

The Pliocene to Pleistocene Succession of the Hyblean Foredeep (Sicily, Italy)*

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Abstract

Hyblean Foredeep (HF) developed in the southeastern part of Sicily and represents the southernmost Pleistocene foredeep basin of the Apennines. This narrow and elongated depocenter is split into 3 sub-basins: Catania, Gela, and Pina basins. The HF inner and outer boundaries are represented by the Gela Nappe front and by the Hyblean foreland ramp.

By means of subsurface data 3 allogroups (late Messinian - LM, early Pliocene - EP, late Pliocene - LP) and 6 sequences (4 in Pliocene: PL1-PL4; 2 in Pleistocene: PS1-PS2) were recognized in the Plio-Pleistocene HF succession. They are bounded by tectonic or eustatic-controlled boundaries, generally corresponding to abrupt changes in depositional systems type and distribution. The proposed new lithostratigraphy for HF includes some new formations: Ponte Dirillo, Irene Sand, Argo, and Zagara formations.

During the first part of early Pliocene, the area was the site for foreland continental sedimentation. Thin sequences (10-20m) of transgressive marls of Trubi Formation (PL1 Seq. - LM Allogroup) were deposited only in limited areas. A phase of strong subsidence at the EP allogroup boundary ("Intra-Zanclean Phase") marks the passage to marine conditions. The PL2 and PL3 Sequences consist of a transgressive succession (40-170m) of lower to middle Pliocene marls and clays of Trubi and Ponte Dirillo formations. As a consequence of a new deformation event, the "Gelasian Phase," the foreland deposits are unconformably overlain by deep-water sediments of the LP Allogroup. They are represented by upper Pliocene-Pleistocene foreland ramp clays of the Ponte Dirillo Formation and by lower-middle Pleistocene foredeep turbidites up to 2000m thick. Turbidite deposits belong to highly-efficient turbidite systems, characterized by basin-scale tabular geometry and axial facies distribution. The Gela Basin turbiditic infill is represented by 800m thick low.

Introduction

In the last decades, the Plio-Pleistocene Hyblean Foredeep (HF) has been deeply studied by Eni as being a new exploration target for biogenic gas in Southern Italy (Gatti et al., 2008, 2011). The Plio-Pleistocene sedimentary succession of the Gela Basin (corresponding to

the central part of the HF) have been analyzed in detail, with a multidisciplinary approach, taking into account 2D and 3D seismic surveys, conventional and image well logs, and core analysis of about 35 wells. A complete and detailed revision of the biostratigraphy, chronostratigraphy, sedimentology, seismic interpretation, and sequence stratigraphy was performed and a new basin-scale geological model of the HF was defined. The new geological model of the Gela Basin is synthetically presented in this article.

Geological Framework

The Hyblean Foredeep (HF), developed in the onshore and offshore of southeastern Sicily (Southern Italy), represents the southernmost turbiditic foredeep depocenter of the Apennines (Figure 1). The HF is an irregularly shaped, very narrow (~10-20 km), elongate basin (~250 km). The sedimentary infill is represented by a thick succession of Pleistocene turbidite sands and muds (Catalano et al., 1997; Patacca and Scandone, 2004). The HF inner boundary is represented by the arched front of the Gela Nappe, an allochthonous complex mainly consisting of Miocene marls and shales and representing the most external part of the Apennine thrust-and-fold belt. Along the outer boundary the HF is limited to the east by the Hyblean foreland and to south by the Sicily Channel bulge. The foreland succession consists of a thin section of upper Miocene marls (Tellarò Formation) and evaporites (Gessoso-Solfifera Formation) superposed to a very thick succession of Mesozoic and Tertiary carbonates, including also the dolostones of the Triassic Sciacca Formation (Gela and Ragusa Oil Fields reservoir) and Liassic Inici Formation (Vega Oil Field reservoir). Two structural highs, the Margi High in the onshore and the Panda High in the offshore, split the HF into three separate sub-basins (from E to W): the Catania Basin, the Gela Basin, and the Pina Basin (Ghielmi et al., 2009) (Figure 1). The Gela Basin corresponds to the central and largest depocenter of the HF. This basin, mainly developed in the Sicily offshore to the south of the Gela Nappe, extends in part also in the onshore of southeastern Sicily.

Sequence Stratigraphy Approach, Chronostratigraphy, Lithostratigraphy

During Plio-Pleistocene the sedimentation in the HF was controlled by an intense synsedimentary compressional Apennine tectonism. Therefore, the stratigraphic analysis of the basin was based on the recognition of tectono-stratigraphic units bounded at base and top by tectonically induced unconformities; i.e., the allogroups, according to the criteria used by Mutti et al. (1994) in the Southern Pyrenees Foreland Basin. This stratigraphic approach has already been used in the analysis of Neogene tectonically active basins of the Apennines (Ghielmi et al., 2010). Allogroups are high-rank and large-scale stratigraphic units (NACSN, 1983). The allogroup boundaries are produced by high-magnitude basin-modification tectonic phases and are usually related to the creation of new and more external foredeep depocenters. These surfaces are synchronous in the foredeeps, as well as in the thrust-top basins and foreland of the Apennine thrust-and-fold belt. In the foreland the allogroup boundaries usually correspond to major events of subsidence and are expressed by clear regional transgressive surfaces. Allogroup boundaries also correspond to abrupt major changes in the type and gross distribution of depositional systems. In fact, the active Apennine deformation strongly influenced the sedimentation, by controlling the elevation and the gradients of the basin margins (specifically of the foreland and foreland ramp), the extension of the sedimentary drainage areas, the location of the main entry-points, and the extension, shape and depth of the deep-water depocenters. The Pliocene-Pleistocene of the HF is subdivided into 3 allogroups (Figure 2): LM (late Messinian), EP (early Pliocene), LP (late Pliocene) (Ghielmi et al., 2009). They span in time 1.5-2.5 My., and reach some thousands of meters of thickness in the foredeep turbiditic depocenters.

The allogroups can be further subdivided in lower rank unconformity-bounded units; these units are named here as Large-Scale Sequences (LSS). The LSS boundaries are still predominantly produced by tectonic phases. Also these surfaces are synchronous in the foredeeps and thrust-top basins of the Apennines, and they usually correspond to significant sedimentary facies changes. Only one LSS of the HF is bounded by eustatic-driven sequence boundary: the lower Pliocene PL1 Sequence. The Plio-Pleistocene LSSs span in time 0.6-1.5 My. and show thicknesses up to several hundred meters in the Pleistocene foredeep depocenters. Six LSSs have been recognized in the Plio-Pleistocene of the study area ([Figure 2](#)): 4 in Pliocene (PL1-PL4) and 2 in Pleistocene (PS1-PS2) (Ghielmi et al., 2009).

In June 2009 the Subcommittee on Neogene Stratigraphy (SNS) of the International Commission on Stratigraphy (ICS) lowered the Pleistocene base to the Gelasian stage (previously included into the Pliocene) (Gibbard et al., 2010). The present work still adopts the „old“ chronostratigraphy (Gelasian as the last stage of Pliocene, according to Rio et al., 1998) because Eni's nomenclature of allogroups and sequences for the Messinian-to-Pleistocene Apennine foredeeps (Ghielmi et al., 2010), developed during the late 1990s and the early 2000s, is based on the former chronostratigraphy.

