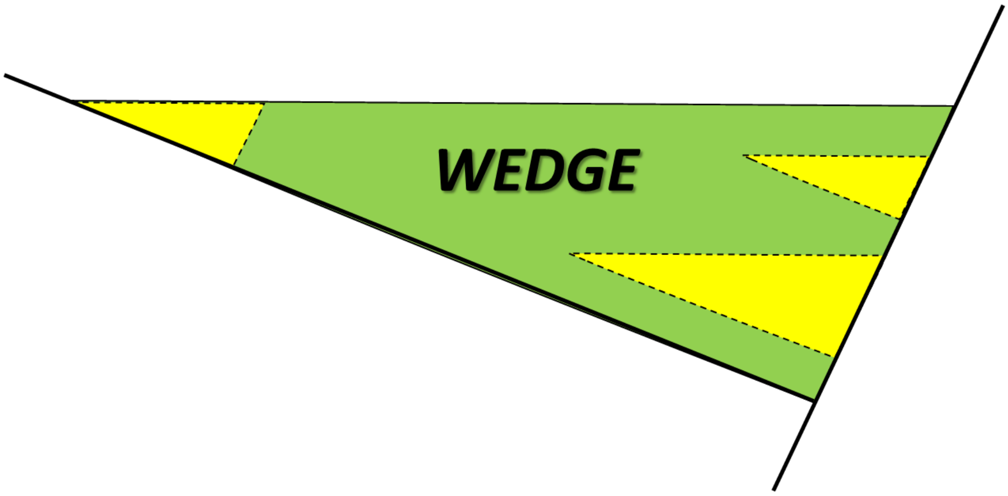
WEDGE

Geometry, facies and reservoir prediction of syn-rift clastic wedges in the Norwegian continental Shelf

A multidisciplinary approach using subsurface data, outcrop analogues and tectonosedimentary modelling



A research project between the University of Stavanger and the University of Basilicata (Italy)

University of Stavanger

UNIVERSITA' DEGLI STUDI DELLA BASILICATA 1982

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Executive Summary

Wedge is a 4-year project aiming to provide detail geological characterization (from the tectonic setting to reservoir properties), predictive scenarios, and petroleum potential of syn- and early post-rift coarse-grained clastic wedges in the Norwegian continental shelf. The project is a collaboration between the University of Stavanger (UiS) and the University of Basilicata (UBas), covering subsurface mapping, outcrop analogues and tectonosedimentary modelling. The cost per company is 2.5 MNOK for the entire length of the project with a minimum of four sponsoring companies. The main deliverables will be all the research results accomplished by two PhD students and a GIS database where all subsurface, outcrop analogues and modelling will be integrated and a final report of the project. Meetings will be held and progress results will be provided every year.

1. Motivation

Syn- and early post-rift coarse-grained clastic reservoirs derived from both footwalls and hanging walls along faulted basin margins are a well-known challenge for hydrocarbon exploration in extensional systems. Syn-rift wedge-shaped geometries are a recognized reservoir in both the UK North Sea (e.g. the Fulmar and Brae oil fields) and in the entire Norwegian Continental Shelf (NCS). Fields such as Johan Svedrup in the North Sea and Fenje in the Norwegian Sea have proved their potential. In addition, Lower Cretaceous sand-prone wedges in the Barents Sea have revealed a good reservoir potential, but they also show the importance of understanding the interaction between tectonics and sedimentation (Marin et al. 2018b).

The syn-rift sandstone reservoirs in the NCS have been interpreted as deposited in a variety of depositional environments and as consequence of multiple processes that includes shallow marine/transgressive wave-dominated shorelines, deep marine gravity flow deposits, and fan delta environments (Nøttvedt et al., 2000; Olsen, 2017; Marin et al., 2018b). It is a challenge to map some of the sandstone packages within these wedges using seismic data. This is because they show high variability in thickness and facies, they can be laterally discontinuous, their geometries are controlled by a complex interaction between tectonics and sedimentation, and for those present near faults, very few wells have been drilled in the hanging walls (Nøttvedt et al., 2000; Olsen, 2017). In addition, the lithology of the provenance area can greatly affect the properties of the reservoir. This complexity and lateral variability in the reservoirs constitute a challenge especially since this target remains under-explored (Fraser et al., 2002). Furthermore, in areas such as the SW Barents Sea and in contrast to the Lower Cretaceous syn-rift to post-rift wedges where drilling shows high prospectivity, the Upper Jurassic syn-rift wedges have not been successfully drilled, despite the fact that on seismic these wedges have been mapped adjacent to the main fault planes and some wells have penetrated them finding sandstone deposits (e.g. wells 7120/2-2 and 7120/12-1) (Sandvik, 2014; Braut, 2018).

Furthermore, the understanding of the tectonic evolution of the region is key for influencing the styles of sedimentation for these wedges. Recent work has shown how the depositional model may change depending on the structural framework and tectonic evolution. Particularly, segmented versus non segmented rift systems and the impact of hard linked versus soft linked (relay ramps) transfer faults provide very different scenarios for sediment routing and depocenter distribution in syn-rift clastic wedges (Zhong, 2019). In order to build a predictive model for the clastic wedges in the NCS it is important to combine different disciplines such as seismic and log interpretations, outcrop studies, structural restorations, and tectonosedimentary modelling. The project aims for a 4-year period that includes at least two PhDs. One PhD will be located at the University of Stavanger and will focus on the subsurface studies and tectonosedimentary modelling. The other PhD will be located at the University of Basilicata and will focus on the outcrop studies, core sedimentology and tectonosedimentary modelling. The PhDs will collaborate to integrate their work.

