Characterization of Permian mixed carbonate-clastic systems in the Jeffara area, Central Tunisia

MSc Thesis Applied Earth Sciences
Delft University of Technology March 2022

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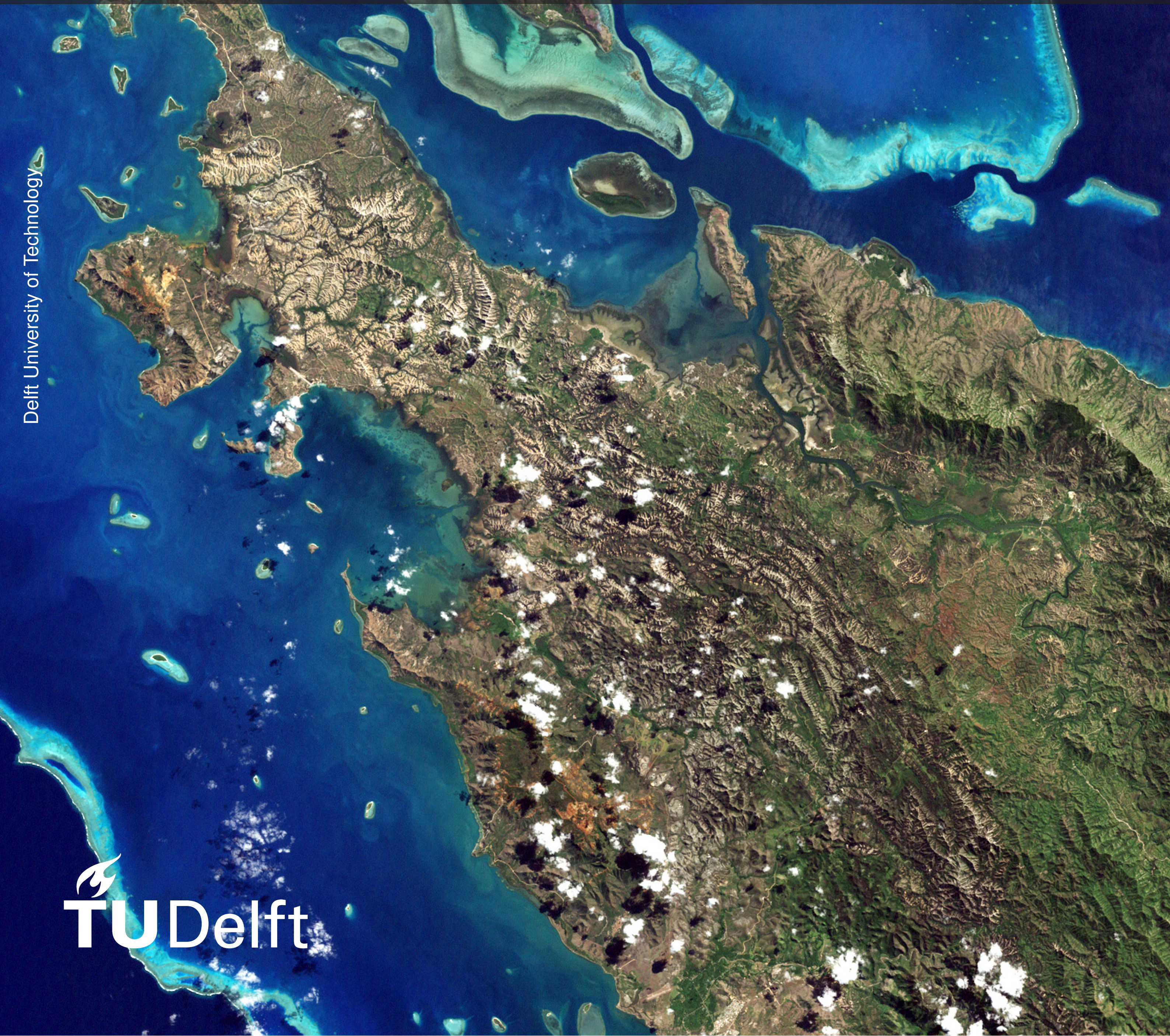

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by

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to obtain the degree of Master of Science (MSc.)

at the Delft University of Technology,

to be defended publicly on the 18th of March, 2022 at 15:00 pm CET.

Student Number:	5059291
Project duration:	December 15, 2020 – March 18, 2022
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Cover Image: NASA's Landsat 7 satellite captured this image of Île Balabio, off the northern tip of Grande Terra, New Caledonia's main island. In this natural-color image, the islands appear in shades of green and brown—mixtures of vegetation and bare ground. The surrounding waters range in color from pale aquamarine to deep blue, and the color differences result from varying depths. Over coral reef ridges and sand bars, the water is shallowest and palest in color. Taken on 10 May 2001 from NASA Earth Observatory.

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Abstract

Permian deposits are found in outcrops and in the subsurface of Southern Tunisia, in the Jeffara Basin. Their stratigraphic and tectonic evolution is not yet fully understood and represents the main focus of this work. Aspects of the Permian system such as, lateral extend of formations, dating and paleo environments are not well constrained. Answering these questions will impact future hydrocarbon exploration and also improve the geological understanding of Tunisia. To achieve this, seismic lines and well data of the Jeffara Basin have been re-interpreted and re-correlated.

The results of the study indicate a lagoon depositional environment for the Early Permian, a carbonate self environment for the Middle-Upper Permian successions, with dimensions of 80 square kilometers and a general east-west orientation. The thickness of the carbonate deposits reaches a maximum of 2500 kilometers to the north of the reconstituted paleoshore. A Sabkha environment has been interpreted for the Upper Permian with significant deposits of anhydrite. Structurally, it was observed that the Permian is not affected by major normal faults.

Conversely, significant folds have been identified at the seismic data, with a general east-west strike and a northwards dip. Based on the displacement of seismic reflectors, two tectonic episodes have been identified. The first is dated to the Upper Carboniferous - Early Permian and the second to the Early-Middle Triassic. Decompaction calculations indicate low subsidence rates and general stability during the Early Permian. This was followed by significantly increased subsidence rates during the Middle and Upper Permian.

Preface

This project was undertaken as part of the broader research conduced by the North African Research Group (NARG) and using seismic and well data provided by Mazarine Energy. Thus, I would like to thank both of those parties for providing me with the opportuinity to conduct a thesis project as fascinating as this.

I would like to thank Dr. Pierre Oliver Bruna for the countless meetings and conversations we had during the past one and a half year, as well as all the technical help and assistance that he so openly provided me with throughout this project. His support made this project much more enjoyable and worthwhile despite all the difficulties that were encountered along the way. I would like to thank Prof. Giovanni Bertotti and Prof. Allard Martinius for their guidance and constructive criticism throughout this project as well. Moreover, I would like to thank Remi Charton from TU Delft, and Richard Dixon from Mancester University for the very stimulating and constructive discussions we had over the geology of North Africa and Tunisia. A lot of ideas were born out of our conversations which allowed me to continue with the project and see things from a different prospective. Additionally, I would like to thank my fellow TU Delft students, whose help and assistance the past two years I greatly appreciate and cheerish.

My last thanks go to my family. Without their support and guidance I would not have achieved half of what I have done in my life. For you faith in me all the way from back home in Greece the past two years, thank you.

Christos Kougioulis
Delft, March 2022

TU Delft

mazarine energy

North Africa Research Group
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Introduction

1.1. Outline

The Jeffara Basin is located to the Southern Tunisia close to the border with neighbouring Libya. The Paleozoic in the basin is composed of the Ordovician, which acts as the basement, the Carboniferous and the Permian. The later is dominated by carbonate deposits, with clastic influence. The Paleozoic deposits are followed by the extensive Mesozoic which is found in multiple outcrops in the region.

Figure 1.1: Location of the area of interest in southern Tunisia.

With regards the geology of the Tunisian Permian, the basin is of special interest for two main reasons. First, the only Permian outcrops of Tunisia are located at its vicinity, at the Tebaga of Medenine

(Burollet et al., 1990). Second, the Permian deposits in the Jeffara Basin are extensive, which is the opposite of what is observed in the Chotts Basin to the West, where the Permian is thin, and at the Ghadames Basin further to the South of the Telemzane Arch, where the Permian is missing (Soua, 2014).

Despite this, the area has yet to been examined thoroughly and its geological history is controversial (Zaafouri et al., 2017) with conflicting theories as to its tectonic evolution (Guiraud et al., 2005; de Lamotte et al., 2013).

As such, a more detailed examination of the basin is timely. This forms the overarching goal of this thesis, namely to improve our understanding of the evolution of the clastic-carbonate system that was active during the Permian in the Jeffara Basin. To achieve this goal, a number of research questions are posed:

1. *What is age of deposition of the Permian lithologies?*
2. *What is the geometry of the Permian deposits?*
3. *What is the structural evolution of the Permian in the Jeffara Basin?*
4. *How did the paleo-environment evolve during the Caboniferous-Permian?*

2
Regional Geology

2.1. Geology of the Jeffara Basin

The Jeffara Basin is located to the South of Tunisia and covers an area of approximately 100 square kilometers. Two other significant sedimentary basins are also located in that region of Tunisia. Namely the Southern Chotts Basin to the west, and the Ghadames (Berkine) Basin to the south (Soua, 2014; Jabir et al., 2020). Paleozoic deposits are found in all three of these basins. The Permian however is only identified in significant thickness at the Jeffara Basin. It is completely absent from the Ghadames Basin and present in small intervals to the West of the Southern Chotts Basin (Soua, 2014).

The most significant structural feature to the south of the Jeffara Basin is the Telemzane Arch. This is one of multiple arches that have been identified at the Paleozoic of North Africa, and is the result of uplift dated to the Late Devonian (de Lamotte et al., 2013) which could be related to the early stages of the Hercynian Orogeny (Jabir et al., 2020). This arch forms the extention of the another such structural feature identified in Libya, the Nafusa Arch (Soua, 2014).

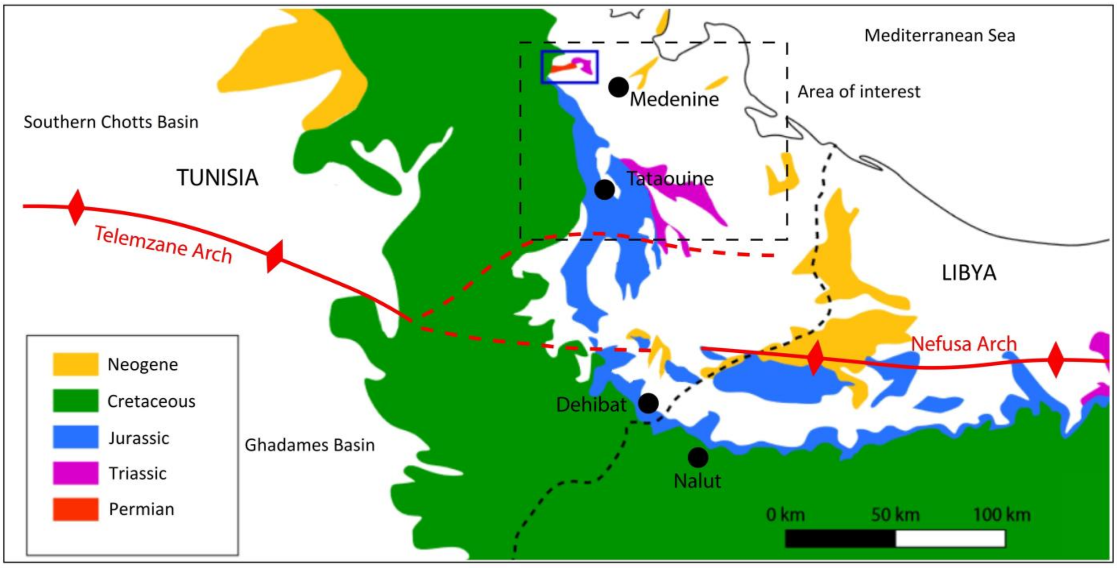

Figure 2.1: Geological setting of South Tunisia (Modified from (Bruna et al., 2019))

The lack of Devonian rocks at the Jeffara Basin indicates either non deposition during that geological period (Soua, 2014) or a significant erosion dated either at the Early Carboniferous (de Lamotte et al.,

2013) or the Late Devonian (Guiraud et al., 2005) identified with the main Acadian event.

During the Early Carboniferous another tectonic event also related to the Hercynian Orogeny took place (Soua, 2014; Jabir et al., 2020) and is responsible for the formation of faults and folds in the region and the further uplifting of the Telemzane Arch, which was already acting as a local high.

Following these structural changes, Carboniferous and Permian rocks were deposited on the Ordovician formations. The tectonic evolution of the Jeffara Basin during the Carboniferous and the Permian is controversial. Rifting (Guiraud et al., 2005) in the form of multiple pulses (Bumby and Guiraud, 2005) is suggested and associated with the early stages of the breakup of the Ghodwana supercontinent, lasting until the Middle Jurassic (Bumby and Guiraud, 2005), early Jurassic (Schettino and Turco, 2011) or the Cretaceous (de Lamotte et al., 2009).

However, the possibility of subsidence as a result of thermal sag initiated during the Upper Permian (Stampfli and Borel, 2002) or during the Upper Carboniferous and lasting until the Middle Triassic (de Lamotte et al., 2013) has also been explored. The completion of the Paleozoic saw the erosion of the Upper Permian at certain areas and the deposition of Triassic deposits (Soua, 2014; Jabir et al., 2020). The tectonic evolution of the Jeffara Basin during that period is also problematic, with rifting associated with the opening of the Neo-Tethys sea being suggested (Guiraud et al., 2005; de Lamotte et al., 2013) while other studies indicate an alternating rifring and a compressional domain (Carpentier et al., 2016).

3

Data Set & Data Integration

In this chapter, the data, data sources and the software that were utilized for this project are presented. The majority of this data was provided for the purpose of this project by Mazarine Energy[1]. This includes seventeen (17) seismic lines and eleven (11) exploration wells at the Jeffara Basin. Moreover, an additional six (6) seismic lines and retrieved from a study of the same region (Zaafouri et al., 2017). In this publication, an additional ten exploration wells are shown, six (6) of which also considered for this project.

[1] https://www.mazarine-energy.com

3.1. Seismic Data

The seismic lines provided by Mazarine Energy also vary in quality (Table 3.1). Eight of these are of high quality, with good resolution and allow for a comprehensive stratigraphic and structural interpretation. The remaining lines are of medium quality. Their interpretation is possible but the reduced quality makes following seismic reflectors more difficult and introduces uncertainty.

The seismic lines retrieved from the Zaafouri et al. (2017) (Figure 3.3) as well as the suggested seismic interpretation found therein were imported into the Petrel Project so that it could used for the generation of surfaces and for quick comparisons with the interpretation suggested from this project. Since the lines in the publication have been completely covered over with color and their resolution is not high, a complete re-interpretation was deemed impractical. However, the offered interpretation was considered during the project for comparisons and guidance.

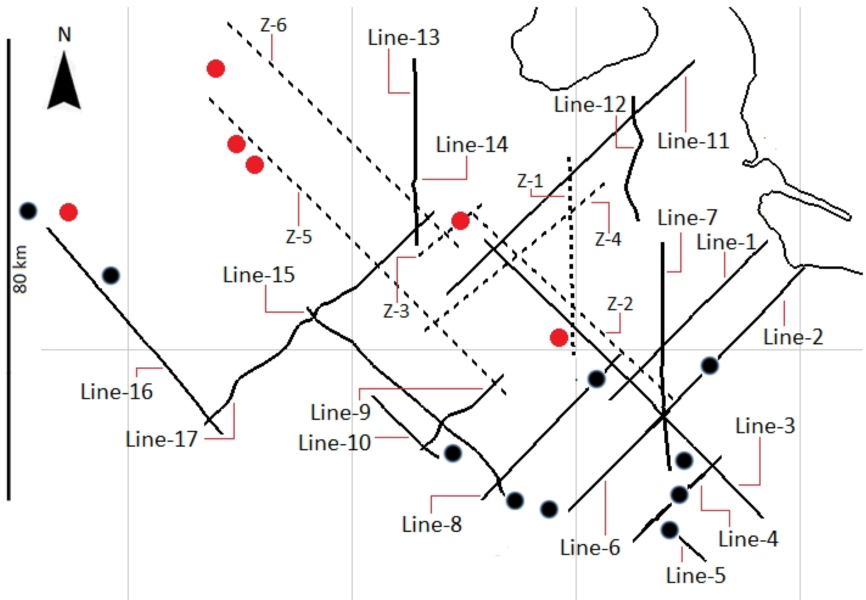

Figure 3.1: Map presenting the location of all seismic lines provided by Mazarine Energy and retrieved from literature.

3.2. Well Data

The information that is provided by the wells is of varying quality (Table 3.2). Due to their stud date, dating from the 1950's and the 1980's, some of the information provided by the completion report, such as geological ages and geological formations, is outdated or inaccurate based on the present understanding of the region. Moreover, the older wells come with only partial completion reports that in turn makes the complete use of the information provided by the log suits impossible, since critical information such as scale or units are not provided.

The well reports are also complimented with micropalaeontological information for the entirety of the drilled columns with varying degrees of accuracy and detail. the information provided from the old wells is nowadays considered too vague to allow for a comprehensive correlation of intervals between the wells unless more information is provided. Lithological interpretation of the well logs is provided for all wells also.

Mazarine Energy also provided well tops for a number of wells, and some of the wells converted in time domain - plottable in TWT seismic data. A preliminary seismic interpretation spanning a section of

Name	Orientation	Corresponding Well	Length (Km)	Quality
Line-1	NE-SW	-	38	High
Line-2	NE-SW	Well-1	37	High
Line-3	NW-SE	-	67	High
Line-4	NE-SW	Well-3	20	High
Line-5	NW-SE	Well-5	10	Medium
Line-6	NE-SW	-	24	Medium
Line-7	N-S	-	38	Medium
Line-8	NW-SE	Well-2	33	High
Line-9	NE-SW	-	18	High
Line-10	NW-SE	-	15	Medium
Line-11	NE-SW	-	57	Medium
Line-12	N-S	-	19	Medium
Line-13	N-S	-	18	Medium
Line-14	N-S	-	13	Medium
Line-15	NW-SE	Well-6	48	High
Line-16	NW-SE	-	45	High
Line-17	NE-SW	-	53	Medium

Table 3.1: Table of seismic lines and corresponding wells projecting on them as provided by Mazarine Energy.

the examined region was also provided. This interpretation and the well tops were used during the first stages of the project during the familiarization with the data stage, and have since been supplemented by the progress of this project.

The wells retrieved from the same publication were not imported into Petrel, due to the lack of accuracy, but were used externally for comparisons the updated well interpretation suggested by this project since some of them are located close to lines provided by Mazarine Energy and thus a relative comparison can be done. More specifically, Wells number 2, 7, 8, 9 and 10 were utilized to greater or lesser degree for this project (Table 3.2).

ZW-6 has been identified with high degree of confidence as Well-11 of our data set, based on its lithology and location. ZW-10 is also of interest since it is located close to Line-3 and Line-8 and Well-2 of our data set. The lithology of Well 10 is shown in the publication and is composed of an interval of sand -dated to the Middle Permian in the publication- followed by anhydrite, and by carbonate deposits with a thin clastic interval towards the bottom. The age of all of these deposits is reported as Middle Permian in the report. The lithological column of this well is identical to what is observed in Well-2 and Well-1 of our data set and thus gives further support for the lateral continuity of these lithologies in the region.

Wells 7, 8 and 9 of the report show the Permian composed of carbonate rocks and they have been used to reinforce the interpretation of certain geometries and seismic facies that have identified in the data due to their close proximity to seismic lines, or since they lie at the path were these features are expected to appear based on their orientation.

Well-2 has been examined in the publication, but it is located isolated and without any seismic lines tied to it. This makes their use problematic since the way the Permian has been defined in that well is not elaborated upon in the paper and thus it is not definitely reliable. Based on its position it could be identified with well Well-10 of our data set, but with a low degree of confidence.

Well	G-ray	Spontaneous Potential	Resistivity	Calcimetry	Sonic Logs	Cuttings	Cores Sketches	Time Domain
Well-1	✓	✓			✓	✓		✓
Well-2		✓	✓			✓		✓
Well-3		✓		✓		✓		✓
Well-4		✓		✓		✓		
Well-5		✓		✓		✓		✓
Well-6		✓	✓			✓		✓
Well-7	✓		✓			✓	✓	
Well-8	✓		✓			✓	✓	
Well-9	✓		✓			✓		
Well-10		✓		✓		✓		✓
Well-11			✓	✓		✓		

Table 3.2: Table of wells from publications that were used during the project in combination with the seismic and well data set.

3.3. Literature Seismic Data

The seismic interpretation provided for the seismic lines at Zaafouri et al. (2017) defines an important horizon for the Permian, namely the Top Permian Carbonate reflector. Above this reflector a significant portion of the reflectors are assigned a Permian age, which is then followed by the overlapping Triassic. This interpretation was taken into account during the examination of the seismic data set.

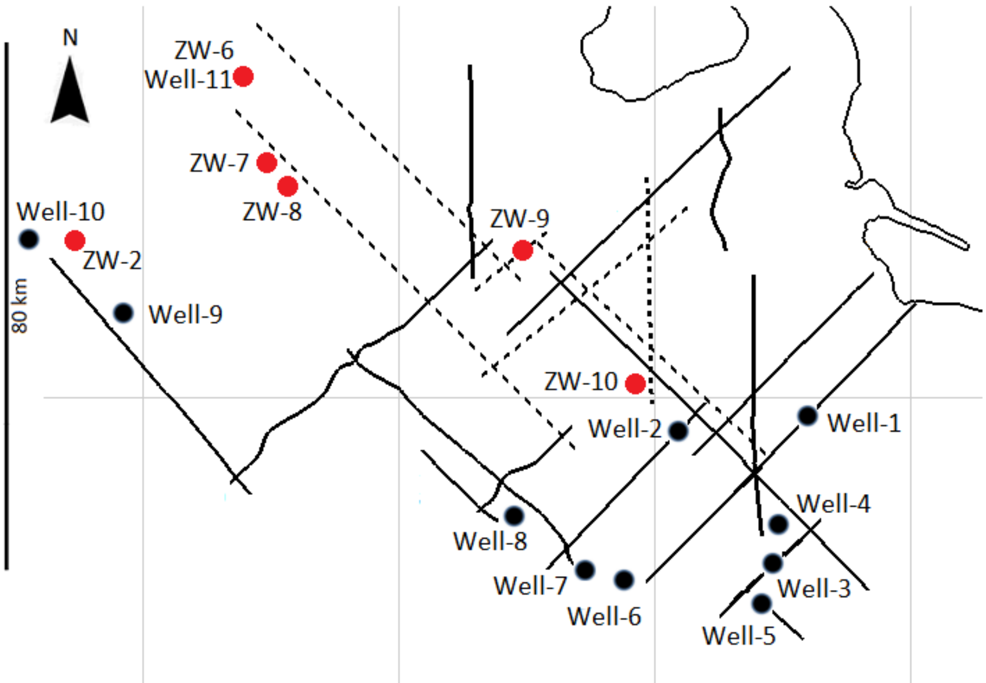

Figure 3.2: Map presenting the location of all wells provided by Mazarine Energy and retrieved from literature.

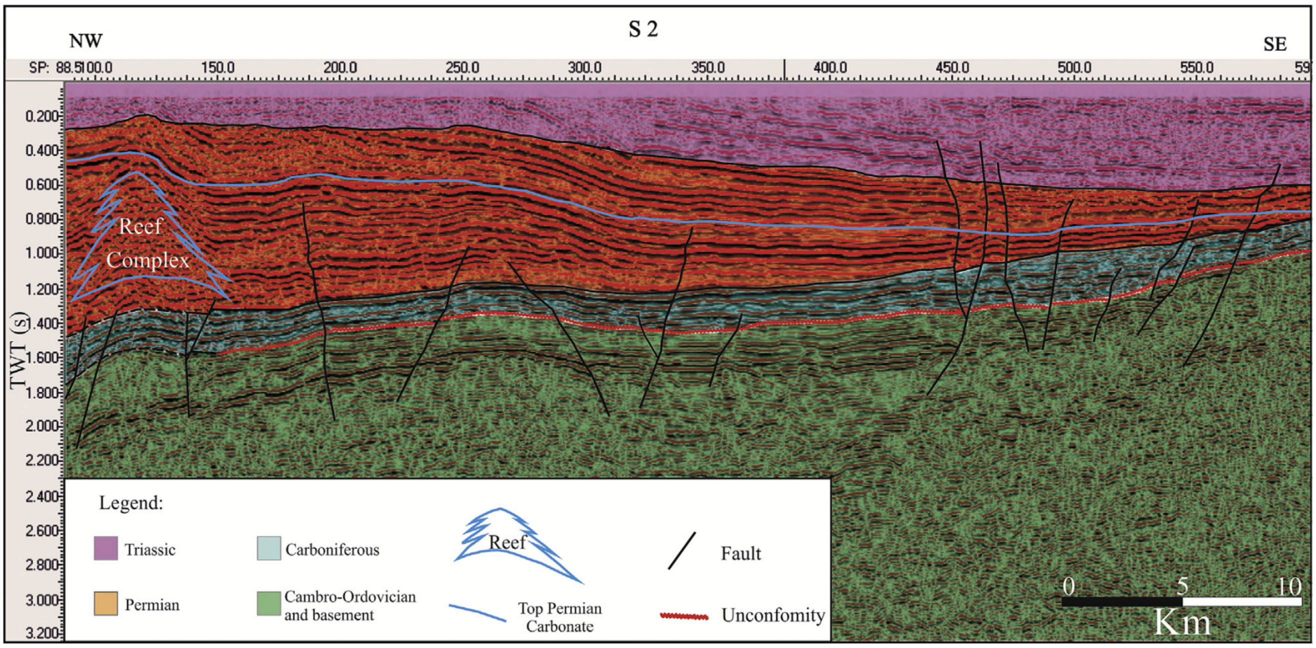

Figure 3.3: In this figure an example of the seismic lines that were exported from the Zaafouri et al. (2017) publication is shown, specifically Line-2. This particular line is of interest because it runs parallel to Line-3 of our data set. The reef complex identified in this line corresponds to the seismic facies with a carbonate lithology defined in this project. Source: Zaafouri et al. (2017).

4

Defining Seismic and Well Contacts

An issue that was encountered multiple times during the examination of the wells was the identification of the contact between the Permian and Triassic/Jurassic geological periods in the area. This issue was compounded by the presence of multiple unconformities which are poorly mapped and understood (Jabir et al., 2020; Zaafouri et al., 2017), as well as the fact that the boundaries suggested in the well reports are often hypothetical or are now considered outdated (Ghazzay et al., 2015). Thus, the upper and lower limit of the Permian had to be re examined in the wells and where appropriate updated - except the one well used for control, well Well-1. This process was performed by fully utilizing in parallel the available seismic data that was also available for this project.

4.1. Defining Seismic Permian Contact

The first stage of this seismic interpretation was the identification of the contact between the Permian, with the overlying Triassic, and the contact between the Permian and the underlying Carboniferous and Ordovician deposits. In order to perform this task, the control Well-1 was used. It was projected on top of the seismic Line-2 and the boundaries that correspond to the upper and lower boundaries of the Permian, the Ordovician and Carboniferous were identified and tied to specific seismic relfectors. At the same time, the micropalaeontological reports of all available wells were examined in detail and the intervals that can be definitively dated either to the Permian or to the Triassic/Jurassic based on their microfossils were identified. The intervals without fossils that reliably indicate either one of these geological periods and those that are azoic were grouped into a transitional group of an indeterminate age, either Permian or Triassic/Jurassic. Afterwards, the wells were projected onto seismic lines, and the identified-tied reflectors from the control well were expanded to the other lines and used to assign the appropriate depth of the Permian-Triassic/Jurassic contact within this transitional group. For the Permian-Ordovician/Carboniferous contact a similar workflow was followed but at a more limited scale since the majority of the wells do not provide sufficient information about the depth that the Permian transitions to the Ordovician/Carboniferous.

Some of wells (e.g. Well-10) have not penetrated deep enough into the subsurface to reach the Carboniferous-Ordovician rocks in the first place and the drilling was completed in the Permian. In others (e.g. Well-6, Well-7) the contact between the Permian and Ordovician/Carboniferous/ Cambrian was assigned at the completion report at an arbitrary depth of a very thick azoic sandstone formation or in other wells (e.g. Well-8) it is left hypothetical. The end result of this process resulted in the identification of four significant contacts/unconformities in the seismic data. The geometry of these contacts is not always the same but it often changes laterally. For example the Permian-Triassic contact is sometimes present in the form of a para unconformity, with no time gap identifiable from the seismic data alone. However, the same contact can be identified as an onlapping unconformity at other locations, as the overlying deposits are onlapping the underlying Permian anydrites and carbonates.

With the boundaries of the Permian identified, the Permian lithology and thickness (Figure 4.7) was examined. Thus, Lithological Units were defined for each of the available wells, and these were afterwards tied to the seismic data to define Geological Formations.

- **Permian - Triassic Contact**

  The contact between the Permian and the Triassic is indicated in the Well-1 well at the lithological transition at 2265 meters based on palynology and micropalaeontological data that are considered reliable, but are not directly available for study. However, more detailed information about it has been located to a recent publication by Ghazzay-Souli et al. (2015).

  An unconformity between the overlying Triassic and the Permian is not directly visible at the vicinity of this well in the corresponding seismic line (Figure 4.2). In fact, the Triassic and the Permian close to the Well-1 and Well-2 wells are conformable, making their transition impossible to accurately identify in the seismic line without additional information being provided. An unconformity between the Permian and Triassic is mentioned in literature for the area however (Jabir et al., 2020; Burollet et al., 1990).