A new lithostratigraphic scheme is proposed for the HF that includes some new informal units: Ponte Dirillo Formation (middle Pliocene-to-Holocene foreland ramp clays), Argille Basali Formation (lower Pleistocene foredeep turbidite clays), Sabbie di Irene Formation (lower Pleistocene foredeep turbidite sands), and Argo Formation (middle-upper Pleistocene foredeep turbidite sands and clays) (Ghielmi et al., 2009) ([Figure 2](#)). The new formations (probably represented only in subsurface) have been introduced in Eni informal lithostratigraphy in the last 5 years.

Plio-Pleistocene Tectono-Sedimentary Evolution of the Gela Basin

During the first part of early Pliocene (PL1 Seq. – LM Allogroup), the Gela Basin (GB) area was emergent and affected by no deposition or subaerial erosion. Thin sections (10-20 m) of transgressive grey-whitish fossiliferous marls of Trubi Formation were deposited only in a relatively limited onshore area north of the town of Gela. Throughout this time interval, the GB area was still included in the Hyblean and Sicily Channel forelands of an Apennine Paleo-Chain located in a more inner area.

The EP Allogroup boundary corresponds to a major deformation event, the *Intra-Zanclean Phase*, that caused an episode of rapid subsidence of the GB area (probably controlled by the plate subduction combined with the flexural subsidence induced by active thrusting in the southern Apennine Chain) during the middle-latter part of the early Pliocene. The boundary corresponds to a drowning unconformity expressed by the basin-scale transgressive surface. All of the remaining emergent areas of the GB rapidly passed to an open-marine environment with sedimentation of the Trubi fossiliferous marls (average thickness of 40-60 m; average sedimentation rate: 0.05-0.10 m/ky) of the PL2 Seq. ([Figure 3](#)). Therefore, as clearly indicated by biostratigraphic analysis, in the GB offshore (and also in part of the onshore) the Trubi Formation is represented only by upper Zanclean-basal Piacentian marls due to the non-depositional hiatus of the lower part of the succession ([Figure 2](#)).

A hiatus, probably due to condensation/non-deposition in a marine environment, has been recognized at the base of the PL3 Seq. (Piacentian p.p.) ([Figure 2](#)). Also this sequence boundary is here interpreted as a tectonically driven unconformity, mainly on the basis of geological data from other basins of the Southern Apennines. Over the whole GB, the succession consists of 20-70 m of middle Pliocene grey-green fossiliferous clays ([Figure 3](#)). These sediments, deposited in a foreland area, have been included in the Ponte Dirillo Formation

The unconformable boundary of the LP Allogroup (late Pliocene-Pleistocene) corresponds to a severe Pliocene Apennine deformative event: the *Gelasian Phase* (Ghielmi et al., 2010). This major tectonic event was responsible for the rapid subsidence and tilting of large sectors of the former Hyblean and Sicily Channel foreland areas, and for the reactivation of high-angle faults of the carbonate substratum, as indicated by the faulting and deformation of Messinian and lower-middle Pliocene foreland deposits ([Figure 3](#)). Probably also a displacement of the Gela Nappe towards south and southeast took place in the same period. The main consequence of the tectonic event was an abrupt deepening and the setting of deep-water foreland ramp and foredeep condition in large sectors of GB.

The PL4 Seq. (late Pliocene-basal Pleistocene) is mainly represented by a relatively thin section of marine grey and grey-green clays of the Ponte Dirillo Formation deposited by fall-out with draping geometry on the foreland ramp and foreland of the Gela Basin ([Figures 2 and 3](#)). The thickness, laterally very variable, usually ranges from 20 to 50 m. In correspondence to the sequence boundary, biostratigraphic analyses have shown an important hiatus (probably due to condensation/non-deposition) comprising large part, or even the whole, of late Pliocene. Two foredeep wedges have been recognized in the innermost part of the present-day foredeep: onshore west and north of the town of Gela, and offshore south of the Gela Nappe. The succession, 110 m as maximum thickness, is made up of grey and grey-green clay and silty clay of the Argille Basali Formation ([Figures 2 and 3](#)).

With the PS1 Seq., for the first time, a deep-water foredeep sedimentation occurred in large sectors of the GB with the deposition of the lower Pleistocene turbidite sands and clays of the Sabbie di Irene Formation ([Figures 2 and 3](#)). The tectonic origin of the sequence boundary is supported by: (1) the local presence of angular unconformities (onlap) at the base of the sequence, (2) the transpressive reactivation of high-angle faults of the carbonate substratum and (3) the evidence of a phase of movement of the Gela Nappe towards south and southeast. The PS1 foredeep shows a very elongated (over 120 km long and 3-14 km wide, and locally irregular shape. The external foredeep margin is represented by a steep foreland ramp or, locally, by high-angle normal faults cutting through the Mesozoic-Tertiary carbonates (the inner one by the Gela Nappe front, [Figure 3](#)). The presence of a narrowing (only 1/1.5 km wide; located onshore close to the present coastline) caused the subdivision of the foredeep in two substantially independent depocenters: one onshore north of the narrowing, the other one (the larger) offshore. The offshore foredeep depocenter was irregular in shape with a width of 3-14 km and a length of about 70 km ([Figure 6](#)). The deposition of thick-bedded coarse- to fine-grained sand of proximal and distal sand lobes facies association occurred over most of the foredeep in the offshore area, while the ponded basin plain deposits, consisting of alternating clays and fine-grained sands, were limited to the more distal sector of the foredeep (south of the Gela Nappe) ([Figures 5 and 6](#)). The ponding and reflection of the turbidity currents of the Sabbie di Irene Formation are indicated by the recognition in the well bottom cores of a number of 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; rhythmic alternation of sedimentary structures (e.g., current ripples of Bouma's tc division and plane laminae of tb or td divisions); rhythmic alternation of different lithologies (e.g., very fine sand and silt) ([Figure 7](#)). In the

offshore sector of GB, the thickness of the PS1 Seq., controlled by the local subsidence rates, ranges from 500 m close to the coastline, up to 900 m in the main depocenter located south of the Gela Nappe. The sedimentation rates have been valued in 0.9-1.6 m/ky. The succession clearly shows an overall Thinning- and Fining-Upward trend (Figure 5), here interpreted as due to a gradual reduction of turbidity currents volumes and consequent back-stepping of the turbidite system. On the basis of the available seismic and well data, the Sabbie di Irene Formation turbidites have been attributed to a highly-efficient Type I turbidite system (sensu Mutti et al., 1999) characterized by remarkable basin-scale tabular geometry (Figures 4 and 5). The gradual downcurrent grading from sand lobes into basin plain deposits indicates paleocurrents mainly from ENE parallel to the foredeep axis (Figure 6). The turbidite system was fed by a major entry-point located close to the present-day coastline on the Gela Nappe. In the onshore depocenter, north of the town of Gela, the sand-rich turbidites have been referred to poorly-efficient turbidite systems fed by different areas of the Gela Nappe. During the deposition of the Sabbie di Irene turbidites in the foredeep, the sedimentation, due to fall-out, of time-equivalent Ponte Dirillo Formation grey clays took place in the ramp and foreland areas (Figure 6). Their thickness, increasing towards the foreland, can locally exceed 100 m with a sedimentation rate evaluated as 0.15-0.20 m/ky.