2. Project objectives

The main objective of this project is to use subsurface data, outcrops, and tectonosedimentary modelling tools in order to understand the complexity and variability of syn-rift clastic wedges in the NCS, as well as better predict their location and reservoir facies. The project is divided into three specific topics:

1) Subsurface studies: The goal is to use seismic data, well logs and cores of some areas of the NCS in order to understand the variability and evolution of the syn-rift clastic wedges. The subsurface studies will include: 1) detailed mapping of faults and syn-rift wedges; 2) seismic attribute analysis (spectral decomposition, amplitude extraction, etc.) and seismic inversion for reservoir characterization; 3) detailed log and core characterization for the selected areas; 4) expansion index, isochore, and fault displacement backstripping analyses to determine the kinematics of fault growth; and 5) structural restoration as a way to reduce the uncertainty of the interpretation, as well as to understand the tectonosedimentary evolution. In case that angle stacks and shear sonic logs are available, the investigation could be extended to rock physics delivering rock moduli, which can be combined with the results of AVO inversion. The result would be a seismic lithology cube including facies probability cubes that

help understanding the variation of the reservoirs. Possible study areas are the Tampen Spur area in the northern North Sea, Fenja in the Norwegian Sea, and the western flank of the Loppa High in the SW Barents Sea (Fig. 1). However, the study areas will be discussed with the sponsors.

2) Outcrop studies: the goal is to study carefully selected outcrops as analogues of the syn-rift wedges of the NCS in order to understand the lateral and vertical variability of facies in this setting. The outcrops are located in Italy and Greece: 1) the Crati Basin (Calabria), which can be a good analog for understanding facies variations; 2) the Sardinia Graben, which can be a good analog for some of the geometries observed in the Upper Jurassic syn-rift wedges in the NCS; 3) the Messina strait; and 4) Gulf of Corinth. The outcrop studies will include lateral and vertical reconstructions of sedimentary successions deposited close to faulted margins, aiming at understanding models of sedimentary facies and their evolution in relation to tectonic activity.

3) Tectonosedimentary modelling: As described earlier, the wedge geometries and facies are controlled by a complex interaction between tectonics and sedimentation. Topics 1 and 2 above provide conceptual, intuitive models to understand this interaction, based on direct observations. However, we can move beyond by physically modelling this interaction through a process simulation model. This model consists of the different paleogeographic conditions (basin size and shape, sediment influx rate, climate, tectonics) through time from topics 1 and 2, and forward sedimentary process modelling to simulate the outcrop and subsurface observations. This strategy places constraints based on physical and geological knowledge on the simulated sedimentary wedges. When a good match between the models and observations is obtained, the models provide insight into the geologic past and their predictions can be used for interpolation and extrapolation between and beyond the observations (Tetzlaff and Priddy, 2001).

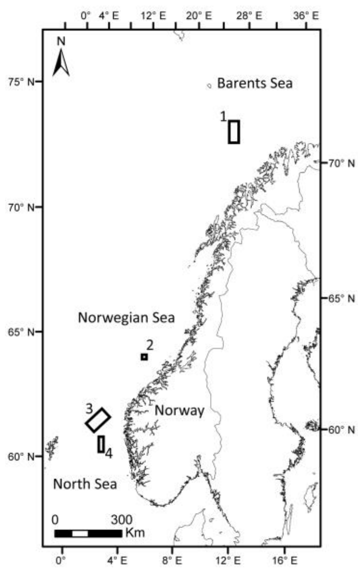

Fig. 1. Location map of the possible study areas on the Norwegian Continental Shelf. 1) Western Loppa High; 2) Fenja; 3) Tampen Spur area; 4) Oseberg-Brage.

3. Background

3.1 Tectonic controls on synrift clastic wedges

Pre-existing tectono-sedimentary models for rift basins were mainly constructed under the framework of extensional relay structures.

However, the interplay between tectonics and sedimentation in the context of rift segmentation has been recently discussed by Zhong (2019) where rift segmentation provides a different sedimentary model for syn-rift basins, where major feeders occur along the axis of segmentation, i.e. transfer faults and related second order segments, resulting in a different distribution of facies than in non-segmented rift basins. Therefore, it is important to understand the underlying structural framework of the basin and related syn-rift subbasins. Two main schools of thought provide explanations on the lateral offset of border faults and sedimentary depocenters in rift basins: (1) the development of extensional relay structures along rift margins that develop into transfer zones or transfer faults (Lister et al., 1986; Morley et al., 1990; Gawthorpe and Hurst, 1993); and (2) along-axis segmentation ("rift segmentation" *sensu* Hayward and Ebinger, 1996). Accommodation zones, transfer fault zones, and large transform faults are commonly developed in segmented rift systems. It is well documented that fault activity plays an important role in controlling the deposition of syn-rift sediments (Karner et al., 1997; Jackson et al., 2002; Richardson and Underhill, 2002). Classic tectono-sedimentary models show that fault growth generate repeated subsidence stages with consequent development of wedge-shaped or tabular growth strata in the hanging-wall of active faults (Crans et al., 1980; Gawthorpe and Hardy, 2002; Osagiede et al., 2014). The courses and routes of stream drainages vary significantly with fault development, generating, deflecting, and splitting of drainage systems along deformed surfaces (Gawthorpe and Leeder, 2008; Trudgill and Underhill, 2002).

3.2 Examples of syn-rift wedges acting as potential reservoirs in the NCS

Western flank of the Loppa High (Barents Sea): Upper Jurassic to Lower Cretaceous syn-rift to post-rift wedge-shaped geometries have been interpreted in the western flank of the Loppa High using seismic data (Fig. 2) (Blaich et al., 2017; Marin et al., 2018a; Kairanov et al., 2019). Sand-prone packages have been drilled in the upper Lower Cretaceous (e.g. 7220/10-1; 7220/5-2; 7219/9-2), and the depositional environment for these is interpreted as lower shoreface to offshore (Figure 3; Ärlebrand, 2017; Marin et al., 2018b). Different observations suggest that faults were active during the Late Jurassic in this area (wedge-shaped geometries, high sedimentation rates, and lower total organic carbon – TOC - in wells adjacent to the main faults). However, there is a lack of proven reservoirs in this Upper Jurassic interval (Blaich et al., 2017; Marin et al., 2018a; Kairanov et al., 2019; Marin et al., in prep.). Only minor siltstone to very fine sandstone stringers were penetrated by well 7219/8-1s, and well 7318/12-2 penetrated Upper Jurassic sandstone (Helleren, 2019).