  Towards the South - South West, the geometry of the contact begins to gradually change - Line-6, Line-4, Line-8 and Line-15 - with Triassic and the Permian no longer parallel to each other. Instead the Triassic begins to gradually exhibit angularity relative to the underlying deposits (Figures 4.1,4.2,4.3). This geometrical change is minor at first but it steadily becomes more prominent as one examines the lines further towards the South where the Triassic and the Permian are eventually clearly separated by an onlap unconformity, with the Triassic onlapping the Permian. The geometry of the later is unchanged and it has continued to remain flat as observed at other

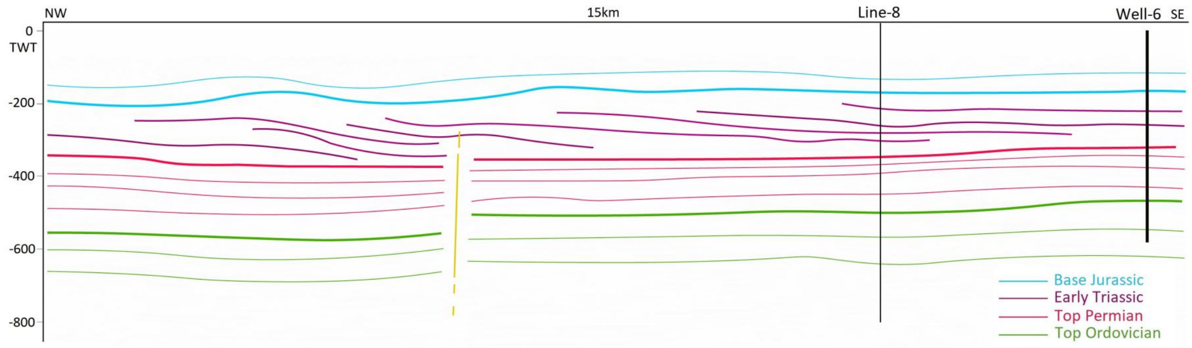

Figure 4.1: The onlapping Triassic - purple reflectors - and the underlying Permian - red reflector - as observed at Line-15. The Triassic in overlying the Permian. Geological periods in this section were calibrated based on wells Well-6 and Well-2.

locations in the seismic data.

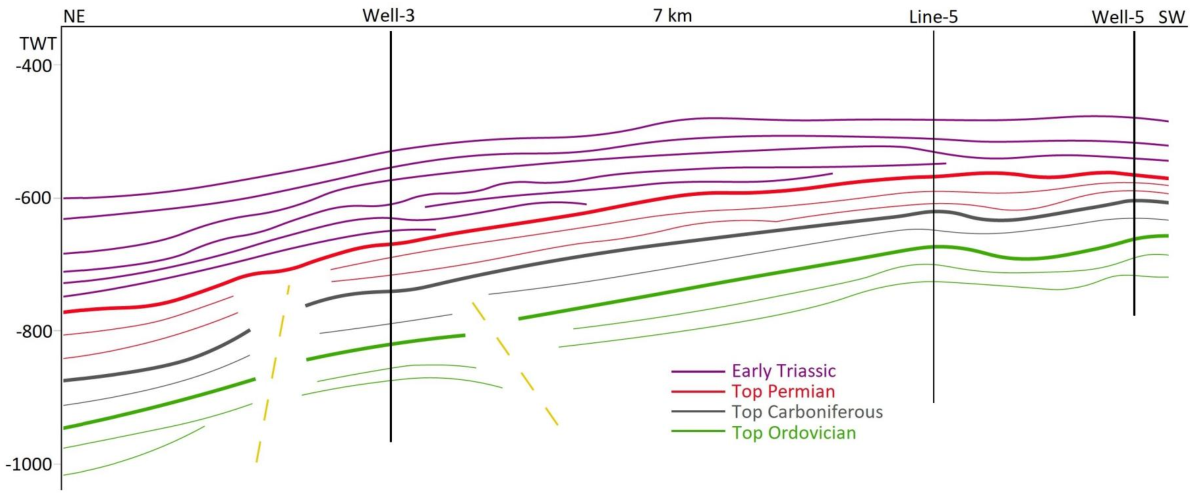

Figure 4.2: The onlapping Triassic - purple reflectors - and the underlying Permian - red reflector - as observed at Line-4 and Line-5. Geological periods in this section were calibrated based on wells Well-4 and Well-5 using input from control well Well-1.

Overall, the presence of these onlapping terminations enables the accurate tracing of the Triassic-Permian contact at the south sections of the available lines. While the onlaps gradually disappear as the contact between Permian and Triassic extends to the North, the amplitude changes of the reflectors allow for its accurate tracing.

- **Permian - Jurassic Contact**

  At the East boundary of the studied area the Permian and the Triassic, which lie parallel to each other, are forming an anticline. This structure has an East-West strike and a North-South inclination. Shallower, an younger package of reflectors can be identified. This package is tilting 20-30 degrees and it can be seen cutting through the Permian and removing the Triassic rocks (Figure 4.3). Southwards, the nature of this unconformity gradually changes and the overlying rocks become more parallel with the underlying Permian (Figure 4.4).

  By tracing the upper seismic reflectors of the Permian it can also be concluded that approximately 150 ms TWT - 500 meters have been removed as a result of this unconformity. This observation indicates that the deposits dated to the Permian at Well-10 and Well-9 were once followed by additional packages which have since been eroded away. Thus, they are missing from the areas were the wells were drilled and are as a result not present at the lithological columns. These 150

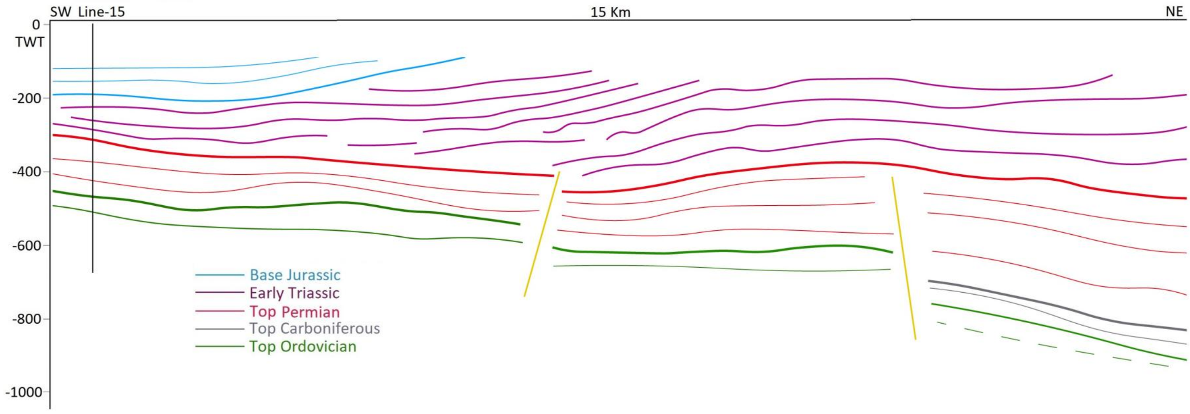

Figure 4.3: At the South-West part of Line-8, the Triassic – purple reflectors - is onlapping the underlying Permian - red reflector.

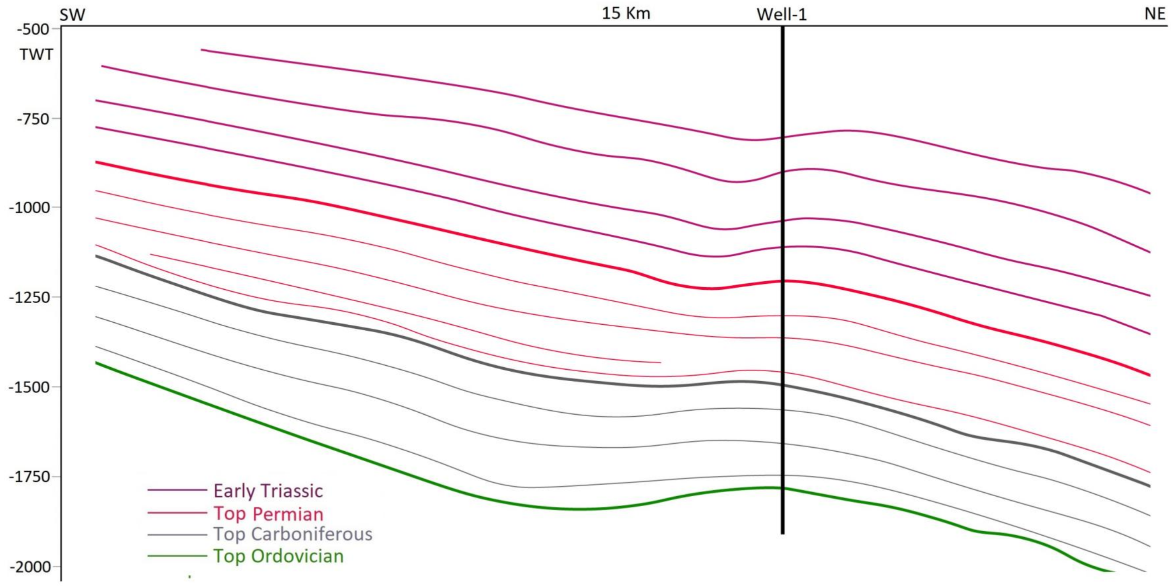

Figure 4.4: The Triassic - purple reflectors - and the top Permian pick - red reflector - are parallel to each other at Line-2, forming a para unconformity. In this line the age of the relfectors was calibrated using control well Well-1. Notice the onlapping Middle Permian against the Lower Permian deposits - red arrows.

ms TWT should be added to the unknown Permian thickness that was removed as a result of the erosion event that caused the unconformity with the Permian in the first place.

The dating of that overlying package is difficult. However, the observed unconformity can be traced further to the West, towards Line-16, where Well-10 and Well-9 are closely located. Well-10 indicates a direct transition from Permian to Middle Jurassic based on microfossils. In Well-9 the unconformity itself has been identified at 1073 meters depth, indicating the top of the Permian. Unlike Well-10, it is followed by a 89 meter interval dated to the Rhaetian. Shallower an interval dated to the Pliensbachian, Toarcian, Oxfordian is found. The dating of the Permian and Jurassic in Well-9 was performed using microfossils but the interval assigned to the Rhaetian is azoic, which makes the dating questionable. Also, the lithology of this interval is identical to the Pliensbachian, Toarcian and Oxfordian intervals that are found shallower in the well, dominated by anhydrite and shale.

Based on the above, and in combination with the observations at the seismic data, it is reasonable to conclude that no Triassic is present at well Well-9, and the Rhaetian interval should be assigned to the Early-Middle Jurassic. Thus, the rocks that overlie the Permian at Line-16, and by extension

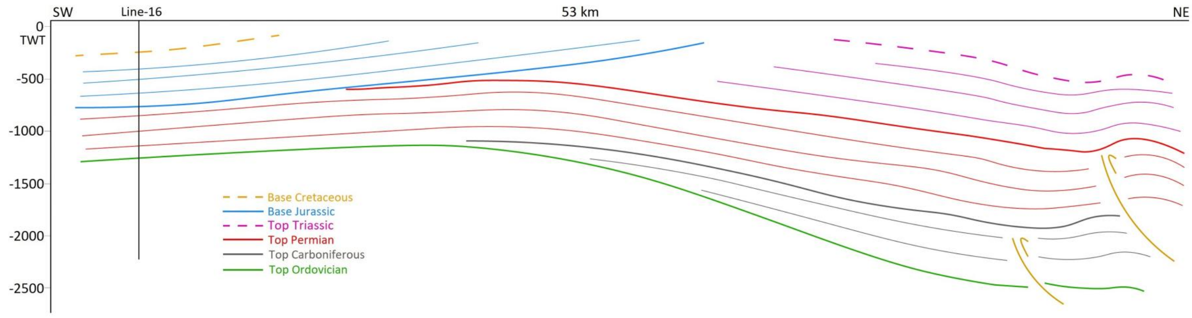

Figure 4.5: The junction where the Permian, Triassic and Jurassic meet, at the middle of Line-17.

at Line-17 belong to the Jurassic period, Pliensbachian, Toarcian the latest. This indicates at least a seventy million age gap between the lithologies.

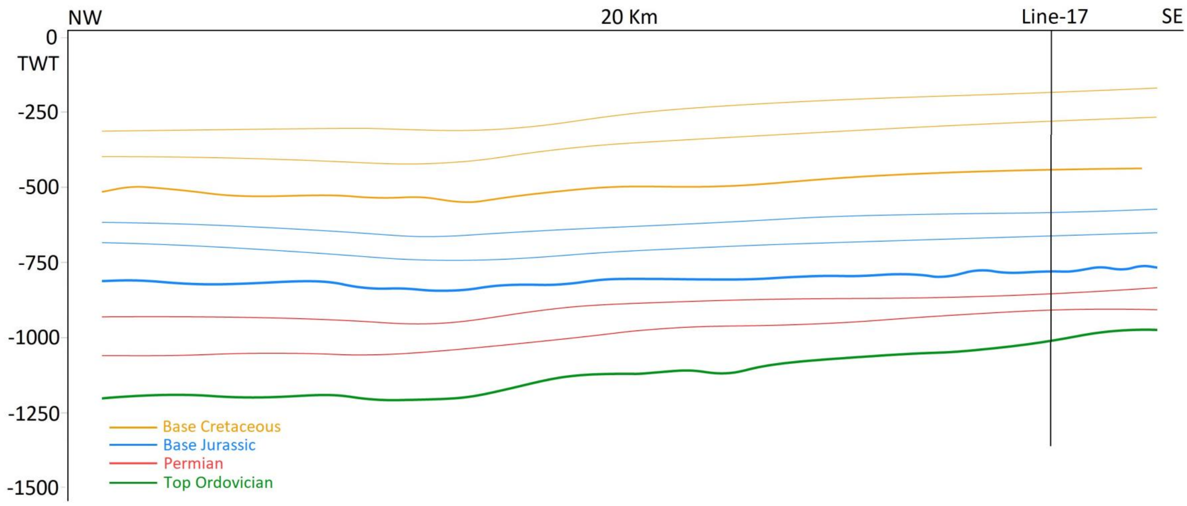

Figure 4.6: The red reflector indicates the Permian/Jurassic unconformity, and is an extension of the reflector from Figure 3.2 towards the SW. The dotted azure line indicates the approximate depth of the Jurassic-Cretaceous contact. The Cretaceous extends until the surface and it is observed extensively in outcrops.

- **Permian - Carboniferous - Ordovician Contact**

  Identifying the contact between the Permian and the underlying formations was more challenging than the Permian-Triassic due to scarcity of available data. More specifically, the majority of the wells do not penetrate deep enough into the subsurface to reach the Carboniferous-Ordovician rocks in the first place while in others the contact between the Permian or underlying deposits is arbitrarily assigned (Well-7, Well-6, Well-8) to a specific depth of continued lithological units.

  Well-10 and Well-9 provide valuable insight into the nature of the formations underlying the Permian towards the East. There, the Permian is deposited directly on top the Ordovician, without any Carboniferous deposits in between which contrasts with what is observed to the West. Examination of the seismic lines indicates a similar trend for the Carboniferous that is gradually becoming thinner towards the West and South of the examined area. In both cases, the Carboniferous is occupying considerable space on top of the Ordovician, it does not cover it completely. Instead, there is sufficient area free of Carboniferous deposits, which is later occupied by the Permian base clastics and carbonate deposits.

4.2. Defining Contacts in Wells

The process of identifying the boundaries of the Permian in the seismic lines was done in parallel with a calibration of the relevant information from the available wells. More specifically, the top and bottom of the Permian was redefined and when necessary the boundaries were updated in order to align both with the fossil record and with what the seismic data indicate.

- **Well-1**

  Well-1 is considered the most reliable wells of the data set as it separates the Triassic and the Permian based on the findings presented in the palaeontology report. While the report itself has not been provided as part of the data set ,its general conclusions have been, and it has also been found at a recent publication (Ghazzay et al., 2015; Lys, 1983)). For the contact between the Permian and the underlying Carboniferous, the conclusions of the palaeontology report have been examined, but again the report itself has not been provided for detailed examination.

  Regarding the Permian-Carboniferous contact, the completion report defines it between the undifferentiated Permian and top of the Carboniferous at 3009 meters. On the other hand, Ghazzay-Souli et al. (2015) assigns the contact at 3009 meters a Middle Pennsylvanian age, with the Late Pennsylvanian, Early and Middle Permian extending until a depth of 2800 meters.

  Regarding the contact between the Upper Permian and the Middle Permian the completion report suggests a depth of 2520 meters. On the other hand,Ghazzay-Souli et al. (2015) suggests that separation between the Upper and Middle Permian is not possible due to the limited fossils present and assigns the deposits between 2520 and 2265 meters a unified Middle-Uppper Permian age instead.

  Based on the above, the Permian-Carboniferous contact has been defined at 3009 meters, but with the acknowledgement that a portion of the deposits shallower of that contact could in fact be dated to the Upper Carboniferous. The Permian-Triassic contact has been set at a depth of 2265 meters. Thus a total Permian thickness of 744 meters is indicated. Above the Permian in this well lie thick deposits of sandstones and shale.

- **Well-2**

  Well-2 is situated 21 kilometers to the West of Well-1. In this well the upper limit of the Permian was moved to a shallower depth of 1108 meters compared to the completion report. This depth corresponds to the last significant occurrence of Globivalvulina, Hemigordius and Ammodiscus fossils in the column-fossils which were cosmopolitan during the Permian Period (Ebrahim Nejad et al., 2015) and went mostly extincting during the P-T extinction event (Korchagin, 2011; Fio Firi et al., 2016).

  This occurrence is overlaid by a thick interval of sand and shale. This interval has a limited presence of fossils, which include species of Hemigordius and Ammodiscus. The age suggested in the well report for these deposits is ambiguous, either Upper Permian or Lower Triassic. The presence of Hemigordius and Ammodiscus point towards a Permian age since these fossils were cosmopolitan then. However, their presence in the well at that depth is limited, and there are documented cases of these fossils present at early Triassic sediments as well (Korchagin, 2011; Fio Firi et al., 2016). Moreover, these deposits can be correlated using seismic data with the sand overlying the Permian at Well-1. These are dated to the Triassic at the paleontology report and in Ghazzay-Souli et al. (2015). Thus it has been decided to assign them a probable Lower Triassic age. It should be noted however that an older report dates these sandstones to the Permian, based on micropalaeontological data (Kilani-Mazraoui et al., 1990).

Regarding the Permian-Carboniferous contact, the depth of 2180 meters suggested in the completion report correlates well with the Permian-Carboniferous contact defined in Well-1.

Based on the above, the Permian-Carboniferous contact lies at 2180 meters and the Permian-Triassic contact has been set at a depth of 1108 meters. This indicates a total Permian thickness of 1072 meters.

- **Well-3**

Well-3 is located to the South of Well-1 and Well-2. The last occurrence of Globivalvulina sp. Fossils lies at 1087m. Above this level, a thick 200 meter interval of azoic sand and shale is present, similar to what is observed at control well Well-1 and at well Well-2. Shallower alternations of carbonate and shale, 300 meters thick, with species of Hemigordius and Ammodiscus are found. These fossils were cosmopolitan during the Permian and generally indicate this age. However, they have been found at Lower Triassic deposits as well (Korchagin, 2011; Fio Firi et al., 2016). In the well report and in literature (Burollet et al., 1990) this 500 meter interval is dated to the Upper Permian.

Using the available seismic lines it was concluded that this 500 meter section cannot be reliably correlated with the reflectors extended from control Well-1. Instead, the depth of 1087 meters correlates well with the observations at the seismic lines. Thus, the Permian-Carboniferous contact lies reliably at 1322 meters as indicated by the presence of Carboniferous fossils and the Permian-Triassic contact has been set at a depth of 1087 meters. This shows a total Permian thickness of 235 meters.

- **Well-4**

Well-4 is located 8 kilometers to the South of Well-3. At a depth of 1356 meters Globivalvulina sp. have been identified. These fossils are found inside a carbonate-shale interval which reaches a depth of 1280 meters. Shallower in the well, an azoic interval of sand and shale of 150 meter thickness follows, similar to wells Well-1 and Well-2 and Well-3. Overlying this is an interval of shale and carbonates with fossils similar to Well-3, Rotaliidae, Opthalmidea and Crinoids which do not allow for a reliable dating. Noteworthy is the lack of Hemigordius and Ammodiscus fossils.

Consequently, the Permian-Carboniferous contact can be defined by the presence of Carboniferous fossils at 1558 meters and in combination with the seismic interpretation, the contact between the Permian and the Triassic has been updated to the transition between the carbonates and the sandstone at 1280 meters. The identification of the onlap unconformity at this depth gives support for this interpretation. Thus the Permian has been assigned a thickness of 278 meters at Well-4. A Lower-Middle Permian age has been assigned to the deposits in this well according to the completion report.

- **Well-5**

Well-5 is located 3 kilometers to the South-East of Well-4. The extended seismic reflector from Well-3, that indicates the transition between the Carboniferous and the Permian correlates very well with what is suggested in the original well report. Contrary to Permian-Carboniferous contact, the Permian-Triassic contact is problematic. Thus, it was decided to calibrate Well-5 by extending the seismic reflectors from the updated Well-3 well. By doing so, the new Permian-Triassic contact lies at an approximate depth of 1050 meters, much shallower compared to the suggestion of the

Well	Upper Permian Contact	Comments	Contact Depth
Well-1	Contact indicated by fossils	Fossils of Permian age	2265 meters
Well-2	Contact indicated by fossils	Fossils of Permian age / Re-correlation	1108 meters
Well-3	Contact indicated by fossils	Fossils of Permian age / Re-correlation	1087 meters
Well-4	Contact indicated by fossils	Fossils of Permian age / Re-correlation	1280 meters
Well-5	Contact unclear	No fossils / Re-correlation using seismic data	1050 meters
Well-6	Contact indicated by fossils	Fossils of Triassic age / Re-correlation	675 meters
Well-7	Contact indicated by fossils	Fossils of Permian age	720 meters
Well-8	Contact indicated by fossils	Fossils of Permian age	872 meters
Well-9	Unconformity identified	Fossils of Permian age / Re-correlation	1073 meters
Well-10	Contact indicated by fossils	Fossils of Permian age	1342 meters
Well-11	Contact indicated by fossils	Fossils of Permian age	93 meters

Table 4.1: In the table above the depth of upper contact of the Permian is shown collectively for all the wells.

well report. Above the Permian, sandstone is present, which has now been dated to the Early Triassic. This dating is similar to what is suggested at Kilani-Mazraoui et al. (1990).

With the bottom of the Permian lying at 1216 meters, a total thickness of 186 meters is calculated. There are no fossils identified in the Permian at this well. A Lower-Middle Permian age has been assigned to the deposits well according to the completion report.

- **Well-6**

Well-6 is located 23 kilometers to the South of Well-2. In this well, the Permian-Ordovician contact has been shifted deeper compared to what is suggested in the well completion report, to 800 meters. An issue that prohibits the definitive contact between of these geological periods is that these intervals are clastic and azoic. Thus, dating can only be done by correlating seismic reflectors. The Permian-Triassic contact has not been changed. The extension of the reflectors traced for Well-2 and Well-1 correspond well to the hypothetical contact that is suggested in the well report.

Thus, the bottom to 800 meters and the top of the Permian in Well-6 has been assigned to 675 meters, indicating a total thickness of 125 meters.

- **Well-7**

Well-7 is located 7,5 kilometers to the West of Well Well-6. The extension of the seismic reflectors indicate that the Permian-Ordovician contact indicated by the seismic reflectors correlates sufficiently with what is suggested in the report and was moved deeper by 50 meters. On the other hand the Permian-Triassic contact corresponds well with what is suggested in the well report.

Thus, the bottom of the Permian has been assigned to 950 meters and the top to 720 meters, indicating a total thickness of 230 meters for the Permian.

- **Well-8**

Well-8 is located 11 kilometers to the North-West of Well-7. The original boundaries that are suggested for the Permian in the well report correlate well with the seismic reflectors that were traced. The bottom of the Permian has been assigned to a depth of 1100 meters, as indicated by Late Permian palynofacies at 1085 meters and by the seismic correlations. The depth of the Permian-Triassic contact lies 872 meters as indicated by Late Permian palynofacies below that depth. The well report dates the overlying deposits to the Early Triassic. This indicates a total Permian thickness of 238 meters.

Well	Lower Permian Contact	Comments	Contact Depth
Well-1	Contact indicated by fossils	Fossils of Carboniferous age	3009 meters
Well-2	Contact indicated by fossils	Fossils of Carboniferous age	2180 meters
Well-3	Contact indicated by fossils	Fossils of Carboniferous age - Moscovian	1322 meters
Well-4	Contact indicated by fossils	Fossils of Carboniferous age - Moscovian	1558 meters
Well-5	Contact unclear	Re-correlation with reflectors	1216 meters
Well-6	Contact unclear	Re-correlation with reflectors	800 meters
Well-7	Contact unclear	Re-correlation with reflectors	950 meters
Well-8	Contact unclear	Re-correlation with reflectors	1100 meters
Well-9	Unconformity identified	Fossils of Ordovician age	2809 meters
Well-10	Contact not reached	Well column terminates in Permian	2815 meters
Well-11	Contact not reached	Well column terminates in Permian	4024 meters

Table 4.2: In the table above the depth of lower contact of the Permian is shown collectively for all the wells.

- **Well-9**

  Well-9 is located 64 kilometers to the North-West of Well-8. During the drilling of this well, the unconformities that divide the Permian and the overlying rocks, as well as the underlying Ordovician were identified based on palynology. Moreover, the Permian deposits are very rich in microfossils, which makes their dating and separation from the other periods very reliable.

  As such, the Permian rests unconformably on the Ordovician at 2809 meters. The top Permian is set at a depth of 1073 meters - bounded by an overlying unconformity. The Permian reaches at Well-9 a total thickness of 1736 meters.

  Here, the precise dating of the package that overlies the Permian is challenging. It is dominated by intervals of anhydrite dominated and carbonates and it has been dated to the Late Triassic, Rhaetian in the well report. This however is not supported by fossils or by what is indicated in the seismic data, which show a direct transition from the Permian into the Jurassic. Thus, the dating of the Triassic intervals in this well is questionable, with a Jurassic age also possible.

- **Well-10**

  Well-10 is located 21 kilometers NW of Well-9. Like in a number of other wells, the Permian can be identified thanks to its rich fossil content. Above the reliably dated Permian deposits lies an azoic 100 meter thick section of similar carbonate lithology, but also with anhydrite intervals, similar to what is observed in Well-9. While it has been dated to the Middle Jurassic in this well report its true age is questionable due to the lack of fossils. However, it was decided not to include it into the Permian, since this package is lithological identical to the Triassic-Jurassic package that overlies the Permian at Well-9.

  Thus, in Well-10, the top of the Permian has been assigned at a depth of 1342 meters. The depth where the contact between the Permian and the underlying Ordovician lies however has not been reached and is thus unknown. Consequently the bottom of the Permian has been assigned to a depth of 2815 meters - the bottom of the well for a thickness of 1473 meters.

- **Well-11**

  Well-11 is located 41 kilometers to the North-East of Well-10. This well has penetrated a thin 93 meter interval dated to the Jurassic which is followed by the Permian. The well did not reach the bottom contact between it and the Ordovician/Carboniferous. Thus, the Top Permian has been assigned to a depth of 93 meters, while the bottom to a provincial depth of 4024 - the bottom of the well. The entire column is very homogeneous lithologically.

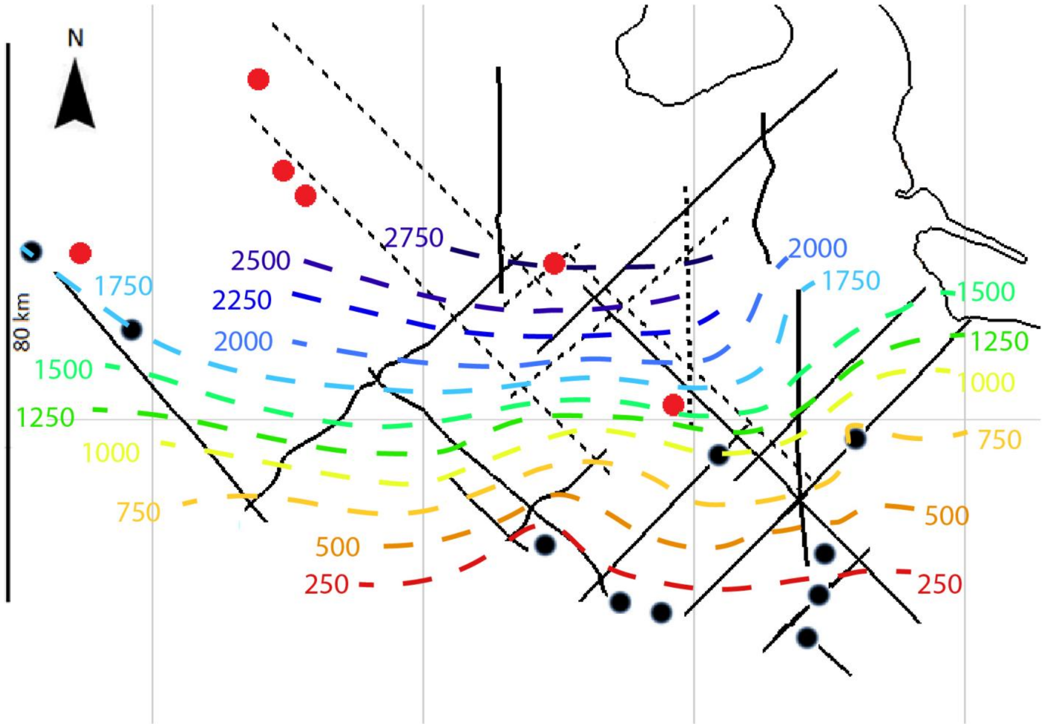

Figure 4.7: The thickness of the Permian deposits in the Jeffara Basin, based on the seismic interpretation and the updated well correlation.