Also the PS2 Seq. boundary shows a tectonic origin. The new compressive event was responsible for: (1) the latest movement of the Gela Nappe towards S/SE, (2) the transpressive reactivation of high-angle faults of the carbonate substratum (Figure 4), and (3) the activation of thrust-propagation folds along the foredeep inner margin with the deformation of the PS1 Seq. turbidites (Figure 3). The thrust planes developed in correspondence with the Messinian evaporites or with the onlap surface of the Pleistocene turbidites on the foreland ramp. During the sedimentation of the PS2 Seq., the last deformation is represented by events of uplift of the Hyblean area. The PS2 foredeep succession is made up of 1300 m of middle Pleistocene-to-present turbidite clays and sands attributed to the Argo Formation (Figure 2). During the sedimentation of the Argo Formation, the foredeep shape rapidly changed from very elongated to a relatively short and wide basin as a consequence of two independent factors (Figure 8): (1) a rapid southward progradation of slope and shelf depositional systems developed from the onshore foredeep apex to the present-day offshore position (Figure 11); (2) the foredeep width increased more rapidly due to the onlap of the turbidites on the outer margin represented by a lower angle foreland area (Figure 4). The PS2 Seq. foredeep succession mainly consists of fine-grained basin-plain turbidite deposits. In the eastern sector of the foredeep, thick-bedded sands of proximal and distal lobes are regularly interbedded with the basin-plain deposits with a high-order cyclicity of climatic/eustatic origin (Figure 8). These sand lobe deposits gradually grade downcurrent into basin-plain alternating clays and subordinate fine-grained thin-bedded sands and, finally, to distal basin-plain mud. The main entry point was located in the northeastern foredeep apex. The paleocurrents were towards W/WSW, longitudinal to the basin axis as documented by the facies distribution pattern. On the basis of these data and of the remarkably basin-scale tabular geometry, the PS2 turbidites have also been attributed to Type I highly-efficient turbidite systems. The sand lobes limited extension and the rapid downcurrent transition to basin-plain deposits indicate a relative minor efficiency, with respect to the Sabbie di Irene turbidite system, probably due to both a reduced sand supply and smaller volume of the turbidity currents. During the middle-late Pleistocene, the already limited efficiency got even more reduced as indicated by the progressive back-stepping of the sand lobes towards the east. Mass-transport deposits are often intercalated in the turbidite succession, mainly along the inner foredeep margin (Figure 9). 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. The slumps of larger volume were able to reach the outer foredeep margin, onlapping directly on the foreland ramp (Figure 9). A mass transport event of

huge 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; [Figure 10](#)). Mass transport processes developed in the GB until the Holocene (Minisini and Trincardi, 2009). In the ramp and foreland the PS2 Seq. extends to the Holocene by clays of the Ponte Dirillo Formation ([Figures 2, 3, and 4](#)). Their thickness increases towards the foreland. During the PS2 Seq., a southward impressive progradation of slope, shelfal, and coastal deposits of the Monte Narbone Formation extensively occurred in the GB ([Figures 2, 3, 11](#)). The fast progradation was favored by the lowstand phases of the middle-late Pleistocene glacial episodes and by the particular tectonic regime (uplift of the Hyblean area and reduced or absent subsidence of the foredeep area. The Pleistocene Prograding Complex rapidly advanced southward along the foredeep axis from the onshore foredeep apex as far as its present-day offshore position ([Figure 11](#)). In the western sector of the basin the progradation developed in the thrust-top basins of the Gela Nappe reaching its southern front ([Figure 4](#)). The progradation thickness ranges from some hundred meters up to 900/1000 m. The progradation average velocity during the last 600 Ky has been evaluated in about 35/40 m/Ky.

Conclusions

Detailed revisions of the biostratigraphy, chronostratigraphy, sedimentology, seismic interpretation, sequence stratigraphy, and lithostratigraphy were performed and integrated in a new basin-scale geological model of the Plio-Pleistocene Gela Basin (GB); i.e., the central sector of Hyblean Foredeep.

Three relevant hiatuses were recognized in the Pliocene succession. The oldest one is due to the subaerial exposure of most of the GB during the early Pliocene. The other ones correspond to tectonic sequence boundaries and were caused by condensation or non-deposition in marine settings.

A new sequence stratigraphy, based on allogroups and large-scale sequences bounded by major tectonically-induced unconformities, is proposed for the GB.

During Plio-Pleistocene a severe synsedimentary transpressive tectonics affected the GB. Two major unconformities were generated: Intra-Zanclean Unc. and Gelasian Unc. (corresponding to the allogroup boundaries). As a consequence of the deformation, the Hyblean and Sicily Channel forelands were progressively affected by subsidence and north/northwestward tilting in association with the reactivation of high-angle fault systems of carbonate substratum, the Gela Nappe moved towards S and SE, and the deep-water foredeep depocenter of the GB was generated. Subsidence and tilting were probably controlled by the plate subduction in combination with the flexural subsidence caused by active thrusting in the Southern Apennines. In the foreland and foreland ramp areas, these major tectonic events were recorded by sharp relative sea-level rises.

The GB foredeep turbiditic infill, up to 2000 m thick, is mostly represented by Pleistocene thick-bedded sand lobes and by more distal basin-plain deposits, made up of clays intercalated with thin-bedded fine-grained sands of the Sabbie di Irene and Argo formations. These turbidites were deposited in deep-marine environments (water depths usually exceeding 1000 m) by Type I highly-efficient turbidite systems fed by

main entry-point located along the inner foredeep margin. The paleocurrents, parallel to the foredeep main axis, were generally westward. Poorly-efficient Type II turbidite systems fed by lateral entry-points were active in the foredeep onshore sector during early Pleistocene.

Mass-transport deposits are often intercalated in the middle-upper Pleistocene foredeep succession of the Argo Formation. These deposits, mainly represented by slumps, were produced by submarine failure of slope and shelf deposits of the Pleistocene Prograding Complex.

The deposition of a monotonous and thick section of clays of the Ponte Dirillo Formation occurred in the ramp and the foreland areas from the middle Pliocene-to-Holocene.

During middle-late Pleistocene, the Pleistocene Prograding Complex, consisting of slope, shelfal, and coastal deposits of the Monte Narbone Formation, rapidly advanced southward along the foredeep axis and in the GB thrust-top basins as far as its present-day offshore position.