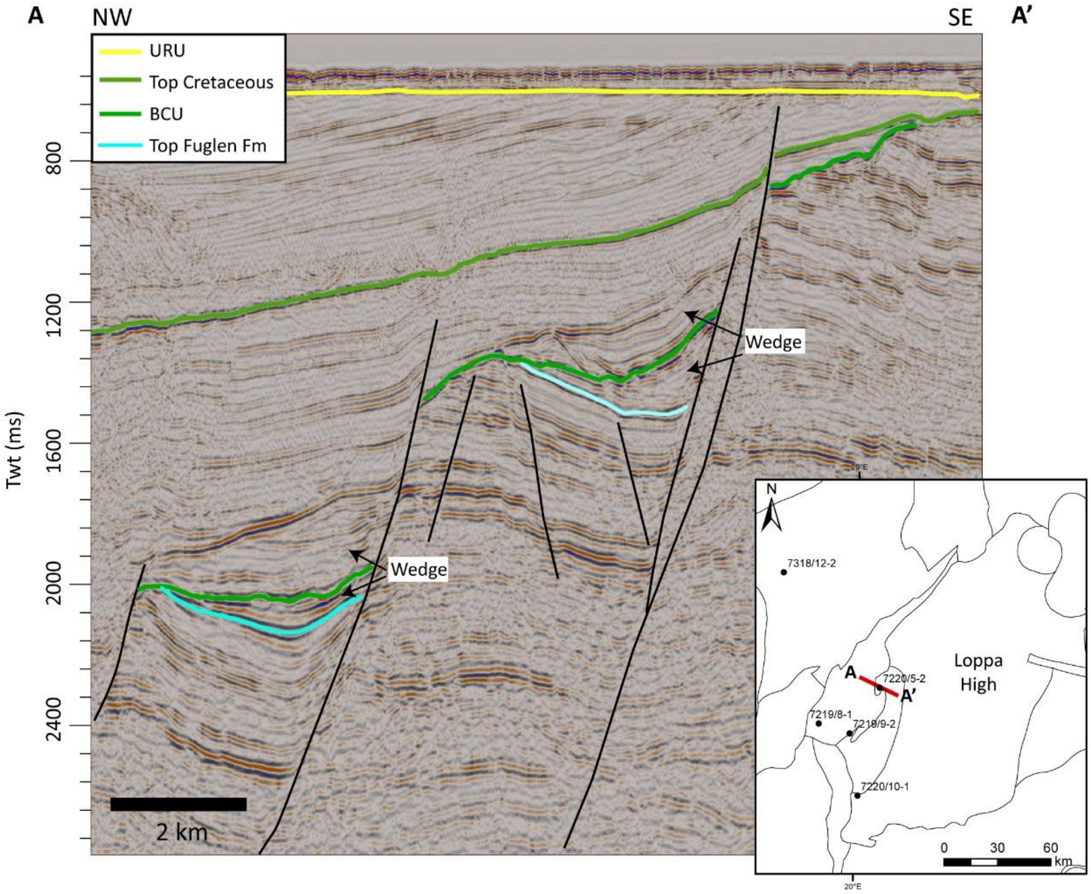

Fig. 2 Seismic line showing the Upper Jurassic to Lower Cretaceous wedge-shaped geometries in the western Loppa High, SW Barents Sea. BCU: Base Cretaceous Unconformity

<u>Tampen Spur area (North Sea):</u> Syn-rift wedge-shaped geometries in the area are composed of the Heather and Draupne formations (Fig. 3). The Heather Formation (mid Bathonian to early Oxfordian) is interpreted to be predominantly fine-grained in this area because of only minor erosion from the uplifted footwalls (Nøttvedt et al., 2000). It is believed that sources of sediment from the uplifted footwall were properly developed during the deposition of the Draupne Formation (late Oxfordian to Ryazanian; Nøttvedt et al., 2000). Sandstone and conglomerate have been drilled in the Draupne Formation and interpreted as shoreline tidal ridges, footwall talus or deep marine deposits (Færseth et al., 1995; Dawers et al., 1999; Nøttvedt et al., 2000; Chiarella et al., 2020). These sand-prone syn-rift packages are associated with footwall erosion of the Brent Group and are usually discontinuous and difficult to map on seismic, because their thickness can be close or under the seismic resolution (Færseth et al., 1995; Nøttvedt et al., 2000). Sand-prone syn-rift wedges have been penetrated by wells 33/9-

15, 33/9-16, 34/7-23-A, 34/7-23-S, 34/7-21, 34/7-20, 34/4-3, 34/8-7 in the Tampen Spur area (NPD, 2019).