5

Defining Lithological Units in Wells

Following the completion of the contact identification, the lithologies of the wells, as indicated by the completion reports, literature, well logs, cuttings etc, were examined in more detail and in combination with other properties, such as color, texture, cement, etc Lithostratigraphic Units were defined for each well.

5.1. Well-1

Lithological Unit **Well-1/4**

This Lithological Unit is composed primarily of shale (black, grey, brown) and marl (gray, beige) of variable thickness. They are interrupted by intervals of carbonate rock (gray, beige, less than five meters thick) and thin deposits of anhydrite (white, less than two meters thick). Anhydrite is additionally found as inclusions in the carbonate rocks. The alteration between these lithologies appears random. This section is dated to the Upper Permian based on algae and ostracod fossils.

The completion report suggests an Upper Permian age while (Ghazzay-Souli et al., 2015) indicates a Upper-Middle Permian age.

Top Depth: 2265 meters
Bottom Depth: 2520 meters
Total Thickness: 225 meters
Primary Lithology: Shale - Marl
Secondary Lithology: Carbonates, Anhydrite
Fossils: Globivalvulina, Hemigordius, Agathamina, Geinitzina, Mizzia, Permocalculus
Comments: Traces of bitumen at 2525 meters

Lithological Unit **Well-1/3**

This Lithological Unit is composed of carbonate rocks (gray, beige, white) and thin intervals of shale and marl (gray, black, less than two meters thick). The shale and marl proportion is gradually increasing towards the deeper sections, but does not become dominant. Rarely, anhydrite is present as inclusions in the carbonate rocks. Microfossils include algae, gasteropods and ostracods. Ghazzay et al. (2015) suggest a Upper-Middle Permian age.

Top Depth: 2520 meters
Bottom Depth: 2791 meters
Total Thickness: 271 meters
Primary Lithology: Carbonates
Secondary Lithology: Shale - Marl, Anhydrite
Fossils: Globivalvulina, Agathamina, Hemigordius, Glomospira, Geinitzina, Mizzia, Permocalculus, Calcitornella
Comments: Traces of bitumen at 2739 and 2750 meters

Lithological Unit **Well-1/2**

This Lithological Unit is composed of shale (gray, black, red), intervals of carbonates (beige, gray, white, black, less than 2 meters thick) and intervals of fine to medium sorting brittle sand (white, gray). The shale and sand alternate with each other frequently and each individual interval is relatively thin (less than one meter, maximum two meters). Ghazzay et al. (2015) suggest a Kasimovian-Wordian age for these deposits.

Top Depth: 2791 meters
Bottom Depth: 2906 meters
Total Thickness: 115 meters
Primary Lithology: Shale
Secondary Lithology: Sand, Carbonates
Fossils: Agathamina, Hemigordius, Geinitzina
Comments: Traces of bitumen at 2867 and 2884 meters

Lithological Unit **Well-1/1**

This Lithological Unit is composed of carbonate rocks (pink, gray, white) and two thin intervals of shale (gray, less than two meters thick). These two intervals of shale are present at a depth of 2930 and 2960 meters respectively. Ghazzay et al. (2015) suggest a Kasimovian-Wordian age for these deposits.

Top Depth: 2906 meters
Bottom Depth: 3009 meters
Total Thickness: 103 meters
Primary Lithology: Carbonates
Secondary Lithology: Shale
Fossils: Globivalvulina, Hemigordius
Comments: Traces of bitumen at 2939, 2943, 2966, 2976, 2982 and 3008 meter

5.2. Well-2

Lithological Unit **Well-2/4**

This Lithological Unit is composed mainly of marl (black, gray) and carbonate (gray, beige) of variable thickness. These are interrupted by thin intervals of anhydrite (gray, black, beige, usually less than one meter thick). At the top section of this lithofacies (1108-1170 meters) the anhydrite is found in the form of plaques within the marl and carbonate intervals. Towards the bottom the anhydrite becomes thicker (five meters at specific locations) and marl becomes the only other rock type present. The upper section (1120-1150 meters) has fossils indicating a Permian age. Also, since this unit is a lateral extention of Well-1/4 and it can be directly correlated to it with seismic data, it has been assigned an Upper-Middle Permian age.

Top Depth: 1108 meters
Bottom Depth: 1426 meters
Total Thickness: 318 meters
Primary Lithology: Marl
Secondary Lithology: Carbonate, Anhydrite
Fossils: Calcitornella, Agathammina, Hemigordius, Globivalvulina, Geinitzina, Mizzia, Permocalculus

Lithological Unit **Well-2/3**

This Lithological Unit is composed exclusively of carbonate rocks (gray, brown) and marl (gray, white). Anhydrite is found in the form of thin plaques from the top until a depth of 1470 meters. The carbonate rocks are become richer in shale, more marly, towards the bottom. The entire interval is rich in fossils. This unit is a lateral extention of Well-1/3 and it has been assigned a Middle Permian age.

Top Depth: 1426 meters
Bottom Depth: 1975 meters
Total Thickness: 549
Primary Lithology: Carbonate
Secondary Lithology: Marl, Anhydrite
Fossils: Calcitornella, Agathammina, Hemigordius, Globivalvulina, Geinitzina, Mizzia, Permocalculus, Ostracods, Vermiporella, Acicularia
Comments: Traces of lignite at 1650 meters

Lithological Unit **Well-2/2**

This Lithological Unit is composed of shale (gray), with intervals of marl (pink, gray) and medium pink sand. The upper section of this lithofacies is composed of alterations between shale, marl and carbonates. Towards the bottom, sand becomes increasingly more common in this alternation until it becomes the only rock type from 2018 meters until the end of this lithofacies at 2035 meters. The completion reports mentions the presence of nodules of anhydrite at 2025 meters depth. No fossils are found in these 60 meters. The well report suggests a lower Permian age. This Unit can be laterally correlated with unit Well-1/2.

Top Depth: 1975 meters
Bottom Depth: 2035 meters
Total Thickness: 60 meters
Primary Lithology: Shale
Secondary Lithology: Carbonates, Marl, Sand, Anhydrite
Fossils: Azoic

Lithological Unit **Well-2/1**

This Lithological Unit is composed of carbonates (white, pink) with very thin intervals of marl. Anhydrite has a limited presence at the top of this section in the form of nodules in the carbonate rocks. Towards the bottom the lithofacies become richer in shale. The well report suggests a lower Permian age. This Unit can be laterally correlated with unit Well-1/1.

Top Depth: 2035 meters
Bottom Depth: 2180 meters
Total Thickness: 155 meters
Primary Lithology: Carbonate
Secondary Lithology: Marl, Shale, Anhydrite
Fossils: Azoic
Comments: Final 80 meters of the Permian are missing from the well report

5.3. Well-3

Lithological Unit **Well-3/3**

This very thin Lithological Unit is composed of marl (gray) and carbonates (gray). Globivalvulina fossils have been identified in this interval.

Top Depth: 1087 meters
Bottom Depth: 1100 meters
Total Thickness: 13 meters
Primary Lithology: Marl
Secondary Lithology: Carbonates
Fossils: Globivalvulina

Lithological Unit **Well-3/2**

This Lithological Unit is composed of shale (brown, pink), with intervals of find to medium white sand. Towards the bottom, shale becomes increasingly more prevalent in this alternation. No fossils are identified in these 100 meters.

Top Depth: 1100 meters
Bottom Depth: 1210 meters
Total Thickness: 110 meters
Primary Lithology: Shale
Secondary Lithology: Sand
Fossils: Azoic

Lithological Unit **Well-3/1**

This Lithological Unit is composed of carbonates (gray, green, white) with thin intervals of (gray, green) shale and marl. These intervals are thin, less than 2 meters. Towards the bottom, 1308-1322 meters, shale becomes the prevalent lithology. At this depth a thin 20cm interval rich in Glomospira has been identified. The whole lithofacies is overall rich in microfossils.

Top Depth: 1210 meters
Bottom Depth: 1322 meters
Total Thickness: 112 meters
Primary Lithology: Carbonate
Secondary Lithology: Shale, Marl, Anhydrite
Fossils: Hemigordius, Calcispheres, Ammodiscus, Solenopora, Glomospira

5.4. Well-4

Lithological Unit **Well-4/2**

This Lithological Unit is composed of carbonate (beige) with thin intervals of (pink) shale and anhydrite. The shale intervals are thick, usually 5-10 meters. At a depth of 1333 meters a 2 two meter thick interval of anhydrite is present. Towards the bottom, carbonates gradually become the prevalent lithology. Those carbonates at 1400-1473 meters are intercalated with marl and plaques of anhydrite (white). This lithofacies is rich in microfossils.

Top Depth: 1280 meters
Bottom Depth: 1473 meters
Total Thickness: 193 meters
Primary Lithology: Carbonate
Secondary Lithology: Marl, Shale, Anhydrite
Fossils: Globivalvulina, Calcispheres, Ostracods, Gasteropods, algae, Ammodiscus, Radiolaria

Lithological Unit **Well-4/1**

This Lithological Unit is composed of shale (pink, green) and fine shaly sand. At the intervals where shale is present, anhydrite can be found in the form of inclusions. This lithofacies is azoic.

Top Depth: 1473 meters
Bottom Depth: 1558 meters
Total Thickness: 85 meters
Primary Lithology: Shale
Secondary Lithology: Sand, Anhydrite
Fossils: Azoic

5.5. Well-5

Lithological Unit **Well-5/2**

This Lithological Unit is composed of alternations between carbonates (beige, white) and shaly carbonates (gray, beige). The first 50 meters are characterized by the presence of inclusions of anhydrite found in carbonate rocks. From 1100 meters and deeper the anhydrite (white) becomes more prevalent and has the form of plaques, two to five meters thick, while also being found in the form of inclusions in the carbonates and the marl.

Top Depth: 1050 meters
Bottom Depth: 1205 meters
Total Thickness: 155 meters
Primary Lithology: Carbonate
Secondary Lithology: Marl, Anhydrite

Fossils: Azoic

Lithological Unit **Well-5/1**

This Lithological Unit is eleven meters thick - it is composed of alternations between fine to medium sand (brown) and shale (brown, pink).

Top Depth: 1205 meters
Bottom Depth: 1216 meters
Total Thickness: 11 meters
Primary Lithology: Sand
Secondary Lithology: Shale
Fossils: Azoic

5.6. Well-6

Lithological Unit **Well-6/2**

This Lithological Unit is composed of carbonates (white, beige) and an interval of sand (white, very fine, occasionally medium or poorly sorted, firm). Dark gray shale is found in these two lithologies in the form of thin intervals. This lithofacies has no fossils.

Top Depth: 675 meters
Bottom Depth: 700 meters
Total Thickness: 25 meters
Primary Lithology: Sand
Secondary Lithology: Carbonate, Shale, Gypsum
Fossils: Azoic

Lithological Unit **Well-6/1**

This Lithological Unit is composed of sand (white, green, beige) and conglomerates-pebbles. The maturity of the sandstone grains changes in maturity within this unit. From firm, well rounded, well sorted and fine to brittle, poorly sorted, angular and coarse sometimes within the span of less than a meter. Shale can occasionally be found in the sandstone in the form of laminae. Sometimes dolomitic cement is present. At depth 725 meters, pebbles and cobbles are present- spherical and well sorted, 5mm-90mm in diameter. At 733 meters the pebbles form a conglomerate.

Top Depth: 700 meters
Bottom Depth: 800 meters
Total Thickness: 100 meters
Primary Lithology: Sand
Secondary Lithology: Shale, Conglomerate
Fossils: Azoic
Comments: Glauconite at sands at 740 meters

5.7. Well-7

Lithological Unit **Well-7/2**

This Lithological Unit is composed of alternations of carbonates (white, beige) and marl (white, gray, green, beige). Between 740 and 750 meters, inclusions of anhydrite (pink) are found in the carbonate rocks. Towards the bottom carbonates become more prevalent compared to the marl. This lithofacies is rich in microfossils.

Top Depth: 720 meters
Bottom Depth: 880 meters
Total Thickness: 150 meters
Primary Lithology: Carbonate, Marl
Secondary Lithology: Shale, Sand, Anhydrite at 740, 750 meters),
Fossils: Glomospira, Opthalmiidea, Crinoids, Endothyra, Ammodiscus, Ostracods

Lithological Unit **Well-7/1**

This Lithological Unit is composed of sand (gray, beige, green) and of conglomerate rocks. The sand has varying degree of maturity and it alternates between fine to medium sorting. At 892 and 902 meters two thin intervals of conglomerates are present, composed of rounded, gray, pink, pebbles. Towards the bottom, a 13 meter interval of conglomerates is found. It is composed of rounded pebbles of gray, pink sand. Occasionally, shale is found within the sand intervals of this lithofacies. No fossils have been described.

Top Depth: 880 meters
Bottom Depth: 950 meters
Total Thickness: 70 meters
Primary Lithology: Sand
Secondary Lithology: Conglomerate, Shale
Fossils: Azoic
Comments: Glauconite at sand at 950m

5.8. Well-8

Lithological Unit **Well-8/3**

This Lithological Unit is composed of carbonates (light gray, light brown), sometimes inter bedded with thin shale intervals (green, 10-30 cm thick beds). The shale deposits have irregular stratification and the transition between them and the carbonates is usually gradual and not abrupt. An interval of marl from 915 until 958 meters follows these carbonates which pick up again from 958 meters until 1028. These carbonates are beige, gray and white and are inter bedded with beds of claystone and anhydrite. Late Permian age according to the well report.

Top Depth: 872 meters

Bottom Depth: 1028 meters
Total Thickness: 156 meters
Primary Lithology: Carbonate
Secondary Lithology: Anhydrite, Marl, Shale, Claystone
Fossils: Late Permian pollen present at the carbonates
Comments: Traces of oil and gas at the carbonates

Lithological Unit Well-8/2

This Lithological Unit is composed of shale (dark brown, gray, green) and thin intervals (less than one meter thick) of sandy carbonate (white, light beige). The sand's granularity in the carbonates is usually fine.

Top Depth: 1028 meters
Bottom Depth: 1075 meters
Total Thickness: 47 meters
Primary Lithology: Shale
Secondary Lithology: Carbonate
Fossils: Pollen present at the carbonates
Comments: Traces of oil and gas at the carbonates

Lithological Unit **Well-8/1**

This Lithological Unit is composed of sand (gray, beige, green), claystone (deep red, purple) and of conglomerate rocks. The sand has varying degree of maturity and it fluctuates significantly in maturity and sorting. Usually intervals of 3-4 meters with well sorted, rounded fine sand are followed by intervals of poorly sorted, angular coarse sand. These sand beds are occasionally interrupted by thin (2-3 meters) of claystone deposits. Clay is also found in the form of laminae as part of the sandstone. A dipping of 10-20 degrees is visible at specific depths at cores. Occasionally conglomerate rocks are found in the sand (4-10 mm thick pebbles), either in the form of beds (less than a meter thick) or as pebbles floating in the sand matrix. At 1085m a very thin, less than 1/2 meter interval of limestone is observed in the cores.

Top Depth: 1075 meters
Bottom Depth: 1110 meters
Total Thickness: 35 meters
Primary Lithology: Sand
Secondary Lithology: Clay, Conglomerates, very rare limestone
Fossils: Azoic
Comments: Traces of oil gas at the sandstone, Glauconite at sands at 1075m

5.9. Well-9

Lithological Unit **Well-9/3**

This Lithological Unit is composed of shale (pink, brown) and marl (gray, beige) with thin intervals of carbonates (beige, less than three meters thick). At deeper sections marl becomes the primary lithofacies, while at the top shale is prevalent. The shale upper section is azoic, but the lower section has a very diverse microfossil record of foraminifera, ostracods and algae indicating a Guadalupian (Murghabian in the well report) age in the completion report (more than 50 taxa).

Top Depth: 1073 meters
Bottom Depth: 1193 meters
Total Thickness: 120 meters
Primary Lithology: Shale, Marl
Secondary Lithology: Carbonate
Fossils: Foraminifera, Ostracods, algae
Comments: Indications of oil and gas

Lithological Unit **Well-9/2**

This Lithological Unit is composed of very thick carbonates (gray, white, beige, brown) with thin beds of marl (gray, white, brown) and shale (gray, brown, black). These intervals are thin, usually no more than one meter - but rarely they reach a maximum thickness of five meters. Fine sand (white) can also be found at five occasions in the form of very thin beds (usually less than one meter thick) between the shale and the carbonate deposits. The entire lithofacies is very rich in microfossils indicating a Guadalupian age similar to the Unit above.

Top Depth: 1193 meters
Bottom Depth: 2613 meters
Total Thickness: 1420 meters
Primary Lithology: Carbonates
Secondary Lithology: Shale, Sand
Fossils: Foraminifera, Ostracods, algae
Comments: Indications of oil and gas

Lithological Unit **Well-9/1**

This Lithological Unit is composed of fine to medium sand (white, gray) and intervals of shale (gray, green), marl (gray, brown) and carbonates (beige, brown). The sand intervals are usually thin (less than two meters thick, occasionally up to ten meters) and are often interrupted by shale or marl beds which are also relatively thin (less than two meters). At specific depths carbonates (less than three meters thick) are found between the sand and shale/marl (gray,brown) beds. Traces of anhydrite and lignite are also found. This interval is azoic. The age suggested in the completion report is Early Permian - Cisuralian.

Top Depth: 2613 meters

Bottom Depth: 2809 meters
Total Thickness: 196 meters
Primary Lithology: Sand
Secondary Lithology: Shale, Carbonates, Marl, Anhydrite
Fossils: Azoic
Comments: Indications of oil gas and lignite, Glauconite at sands at 2700m

5.10. Well-10

Lithological Unit **Well-10/2**

This Lithological Unit is composed of shale (gray) thin intervals carbonates (gray, green, less than five meters thick), and marl (gray, brown). Towards the bottom marl becomes gradually more common. This lithofacies is rich in fossils. Dated to the Upper Permian in the completion report.

Top Depth: 1342 meters
Bottom Depth: 1643 meters
Total Thickness: 301 meters
Primary Lithology: Shale
Secondary Lithology: Carbonates
Fossils: Foraminifera, Algae

Lithological Unit **Well-10/1**

This Lithological Unit is composed of very thick carbonates (gray, beige, brown). Inter bedded in them is marl (gray, black, brown) and shale (gray, brown, black). These intervals are thin, usually no more than a couple meter. The entire Unit is very rich in microfossils - foraminifera and algae similar to the Unit above. Dated to the Upper Permian in the completion report.

Top Depth: 1643 meters
Bottom Depth: 2815 meters
Total Thickness: 1172 meters
Primary Lithology: Carbonates
Secondary Lithology: Shale
Fossils: Foraminifera, Algae

5.11. Well-11

Lithological Unit **Well-11/1**

The only Lithological Unit of Well-11 is composed of very thick shale deposits (gray, green, brown, red), with very rare and thin carbonate intervals (gray, black, brown, less than 5 meters thick). Very rarely, sand (white, pink, very fine) can also be found in very thin layers less than 2 meters thick, or mixed in the with the shale deposits. The entire Permian is very rich in fossils indicating marine environment.

Top Depth: 93 meters
Bottom Depth: 4024 meters
Total Thickness: 3931 meters
Primary Lithology: Shale
Secondary Lithology: Carbonate, Shale
Fossils: Foraminifera, algae
Comments: Possible repetition of sequence

6

Defining Seismic Facies and Architecture

During the interpretation of the seismic lines, six major seismic facies were identified. Each has specific seismic attributes, internal geometry and is laterally persistence. These seismic facies have been with a good level of confidence in the southern and eastern part of the area of interest. Towards the north and west the level of confidence was reduced as a result of the scarcity of the well data.

Moreover, the seismic facies have been tied to control wells and as a result they have been correlated with specific lithostratigraphic units. Thus, lithologies and depositional environments could been be tied to the seismic data.

The seismic facies are very persistent laterally and they often transition from one to another. At locations they stop being present due to the existence of an unconformity.

6.1. Seismic Facies 1 (SF1)

This Seismic Facies (SF) (Figure 6.1) is identified at the upper sections of the Permian in the seismic lines. It is composed of a main seismic body of low seismic amplitude, a trough. Inside this dim body thinner parallel reflectors are identified, peaks. These have usually a limited continuity and thickness. Their lateral dimensions are normally couple hundred meters, and are not thicker than 15 ms TWT. Their width can increase and reaches a maximum of up to two kilometers while there is no corresponding increase in thickness.

The total maximum thickness of this SF is 100 ms TWT, with an average of 50 ms TWT. This facies thins towards the North-West and thickens towards the North-East and South. There are two reasons for this change. First, this SF transitions laterally into the Seismic Facies 2. Second, the rocks that compose this facies appear to have been removed by the erosion event that is responsible for the unconformity that separates the Permian and the overlying Triassic at certain locations. Thus, the complete package of this SF is partially or completely missing from some lines, making its identification impossible.

By projecting Well-1 and Well-2 on their corresponding lines the lithology of this facies can be characterized with accuracy as It corresponds with the upper sections of Well-1 and Well-2 that were described the previous chapter. The primarily rock type is shale (gray, brown, black), with secondary marl (gray, brown, beige), carbonates and significant deposits of white anhydrite.

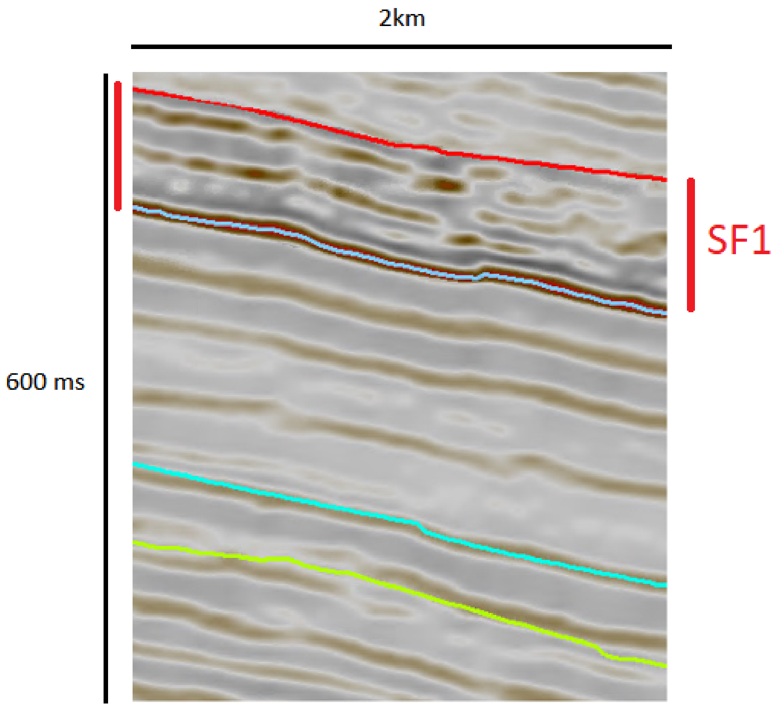

Figure 6.1: The Seismic Facies 1 (SF1) - as observed in the seismic data.

6.2. Seismic Facies 2 (SF2)

This Seismic Facies (Figure 6.2) is composed of a alternations of parallel reflectors, peaks and troughs, of very strong amplitude. To the North-East and South it is traced below SF1. Along with SF1 described earlier and it forms along the main section of the Permian reflectors. ItThese reflectors are very persistent laterally and they extend for dozens of kilometers without any interruption. Their thickness is also relatively consistent, and ranges from 15 to 20 ms TWT. These characteristics make this SF very easy to track laterally and it also allows its identification in lines where uncertainty is high.

The total thickness of this SF varies depending on the location. At the central and South areas of the examined area the thickness ranges from 70 to 100 ms TWT. Towards the South this SF is gradually thinning, until it becomes no longer traceable as the overall Permian thickness gradually decreases. Towards the North the opposite is observed, and its thickness is increasing, with additional packages of reflectors being added reaching a maximum thickness of 600 ms TWT. This SF transitions laterally to SF1 and SF3 at certain points, indicating a potential change in depositional environment. By projecting wells Well-1 and Well-2, the lithology of this SF has been characterized, similarly to SF1. In this case it is composed of carbonate rocks, with very thin intervals of shale and marl, indicating a carbonate platform depositional environment.

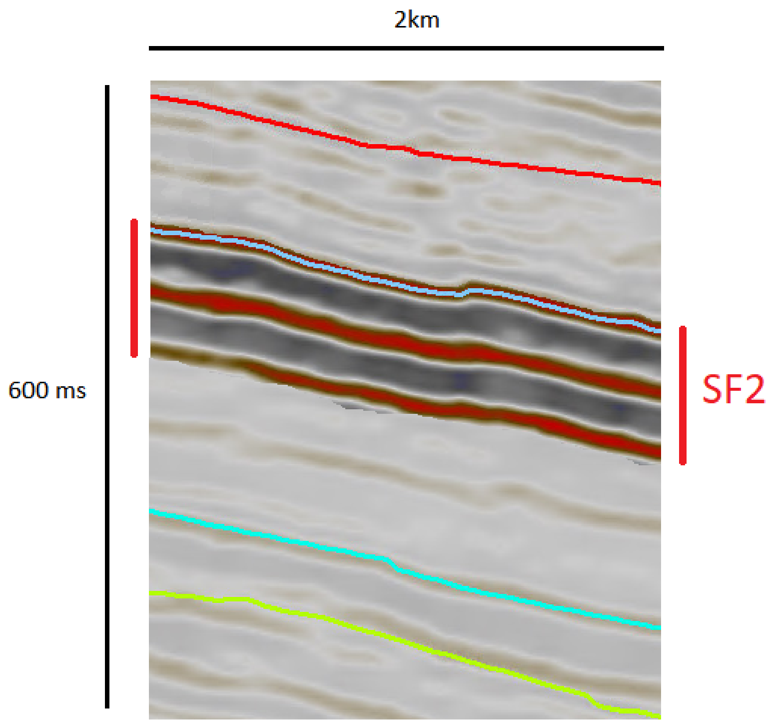

Figure 6.2: The Seismic Facies 2 (SF2) - as observed in the seismic data.

6.3. Seismic Facies 3 (SF3)

This Seismic Facies (Figure 6.3) are composed of a main body with low seismic amplitude, that is interrupted by parallel of slightly higher seismic amplitude. To the North-East and South it is traced below SF2. Within the main body smaller wavy reflectors can sometimes be observed. This description is similar to SF1, however the main difference between the two is the lateral extend of the parallel reflectors, which in this case can extend for multiple kilometers without any interruption. The thickness of these reflectors is usually 15 to 20 ms TWT.

The total thickness of this SF varies depending on the location, but there is an overall trend similar to the facies described above. At the central and South areas of the area the thickness ranges from 100 to 150 ms TWT. Towards the South this SF is gradually thinning, until it becomes no longer traceable as the overall Permian thickness gradually decreases, similarly to SF2. Towards the North the the thickness remains constant, but it gradually transitions into SF2, ultimately being no longer traceable as a distinct unit. By projecting wells Well-1 and Well-2, the lithology of this Seismic Facies has been characterized, similarly to the Seismic Facies described earlier. Here it is composed of carbonate rocks, with and increased percentage of shale and marl, as indicated by the well completion reports.

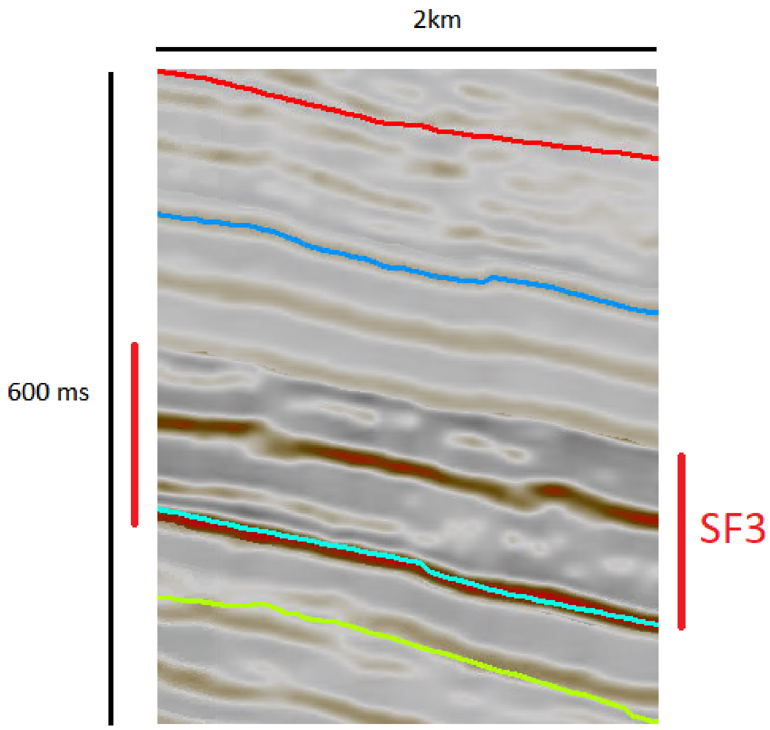

Figure 6.3: The Seismic Facies 3 (SF3) - as observed in the seismic data.

6.4. Seismic Facies 4 (SF4)

This Seismic Facies (Figure 6.4) can be dated to the Upper Carboniferous – Early Permian. It is composed of three parallel reflectors of very strong amplitude. This group is very persistent laterally, and it can be traced in all lines that compromise the South and central parts of the examined area. They extend for dozens of kilometers uninterrupted, without any lateral transitions or any significant thickness change. They are relatively thin compared to the other Seismic Facies, varying between 40 and 50 ms TWT. Using the Well-1 and Well-2 wells the lithology of these reflectors has been characterized as a sand unit, comprise the top reflectors, followed by a unit of carbonates, comprise the bottom reflectors. More specifically, the sand intervals are identified with the Well-1/3, Well-2/3, Well 4/2 units, and the carbonates with the Well-1/4, Well-2/4 and Well 4/3 units.