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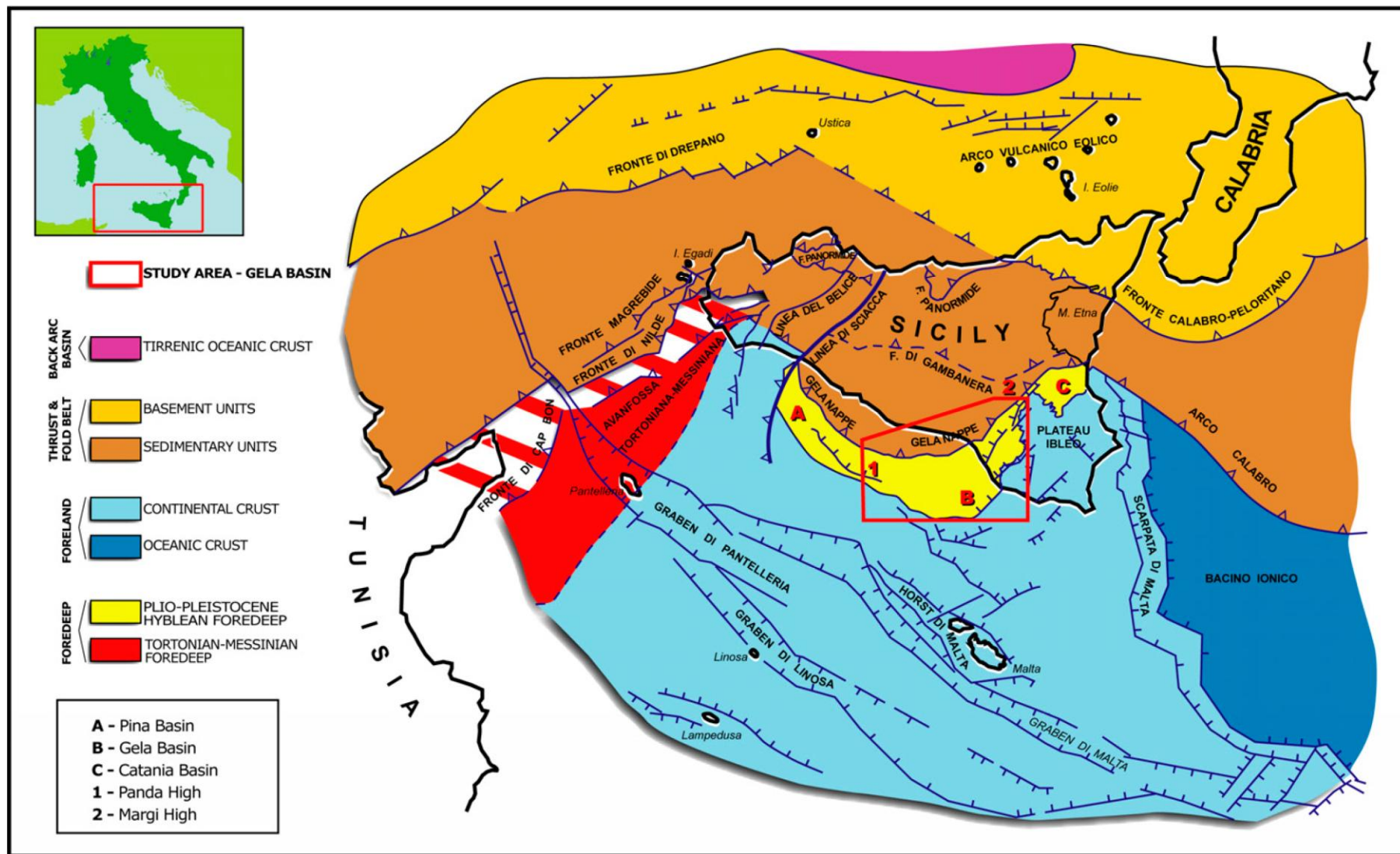


Figure 1. Regional geological map showing the Hyblean Foredeep main depocenters.

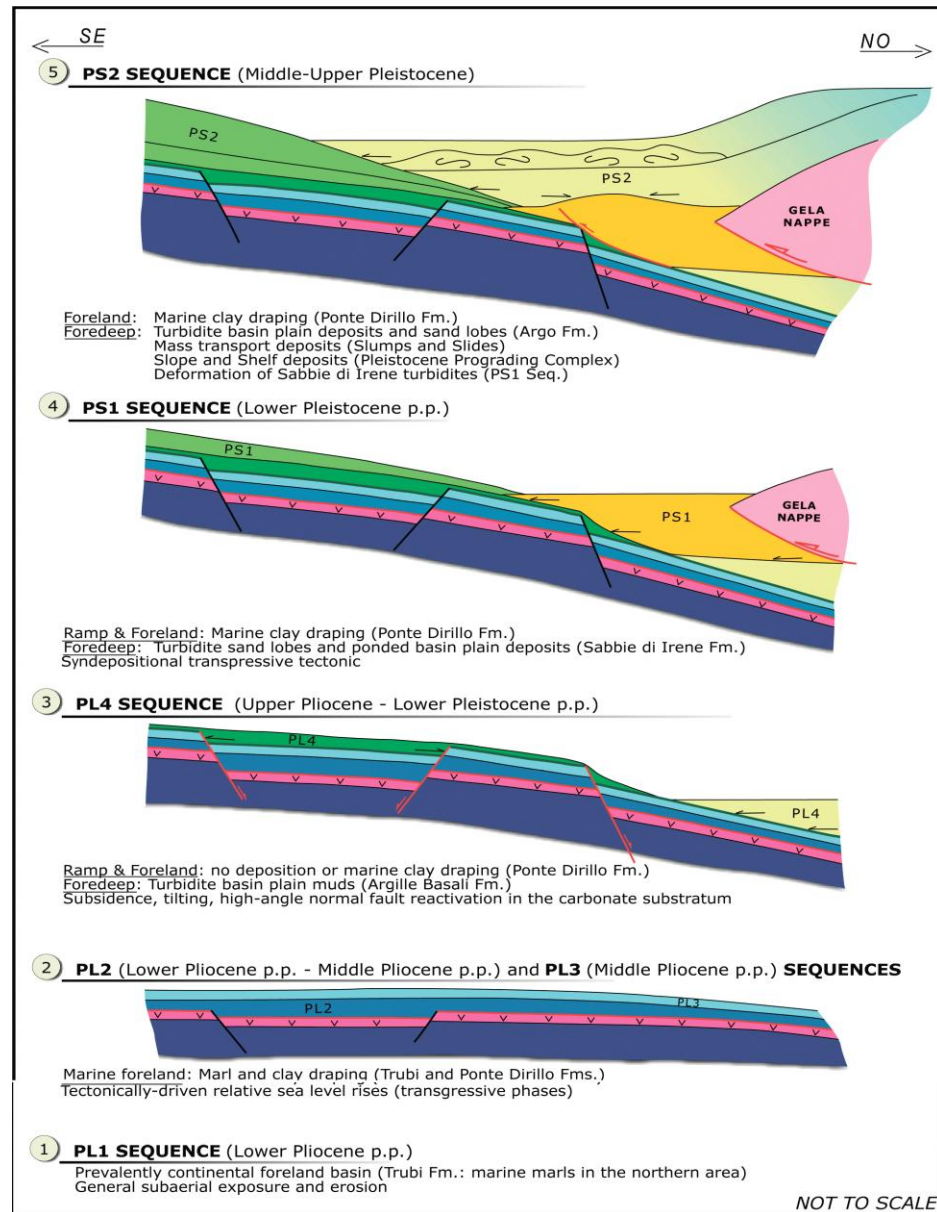


Figure 3. Simplified model of the structural-sedimentary evolution of the Gela Basin.