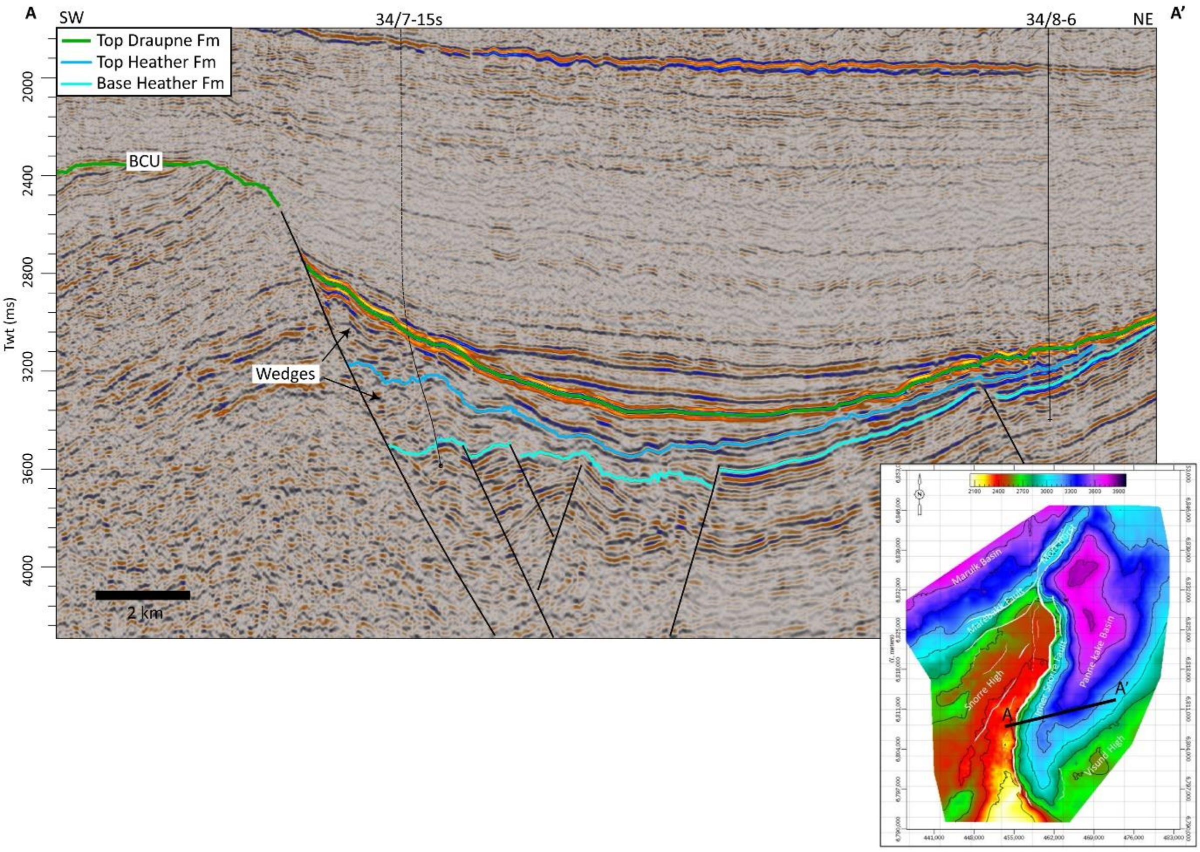

Fig. 3. Seismic line showing the Upper Jurassic wedge-shaped geometries in the Tampen Spur area. Structural map at the Base Cretaceous Unconformity (BCU; Eskandari, 2019).

<u>Oseberg-Brage (North Sea):</u> In the Oseberg-Brage area, syn-rift wedge-shaped geometries have been interpreted in the Heather and Draupne formations (Fig. 4). In contrast to the Tampen Spur area, sand-prone packages were deposited contemporaneously to the Heather Formation in this area (Ravnås and Bondevik, 1997). These sand-prone packages belong to the Fensfjord (Middle Callovian to early Oxfordian) and Sognefjord formations (late Oxfordian to Kimmeridgian). The depositional environments of these packages are interpreted to be shallow-marine, storm-to-wave dominated shoreface during an initial regressive period, and current dominated during the transgressive period (Ravnås and Bondevik, 1997). Intra-Draupne sand-prone packages also have been drilled in the area and they are interpreted as gravity-flow deposits (Ranvnås and Steel, 1997 and Ravnås et al., 2000).

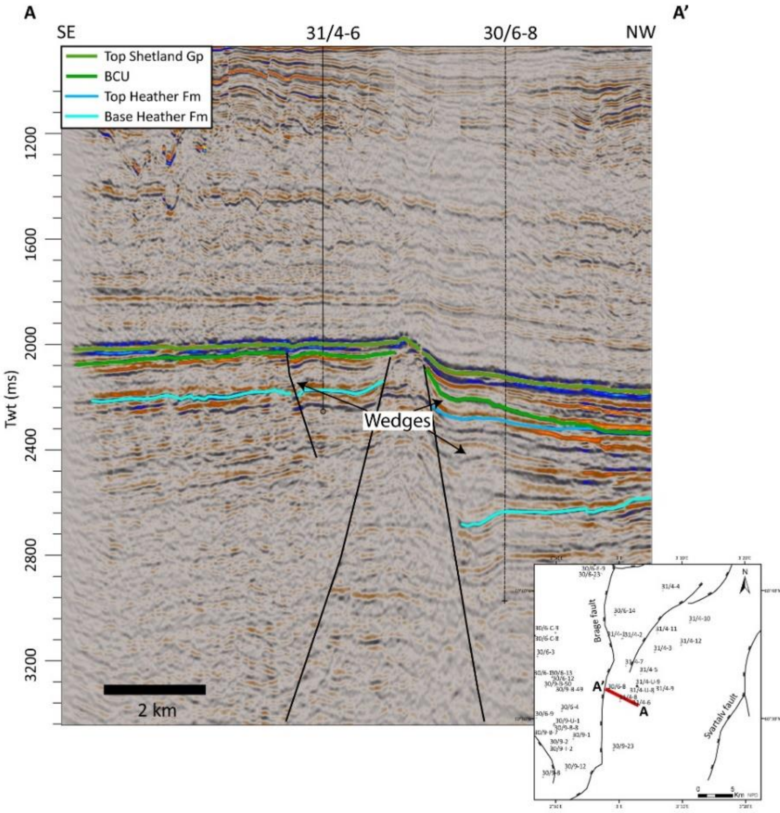

Fig. 4. Seismic line showing the Upper Jurassic wedge-shaped geometries in the Oseberg-Brage area.