This SF appears to form a base, the first Permian rocks deposited following the Carboniferous period. Overlying them, the remaining Permian developed with significant thickness changes and lateral facies transitions as observed in the seismic lines and the wells. These reflectors terminate on certain locations against the Carboniferous or Ordovician basement, forming onlaps.

6.5. Seismic Geometry (SG1) - Convexed Reflectors

This Seismic Geometry (SG1) can be identified at multiple lines and usually is the final lateral transition of the Seismic Facies described earlier. It is composed of numerous reflectors, some with dim and others with strong seismic response. Some of these reflectors show a parallel alignment in small groups, of three or four reflectors with an overall convexed geometry. In certain depths the reflectors become very thin, wavy or even chaotic (Figures 6.5,6.6).

The fact that some of these reflectors are located at an anticline structure is an indication that their curved geometry may is not primary, but it could have been caused by a compressional tectonic event following their deposition which caused fracturing (Figures 6.5,6.6).

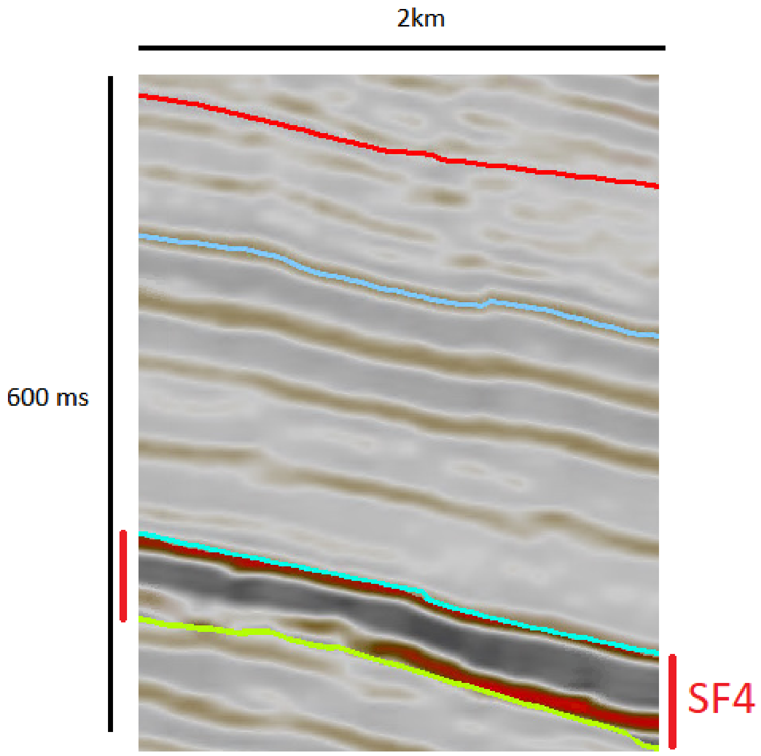

Figure 6.4: The Seismic Facies 4 (SF4) - as observed in the seismic data.

The dimensions of these reflectors varies, from five up to ten kilometers in width, and 500 to 1500 ms TWT - 1000-2000 meters in depth. The reflectors that compose them also show variation in dimensions, with the most prominent parallel reflectors having a maximum length of 1 kilometer and an average thickness of 10-15 ms TWT. They are also identifiable at Seismic Lines 1,4, 5 and 6 of Zaafouri et al. (2017).

Well-10 from our data set is located very close to these reflectors. Also, wells ZW-7, 8, and 10(Zaafouri et al., 2017) are at the path of where they are expected to be located based on their W-E orientation. These wells are also located close the Permian outcrops at Medenine whose lithology and architecture has been examined in field studies. Combining the seismic and well information yields a the primary lithology composed of carbonates, with thin intervals of shale and rare intervals of sand at the upper sections of the Permian.

6.6. Seismic Geometry 2 (SG2) - Concaved Reflectors

At the lines with a NE-SW orientation, mainly at Line-15 and Line-16, small scale concaved units have been identified (Figures 6.8,6.9 in the Middle-Upper Permian deposits. Two types of these units are identified, the solitary and the stacked. They are only observed were carbonate lithologies are present, which is indicated by the seismic facies identified previously and the nearby wells when these are available.

The first type is quite common. It has a simple architecture composed of a single curved reflector that forms the base, and a flat reflector that forms the top. Between them, a fill is sometimes observed with an amplitude change as a single reflector. These units have dimensions ranging from 150 to 300 meters, and a thickness of approximately 20-30 meters. They often appear either in pairs, with two units located next to each other. Sometimes these are connecting to form a larger structure. The second stacked category is more rare with a more complicated architecture of multiple levels and subdivisions. Their dimensions are usually 1,5 km wide, and have a thickness up to 400 meters with the internal

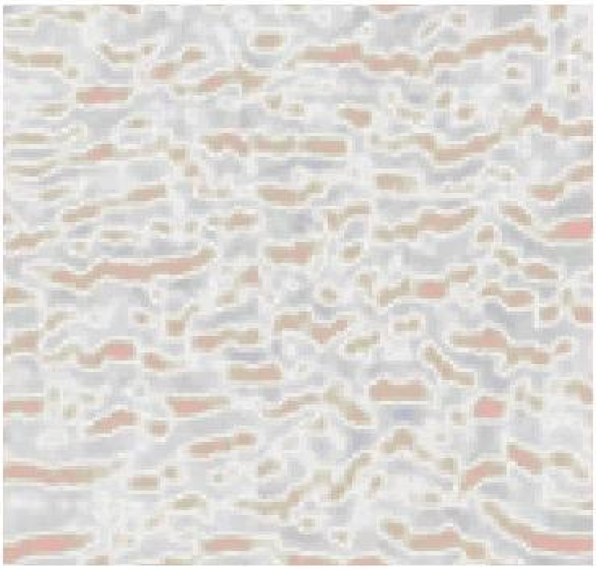

Figure 6.5: The Seismic Geometry (SG1) - Convexed Reflectors.

divisions being 150 to 300 meters wide 20-30 meters thick.

A number of interpretations for these reflectors can be excluded or put forward based on the overall geology of the Permian, the climate, the lithology that is associated with them and their location on the Permian carbonate platform. Since the climate during the Middle-Upper Permian is dry (Kidder and Worsley, 2004; Roscher et al., 2011) and the local topographic relief low (Scotese and Schettino, 2017), it is difficult to interpreted these unit as the result of a river system that was active in the region that could result into deep incised valleys. An interpretation related to karst features is unlikely, considering that no collapses or caving has been identified in any of the wells that have penetrated the carbonate formations in the examined region Finally, an interpretation related to slope gravity channels is also challenging, considering that these channels are present in locations with very shallow water depth. A more likely explanation for a channel-like system developing in the shallow marine water column areas of a carbonate platform, with synchronous carbonate deposition surrounding it, would be tidal channels. The widths observed in the seismic data are within what is normally expected of carbonate platform tidal channels (Grélaud et al., 2010), but the thickness is higher than average. For the stacked type this is to be expected and could be attributed to the stacking effect that is observed. For the single type, smaller scale stacking is possible, but due to the limitations of seismic resolution, further conclusions regarding their internal architecture can not be reached.

6.7. Permian Onlaps and Backstepping

At the lines with a SE-NW orientation it was observed that the Middle Permian is onlapping (Figure 6.10) the deposits of the Lower Permian at certain locations. More specifically, it was noted that the Upper Carboniferous and Lower Permian rocks appear to have been deposited parallel to each other and then folded, and as a result acquiring the same geometry. The Middle Permian is then deposited horizontally to these folds, first filling the lower sections and gradually building in thickness, eventually covering the fold Lower Permian and Carboniferous sediments. This is an indication that during the first stages of the Middle Permian, the underlying rocks were acting as paleotopography in the region, restricting deposition to the shallower sections until these were filled up.

Another observation regarding the geometry between the Carboniferous, Lower Permian and the Middle Permian, is that the later is observed as backstepping on the former in multiple lines, especially those with a N-S or a NW-SE orientation. More specifically, the Middle Permian is gradually building

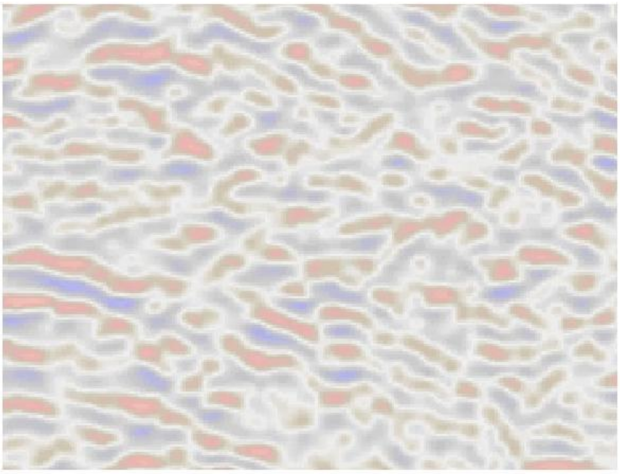

Figure 6.6: Another example of the Seismic Geometry (SG1) - Convexed Reflectors.

upwards and covering the exposed Lower Permian, Carboniferous and Ordovician rocks as it expands towards the Telemzane Arch to the south (Figure 6.11).

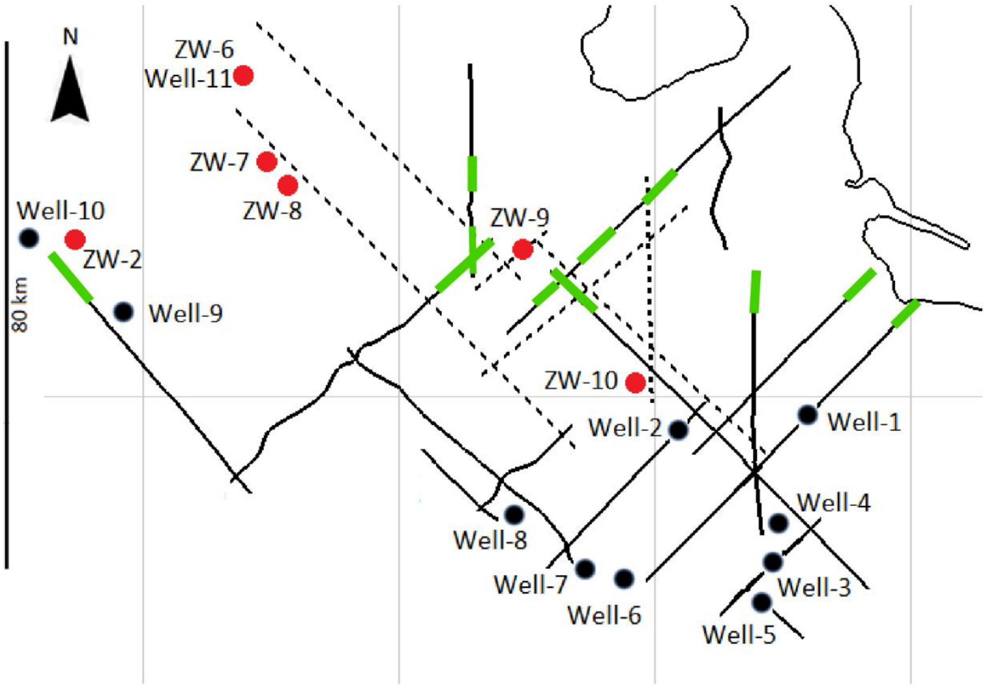

Figure 6.7: In green, the locations where SG1 has been identified, showing its E-W distribution.

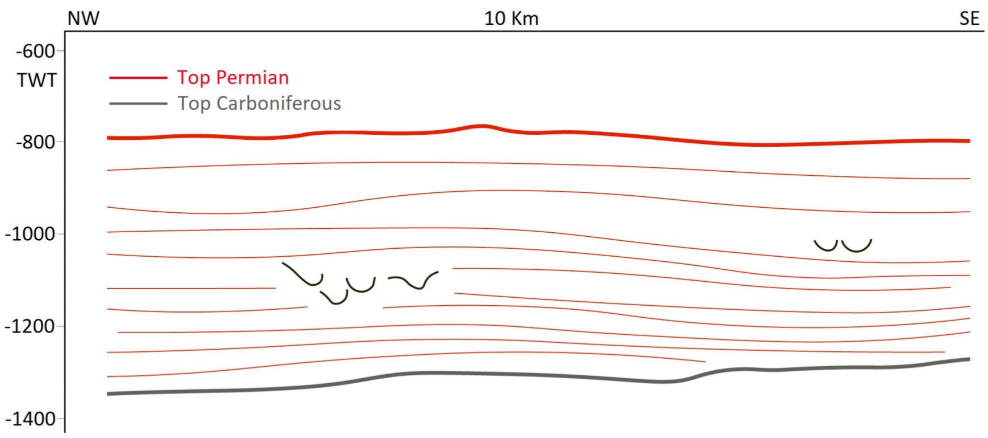

Figure 6.8: Staked and concaved reflectors identified at Line-16.

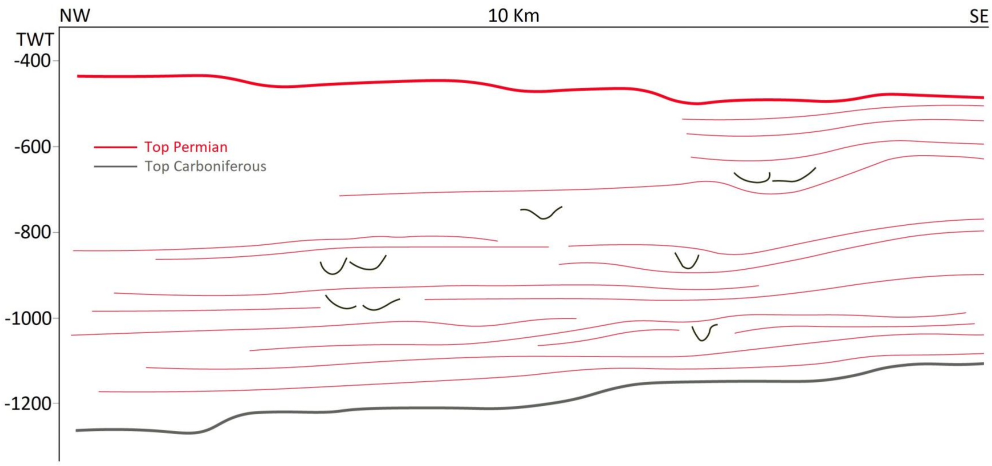

Figure 6.9: Staked and solitary concaved reflectors identified at Line-15.

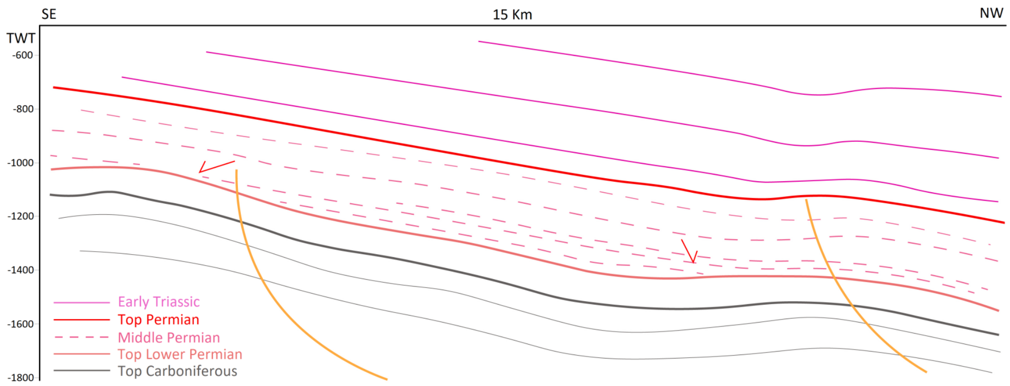

Figure 6.10: The Middle Permian onlapping the Lower Permian as seen in Line-2.

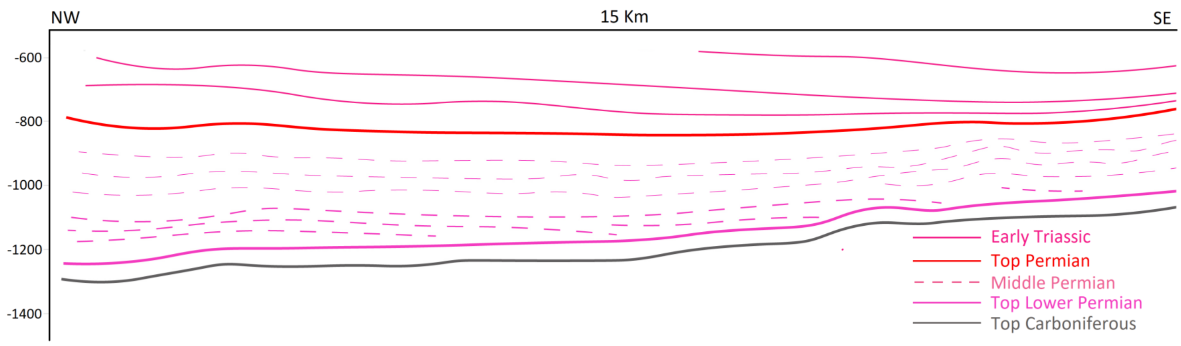

Figure 6.11: The Middle Permian backstepping on the Carboniferous at Line-3.

7

Defining Geological Formations

Based on Environmental Units, the Seismic Facies and the Boundaries defined earlier, a number of Geological Formations have been defined for the Permian at the examined area. These formations can be identified and correlated with eight wells and are also traceable for considerable distances at the seismic data, covering the majority of the region for dozens of kilometers. Three regions have been defined, Center-East (CE), West (W) and South (S).

7.1. Defining Center-East Formations

- Permian CE-IV Formation

  Permian CE-IV Formation is composed of shale, marl, carbonates and anhydrite.It corresponds to the Lithological Units Well-1/4 and Well-2/4. It can be dated to the Upper-Middle Permian (Ghazzay et al., 2015) or the Upper Permian (Well-1 completion report). Above this formation lie sandstone deposits dated to the Early Triassic as suggested by the completion report of Well-1 and Ghazzay et al. (2015), Figures 7.1-7.3.

- Permian CE-III Formation

  Permian CE-III Formation is composed of thick carbonate deposits, calcite and dolomite, with presence of shale, anhydrite at the shallower intervals and very rarely sand. It corresponds to the Lithological Units Well-1/3, Well-2/3 and Well-4/3 as correlated with seismic data. It has been dated to the Upper-Middle (Ghazzay et al., 2015) or Upper Permian (Burollet et al., 1990).

- Permian CE-II Formation

  Permian CE-II Formation is composed of sand, shale and carbonates.It corresponds to the Lithological Units Well-1/2, Well-2/2 and Well-4/2 as correlated with seismic data. It has been dated to the Upper Carboniferous - Middle Permian (Ghazzay et al., 2015).

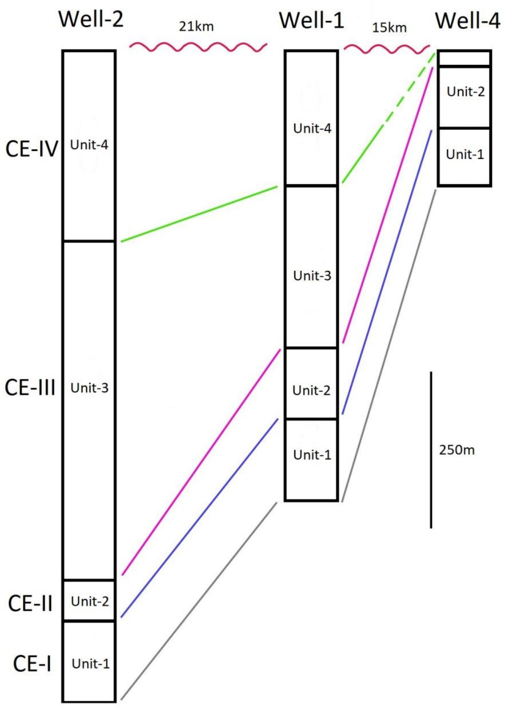

Figure 7.1: Updated correlation of Well-1, Well-2 and Well-4 based on seismic data with the defined Geological formations traced.

- Permian CE-I Formation

  Permian CE-I Formation is composed of carbonates, calcite and dolomite, shale and marl. It corresponds to the Lithological Units Well-1/1, Well-2/1 and Well-4/1 as correlated with seismic data. It has been dated to the Upper Carboniferous - Middle Permian (Ghazzay et al., 2015) or Lower Permian (Burollet et al., 1990). This formation, along with CE-II is the base of the Permian and it can be observed parallel with the underlying Carboniferous deposits at considerable distances, dozens of kilometers, in the seismic data.

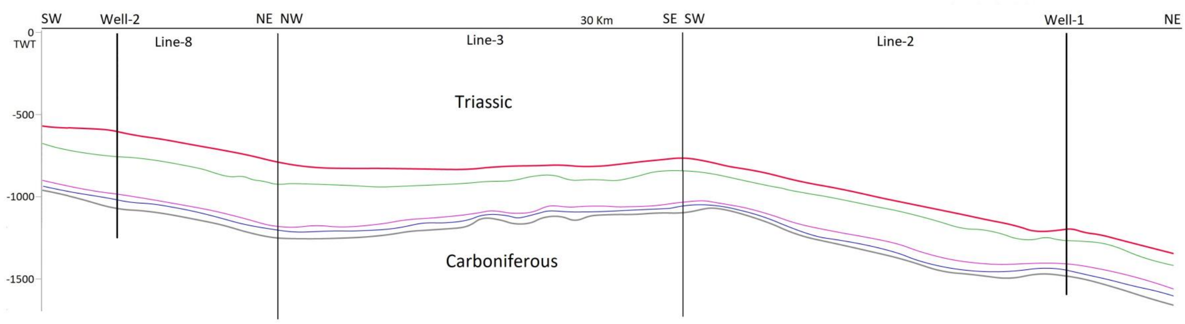

Figure 7.2: The Geological Formations defined above as observed in three seismic lines, connecting Well-1 and Well-2.

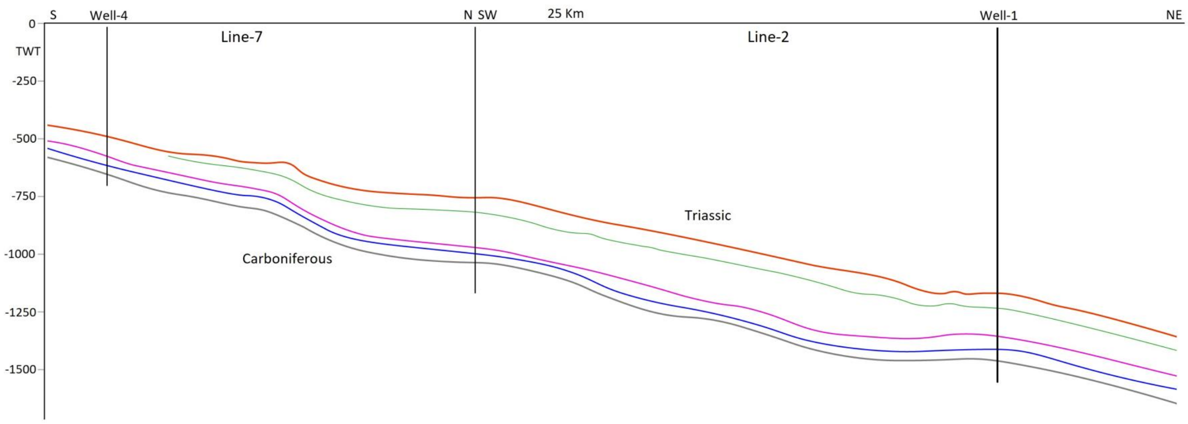

Figure 7.3: The Geological Formations defined above as observed in two seismic lines, connecting Well-1 and Well-4. The later well is projected as it does not lie directly on the seismic line but is located 3 kilometers to the NE.

7.2. Defining South Formations

Towards the South the seismic data interpretation indicates a thinning of the Permian (Burollet et al., 1990) and a change in seismic facies also further suggests changes in lithologies. There, two Geological Formations have been defined for the Permian in three wells, Well-8, Well-6 and Well-7. The lithological units of Well-3 and Well-5 to the South-east are similar to the aforementioned wells but due to the lack of seismic coverage and reliable dating, correlation has not been performed (Figures 7.4-7.5).

- Permian S-II Formation

  Permian S-II Formation is composed of carbonates, marl and shale. It corresponds to to the Lithological Units Well-8/3, Well-8/2, Well-6/2 and Well-7/2. It has been dated to the Upper-Middle Permian based on the fossil record of well Well-8, and the presence of Early Triassic Fossils at slightly shallower depths in Well-7.

  The upper boundary of this Formation is the Permian-Triassic Unconformity that has been identified and traced at the seismic data. The deposits of the Early Triassic are composed mainly of sandstone, similar to what is observed towards Well-2, Well-1 and Well-4, but also of carbonates at Well-7. In the seismic data these sandstones are identified as the low amplitude dipping reflectors shallower of the P-T Unconformity.

- Permian S-I Formation

  Permian S-I Formation is composed of sand with varying degrees of maturity and sorting, claystone, conglomerate rocks, pebbles and cobbles. It corresponds to the Lithological Units Well-8/1,

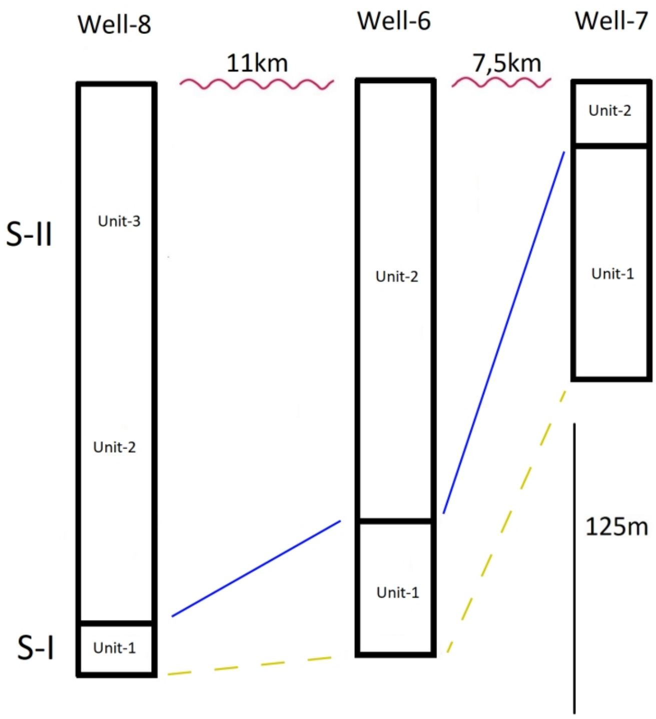

Figure 7.4: Correlation of Well-8, Well-6 and Well-7 based on seismic data, and the defined Geological Formations.

Well-6/1 and Well-7/1. At the bottom of this Formation lies the contact between the Permian and the Ordovician, although precise identification of its depth is challenging since both geological periods are composed of clastic rocks and they are azoic.

The dating of this Formation has been done relative to the shallower Permian S-II, and by lateral correlation of other Geological Formations from the North-East, which can be dated more reliably. It has been assigned a Middle-Upper Permian age based on the seismic correlation and well data.

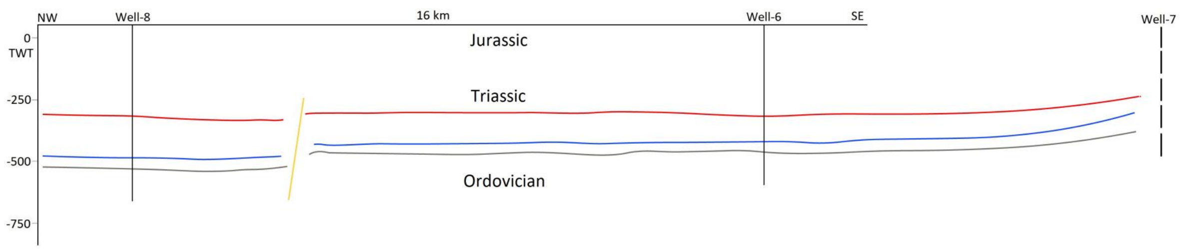

Figure 7.5: The Geological Formations defined above as observed in Line-15, connecting Well-8, Well-6 and Well-7. The later well is plotted with dashed lines since it is not projected directly on the seismic line but is located 6 kilometers to the North-East respectively.

7.3. Defining West Formations

Towards the West two additional Geological Formations have been defined for the Permian used seismic line Line-16 and two wells, Well-10 and Well-9. Since neither of these wells correlate directly with the seismic line, accurate seismic interpretation is challenging at that area (Figure 7.6).

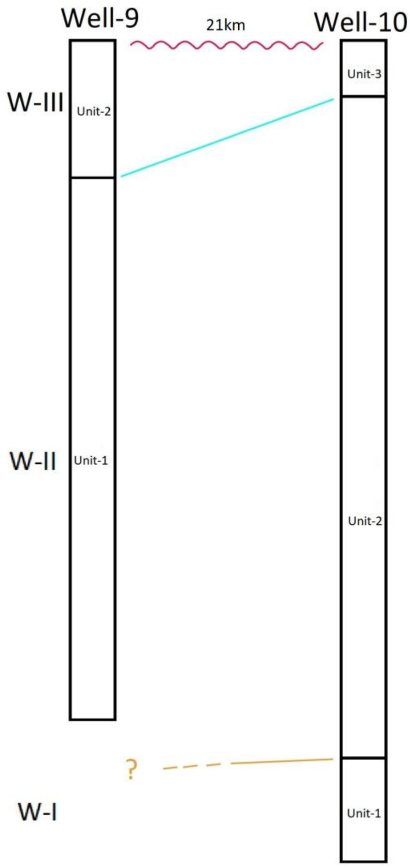

Figure 7.6: Correlation of Well-9 and Well-10 based on lithologies and with seismic data.

