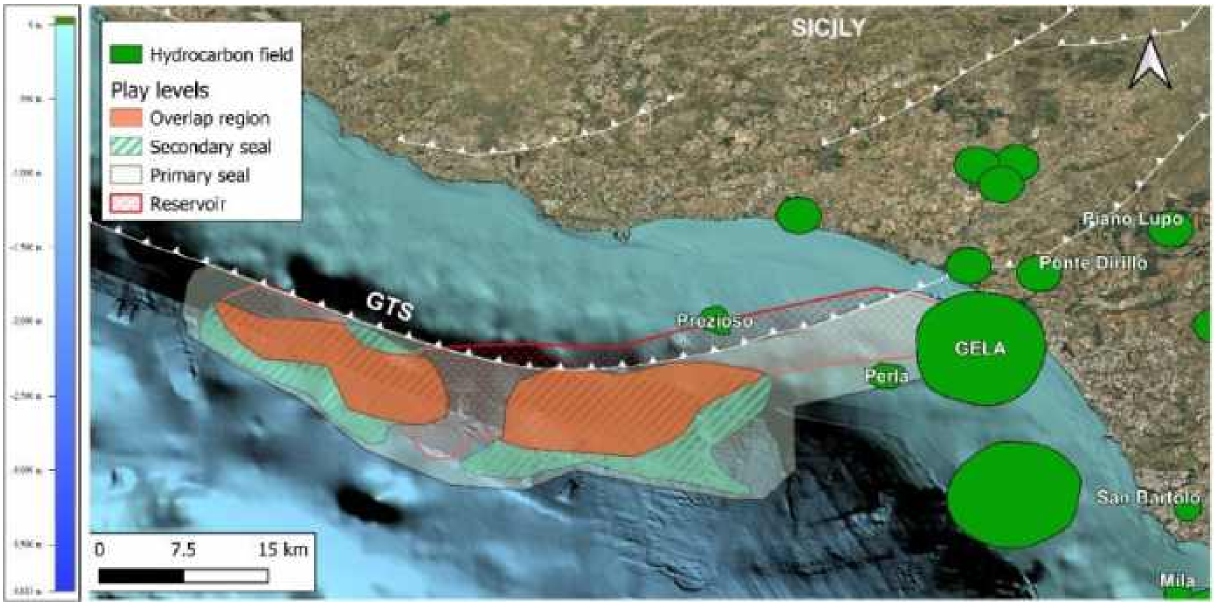

Fig. 15. overlap regions between reservoir and seals levels identifying the best play area for CCS. GTS: Gela Thrust System.

re-opening of the Strait of Gibraltar at the end of the crisis led to the dramatic reflooding of the Mediterranean, known as the Zanclean flood. The Messinian Unconformity, which cuts across various stratigraphic layers and is associated with the retrogressive erosion from the Mediterranean Sea's drawdown.

2) Drowning phase and setting up of the GTS: During the Zanclean (5.33 Ma), the return to open marine conditions and progressive subsidence led to the deposition of Trubi Fm. marly limestone (Gennari et al., 2008; Lentini and Carbone, 2014; Riforgiato et al., 2011), the fossil content of which suggests a general deepening over time (Di Grande and Giandinoto, 2002).
3) Deposition of Sand Turbidites and Continued Advancement of the GTS: In the Piacenzian (3.6 Ma), as the GTS advanced further, (Cavallaro et al., 20; Maiorana et al., 2023), the Lower Pleistocene turbidite sands and clays of the Sabbie di Irene Formation were deposited. The parimary entry point of these turbidite was located at the northeastern apex of the foredeep, near the town of Gela (Ghielmi et al., 2012). Their deposition was influenced by palaeocurrents oriented longitudinally to the basin axis, with W/WSW direction (Ghielmi et al., 2012).
4) PS2 Level Deposition and Last GTS Advancement: Around 0.8 Ma, in the Calabrian, the final stage of GTS occurred (Di Stefano et al., 1993), followed by the deposition of the PS2 level. This level is characterized by highly efficient Type I turbidite systems with a clayey composition and shares a common entry point with the Sabbie di Irene Formation (Ghielmi et al., 2012).
5) Gravitational Instability: From the Upper Pleistocene to the Holocene mass transport processes developed in the GB (Minisini and Trincardi, 2009). Most of the chaotic deposits are slumps resulting from submarine failure of slope sediments of the Pleistocene progradation originally deposited on the GTS (Ghielmi et al., 2012). A slump of larger volume (500–600 m thick, about 17 km long, about 10 km wide), produced by a submarine slide of exceptional volume, has been documented in the upper part of the foredeep succession (Trincardi and Argnani, 1990).