3.3 Examples of outcrop analogues and implications of increase knowledge of the subsurface

Southern Italy is a key region for the analysis of outcrop analogues for the NCS. During the Neogene-to-Quaternary, a number of extensional basins developed in this area of the central Mediterranean and the present-day exposure of their basin-fill sedimentary successions serves greatly to reveal depositional architectures, sandbody geometries and facies variability for a variety of environments, recorded within terrestrial, to shallow-marine, to deep-water deposits (Longhitano et al., 2012). Moreover, the degree of exposure, the accessibility of the various outcrops and facies vertical/lateral stratal continuity allow the understanding of crucial information for characterization of subsurface reservoirs accumulated under very similar geological conditions.

Fig. 5 Location of the three areas which will be used as outcrop analogues in southern Italy.

Four main field areas have been selected to serve as outcrop analogues for the investigated subsurface sites of the NCS: 1) the Crati Basin, 2) the Sardinian Graben, 3) the Messina Strait (Fig. 5) and 4) Gulf of Corinth Greece.

The Crati Basin: The Crati Basin is a Pliocene-Quaternary, ~50x20 km extensional depression developed as a wide embayment in a general extensional regime on top of the Calabrian Orogen, in southern Italy (Fig. 6). The margins of the basin were active during the sedimentation, mainly dominated by differential dip-slip kinematics that greatly controlled along-dip and along-strike variation of accommodation space. This setting resulted in the accumulation of 100s m-thick successions, including continental, shallow-marine (shorefaces and fan-deltas) and offshore strata. Today, these deposits are exposed in a number of outcrop sections (Fig. 6B to D) that allow detailed observations on the geometrical relationships with major faults active during the sedimentation, the reconstruction of the timing of the faulting, and the resulting facies/system relationships.

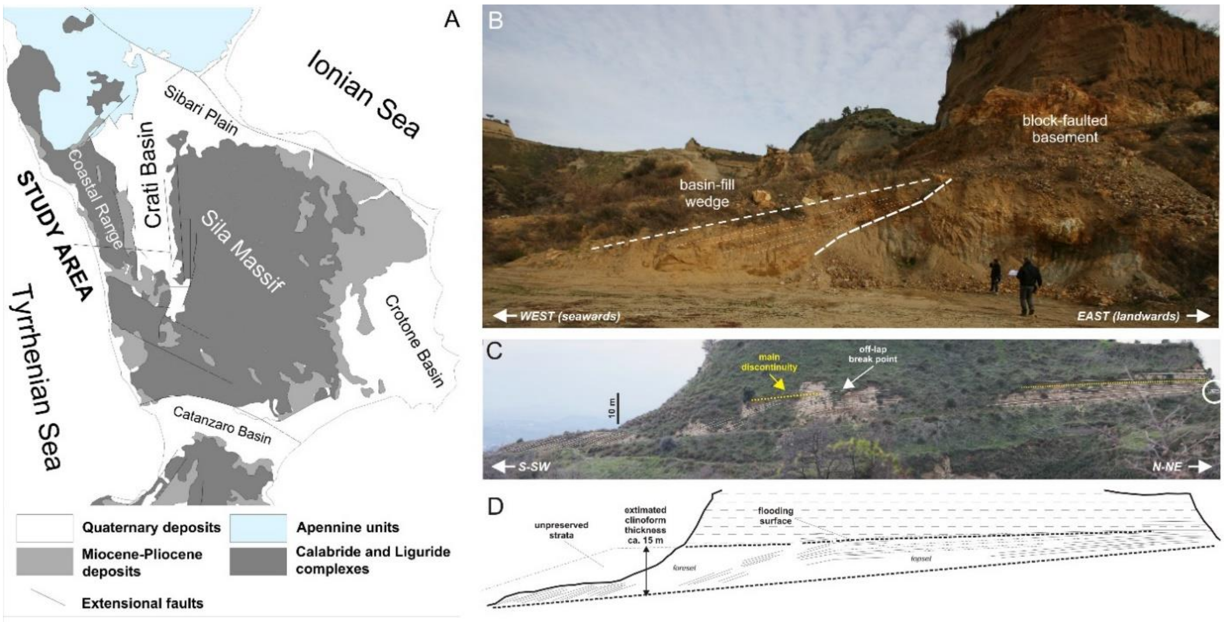

Fig. 6 (A) The Crati Basin in southern Italy. A possible preferential area is indicated from where outcrops in B and C were depicted. (B) Example of fault-attached shallow-water wedge. (C) Case of clinoform sandbody encased within offshore fines (D) Lined drawing of the previous outcrop.

Moreover, very-well exposed outcrops may reveal the superimposition of high-frequency eustatic signals over the tectonic subsidence, responsible for the nucleation of individual sandbodies and their relative position respect to master faults. This setting seems to be particularly advantageous for supporting the interpretation of subsurface successions preserved in the Oseberg-Brage area, North Sea.

<u>The Sardinian Graben:</u> The Sardinian Graben consists of a series of coalescent half- and symmetric grabens, developed along a N-S-oriented main rift systems during the Miocene, in the western Mediterranean (Fig. 7A). The whole system is ca. 200 km long and 20-to-60 km wide and host three main depositional sequences separated by regional-scale unconformities, whose remnants are variously exposed in a number of sub-basins composing the graben. These depressions experienced endoreic settings during various stages of the Miocene but became interconnected during some major phases of marine transgression. As a consequence, the graben turned into a seaway (i.e., the Sardinian Seaway, *cf*. Longhitano et al., 2017; Telesca et al., in press) several times during the Miocene, promoting along-shore oceanographic circulation and the transfer of huge quantity of sands as shorefaces and elongated sand ridges. One of this is represented by the Logudoro Basin, located in northern Sardinia (Fig. 7A). This basin hosts a variety of sections and stratigraphic windows on two of the three major sequences and allows the detailed characterization of fan-deltas and sand ridges whose sedimentation was dominated by the continuous interplay of waves and (tidal) currents (Figs. 7B to D). The Logudoro Basin includes deposits suitable as outcrop analogues for the Tampen Spur area in the NCS.