- Permian W-III Formation

  Permian West III Formation is composed of deposits of shale and marl, with more rare intervals of carbonates. It corresponds to the Lithological Units Well-9/3 and Well-10/2 and it has been dated to the Upper Permian in the well reports. However, the presence of the P-J unconformity indicates that a significant portion of the Permian deposits have in fact been eroded and are thus missing from the sections.

- Permian W-II Formation

  Permian West II Formation is composed the Lithological Units Well-9/2 and Well-10/2. It has been dated to the Middle-Late Permian (Murghabian in the well report of Well-9).

- Permian W-I Formation

  Permian W-I Formation corresponds to the Lithological Unit Well-9/1. The age suggested in the completion report of Well-9 is Early Permian.

Formations CE-I and CE-II span a significant age of deposition, from the Upper Carboniferous and the Early Permian, and possibly extending until the Middle Permian (Ghazzay et al., 2015). Their total thickness is relatively constant in the examined area, as indicated by Well-4 - 220 meters, Well-2 - 215 meters, and Well-1 - 245 meters.

The Formations CE-III, CE-IV and W-II, W-III have of deposition age that spans the Middle Permian until the Upper Permian. During that time period the massive carbonate and the shale-anhydrite deposits typical of the Upper Permian were deposited and their thickness reaches a maximum of 2500 meters.

It is known that during the Permian the global base level was relatively constant (Haq and Schutter, 2008) and during the Wuchiapingian-Changhsingian, it had reached its lowest point during the entire Paleozoic (Figure 7.7). This corresponds well with the deposition of the anhydrite facies of Geological Formation CE-IV.

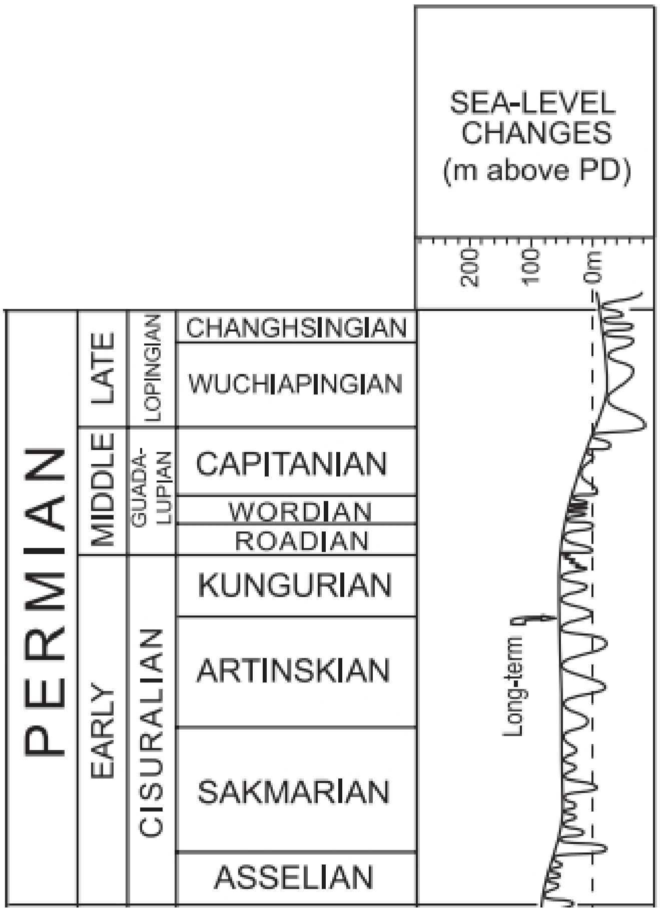

Figure 7.7: Long term and short term base level changes compared to present day PD levels during the Permian. Note the relative stability of the base level, and the significant drop during the Wuchiapingian-Changhsingian periods (Haq and Schutter, 2008).

8
Structural Interpretation

During the interpretation, lateral tracing of reflectors, and the overall study of the seismic data, areas of structural interest were identified and examined. As a result of this process a number of normal and reverse faults, and well as a number of fault-propagating folds were identified. These were later mapped, correlated with each other and dated used information from the well reports and the seismic interpretation.

8.1. Normal Faults

A limited number of normal faults have been observed at the seismic data. Where they occur their displacement is relatively small for the top Permian reflector, approximately 100-150 meters based on the Time-to-Depth conversion. The displacement observed for the top Ordovician reflector is more significant, approximately 400-500 meters (Figures 8.1,8.3).

The dating of these faults is challenging. What is observed in the seismic data is that they exhibit is low displacements during the Ordovician, Carboniferous, Permian and the Lower Triassic. The deposits of the Upper Triassic are not influenced by them, indicating the geological period when they were last active. The age when these faults were first activated could be dated to the Ordovician and were later subjected to sporadic small scale re-activation until the Middle Triassic, when their activity finally ceased.

Moreover, based on seismic data observations, the orientation of their strike is East-West, or North East - South West with their slip orientated towards the North, North-West (Figure 8.2).

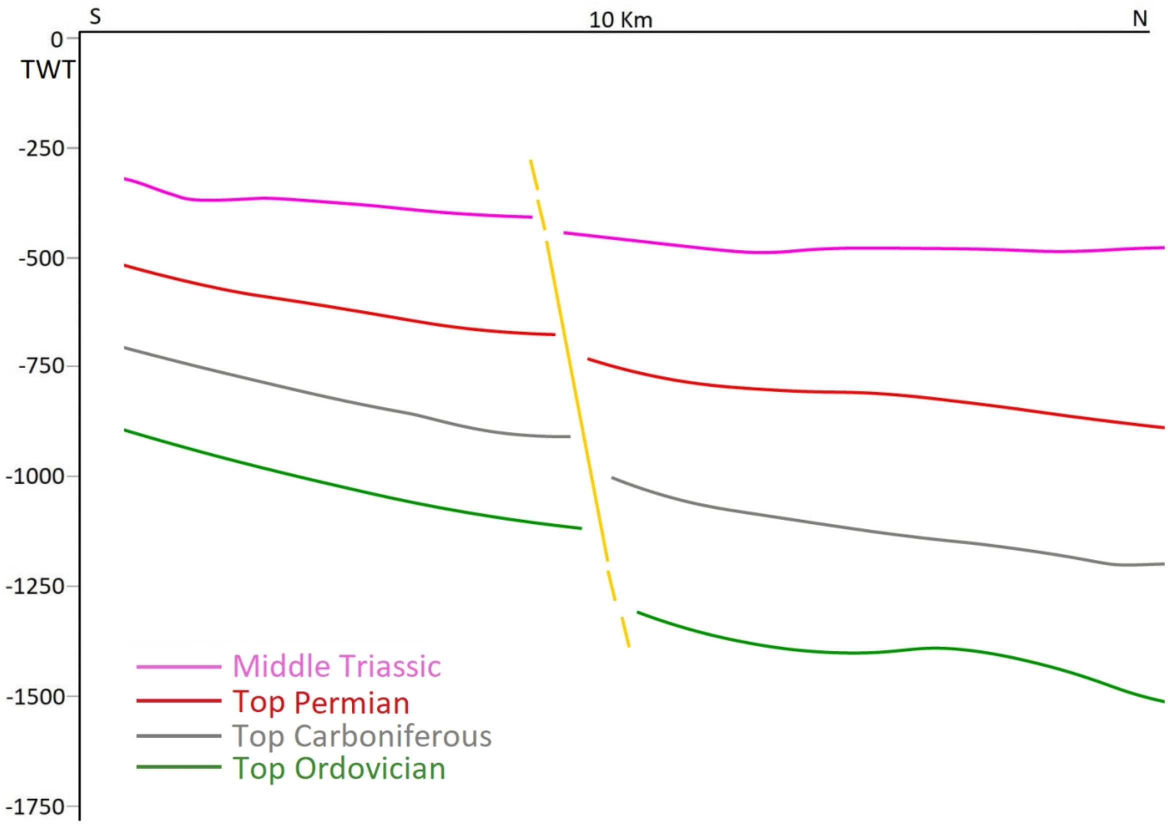

Figure 8.1: An identified normal fault at the South section of Line-7. The purple reflector at the top of the fault is dated to the Middle Triassic using Well-1.

8.2. Thrusts

In addition to normal faults, structures that have interpreted as thrusts have been observed in the seismic data. These structures have a North West - South East strike and move sections of the Paleozoic and Triassic from the North East towards the South West.

Based on the interpretation and the displacement of these thrusts, two episodes could be inferred. The first episode can be dated to the Upper Carboniferous - Early Permian. This can be concluded

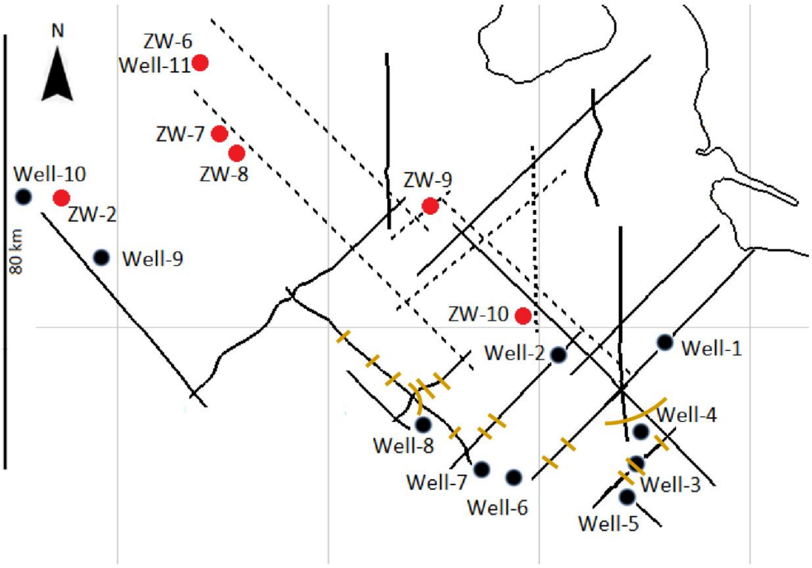

Figure 8.2: Map with the location of identified normal faults.

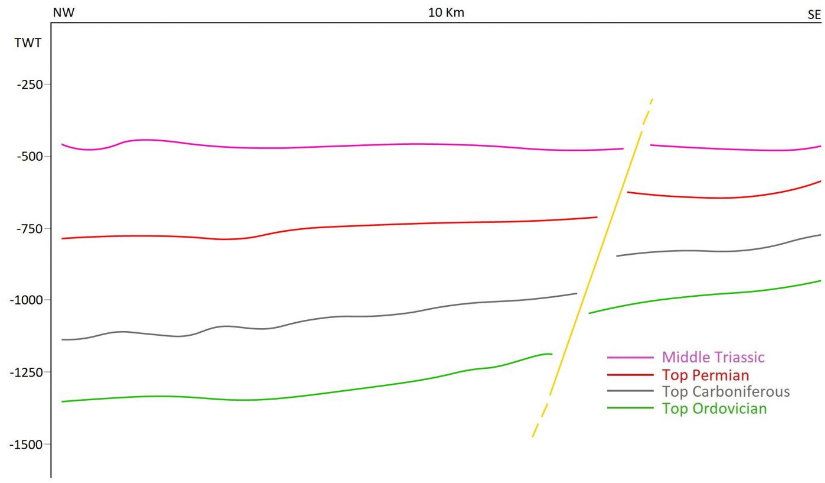

Figure 8.3: A normal fault as observed at the South section of Line-3. The purple reflector at the top of the fault is dated to the Early-Middle Triassic using Well-1.

since some of the thrusts displace the Ordovician, Carboniferous and Early Permian deposits, but they appear to influence neither the Middle-Upper Permian nor the Triassic rocks. Following this episode, a second event appears to have reactivated these thrusts. As a result some of them can be seen propagating into the Permian and the contact between Middle and Upper Triassic (Figures 8.4-8.6).

Towards the Northern sections of the seismic lines, deposits dated to the Cretaceous and Jurassic are prevalent (Bibonne, 2014; Ghedhoui, 2014). This could indicate a possible reactivation of the Permian-Triassic folds during the Mesozoic, which enabled the deposition of the aforementioned sediments.

These structures can be identified at multiple lines covering the East section (Figure 8.8) of the examined area and they have a significant lateral extend of at least 60 kilometers. Of interest, is the fact that towards the North-West, their inferred trajectory correlates well with the location of Well-11 (Figure 8.7).

The presence of a fold at the vicinity of this well could explain the thickness of its Permian deposits, as well as the apparent repetition of the Permian that is suggested in the original completion report. If this is the case, then the thickness of the Permian in Well-11 could be inaccurate, since it corresponds to two overlapping sections with similar lithology and age, whose separation purely on well data is not possible.

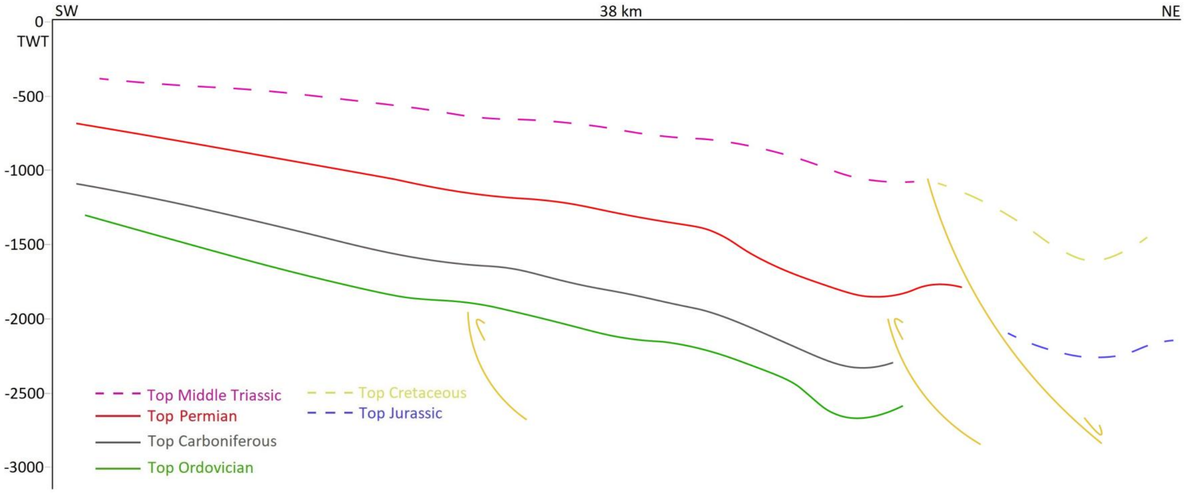

Figure 8.4: Thrusts that have been identified at the Line-1. A number of these appear to have been reactivated and extend into the Permian. Using Well-1 the shallower sections influenced by these structures have been dated to the Middle Triassic. The displacement to the NE of the line indicates possible reactivation of the folds during the Mesozoic period to accommodate the Jurassic and Cretaceous.

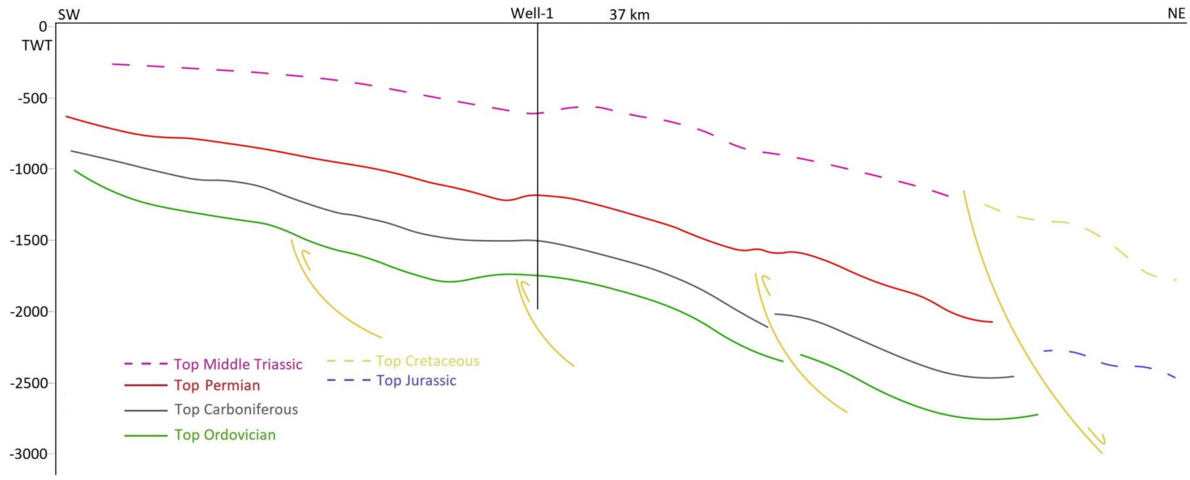

Figure 8.5: Thrusts that have been identified at the Line-2. A number of these appear to have been reactivated and extend into the Permian. Using Well-1 and seismic Line-1 the shallower sections influenced by these structures have been dated to the Middle Triassic. The displacement to the NE of the line indicates possible reactivation of the folds during the Mesozoic period to accommodate the Jurassic and Cretaceous.

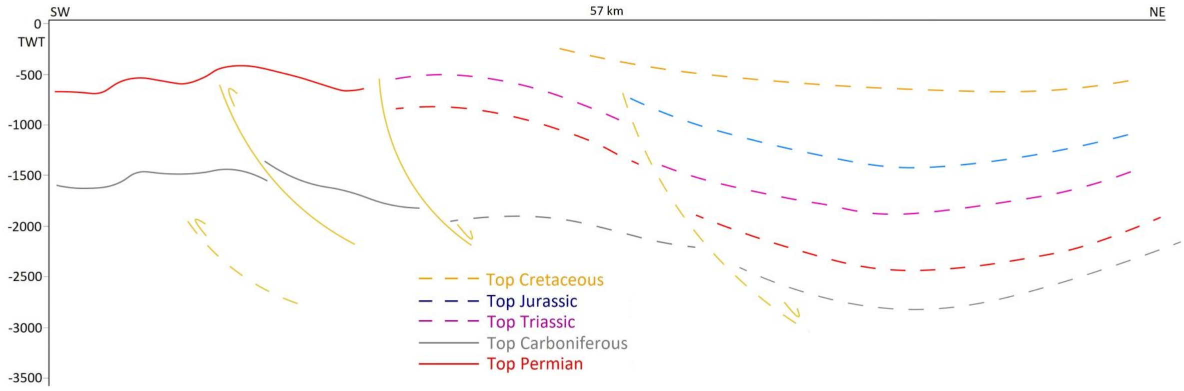

Figure 8.6: Thrusts that have been identified at the Line-11. Due to the distances from the areas close to Well-1 and Well-2, accurate interpretation to the South-East of this line is challenging. The presence of chaotic reflectors, observed at the center of Line-11, further inhibit accurate tracing of reflectors and vertical movement. Similar to Line-1 and Line-2 the displacement to the NE of the line indicates possible reactivation of the folds during the Mesozoic period.

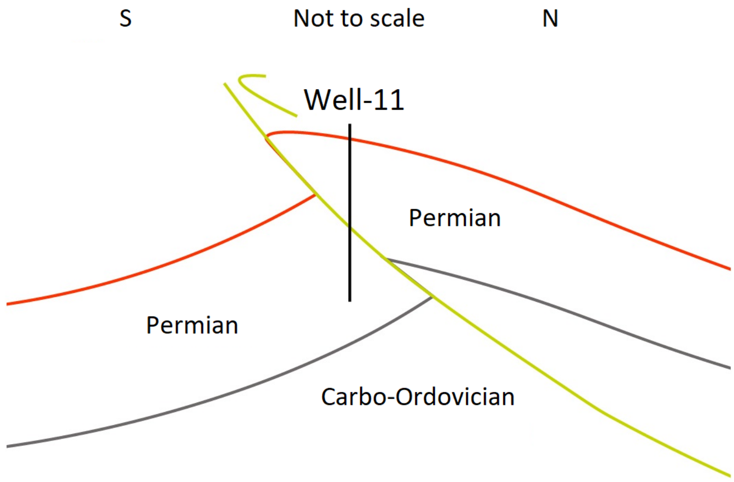

Figure 8.7: Idealized conception of a western extension of the identified thrusts, increasing the apparent thickness of the Permian at Well-11. The thickness of the Permian, the Carbo-Ordovician as well as their lateral dimensions are not to scale in this figure.

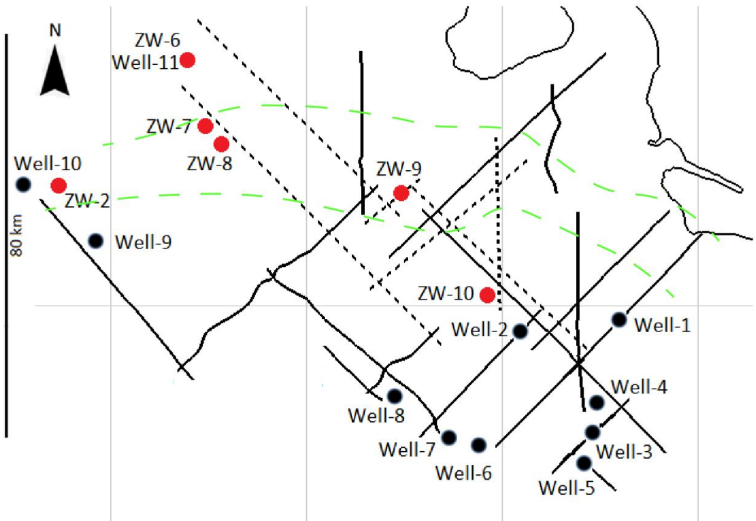

Figure 8.8: Map with the location of identified folds. The trajectory of the folds corresponds well with the areas were the chaotic seismic reflectors are identified, further highlighting the fractured nature of the subsurface there.

9

Subsidence Study

Following the definition of Lithological Units and Formations for each of the available wells, we proceed with decompaction calculations to acquire a quantitive approximation about the overall subsidence rates in the Jeffara Basin during the Permian.

9.1. Outline

For the decompaction procedure a number of parameters need to be known (Angevine et al., 1990; Allen, 1990). First, the current thickness of a formation at the subsurface, which has already been defined earlier based on the seismic and well correlation.

Second, the current total porosity values of the lithologies that compose these formations. Here, this parameter is constrained by utilizing the porosity measurements that are provided at the well completion reports. A limiting factor that increases uncertainty in the calculations is the scarcity of this information and the fact that sometimes only effective porosity values are only given, while rarely no porosity values are provided at all for the well thus necessitating the use of average values extracted from porosity-depth curves.

The third parameter that is needed is the geological age of the decompacted formations. In this project, the age of the formations has been approximated based on the conclusions of the well completion reports and further constrained by the seismic interpretation and information provided by literature. However, while the beginning and final age of the formations are known, there is no constrained as to the subsidence rates.

A forth parameter that is usually needed for the construction of subsidence curves is the paleobathymetry of the region. However, in the case of this project this is considered negligible due to the very shallow waters column typical of carbonate platform settings.

An inherent limitation that further increases uncertainty is that the total amount of porosity loss is attributed solely to sediment compaction. In reality other factors can be responsible to the reduction of the total porosity of a rock. These include chemical dissolution or cementation, crystallization or an abnormal change in pressure conditions in a specific area. Thus, it can be inferred that the calculated decompacted thickness is in fact an idealized maximum, since all porosity loss is attributed to sediment compaction alone. Moreover, the subsidence rate variation during the examined geological periods is not known. Thus, it is assumed that the decompacted areas were under a relatively constant subsidence rate.

For the decompaction of the Permian the following equation, simplified from Angevine et al. (1990); Allen (1990) was used.

$$T_0 = \frac{(1 - \Phi_p) \cdot T_p}{(1 - \Phi_0}$$

where T_0 is the original thickness, T_p the present thickness, Φ_0 the original total porosity and Φ_p the present total porosity.

Thickness is expressed in meters, and the total porosity as a percentile fraction.

9.2. Formations CE-I, CE-II, CE-III and CE-IV

Formations CE-I to CE-IV are composed of Well-1, Well-2 and Well-4. Based on the calculations the decompacted thickness for the formations in these three wells has been plotted in diagrams (Figure 9.1). It can be observed that in all three wells CE-I and CE-II indicate a relatively slow subsidence rate during the Upper-Carboniferous - Early Permian. On the other hand, the subsidence rate is increasing considerably during the Middle and Upper Permian in Well-2 and Well-1, during the deposition of CE-III and CE-IV. For Well-4 the curve is different, with the subsidence rate being reduced during that time. This however could be the result of the Middle-Upper Permian deposits being eroded away during the Triassic.

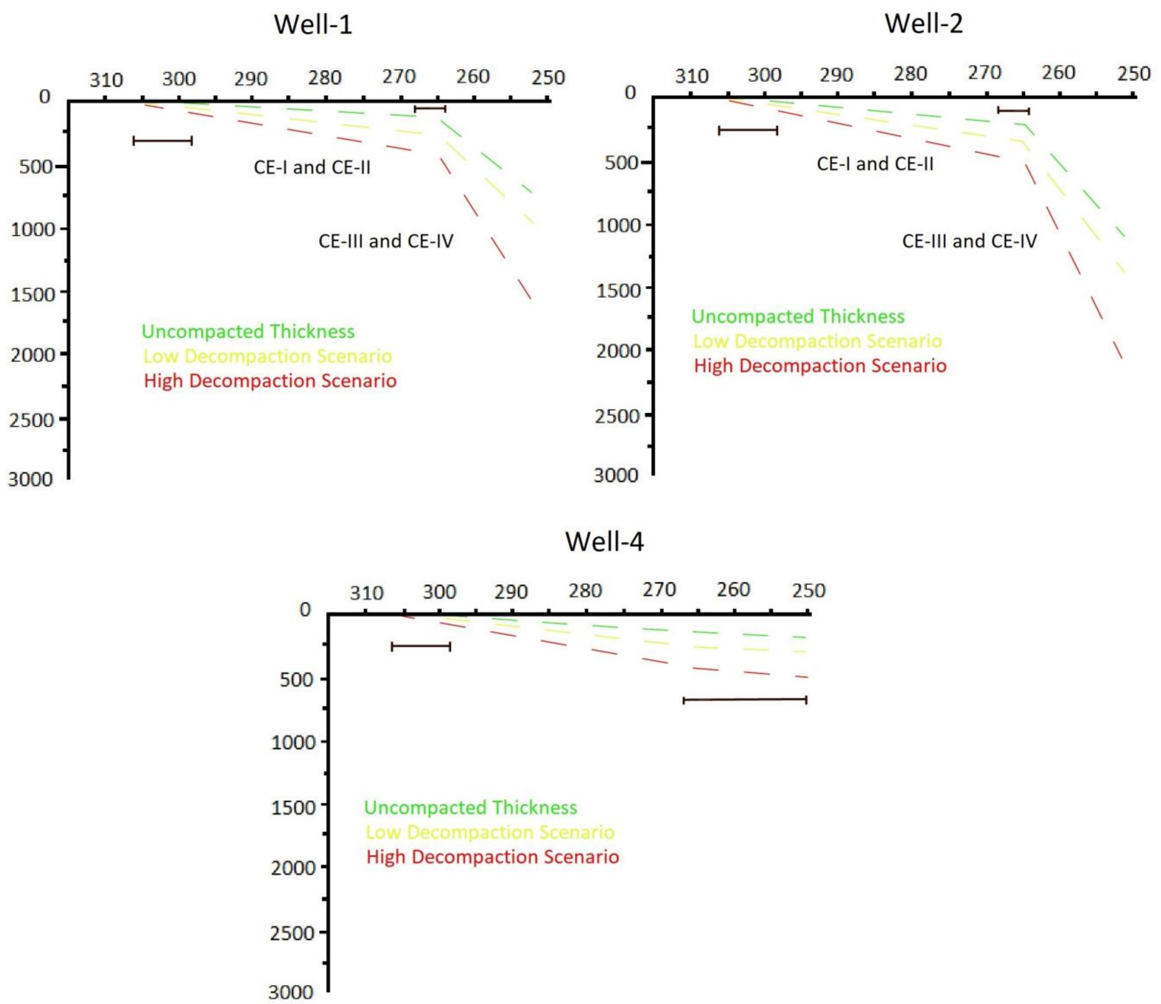

Figure 9.1: Corrected and uncorrected subsidence curves for the CE-I to CE-IV Geological Formations, and Well-1, Well-2 and Well-4.

9.3. Formations S-I and S-II

Formations S-I and S-II are composed of Well-7, Well-8 and Well-6. Based on the calculations the decompacted thickness for the formations in these three wells has been plotted in diagrams (Figure 9.2). It can be observed that in the locations of these wells during the Middle-Upper Permian a low subsidence rate was prevalent.

9.4. Formations W-I, W-II and W-III

Formations W-I to W-III are composed of Well-9 and Well-10. Based on the calculations the decompacted thickness for the formations in these wells has been plotted in diagrams (Figure 9.3). They indicate a relatively slow subsidence rate during the Early-Middle Permian and deposition of W-III. This is similar to what is observed at the CE Formations (Figure 9.1). The subsidence rate is increasing considerably during the Middle and Upper Permian during deposition of W-I and CE-II.

The starting point of the subsidence figure for Well-10 is problematic because the contact between the Permian and the underlying Ordovician was not reached when the well was completed. Thus, it is possible that Early Permian deposits are located deeper than what was reached.