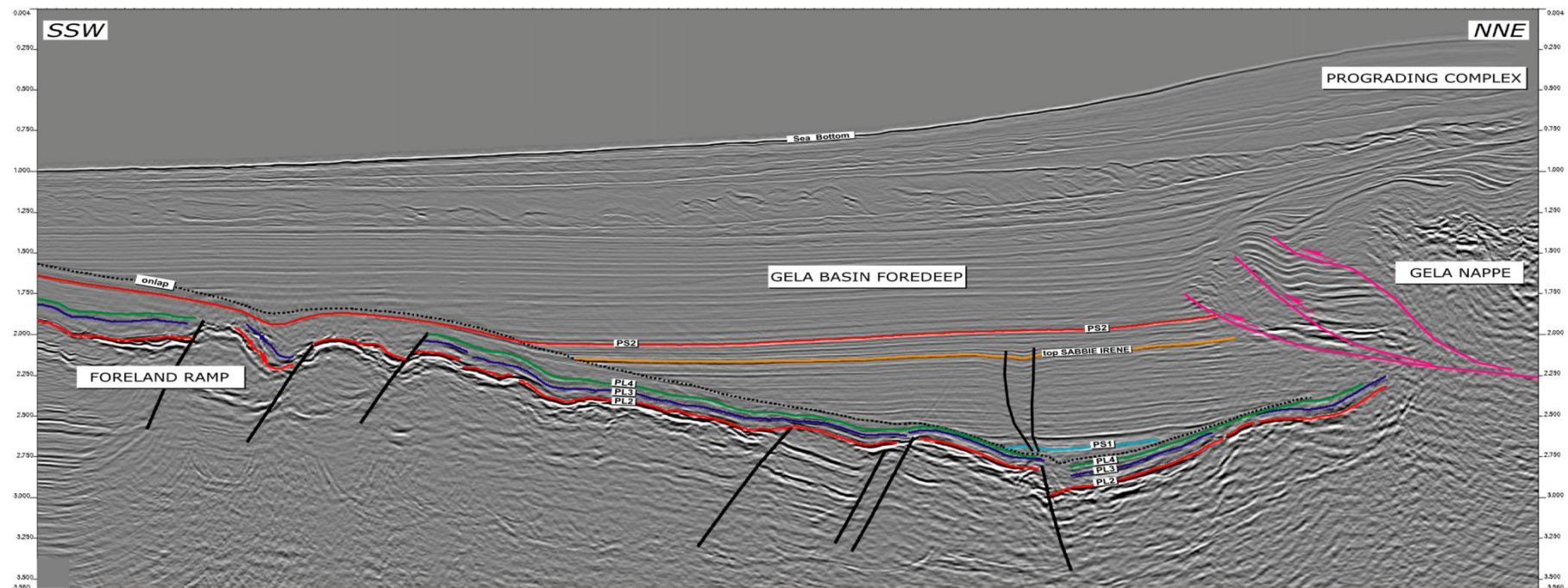


Figure 4. Seismic section of the Gela Basin offshore sector (see [Figure 6](#) for location; section length about 16 km).

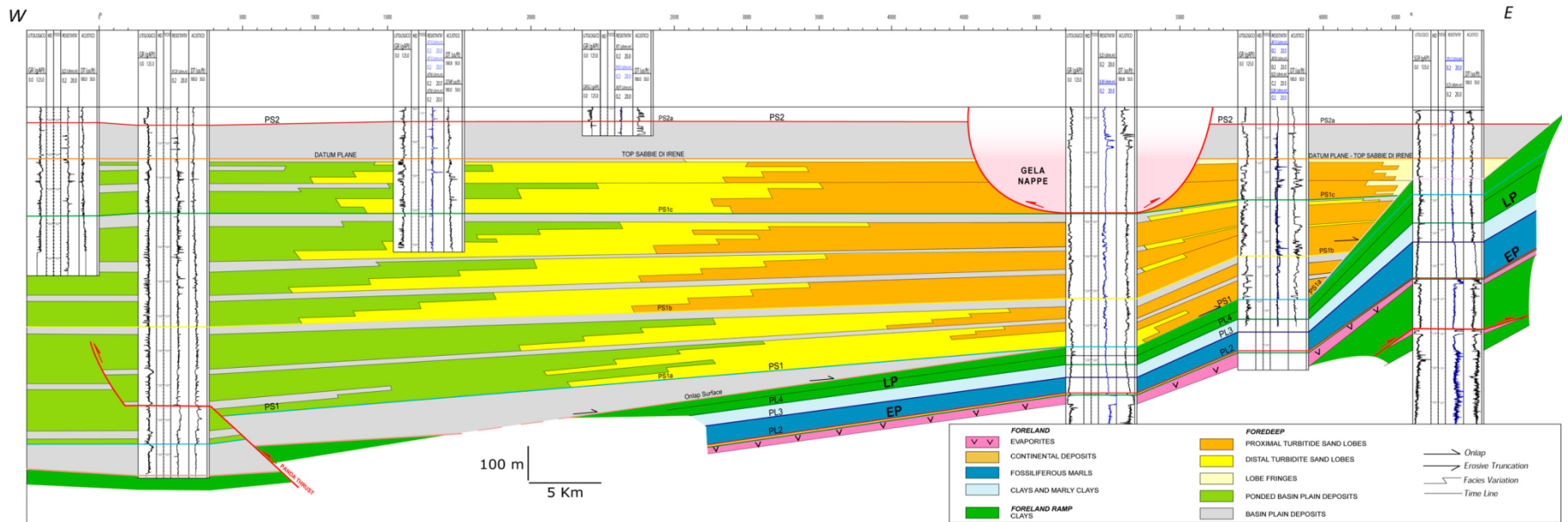


Figure 5. PS1 Sequence: longitudinal well correlation of the Sabbie di Irene Formation in the offshore Gela Basin (see [Figure 6](#) for location).