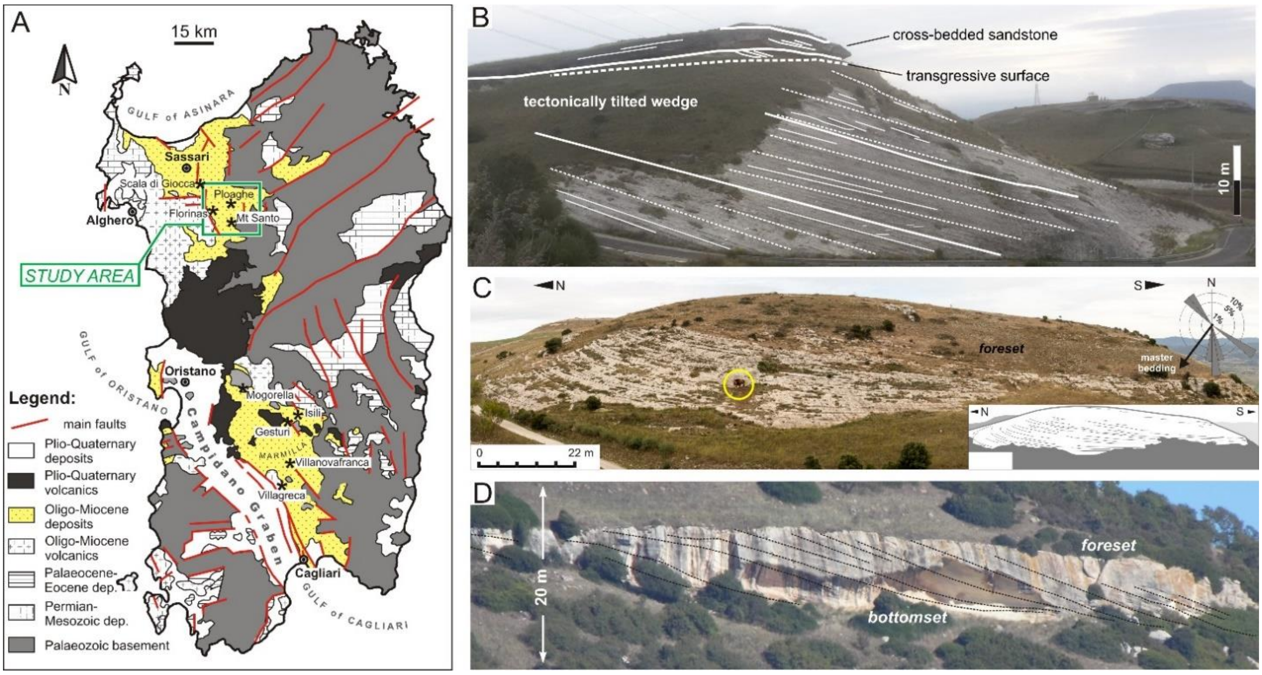

Fig. 7 (A) The Sardinian Graben deposits are indicated in yellow. Note the location of the Loguoro Basin. Asterisks shows the position of additional sections with some potential interest. (B) Outcrop section from the Logudodo Basin showing tectonically inclined beds belonging to deltaic facies and erosionally overlain by offshore cross-bedded sandstone. (C) Clinoform architecture attributable to an individual tidal sand ridge. (D) Detail of foreset-bottomset sandstone encased into offshore fine sands (modified, after Telesca et al., in press).

The Messina Strait: The Messina Strait is a Pliocene-Quaternary extensional basin that today separates Sicily from the peninsular Italy in the central Mediterranean (Fig. 8A). The modern channel is ca. 3 km-wide in its narrowest point, which is continuously crossed by powerful bi-directional and collinear tidal currents that erode and accumulate huge quantity of clastic sediments along the strait areas (Fig. 8B), producing very specific sedimentary dynamics and facies partitioning (Longhitano, 2018a). Its uplifted margins preserve sedimentary sequences that are magnificently exposed in a number of sections (Fig. 8C). These cliffs reveal structural features, sandbody geometries and facies variety of systems developed in a tectonically-confined setting very similar to the one developed in more recent time in the modern strait (Longhitano, 2018b). In particular, marginal faults that were active during the early Pleistocene are visible in many areas of the eastern strait margin (Fig. 8D). They can be followed for kilometers, offering the possibility to observe how fault-attached stratal wedges were influenced by the tectonic displacement and how internal facies changes, moving from hanging-wall to foot-wall segments along discrete transects oriented normally to the master faults (Fig. 8E). Sedimentary deposits consists of fan-deltas, detritic talus, shorefaces and shelves, whose deposition was governed by local factors, but variously influenced by tidal currents flowing normally to the coastline, at that time (Fig. 8F). This specific setting is useful for disentangling tectonically-confined depocentres and related wedge-shaped successions of the Oseberg-Brage area in the NCS, as well as the western flank of the Loppa High, in the Barents Sea.

Gulf of Corinth: UiS has considerable experience of the Gulf of Corinth, especially in the Kalavrita–Derveni region where several rotated fault blocks are exposed with syn-rift infill. The syn-rift infill varying from alluvial fans, fluvial deposits, lacustrine environments, Gilbert deltas and deep marine turbidite systems. UiS have supported 19 MSc thesis projects covering a range for topics from structural modelling, transfer fault evaluation, fault displacement analysis, rift-related sedimentation processes and development syn-rift graben in-filling. In addition, one PhD has studied the impact of border fault evolution in the development of gilbert-type fan deltas, plus UiS has run a yearly field course in mapping and geomodelling for MSc students. The outcrops in the Gulf of Corinth allow 3D syn-rift graben in–filling processes and their sequence geometries to be studied in detail. In particular, the control of normal faulting can be easily established in this region and the important influence of lateral transfer faults can be studied.