6.2. *The role of the Gela Gravitational Slide*

The Gela Gravitational Slide (GS) is a vast 1500 km^2 slide that covers most of the Gela Foredeep basin with its extensive detachment surface. Its headwall traces the tip of the south-verging Gela Thrust System (GTS; Argnani, 1990; Butler et al., 1992; Catalano et al., 2013; Lickorish et al., 1999) the youngest tectonic wedge of the Sicilian FTB (Catalano et al., 1993a; Lickorish et al., 1999; Ghisetti et al., 2009) commonly acknowledged as a thin-skinned, accretionary wedge. The last stage of advancement of the GTS is recorded in the Early Pleistocene, at 0.8 Ma (upper Calabrian) (Di Stefano et al., 1993; Cavallaro et al., 2017).

Gardiner et al. (1993) suggested that the deposition of the Gela Slide, as documented by Trincardi and Argnani (1990) was triggered by the uplift of the mainland region during the Quaternary. The movement of the Gela Slide occurred along a decollement level of basin-wide extent, which biostratigraphic analysis dates at 0.6 Ma by (Ghielmi et al., 2012). Trincardi and Argnani (1990) proposed that an abrupt lithologic or diagenetic change at its boundary, potentially linked to fluid overpressure, reduced friction on the basal plane. This suggest that the basal shear level of Gela GS might serve as a seal due to its consolidation and differences in capillary pressure and porosity, as documented in similar geological contexts, as in the Pearl River Mouth Basin (South China) by Sun et al. (2017) and for the Gulf of Squillace by Mangano et al. (2023).

The internal levels and the deformational structures of the Gela GS indicate a SW transport direction, consistent with the GTS primary movement. This suggests a close relationship between the Gela GS and the GTS structure. Identifying the Gela GS as a potential secondary seal highlights its significance and could aid in locating other gravitational slides and potential seals on a regional scale. The Gela GS relation with the GTS structure, extending for at least 200 km within the Gela Foredeep basin, indicaqtes the potential for a widespread distribution of this important sealing layer within the saline aquifer of the Sicily Channel, represented here by the Gela Foredeep.

6.3. *The Gela Play characteristics (depth domain)*

Based on the performed study, we have linked the interpreted seismo-stratigraphic units to the key elements that characterize the Gela Play and compared them with the depths and thicknesses requirements for CCS (refers to Introduction chapter), retrieved after a time-depth conversion (see Section 4.1). Considering the lithology, depth, thickness and closure of specific units, we identified the primary units of the Gela Play (Table 2), as follows.

- The Reservoir: The Sabbie di Irene Fm. stands out as the unit with the greatest thickness in the study area, reaching up to 950 m (Fig. 11b).

Table 2
Interpreted seismo-stratigraphic units, depth data, and association with the elements of the Gela Play.

Seismic Unit	Formation	Facies	Age (Ma)	Depth range (m)	Max thickness (m)	Interpretation
Unit 5	Argo Fm.	Foredeep turbidite sands and clays with GS intercalation	0.6	800–1320	50	Potential 2_{nd} seal (base of GS intercalations)
Unit 4	Argo Fm.	Foredeep turbidite sands and clays	0.3	1200–1800	600	Interval level
Unit 3	PS2- Lower Argo Fm.	Turbidites pelites	0.8	860–1740	190	1° Seal
Unit 2	Sabbie di Irene Fm.	Turbidite sands and clays (Type I) Average porosity **33.9 %**	0.98	1140–1880	950	Reservoir
Unit 1	Argille Basali Fm. Trubi Fm.	Turbidite clays Marls and turbidite clays	1.79 5.33	1500–2600	100	Base reservoir (*Top Trubi*)

Its high porosity values (33.9 %) are due to the sand-dominated turbiditic deposits. Additionally, the unit is found at an ideal depth (below 800 m, Fig. 13a), which is necessary for maintain the CO_2 in a supercritical state upon injection. Onlap terminations of the top of Sabbie di Irene Fm. are observed against the regional monocline covered by the Trubi Fm. and against the GTS (Figs. 9 and 10). The characteristics of this unit, including its thickness, facies and lateral closure, make it a highly suitable reservoir for CCS applications.