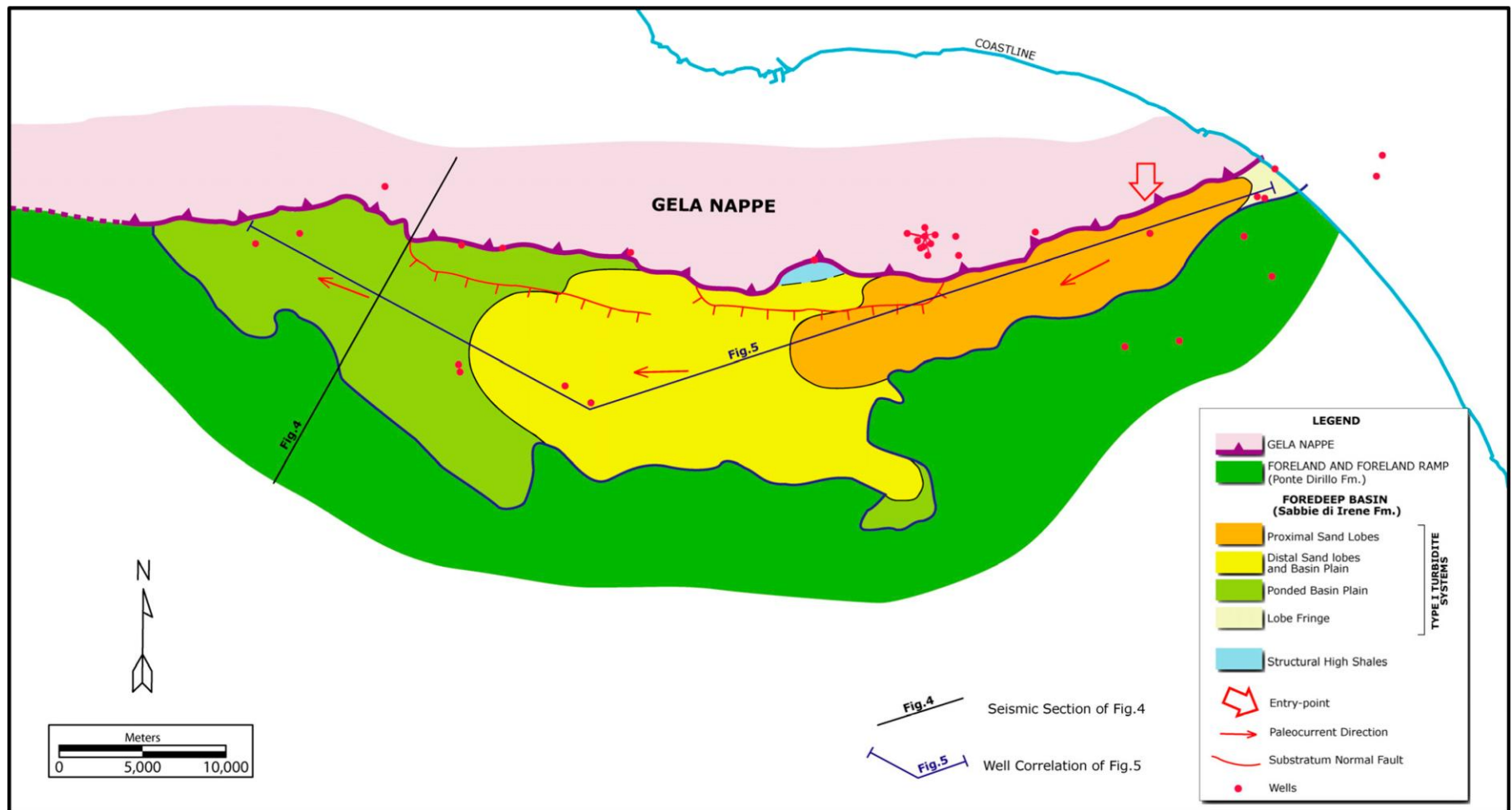


Figure 6. Facies distribution map of the PS1 Sequence in the offshore area (Top Sabbie di Irene Formation).

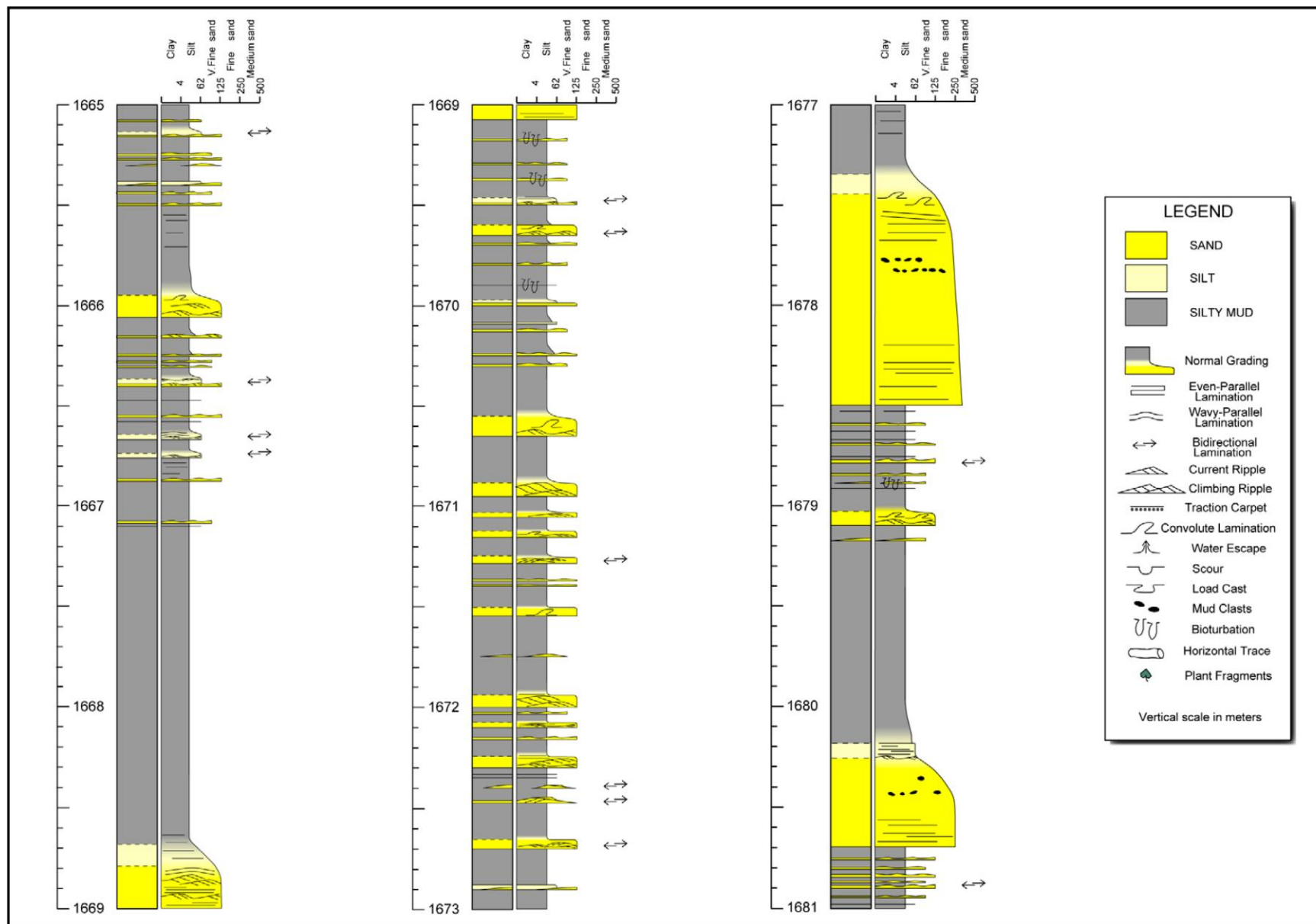


Figure 7. Selected cored sections of the ponded basin plain deposits of the Sabbie di Irene Formation.