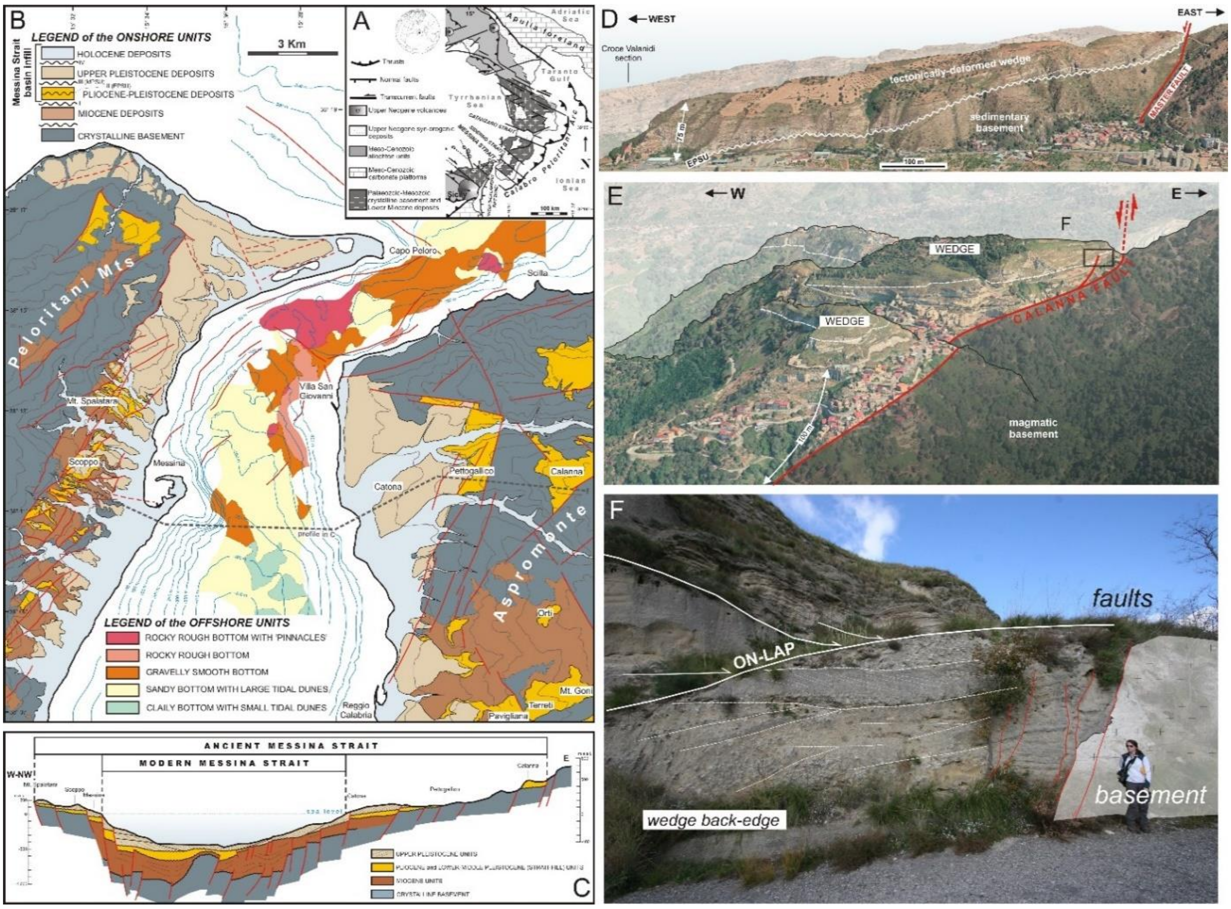

Fig. 8 (A) The Messina Strait represents an extensional basin superimposed onto a small orogeny. (B) Geological sketch map of the strait and of the modern deposits in the strait bottom. (C) Geological cross section showing the comparison between the modern and the ancient strait. (D) Outcrop section showing a faulted wedge including conglomerates and sandstones, overlying a basal unconformity and overlain by a transgressive ravinement surface (E) Additional example of outcrops located along fault-attached wedges (F) Detail from the previous photograph (modified, after Longhitano, 2018a,b).

3.4 Advantages of tectonosedimentary modelling

Tectonosedimentary models are more difficult to condition to observations than geostatistical models. Also, the tectonic and sedimentary processes taking place over long periods of time are complex and difficult to represent mathematically. Nevertheless, these models offer an improvement over geostatistics in that they incorporate geologic knowledge and basic physics laws. The main advantage of the models is that they provide robust physical means for interpolating and extrapolating between and beyond observations (Tetzlaff and Priddy, 2001). A good example is Nguyen et al. (2019) who modelled a Lower Cretaceous turbiditic reservoir in the Måløy Slope, northern North Sea (Fig. 9). From a paleobathymetry map, two wells, and seismic slices highlighted by spectral decomposition, they were able to match the observations and simulate with unprecedent detail the reservoir unit and its spatial facies and property (petrophysics) variability. Models matching selected outcrops (topic II) can increase their spatial and temporal coverage, and forward seismic modelling can provide a link with the seismic data and interpretations (topic I) (Drinkwater et al., 2003). The modelling will be performed using the "geological process modelling" (GPM) Petrel plugin (Tetzlaff et al., 2014). We have experience combining tectonic and GPM modelling in extensional (Malde, 2017; Nguyen, 2019), compressional (Jaimes, 2019), and salt tectonics settings (Rojo et al., 2019).