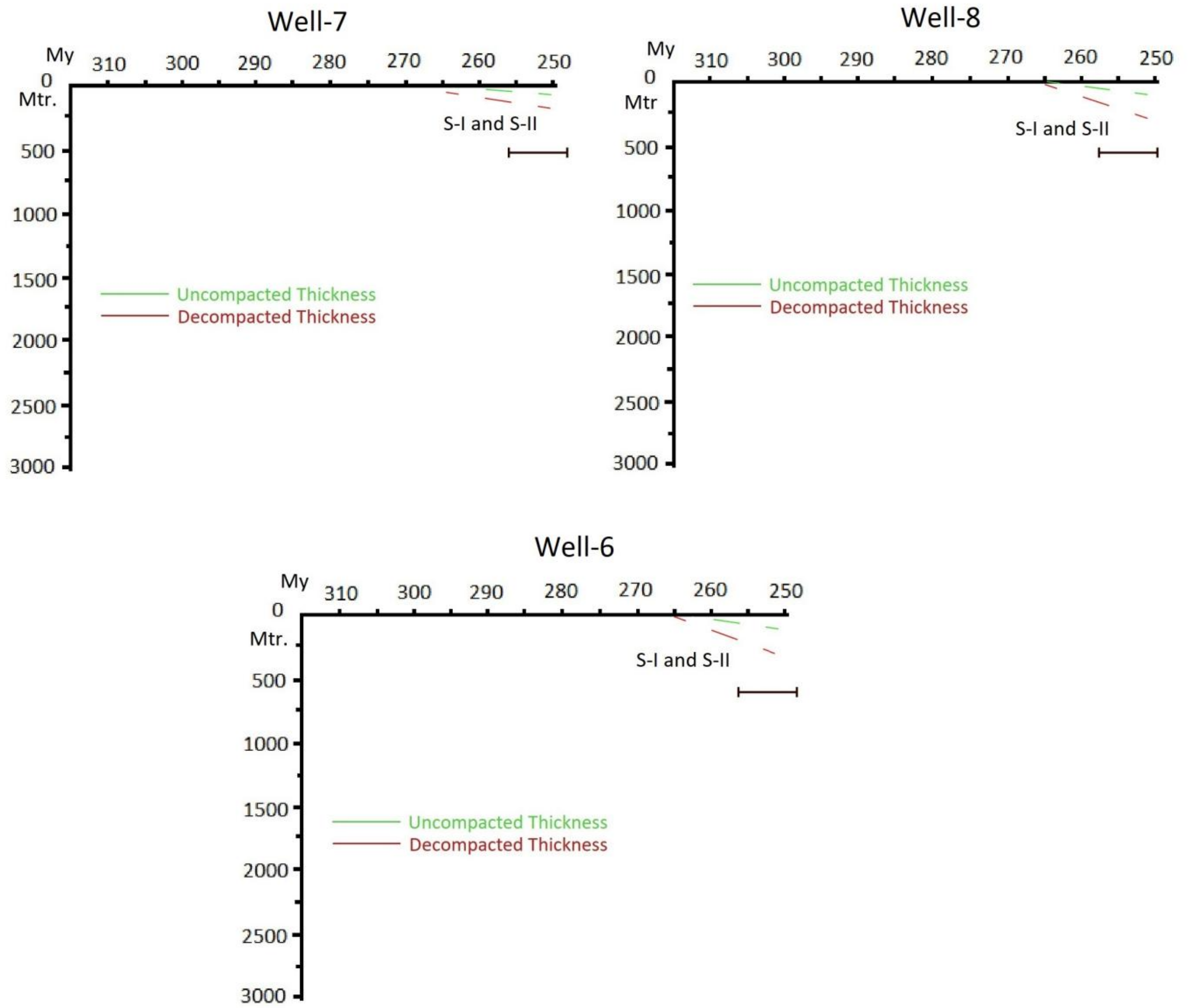

Figure 9.2: Corrected and uncorrected subsidence curves for the S-I and S-II Geological Formations, and Well-7, Well-8, Well-6.

An additional limitation of the calculations is related to the terminal age of the uppermost Permian deposits of wells Well-9 and Well-10. This is because the seismic data interpretation indicates that a considerable portion of Upper Permian (Figure 4.5 and 4.6) has in fact been eroded by the Jurassic Unconformity - approximately 500 meters. Thus, it is highly probable that the end point of the curves is reached before the 252 Mya mark.

9.5. Well-3 and Well-5

Based on the calculations the decompacted thickness for Well-3 and Well-5, the subsidence curves been plotted in diagrams (Figure 10.1). They indicate a low subsidence rate at their location during the Permian. A limitation of these curves is that these two wells are relatively isolated from the remaining data, and thus their dating is uncertain beyond the Early Permian age suggested by the well completion reports.

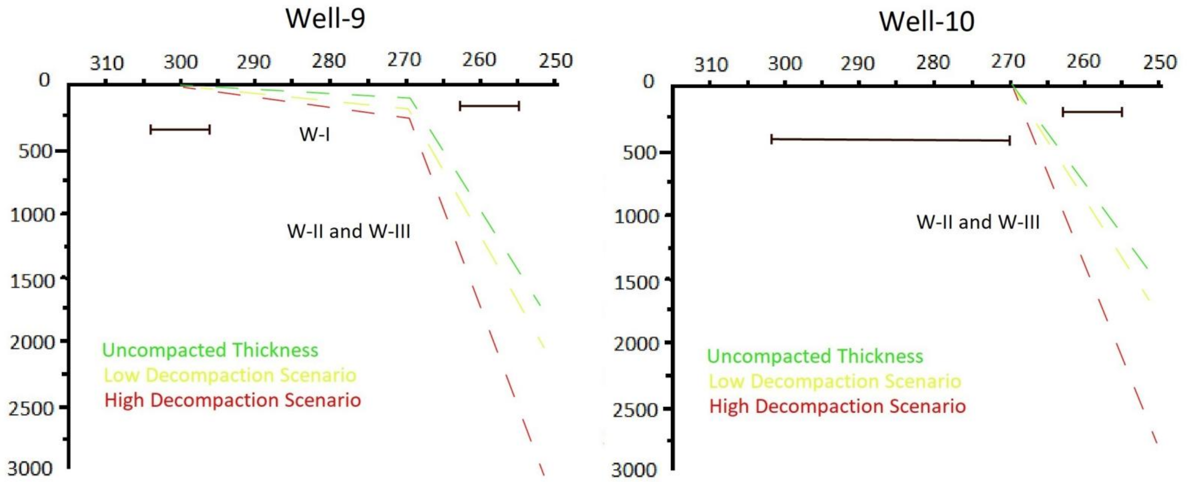

Figure 9.3: Corrected and uncorrected subsidence curves for the W-I, W-II and W-III Geological Formations, and Well-9, Well-10.

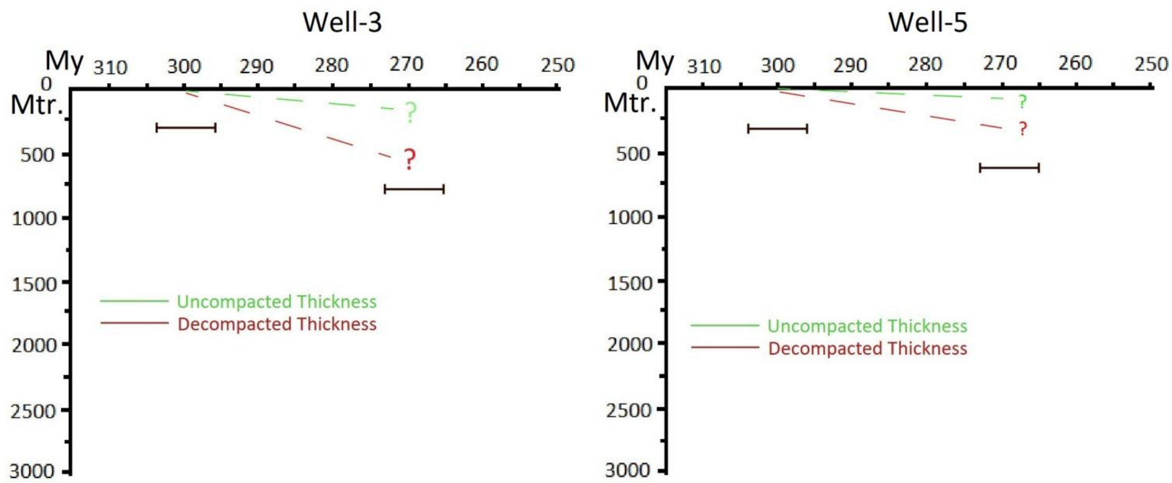

Figure 9.4: Corrected and uncorrected subsidence curves for Well-3 and Well-5.

	Lower Permian	Lower - Middle Permian	Middle - Upper Permian
Center East Region			
Well-1	10m / My		40m / My
Well-2	10m / My		60m / My
Well-4	10m / My		-
South Region			
Well-6	-		20m / My
Well-7	-		10m / My
Well-8	-		20m / My
West Region			
Well-9	10m / My		70m / My
Well-10	-		70m / My
Well-3 Well-5	- -	15m / My 15m / My	

Table 9.1: Average subsidence rates for the wells according to the decompaction calculations.

10

Environmental and Structural Reconstructions

Based on the analysis of the wells and the seismic data, environmental units have been defined. In combination with the definition of geological formations and subsidence calculations, environmental and structural reconstructions for the Permian have been performed.

10.1. Defining Environmental Units

- Environmental Unit I - Carbonate Platform Deposits

  This Environmental Unit is composed primarily of thick carbonate deposits, mainly dolomite but also calcite. Shale and marl of gray, beige, black, brown or reddish color can occasionally be found as thin intervals (less than a couple meters thick) between the carbonates. More rarely, sand is found dispersed inside the carbonates, shale, marl, or in the form of thin intervals (usually less than a meter thick. White anhydrite can also be found in this facies group as inclusions in the carbonates or as thin plaques. This is observed at lithological units Well-2/4 and Well-2/1, Well-1/4, Well-4/1 and Well-8/3. The carbonates are very rich in microfossils - foraminifera, algue, ostracods etc.

  The depositional environment of these sediments is interpreted as shallow marine where the conditions for were conducive to carbonate growth (Pomar and Kendall, 2008). The presence of anhydrite, usually towards the upper boundary of the lithologies, points towards a fluctuation in water depth that gradually influenced the areas of carbonate deposition (Schlager, 2005). These areas transitioned for a brief period of time from a marine to a terrestrial environment or to a very shallow marine, allowing the evaporation of sufficient volume of water and the formation of the anhydritic plaques and inclusions before the water level rose again, which in turn enabled further carbonate growth (Schlager, 2005).

  The rare presence of fine-medium sorted sand of white, pink or gray colour, indicates that the deposition of the carbonates took place a considerable distance away from any possible active rivers or sediment input sources in the area. The white and reddish color of the sand shows a mineralogy of pure or almost pure quartz, sediment of high maturity. The marl found in this facies could be the result of clastic input, related to the sand, or a product of microorganisms.

  This depositional environment is identified at the carbonate deposits of most of the well of the data set, Well-1, Well-2, Well-9, Well-10, Well-4, Well-8. While in lithological units Well-2/1 and Well-4/1 anhydrite is present, unit Well-1/4 has no anhydrite. This could indicate that Well-2 and Well-4 were perhaps closer to shore/shallower water overall compared to Well-1.

- Environmental Unit II - Coastal Deposits

  This Environmental Unit is composed primarily of sand (gray, beige, green, sometimes glauconitic) and secondarily of shale, claystone (black, red, purple), conglomerates and pebbles. The maturity of the sand deposits varies in these lithofacies. It can change from very fine and well sorted, to immature, angular and poorly sorted in the span of less than a meter. However the common succession displays a specific maturity level of 3-5 meters and a gradual transition to another maturity level. Sometimes thin intervals of shale are found within the sandstones. Occasionally pebbles and loose rocks can be identified in the sand. These can form thin layers or appear suspended in a sandstone matrix. These conglomerate pebbles can vary in size, from 4mm up to 90mm in diameter. At specific depths they form thick conglomerate rocks, of up to 15 meters thick. The sands and conglomerates are followed by of marl (brown, gray, green), shale (gray, brown, black, red) with a gradual increase in carbonate deposits. This change is followed by a reduction in the proportion of sand. At Well-3, anhydrite is also present.

  The depositional environment of these sediments is interpreted as terrestrial with a significant marine influence. The presence of glauconite in the sandstones as well as the significant variation in maturity level indicates shallow marine, shoreline deposits (Chafetz and Reid, 2000). Since no river related geometry has been identified in the seismic data, fluvial deposition is deemed unlikely. Additionally, the climate during the Middle Permian in the region was dry. The change in lithology towards finer granulometry and more carbonate rich deposits above these sandstones can be interpreted as a transition towards a shallow marine environment, more prone to carbonate deposition. The presence of anhydrite is also an indication of shallow marine influence, with the shoreline covered for brief time intervals with water, which was afterwards evaporated - similar to sabkha deposition.

This Environmental Unit is identified at six wells, Well-8, Well-6, Well-7, Well-9, Well-3 and Well-5. At the first three wells it has been assigned a Middle-Late Permian age. On the other hand, at Well-9 the fossils indicate a likely Early Permian age. At Well-3 and Well-5 dating accurately is not possible but an Early Permian age is suggested in the well reports.

- Environmental Unit III - Sabkha Deposits

  This Environmental Unit is composed primarily of shale (gray, brown, black, green), marl (gray, brown, beige), carbonates (usually dolomite, white or beige) and significant deposits of white anhydrite. The intervals of anhydrite are usually thin, less than one meter, and are found inter-bedded between the shale and the marl. However at certain depths, the anhydrite intervals can reach a thickness of up to five meters (Well-2). This proliferation of the evaporites is what distinguishes this Environmental Unit from the previous.

  To the Center and East parts of the examined region, these lithologies are observed at the top of the massive carbonates identified as shallow marine deposits, such as Units Well-1/1 and Well-2/1 are shallower than Well-1/2 and Well-2/2. These carbonates are themselves occasionally interrupted by thin deposits of anhydrite at their shallower intervals. This indicates that a minor water depth variation gradually become more impactful, until the paleo environment transitioned from shallow marine, to an environment were significant areas were occasionally isolated and the trapped water within them evaporated, leading to the deposition of anhydrite (Whitaker et al., 2014) This could be attributed to an overall decrease in water depth, which could had also been accompanied by a warmer, or to the more arid climate of the Upper Permian (Kidder and Worsley, 2004; Roscher et al., 2011), which could facilitate the evaporation of significant volume of water (Schlager, 2005; Whitaker et al., 2014).

  Moreover, the lack of sand in any of the deposits indicates that there were no significant river systems active during that period to transport sediment to the. This is also an additional indication that the overall climate during that time period became more arid and warmer. Overall, the paleo environment for these anhydrite deposits could be characterized primarily as a sabkha, but it would had varied in time.

  This Environmental Unit is identified in three wells, the upper sections of Well-2 and Well-1 and Well-5. A likely upper Permian age for these deposits is likely base on the well reports and the papers that have examined them.

- Environmental Unit IV - Lagoon Deposits

  This Environmental Unit is composed primarily of shale (black, gray, beige, green, pink), marl (pink, beige, black) and fine to medium sand (white, pink, gray), with occasional thin carbonate (gray, white, beige) intervals. In rare cases white anhydrite is found in the form of inclusions (Well-9) or thin plaques. These intervals are azoic.

  The presence of marl and carbonate rocks indicates that the depositional environment was marine. Also, the fine to medium sand indicates that deposition took place after the original sediment had been transported a considerable distance from source. This is compounded by the color of the sand, white or pink, which is a sign of a purely quartz mineralogy.

This Environmental Unit indicates a lagoon-estuary depositional environment. A combination of sufficiently shallow water column for the production and accumulation of thin carbonate intervals, combined with the deposition of clastic sediments carried by a river system. The anhydritic inclusions that are present in certain depths further signify that the water column at these areas was variable and at some point in time certain sections of the lagoons were, at least partially, cut off from water supply. The presence of lignite and bitumen at certain intervals of the lithofacies could also indicate anoxic conditions with high organic content.

This Environmental Unit is identified in Well-1/2, Well-2/2, Well-6/2 and Well-7/2, where their deposition was not synchronous but ranged from the Early until the Upper Permian.

10.2. Environmental Reconstructions

- Upper Carboniferous - Lower Permian environmental reconstruction

The Carboniferous in the Center-East region of the Jeffara Basin was characterized by shallow marine carbonate deposition as indicated by Well-1 and Well-2. The deposition of carbonates continued at the Early Permian - Geological Formation CE-I. During the Early and Middle Permian, a transition took place from a shallow marine to a lagoon depositional environment, rich in shale and marl - Geological Formation CE-II. To the north, these deposits are situated above the Lower Carboniferous and the Ordovician deposits. To the south no deposition appears to have taken place during the Upper Carboniferous - Early Permian periods as indicated by the lack of Early Permian deposits in Well-7, Well-8 and Well-6.

Towards the West, shoreline and shallow marine sediments were deposited during the Early Permian and are found in Well-9 - Geological Formation W-I (Figure 10.1).

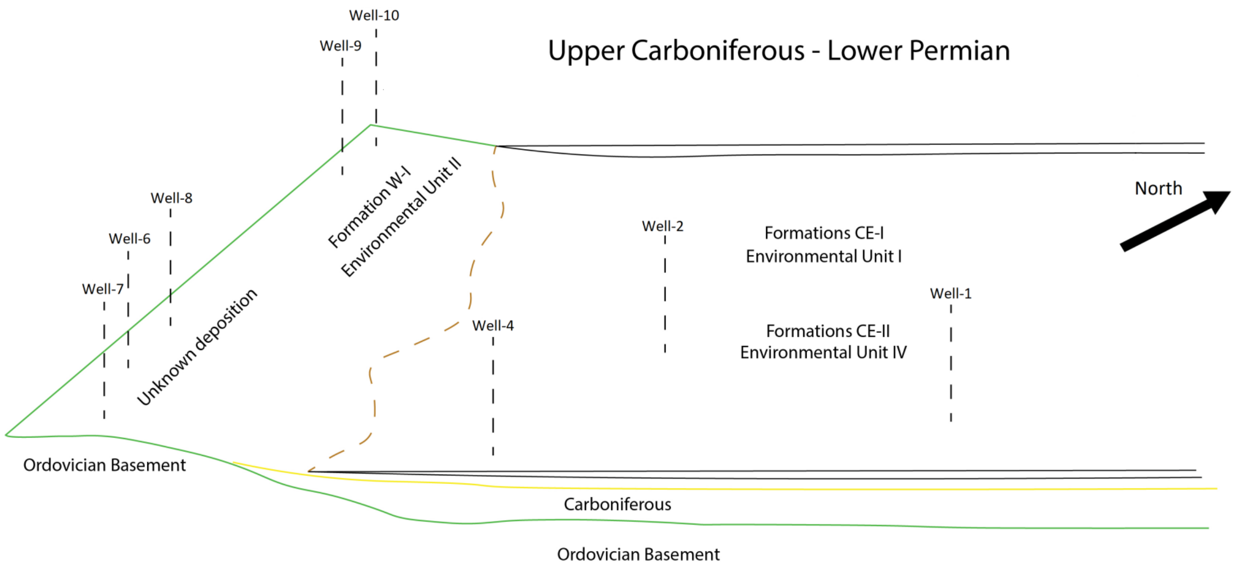

Figure 10.1: Idealized environmental reconstruction of the Upper Carboniferous-Lower Permian. The brown dashed line indicates a shoreline and its placement is hypothetical.

- First stage Middle Permian environmental reconstruction

he Middle Permian in Center-East and West region of the Jeffara Basin was characterized by extensive shallow marine carbonate deposition as indicated by Well-1 and Well-2. The carbonate platform extended approximately 80km towards the North - Geological Formation CE-III, W-II.

Towards the South, shoreline deposits of sand and conglomerates have been identified at Well-7, Well-8, Well-6, dating to the Middle - Upper Permian - Geological Formation S-I.

Towards the West, thick carbonate deposits have been identified at Well-9 and Well-10, Geological Formation W-II. In addition to the carbonate facies, tidal channels have been identified in the seismic data towards the West. These are not present at the Center-East and South regions (Figure 10.2).

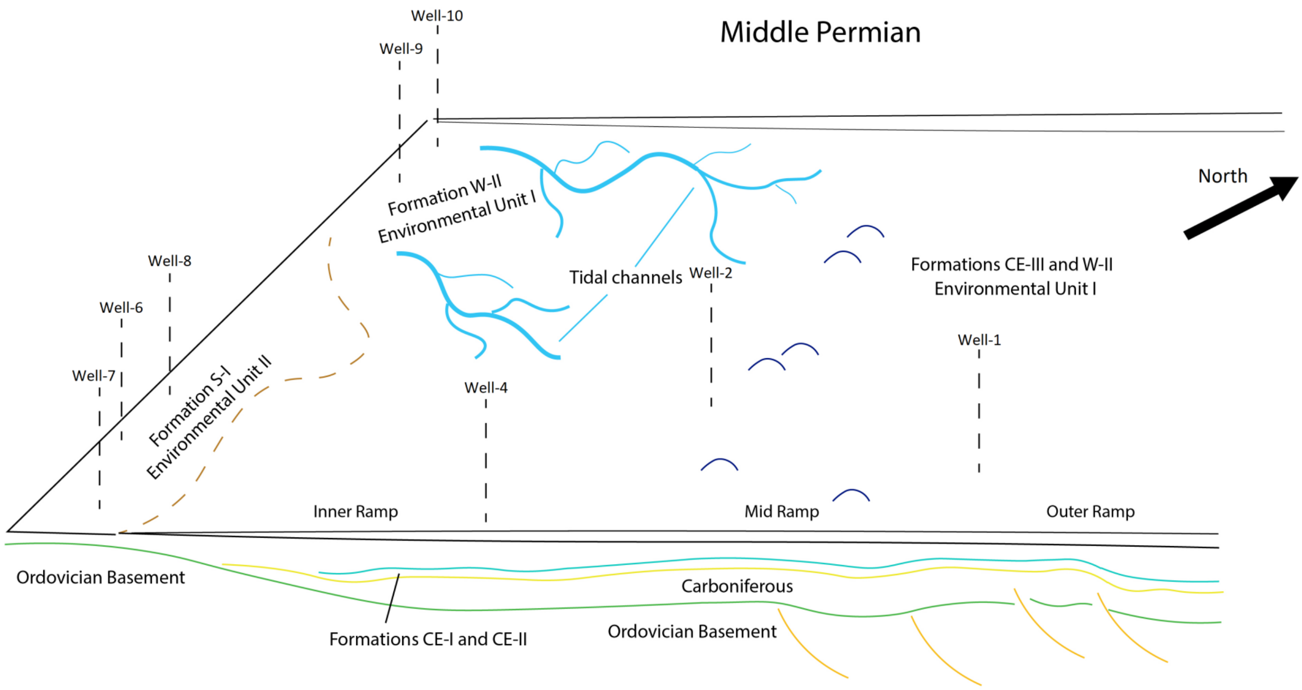

Figure 10.2: Idealized environmental reconstruction of the Middle Permian. The brown dashed line indicates a shoreline and its placement is hypothetical. The position of the tidal channels is proximal based on the seismic interpretation.

- Second stage Middle Permian environmental reconstruction

At a later stage of the Middle Permian the carbonate deposition was expanded to cover the South region of Jeffara Basin, with carbonate deposits backstepping on the Carboniferous and later the Ordovician. This change is reflected on Wells Well-7, Well-8 and Well-6, where the clastic shoreline deposits of Formation S-I, are followed by younger carbonates, marl, anhydrite and shale deposits, indicating a transition towards a more marine environment, Formation S-II.

Towards the West, carbonate deposition continues, as identified at wells Well-9 and Well-10, Geological Formation W-II. In addition to the carbonate facies, tidal channels are still present in the seismic data towards the West. These are not present at the Center-East and South regions (Figure 10.3).

The paleo current during the Middle Permian in Tunisia is expected to have a W-E, NW-SE direction as the ocean currents from the Paleo Tethys sea were been deflected against the Pangaea continent (Angiolini et al., 2013). The waters were warm (Shen et al., 2009).

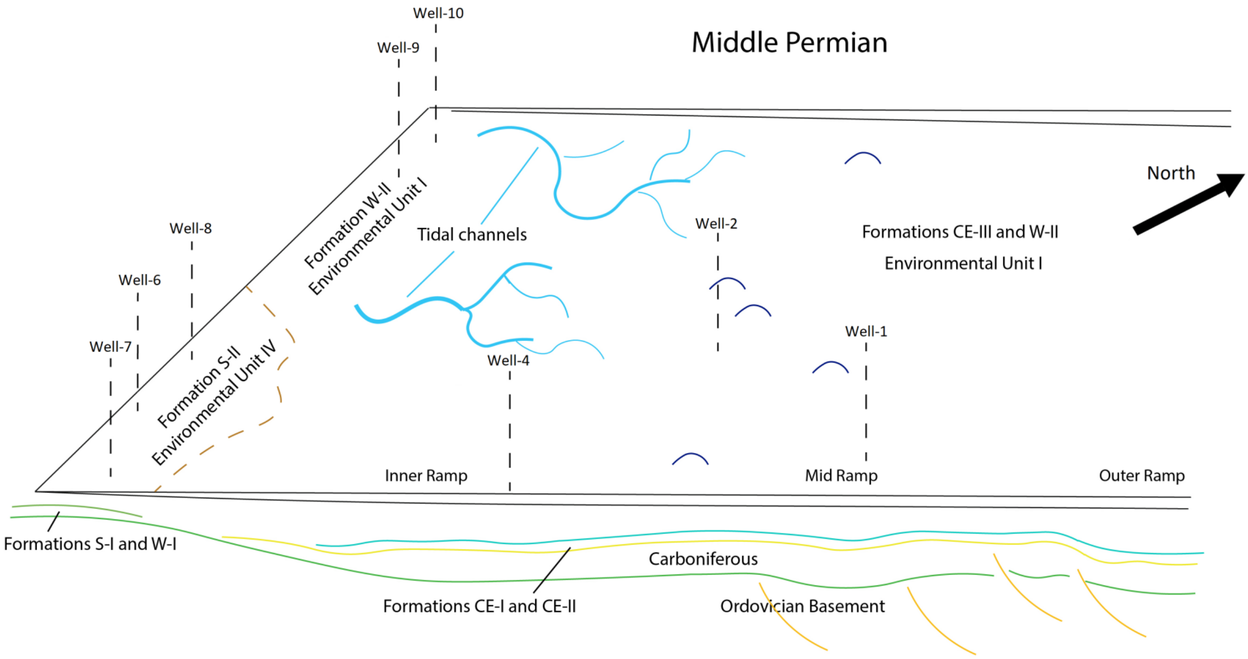

Figure 10.3: Idealized environmental reconstruction of the Middle Permian. The brown dashed line indicates a shoreline and its placement is hypothetical. The position of the tidal channels is also proximal based on the seismic interpretation.

- Upper Permian environmental reconstruction

  During the Upper Permian the carbonates are followed by thick shale, marl and anhydrite deposits at wells Well-1 and Well-2. This indicates a transition towards shallower and drier conditions, more akin to a sabkha. These anhydrite deposits cover significant area in the Center-East section of the Jeffara Basin, Formation CE-IV (Figure 10.4). This indicates a dry and hot climate during Upper Permian which is supported by literature (Kidder and Worsley, 2004; Roscher et al., 2011).

  However, towards the South and West, accurate interpretation is challenging due to the presence of two significant unconformities. To the South, the Permian-Triassic Unconformity has been identified and it is cutting through the Upper Permian deposits of wells Well-6, Well-7 and Well-8 (Figure 4.1 and Figure 4.3). Similarly to the West, the Permian-Jurassic Unconformity has been identified and it is also removing a significant section of the Upper Permian in wells Well-9 and Well-10 (Figure 4.5 and Figure 4.6). Towards the North, seismic facies suggest that carbonate deposition continued during the Upper Permian.

  Consequently, reaching an accurate conclusion about the depositional environment during the Upper Permian to the West and South of the Jeffara Basin is challenging.

10.3. Structural Reconstructions

For the structural reconstructions (Figure 10.5, 10.6) the values from the decompaction calculations were used.