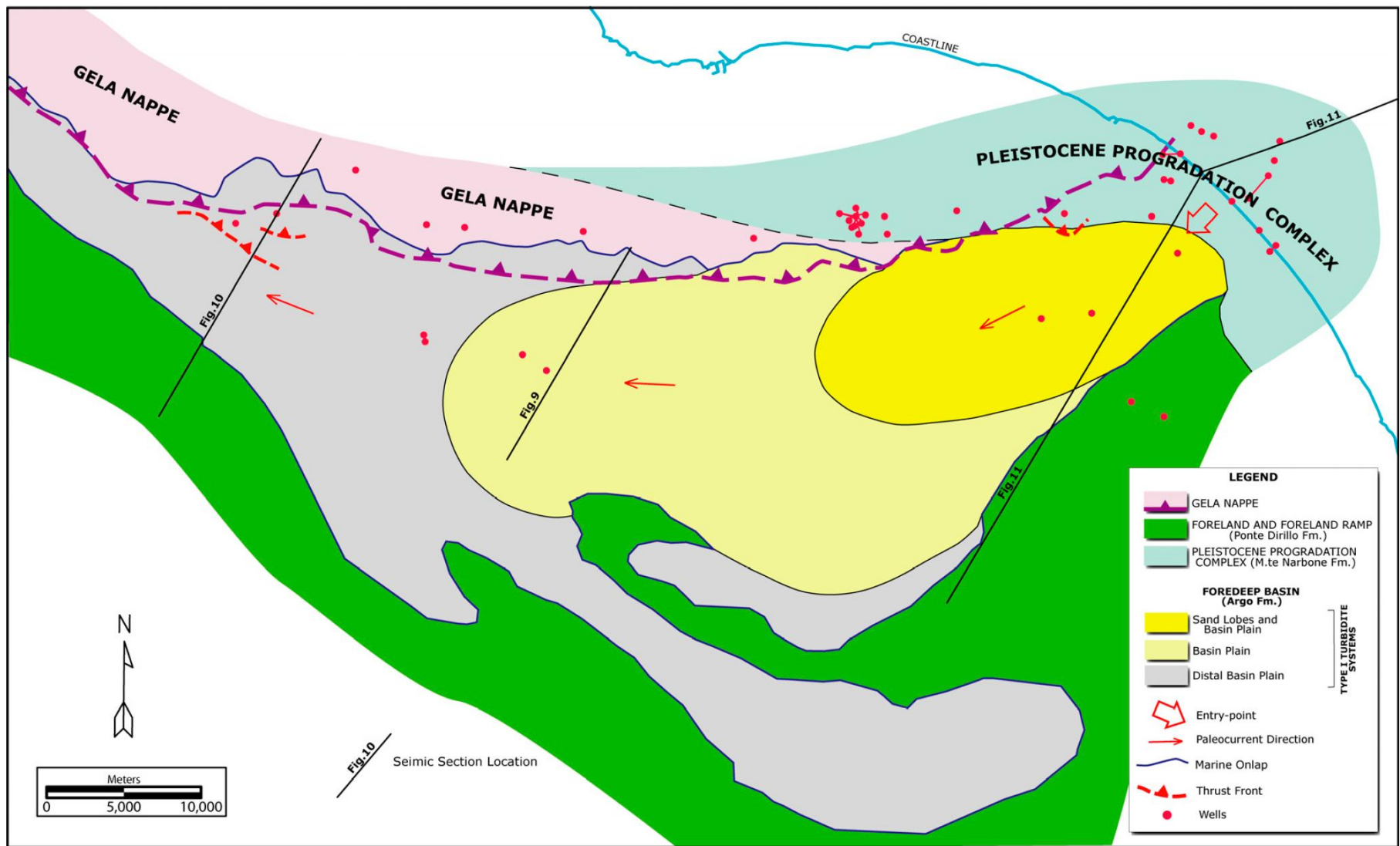


Figure 8. Facies distribution map of the PS2 Seq. (middle part; about 600 Ky BP) in the offshore area of Gela Basin.