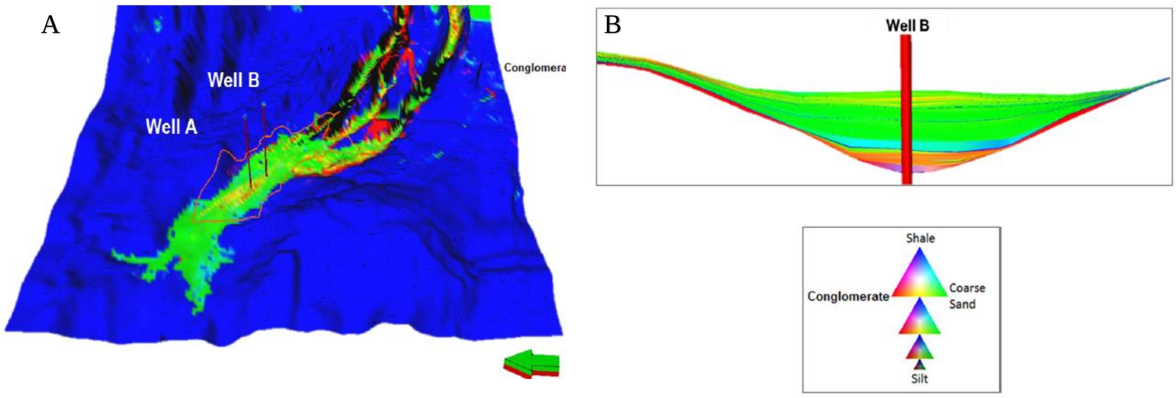

Fig. 9 Tectonosedimentary model for a turbidite system fed by 2 point sources in the northern North Sea; A) model in 3D view; B) Cross section along well B (Nguyen, 2019)

4. Project plan and management

The initial structure of the project includes two PhDs that will cooperate and complement each other in order to achieve the goals of the project. They will work on the main tasks and deliverables. The PhDs will be co-supervised by the various researchers involved in the project, who have expertise from field data, reservoir characterization, subsurface mapping and tectonosedimentary modeling. Upon funding, more PhDs may work on the project.

4.1 PhD at University of Stavanger:

This PhD will focus on subsurface characterization and tectonosedimentary modeling. The main tasks are:

- Seismic and well characterization and mapping of syn-rift infill half grabens where clastics wedges are suspected or have been recognized.
- Understand the different tectonic elements that control the sedimentation and preservation of syn-rift clastic wedges. Sediment growth analysis, fault displacement backstripping, and structural restorations are key to understand that.

- Model the interaction of tectonics and sedimentation and develop different, geologically and physically possible scenarios for the deposition and preservation of the clastic wedges.
- Integrate the field analogue data into the various elements of the subsurface studies.
- Evaluate the reservoir potential.

4.2 PhD at University of Basilicata:

This PhD will focus on outcrop characterization and tectonosedimentary modeling. The main tasks are:

- Investigate and describe field areas that resemble various scenarios of coarse-grained syn-rift clastic wedges in extensional systems and basin margins.
- Construct detail facies distribution maps and understand the tectonic mechanisms that control the facies variability.
- Develop seismic scale models that can serve as a foundation for the subsurface mapping.
- Model the interaction of tectonics and sedimentation at the outcrop scale.

We also expect to have several master students working on various more specific problems in the form of thesis projects.

The main deliverables will be all the produced interpretations, including maps, correlations and cross-sections as well as all modelling results. A main result will be the PhD dissertations, which will represent the compilation of all material in addition to conference presentations and peer-reviewed papers. An annual meeting will be held during the duration of the project with the sponsors to show progress. The meetings will provide an arena to provide feedback to the project and PhDs. A GIS database and a detailed final report will be provided at the end of the project, where all analyzed subsurface and field data will be located, so that they can be easily accessible by the companies. In addition, a field trip to the proposed outcrop areas will be offered upon agreement between the sponsors and researchers. Sponsors need to cover their own travel expenses.

The main data to be used in the project include publically available seismic and well data via the Petrobank, and field data from southern Italy (at least from two localities) and Greece. In addition, we aim to get more recent data via seismic service companies, or via the sponsors.

4.3 Project management

The project will be managed by project leader Professor Alejandro Escalona and Associate Professor Dora Marin (both with expertise in subsurface mapping and syn-rift clastic wedges) at the University of Stavanger, and by Professor Sergio Longhitano (expertise in sedimentology, depositional systems and outcrop studies) at the University of Basilicata. Other key researchers in the project are Professor Nestor Cardozo (UiS, expertise in structural geology and tectonosedimentary modelling); Associate Professor Carita Augustsson (UiS, expertise in sedimentology and reservoir characterization); Associate Professor Wiktor Weibull (UiS, Geophysics and seismic modelling), Adjunct Professor Christopher Townsend (UiS expertise in structural geology and modelling); and Dr. Lothar Schulte (Schlumberger; expertise in geophysics and tectonosedimentary modelling, specifically GPM).

The project funds will be used mostly to support the PhDs, field work, travel, and Master theses derived from the project. The University of Stavanger has excellent seismic and well data infrastructure, and it is close to the Norwegian Petroleum Directorate for access to key well cores. The University of Basilicata has large experience in fieldwork in extensional settings with easy access to excellent outcrops.

<u>Budget</u>

In million NOK

	2020	2021	2022	2023
PhD 1	1.2	1.2	1.2	1.2
PhD2	0.5	0.5	0.5	0.5
Adjunct prof	0.3	0.3	0.3	0.3
Travel and field work	0.3	0.3	0.3	0.3
Equipment	0.2	0.2	0.2	0.2
Total	2.5	2.5	2.5	2.5

Estimated Total: 10 MNOK

We aim for a minimum of four sponsors and estimate a total budget of 10 MNOK for the four-year period. The cost per sponsor is 2.5 MNOK for the entire project or 625.000 NOK per year with a four-year financial commitment. The desired start period is August 2021, but it will depend upon discussion with all the sponsors interested in the project.

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