Following the deposition of the Lower Carboniferous, the Upper Carboniferous and the Lower Permian were deposited. They appear comformable with the underlying Lower Carboniferous, and they are

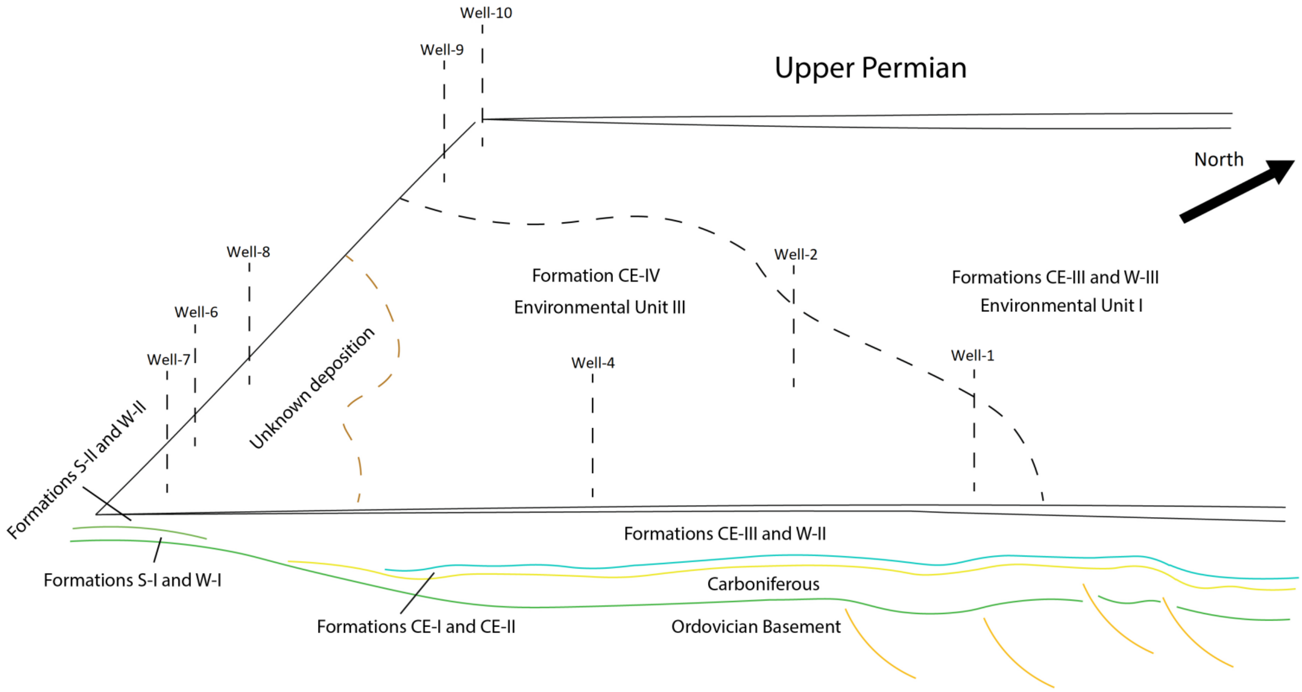

Figure 10.4: Idealized environmental reconstruction of the Upper Permian. The brown dashed line indicates a shoreline and its placement is hypothetical. The black dashed line indicates the transition between Sabkha and shallow marine carbonate deposition. Its position is relative, but according to the seismic facies interpretation. The South and West section of the figure are hypothetical since the P-T and the P-J unconformities have eroded portion of the Upper Permian there.

onlapping it towards the South of the basin (Figure 10.5, 10.6 B).

A number of folds have been traced in the seismic data. They appear to have influenced the Ordovician, Carboniferous and Lower Permian deposits (Formations CE-I and CE-II) with the north sections being pushed towards the south (Figure 10.5, 10.6 C). The Middle Permian appears to not have been influenced by these thrusts and is instead onalpping the Lower Permian at certain locations, indicating that it acted as paleotopography in the region (Figure 10.5, 10.6 C).

During the Middle-Upper Permian, carbonate deposition was prevalent ranging up to 3km in thickness. These deposits (Formation CE-III) are back stepping towards the South and they are gradually covering the exposed Ordovician (Figure 10.5, 10.6 C). At the same time, clastic deposition was taking place towards the South (Formation S-I). Following the deposition of the carbonates Sabkha deposition was prevalent (Formation CE-IV) - likely during the Upper Permian.

The completion of the Permian was followed by the Permian-Triassic unconformity and the deposition of Early and Middle Triassic deposits, dominated by sandstone and shale. At the end of the Early-Middle Triassic, the original folds appear to have been reactivated, and deposits of the Early-Middle Triassic, Permian and Carboniferous have been folded (Figure 10.5, 10.6 D).

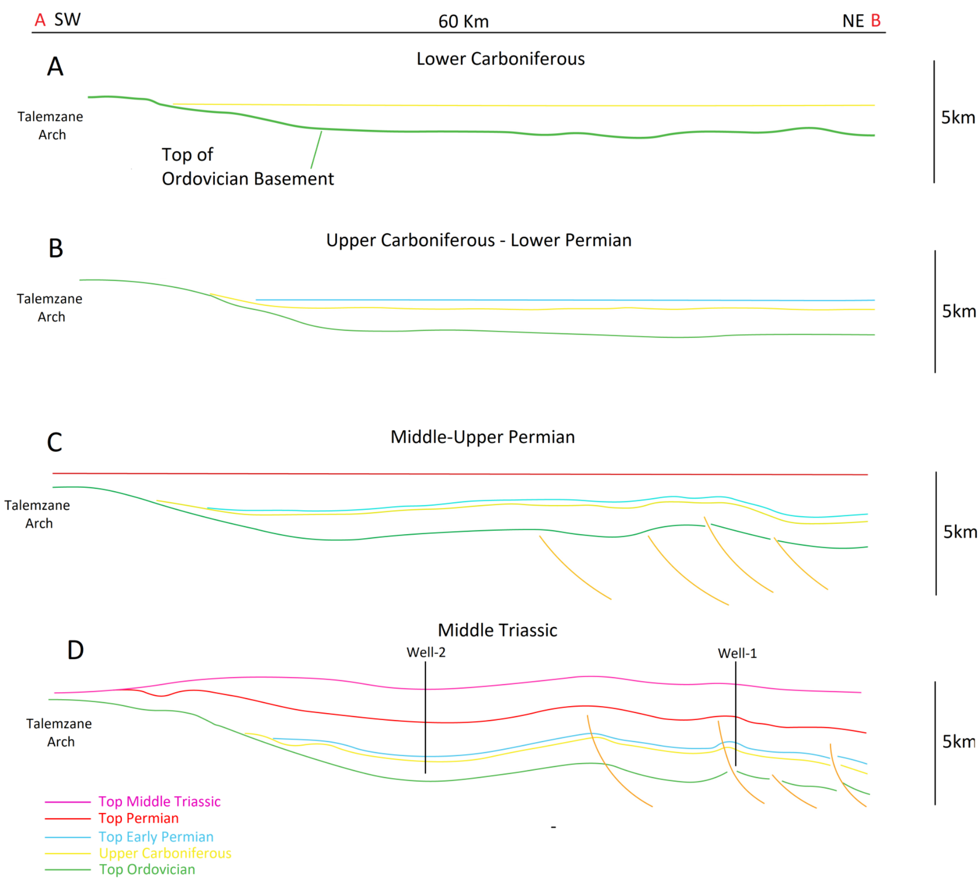

Figure 10.5: Structural reconstruction of the Carboniferous, Permian and Triassic Periods at section A-A'.

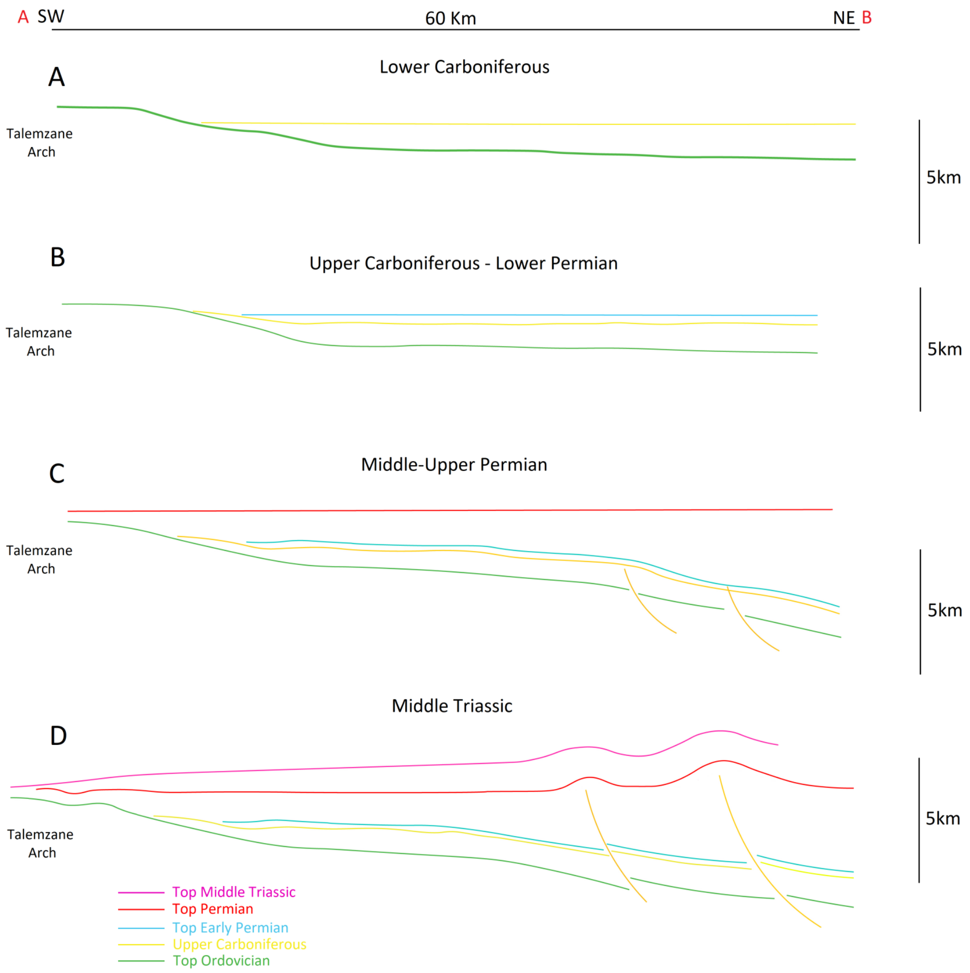

Figure 10.6: Structural reconstruction of the Carboniferous, Permian and Triassic Periods at section A-B.

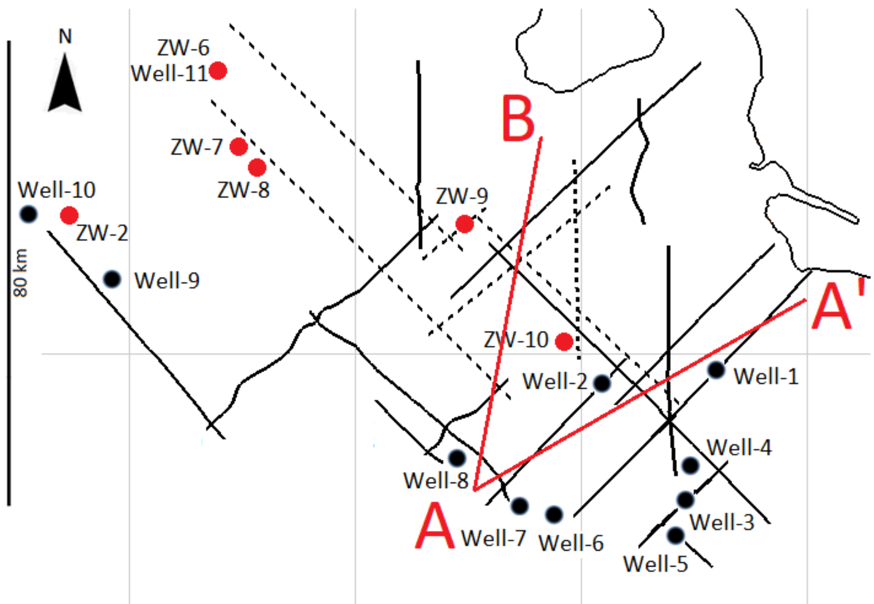

Figure 10.7: The location of the reconstructed regions correspond to the red lines as shown on the map above.

11
Conclusions

11.1. Discussion

- **Seismic Interpretation**

The interpretation of the seismic lines leaves room for future discussion. The interpretation quality of the seismic lines covering the center and east section of the examined area is considered high. This is because of the high coverage of seismic data, which enabled the construction of composite lines for more accurate tracing of seismic reflectors. Also, the majority of the available wells are located in this region. Since some of these wells were provided converted into TWT domain, and were plottable in the seismic lines, accurate correlation between seismic reflectors and the depth of the well column was possible. As a result seismic facies could be more accurately tied to lithologies.

To the North, the quality of the interpretation is decreased. This is attributed to two factors. First, the lack of well data to the North reduced the accuracy of the interpretation, since the seismic interpretation could be validated with accurate information about the subsurface which can only come from wells. Second, the presence of extensive regions with chaotic reflectors in the lines further reduced the accuracy of the tracing. These chaotic zones act as barriers between regions with better defined reflectors. As a result, overcoming them required a considerable amount of assumptions about vertical movement and lateral continuity. Thus, the sections to the North of these chaotic reflectors is left hypothetical for this project.

Towards the West, a similar issue was encountered. Seismic coverage and the quality of the lines is reduced. Additionally, the two wells that are located in this area, Well-9 and Well-10, are not converted into Time domain and thus cannot be projected on the seismic lines correctly. Even if they were however, they lie kilometers away from them, which is a disadvantage for accurate correlation between them. Finally, the Permian-Triassic and Permian-Jurassic unconformities merge together into this region, making their correct tracing challenging.

For future research, it is recommended that additional seismic data are used in order to increase seismic coverage. In doing so more composite lines could be constructed, which would enable the tracing of reflectors in a more accurate manner. Moreover, additional wells that are located in the region should be retrieved and correlated with the seismic data. A number of wells lie directly over seismic lines used in this project and could provide valuable insight about the subsurface to the West and North of the region respectively.

- **Structural interpretation**

  The structural interpretation of this project has identified two tectonic events. The first event is dated to the Upper Carboniferous-Early Permian, and is responsible for folds with E-W orientation, that are influencing rocks of Carboniferous and Ordovician age. The second event is dated to the Upper Triassic and is responsible for the reactivation of a number of older Middle Carboniferous folds. This event is impacting the rocks of the Upper Carboniferous, Permian and Lower-Middle Triassic that were deposited after the completion of the first of the first event. Currently, dating these events more accurately is not feasible and future research could focus on resolving this issue.

  The normal faults that were identified in the region are small in number, and appear to have been active at least since the Ordovician. They influence deposits until the Middle Triassic with a gradual reduction of displacement.

  The decompaction calculations provide insight into the depositional history of the Jeffara Basin. However, simplifications had to be made in order to perform the calculations with the data that was available. As a result significant error margins were introduced and this is reflected into the results. In order to increase the accuracy of the calculations, the quality of the input parameters has to be improved. Future studies should focus on this topic and acquire better porosity measurements for the subsurface. This could be done by retrieving additional sections of the completion reports if they are still available, or by performing new laboratory tests by acquiring new plugs from the cores of the wells. Performing a decompaction per Lithological Unit instead of per Geological Formation should also reduce uncertainty and increase accuracy.

  Moreover, the start and end ages of the decompaction are not well constrained in this study. Future examination of the Jeffara Basin could focus on this issue as well.

- **Reconstructions**

  The reconstructions that have been made in this project for the Jeffara Basin leave room for future improvement. More specifically, the environmental reconstructions are limited by the quality of the well data and the coverage of the seismic lines. Access to additional information from the well completion reports, or direct access to the cores could alleviate this deficiency. Also, utilizing more seismic lines will help with better identifying seismic facies transition, the location of paleoshores, the extend of the defined geological formations and can improve the tracing of the tidal channels that were interpreted in the data. This new information can lead to an increased accuracy of a reconstruction.

  This also applies to the structural reconstruction. This is limited by the quality of the decompaction calculations which are in turn depended on porosity measurements from the wells. Additional information could increase the accuracy of the calculations and thus the accuracy of the reconstructions.

- **Future research**

  The results of this thesis could form a good basis for future research into the environmental and structural evolution of the Jeffara Basin. The identification of two possible deformation events, the decompaction calculations, the definition of environmental units and Formations can provide valuable control for any forward stratigraphic modeling analysis of the Basin.

  Future research could focus on a number of aspects that were covered in this project, and can be further improved. Thus, it is highly recommended that the boreholes of the wells in this data set be re examined in order to update their biostratigraphy. Considering that some of these wells were drilled in the 1960s, this process is long overdue. This will enable the more reliable dating of the deposits, which was a major difficulty encountered in this project. With a more accurate dating in place, correlation of lithological units and formations could be performed with higher accuracy as well. Additionally, an updated biostratigraphy will further allow for a more accurate understanding of the environmental evolution of the region.

Proving a more accurate dating of the subsurface will open up multiple other possibilities. The uncertainty of decompaction calculations could be reduced, since the start and final date of the deposits will be known. This will be especially useful for the decompaction curves of wells where there are indications that portions of Permian deposits have been eroded by the Triassic Unconformity, such as Well-4, or the Jurassic Unconformity, such as Well-9 and Well-10. This will allow for a more accurate dating of the two tectonic events that have been identified in the seismic data, currently dated roughly to the Upper Carboniferous-Lower Permian and the Upper Triassic.

With the above questions regarding the age of deposition and deformation solved, forward stratigraphic modeling analysis of the Jeffara Basin could be attempted with an increased degree of accuracy and confidence. The work presented in this manuscript could already provide a foundation for such a project.

11.2. Results

At the introduction of this manuscript, four research questions were posed:

1. *What is age of deposition of the Permian lithologies?*

   The age of deposition covers the entire Permian Period but varies by location. Towards the South, deposits of the Middle and Upper Permian are present. They are in contact with the Ordovician basement, and the Early Triassic which forms an onlap unconformity with the Permian. Towards the East and North, the age of deposition spans the entire Permian Period. The deposits there appears conformable with the Lower Triassic and the underlying Carboniferous. Towards the West, the age of deposition also spans the Early Permian and the Upper Permian with a portion of the Permian being eroded away during the Triassic and the Jurassic.

2. *What is the geometry of the Permian deposits?*

   The Permian deposit are thinning towards the South and are thickenning towards the North. They reach a minimum of 120 meters at Well-7 and a maximum of 3931 at Well-11, while this thickness should be examined in more detailed due to the possibility of repetition of the Permian in that well. The maximum thickness observed at the seismic data reaches approximately 3000 meters towards the center of the examined region. The Permian is deposited on the Carboniferous and is back stepping towards the south where it is gradually covering the Ordovician basement. The Middle Permian is observed onlapping the underlying Lower Permiand and Upper Carboniferous rocks at certain locations.

3. *What is the structural evolution of the Permian in the Jeffara Basin?*

   Two evens with structural significance have been identified based on the seismic interpretation. The first has been dated to the Upper Carboniferous - Lower Permian and is responsible for the folding of the Lower Permian, Carboniferous and the Ordovician. A second event has been dated to the Upper Triassic and is responsible for the renewed folding of the Carboniferous, Lower Permian and the folding of the Middle - Upper Permian as well as the Lower-Middle Triassic by reactivating the folds that were caused by the first episode.

4. *How did the paleo-environment evolve in the region dung the Caboniferous-Permian?*

   During the span of the Permian Period the paleo-environment changed significantly. The Upper Carboniferous and Early Permian are characterised by a shallow marine, lagoonal environment, with deposition of shale, marl, carbonate and sand. The deposits of this period have been correlated with wells and seismic data, which indicate that they have a relatively constant thickness of 250 meters.

   Afterwards, during the Middle-Upper Permian, the Jeffara Basin was characterised by shallow marine carbonate deposition, typical of a carbonate platform. The platoform was gradually backstepping towards the south and eventually covered older the Carboniferous and Ordovician. The carbonate deposits can reach a maximum thickness of $2,5$ kilometers towards the North of the basin. Deposits that indicate shorelines suggest that at the South a paleoshore was active during that time.

   The Upper Permian is characterised by significant deposits of marl and anhydrite towards the center of the region. Towards the South and West, portion of the Upper Permian has been eroded by the Triassic and Jurassic unconformities making environmental interpretation challenging. Towards the North, seismic facies suggest continued carbonate deposition.

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A

Appendix

Fossil/Order-Family	Well-1	Well-2	Well-3	Well-4	Well-5 No R.	Well-6	Well-7	Well-8	Well-9	Well-10	Well-11
Agathammina / Miliolina	×	×							×		
Ammodiscus / Textulariina			×				×				
Baisalina / Miliolina									×		
Bellerophon / Mollusc											×
Calcitornella / Miliolina	×	×	×	×					×		
Climmacamina / (?)									×		×
Clipeodiscus / (?)											×
Cornuspira / Miliolina				×							
Deckerella / Palaeotextularoidea									×		
Dunbarula / Fusulinoidea									×	×	×
Geinitzina / Geinitzinidae	×	×							×		
Globivalvulina / Palaeotextularoidea	×	×	×	×					×		×
Glomospira / Ammodiscidae	×		×				×		×	×	×
Hemigordiopsis / Miliolina										×	
Hemigordius / Miliolina	×	×	×						×	×	
Kahlerina / Fusulinoidea										×	
Lasciotrochus / (?)											×
Leella / Algae				×						×	
Minojapanella / Fusulinoidea									×	×	
Mizzia / Algae	×	×							×		
Nankinella / Fusulinoidea									×		
Neoschwagerina / Fusulinoidea											×
Ophtalmidiidae / Miliolina				×			×				
Palynofacies	×	×				×		×	×		
Parafusulina / Fusulinoidea										×	
Permocalculus / Algae	×	×							×		
Rotalidea sp.			×								
Schubertella / Fusulinoidea									×		
Schwagerina / Fusulinoidea										×	×
Stafella / Algae		×							×		×
Staffella Tunetana / Algae									×		
Sumatrina / Fusulinoidea									×	×	×
Verbeekina / Algae										×	×
Vermiporella / Algae		×									

Table A.1: The table above shows the fossil record of the Permian rocks in the wells. The table is not exhaustive - the paleontology reports of Well-9 and Well-1 are very thorough and mention dozens more foraminifera, ostracods and algae species not shown in other well reports.

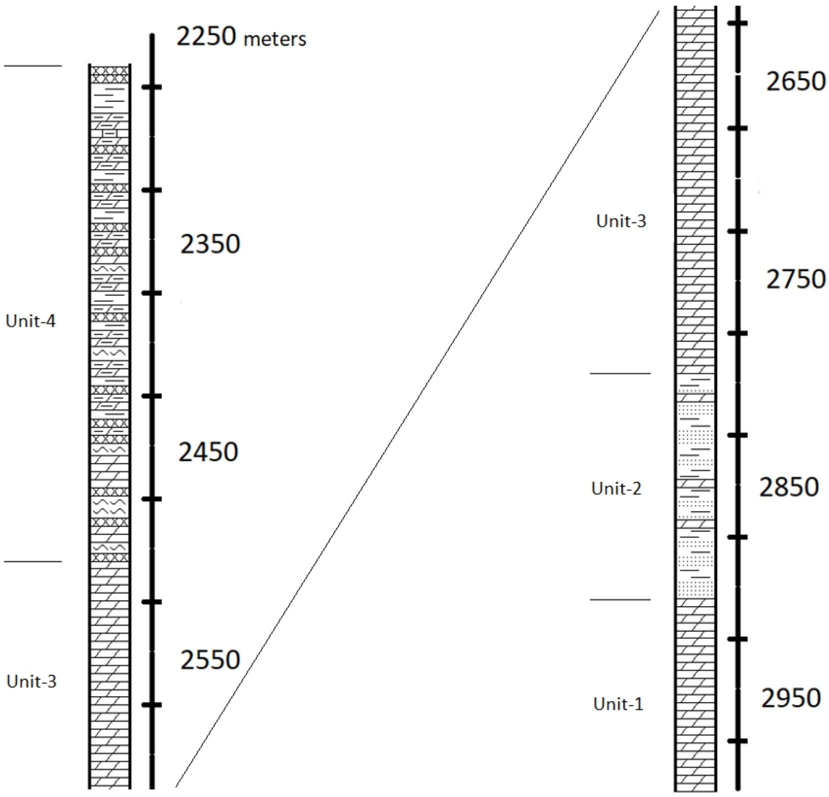

Figure A.1: Lithological column of well Well-1.

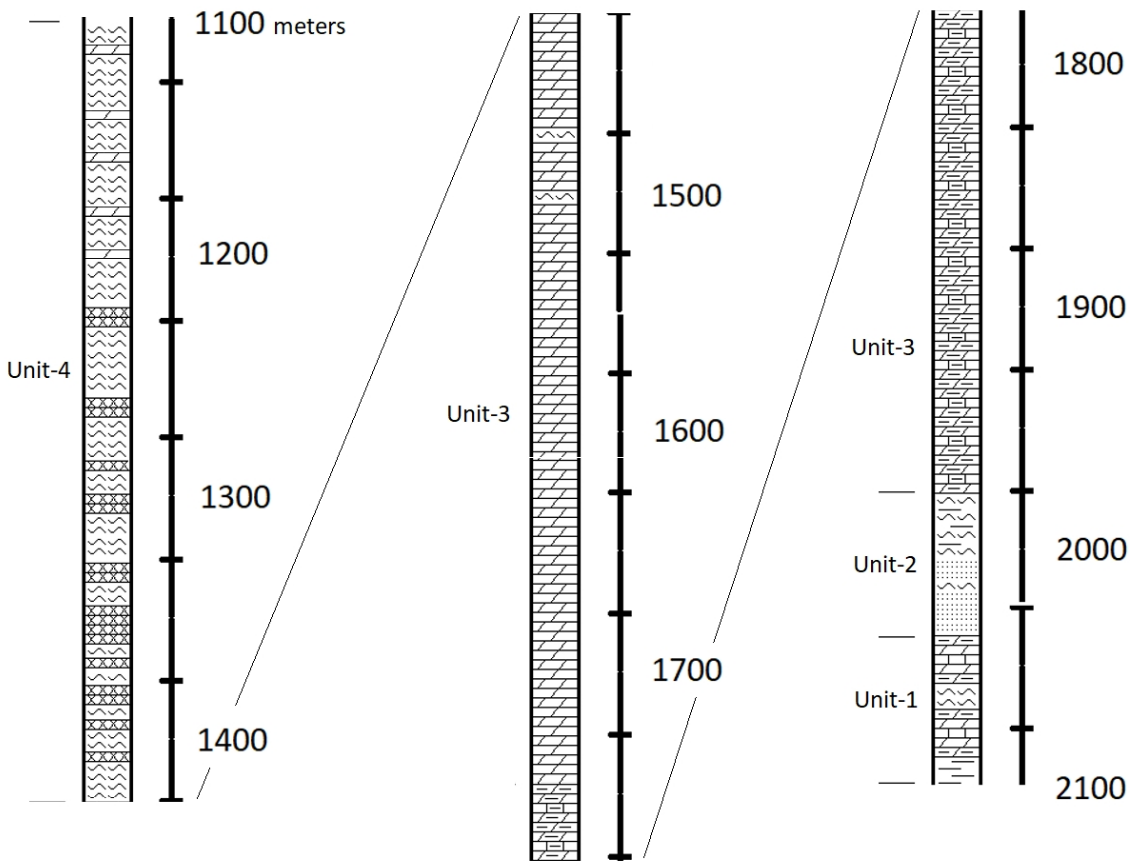

Figure A.2: Lithological column of well Well-2.

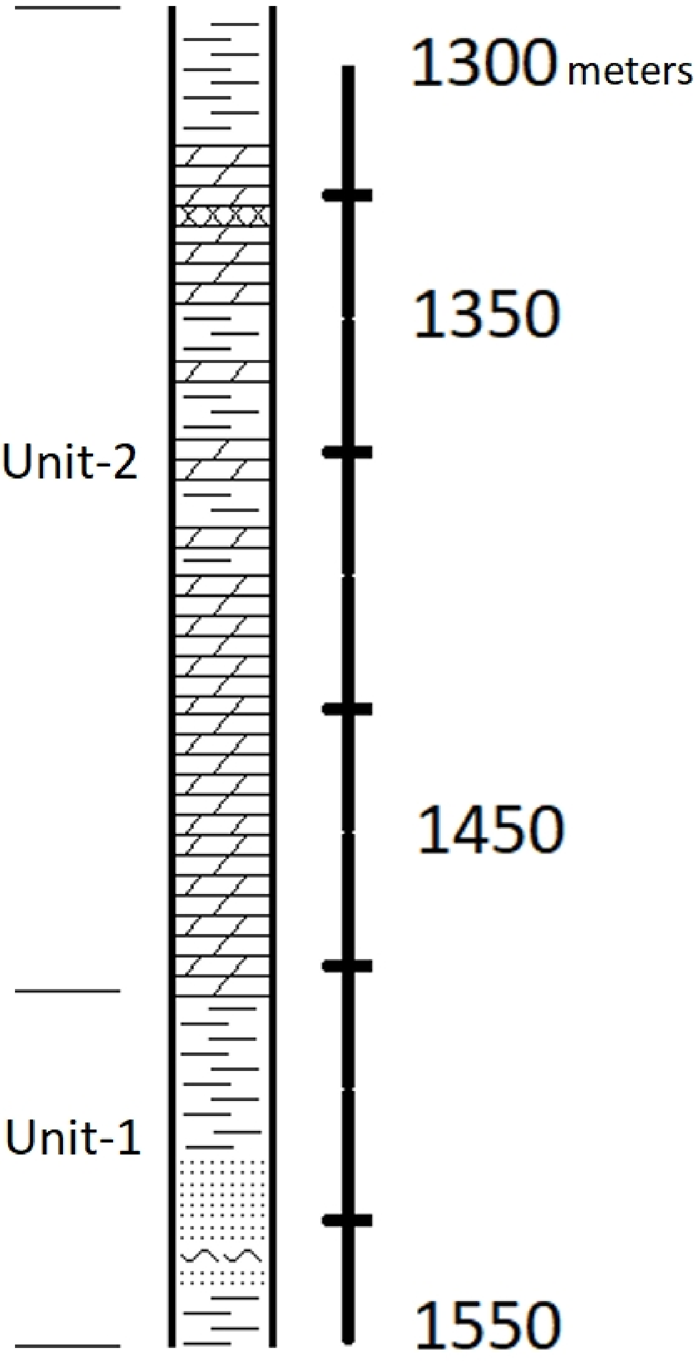

Figure A.3: Lithological column of well Well-3.