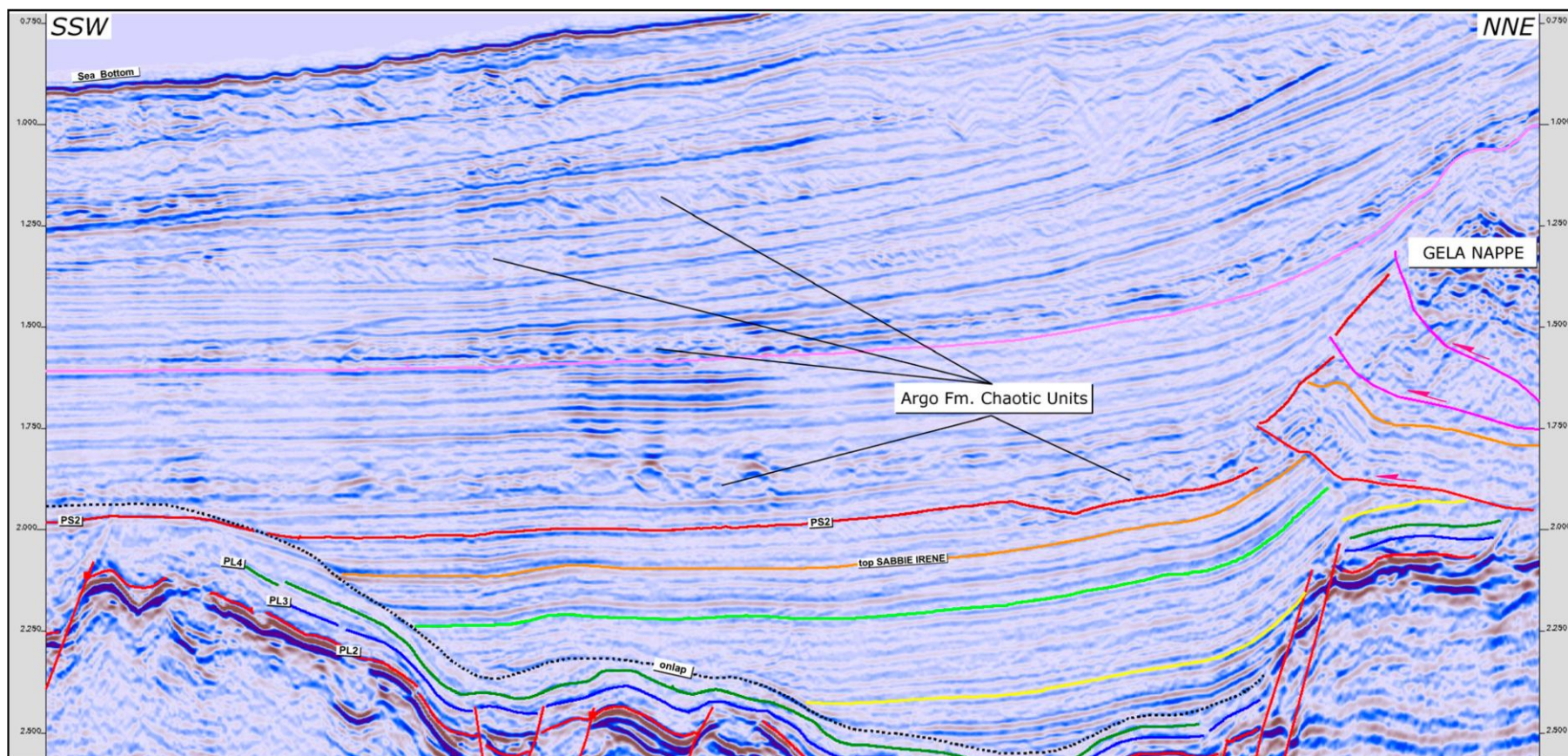


Figure 9. PS2 Seq.: seismic section showing Argo Formation slump deposits (see [Figure 8](#) for location; section length about 14 km).

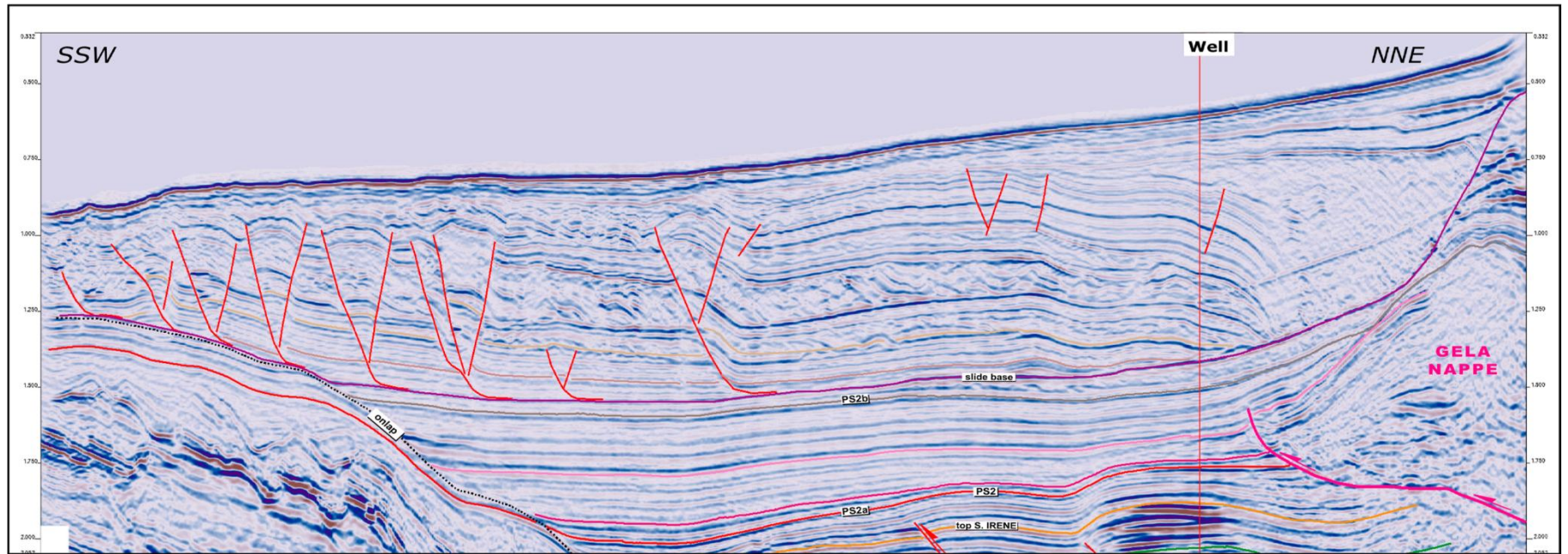


Figure 10. Seismic section showing the basin-scale slide (see [Figure 8](#) for location; section length 17 km). Note: the slide scar above the Gela Nappe; the extensional faults in the rear part of the slide; the compressive deformation in the middle-frontal part.

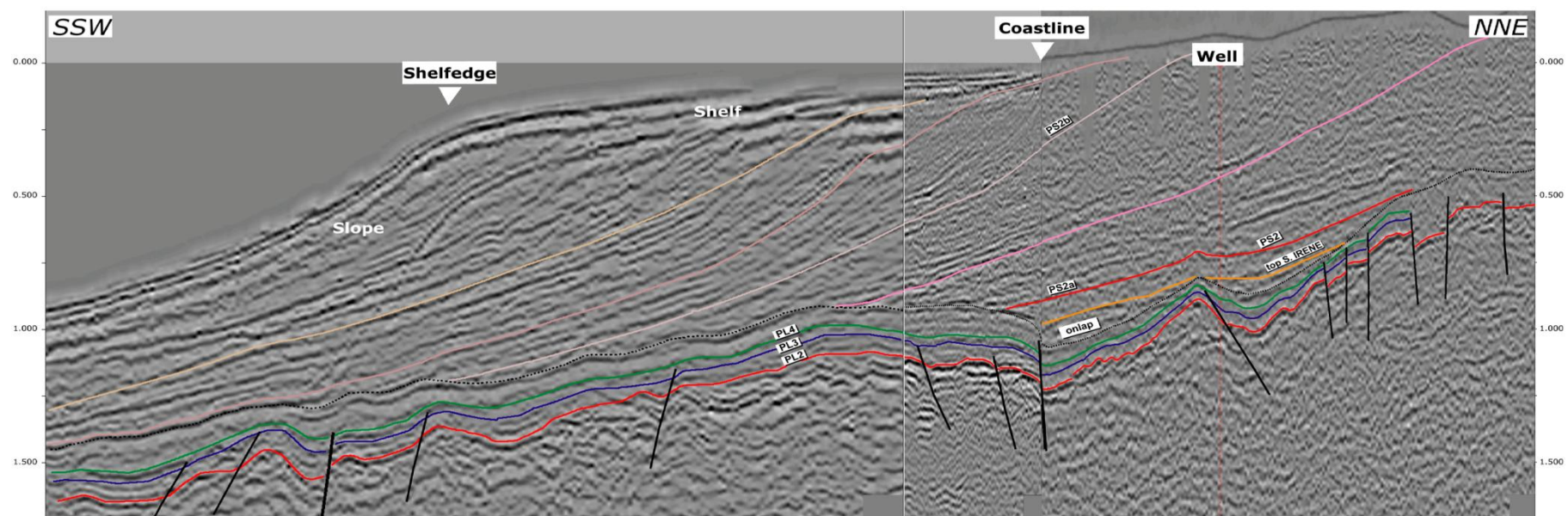


Figure 11. Composite seismic section longitudinal to the “Pleistocene Prograding Complex” (see [Figure 8](#) for location; section length 48.5 km).