- The Primary Seal: The PS2 level is a turbidite pelitic layer, that can serve as a primary seal due to it extensive coverage over the Sabbie di Irene Fm. and its low permeability, given its facies. Its thickness is mostly between 50 and 190 m; the minimum thicknesses, less than 50 m, are found only in the marginal sectors of the area investigated (Fig. 11a). Onlap terminations of the top of PS2 level are observed against the regional monocline covered by the Trubi Fm. and against the GTS (Figs. 9 and 10);
- The Potential Secondary Seal: The basal level of the Gela GS may acts as a secondary seal due to its intensive consolidation in response to differences in capillary pressure and porosity. However, this level is not well-documented by the available well data (and thus by the synthetic), and its exact thickness cannot be precisely defined from the 2D seismic dataset. Nevertheless based on the high-resolution 3D section provided by Ghielmi et al. (2012) (Fig. 10), the basal level is estimated to be between 5 and 10 m thick, assuming a velocity of 2200 m/s. Additionally, an unconformity at ~1200 m depth limits the top of the level (Fig. 10) dated to around at 0.6 Ma by the biostratigraphic analysis of Ghielmi et al. (2012).

6.4. CO_2 storage perspectives

Given the high storage potential of the saline aquifers (Hughes, 2009), we examined the Gela Foredeep, a narrow and elongated basin that, due to its structure and composition, can be deemed as a significant saline aquifer whitin the Sicily Channel. Buttinelli et al. (2011) identified the Gela Foredeep as a potentially suitable areas for studies on CO_2 geological storage, noting its favourable caprocks far from seismogenic sources and from Diffuse Degassing Structures. Our analysis aimed to evaluate the Gela Foredeep's suitability for CCS projects based on established criteria (see Introduction chapter). Using 2D seismic reflection profiles, calibrated with well-tie, and time-to depth converted, allowed us to identify the Gela Play as a viable CO_2 storage site.

The Gela Play encompasses Plio-Pleistocene deposits within the Gela Foredeep. It features a reservoir level composed of the Sabbie di Irene Fm. (Early Pleistocene), which is covered by a primary seal, the PS2 level of the Argo Fm. (Middle Pleistocene). Additionally, there is a potential secondary seal corresponding to the basal level of the Gela Gravitational Slide, with its top dated at 0.6 Ma. These layers exhibit suitable thickness and depth for effective storage. The play is confined by both stratigraphic and structural closures: the regional monocline to the south and the GTS to the north. The Gross Rock Volume of the reservoir, calculated at 3.2832E+11 m^3, is a critical metric for assessing the storage capacity of the Gela Play (Hedley and Gluyas, 2015).

The results of this study integrate build on the findings of Donda et al. (2011) and Civile et al. (2013), which overview suitable areas for CO_2 geological storage in Italy. Most identified sites are located in carbonate environments (Civile et al., 2013). Sun et al. (2020) highlighted a potential CO_2 storage site in clastic sediments within the Mesopotamian Foredeep Basin, a foreland basin formed from the Cretaceous to the Miocene due to the subduction of the Arabian Plate beneath the Eurasian Plate. In Fig. 13 we mapped two overlapping regions between reservoirs, primary and secondary seal, indicating two potentially suitable zones for CCS investigations. Is is crucial to consider both primary and secondary seal, as each plays a role in preventing or mitigating CO_2 leakage (Ingram et al., 1997).

7. Conclusions

This study provides the first comprehensive evaluation of Gela Foredeep's filling along the southern Sicilian coast, aimed at identifying potential CO_2 geological storage sites within a saline aquifer in the Sicily Channel.

Utilizing 2D multichannel reflection seismic profiles, calibrated with well-to seismic tie, we conducted a seismo-stratigraphic analysis to reconstruct the tectono-stratigraphic evolution of the Gela offshore area. This analysis let to the identification of the Gela Play, which features a reservoir (Sabbie di Irene Fm.) covered by a primary seal (PS2 level-Lower Argo Fm.) and by a potential secondary seal (the basal level of Gela Gravitational Slide).

This study also highlighted the presence of adequate stratigraphic and structural closures within the Gela Foredeep, indicating that the Gela Play is a potential prospect for further CCS investigations.

The basal level of the Gela Gravitational Slide, exhibiting potential sealing layer characteristics, could serve as a regionally significant sealing unit. However, additional well-logs data and further analysis are necessary to confirm its suitability.

A comprehensive assessment of the CO_2 storage potential in this sector of the Gela Foredeep will require several supplementary data and analysis, such as sedimentological analysis, identification of best sites and migration modelling. Despite this, the current evaluation provides a crucial foundation for understanding the area's capacity for CO_2 storage.

CRediT authorship contribution statement

Mariagiada Maiorana: Writing – original draft. **Attilio Sulli:** Supervision. **Matteo Marelli:** Methodology. **Mauro Agate:** Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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