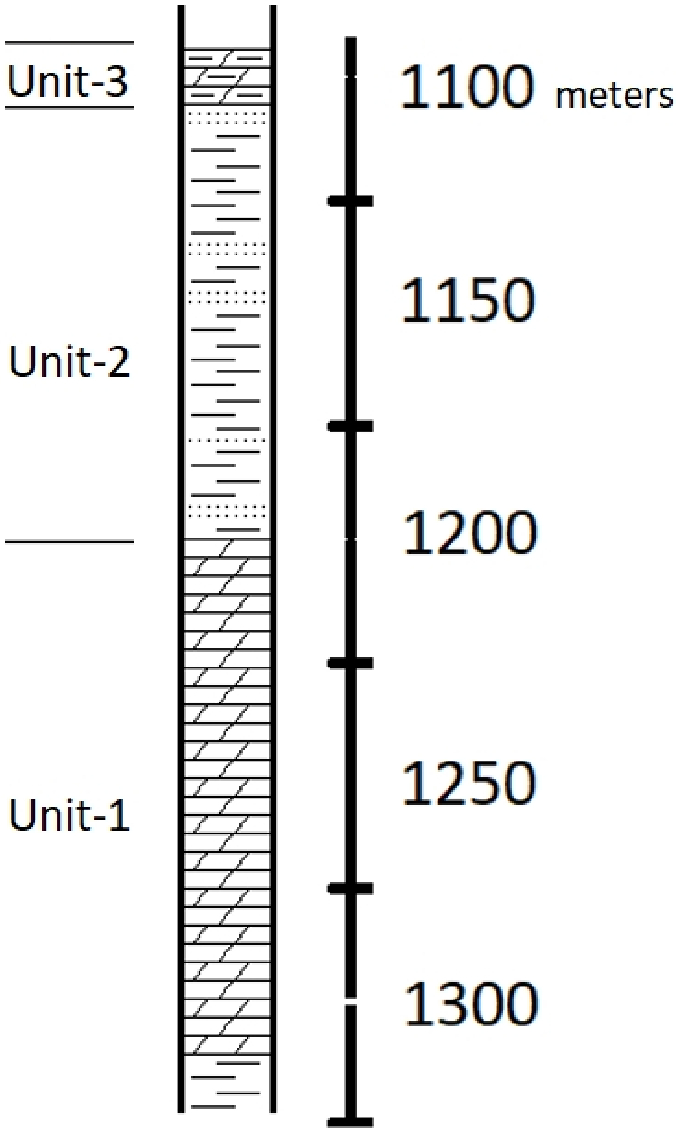

Figure A.4: Lithological column of well Well-4.

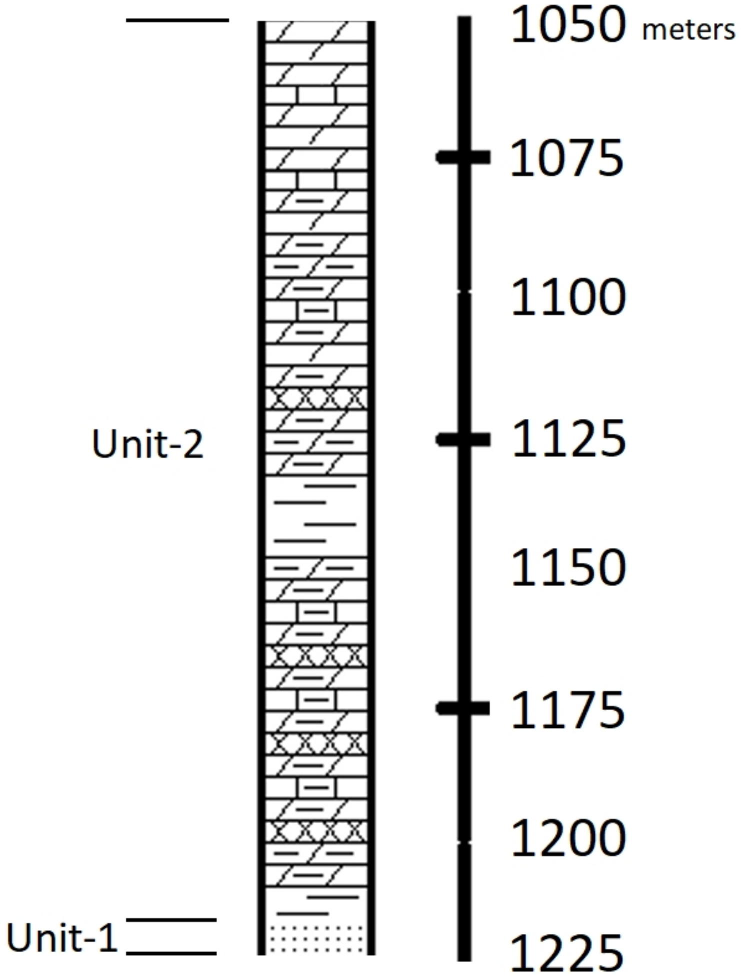

Figure A.5: Lithological column of well Well-5.

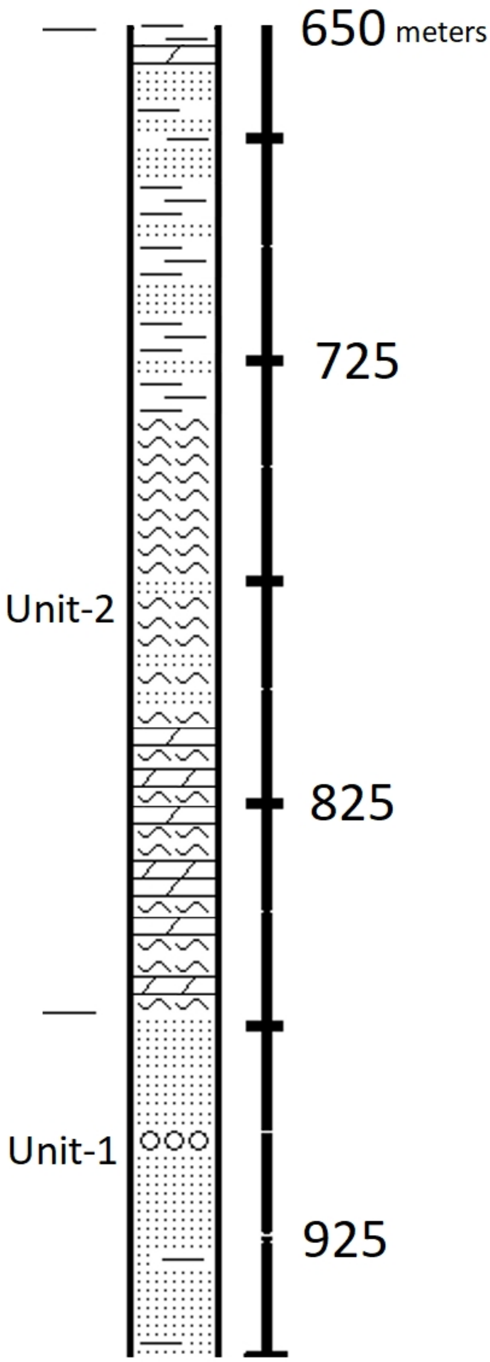

Figure A.6: Lithological column of well Well-6.

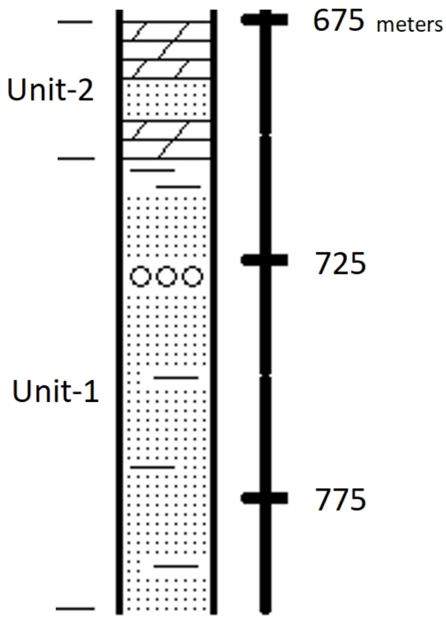

Figure A.7: Lithological column of well Well-7.

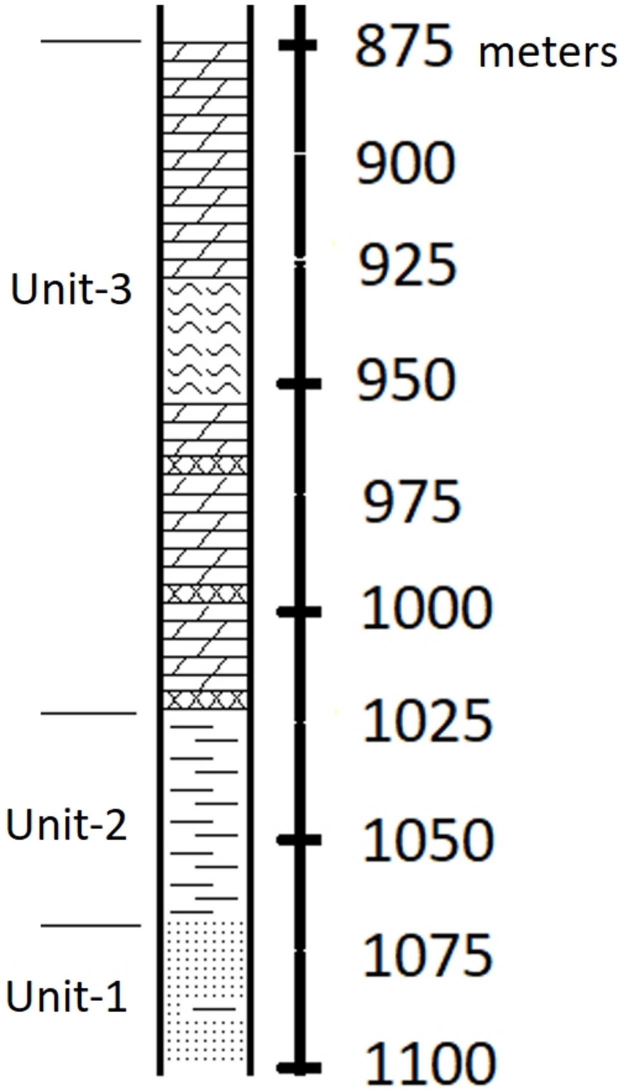

Figure A.8: Lithological column of well Well-8.

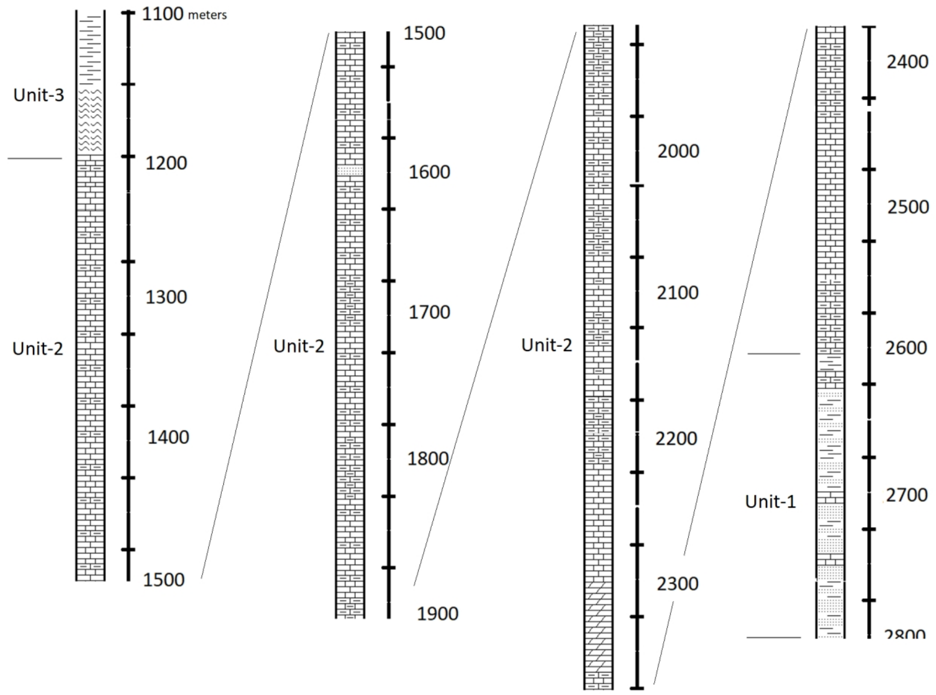

Figure A.9: Lithological column of well Well-9.

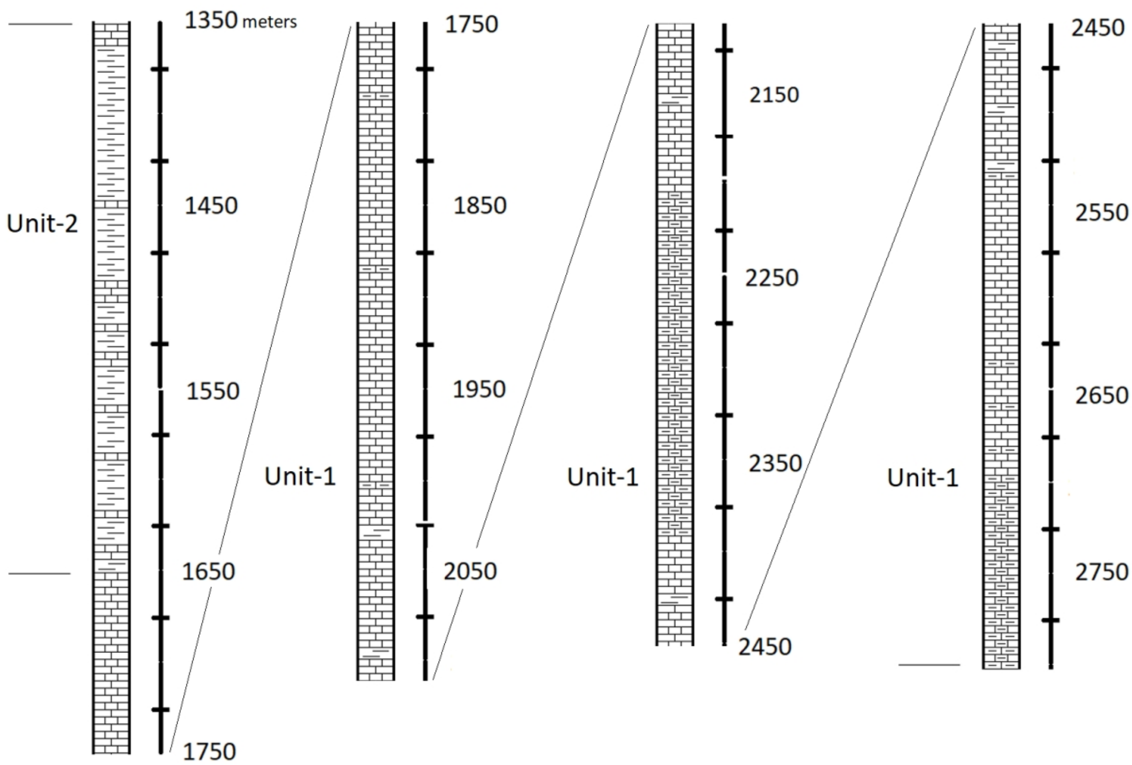

Figure A.10: Lithological column of well Well-10.

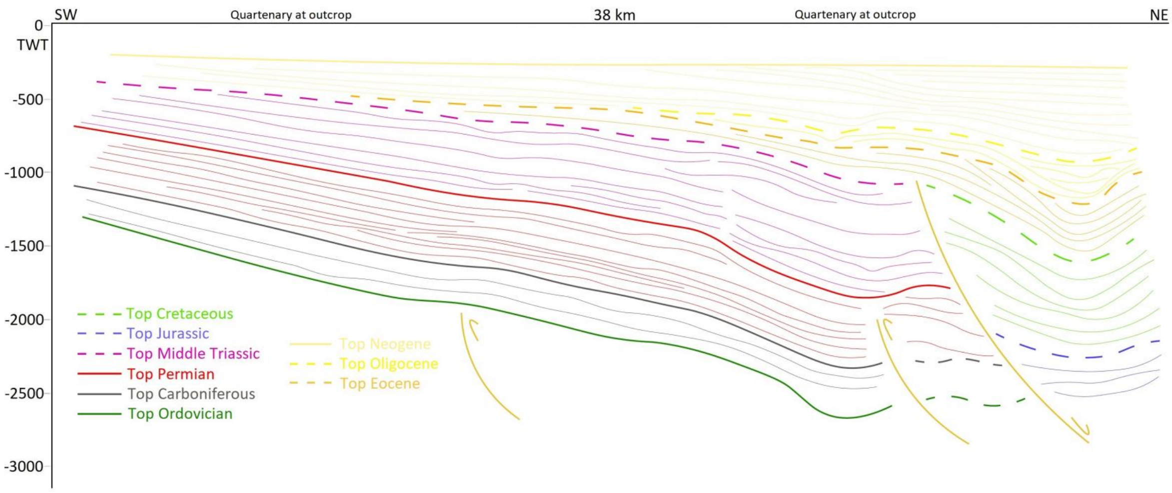

Figure A.11: Interpretation of Line-1.

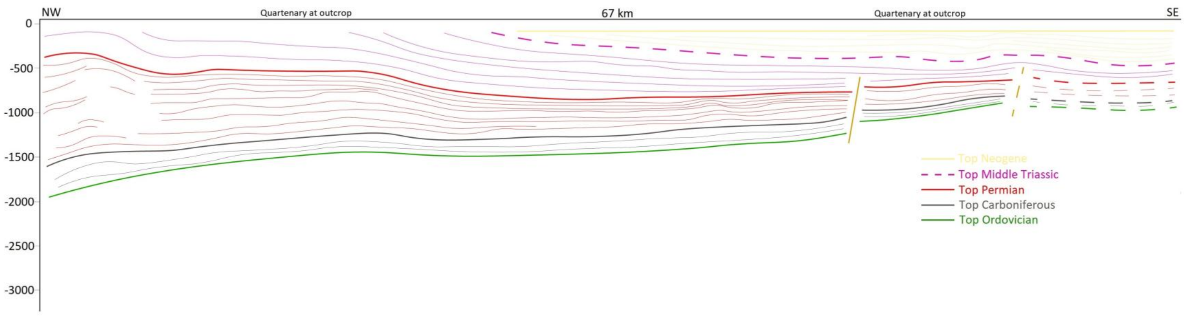

Figure A.12: Interpretation of Line-2.

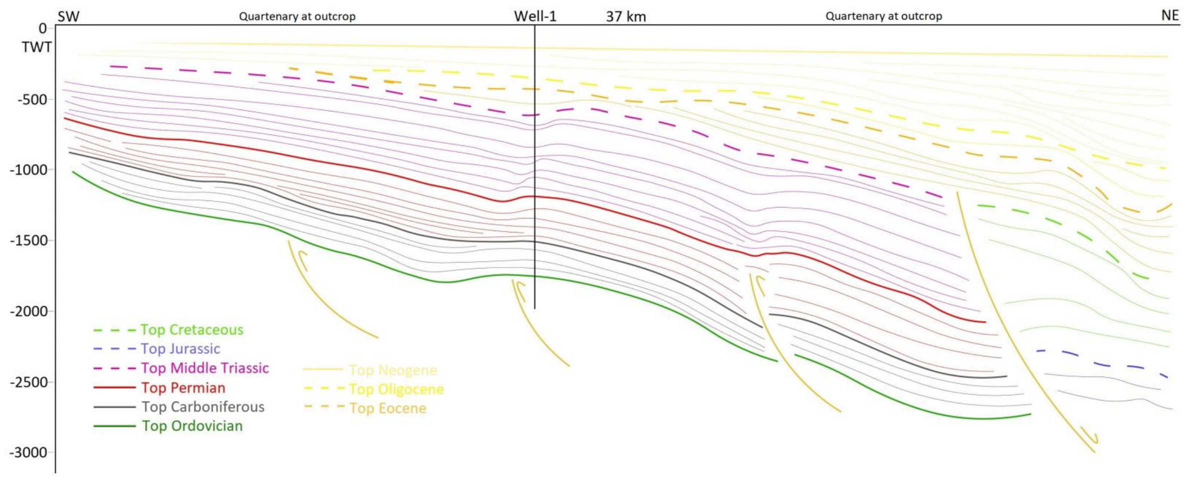

Figure A.13: Interpretation of Line-3.

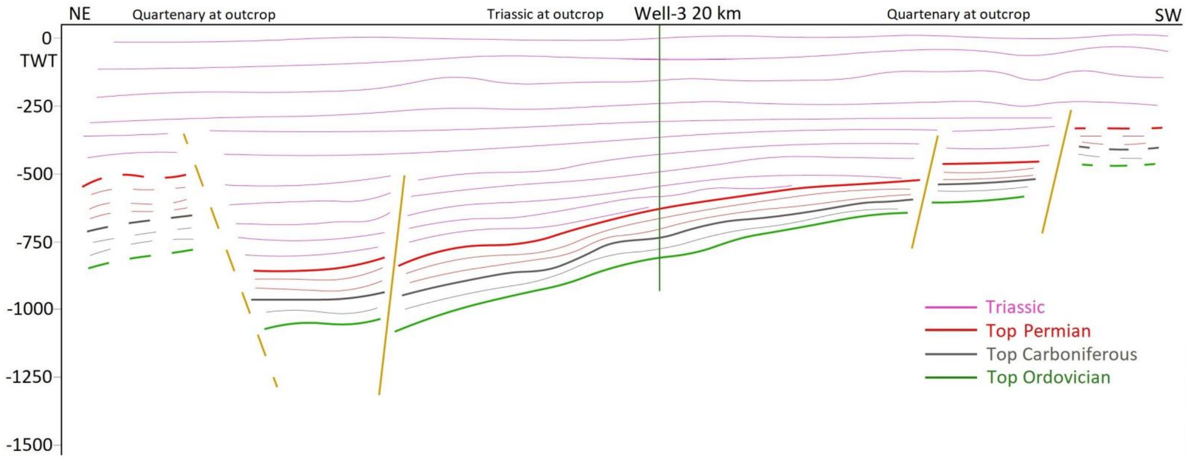

Figure A.14: nterpretation of Line-4.

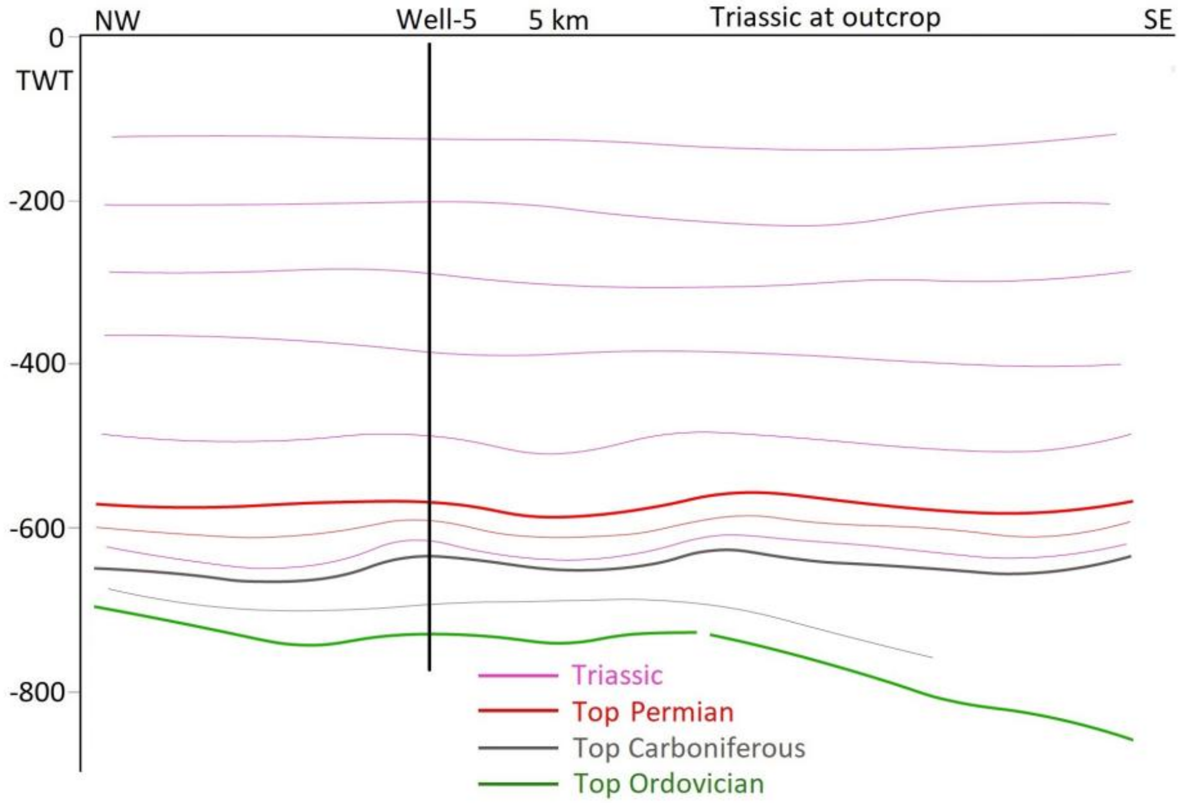

Figure A.15: Interpretation of Line-5.

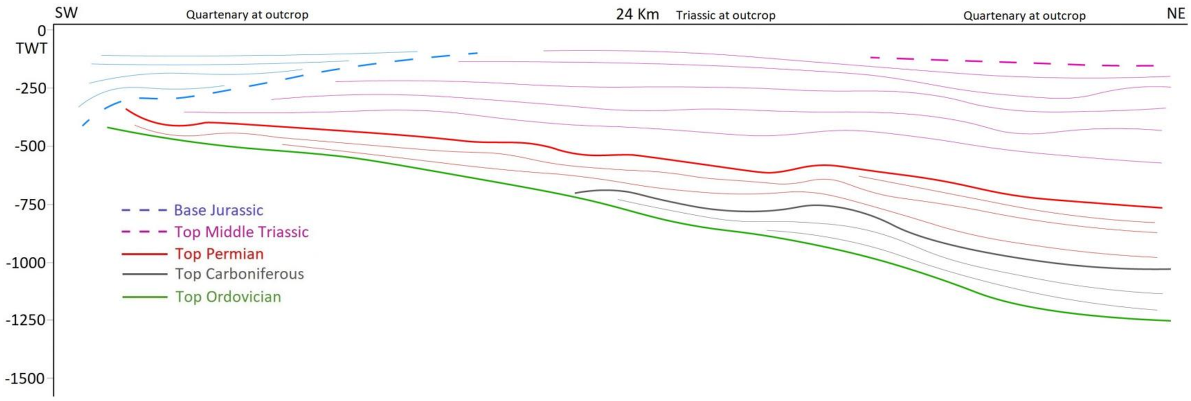

Figure A.16: Interpretation of Line-6.

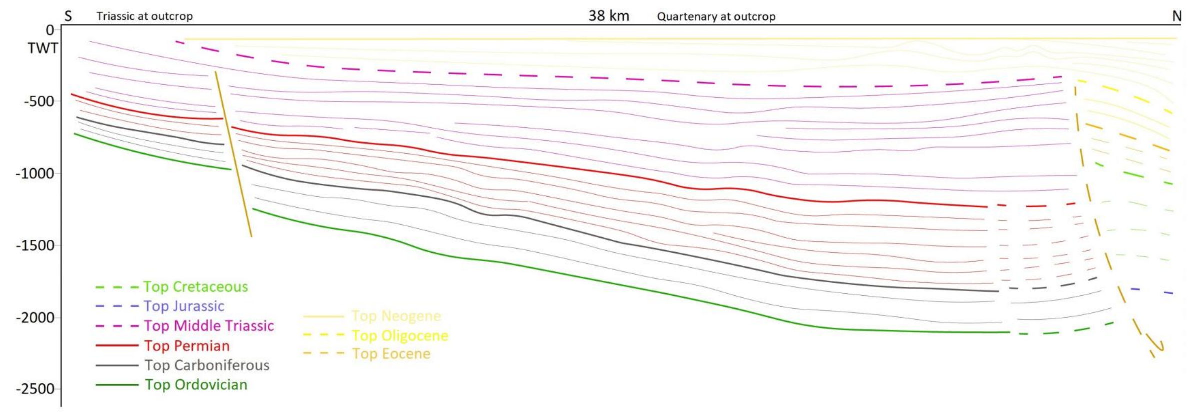

Figure A.17: Interpretation of Line-7.

Figure A.18: Interpretation of Line-8.

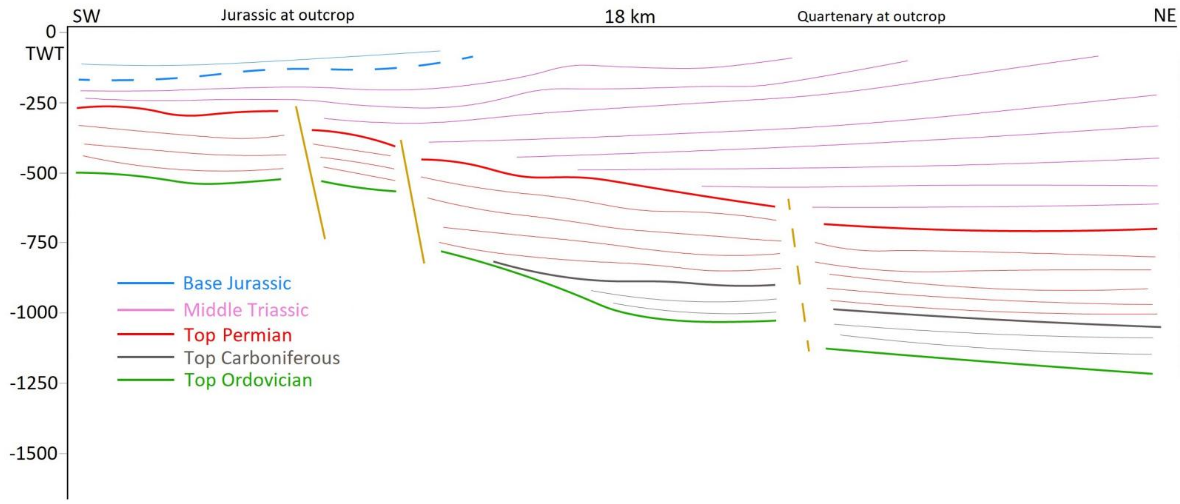

Figure A.19: Interpretation of Line-9.

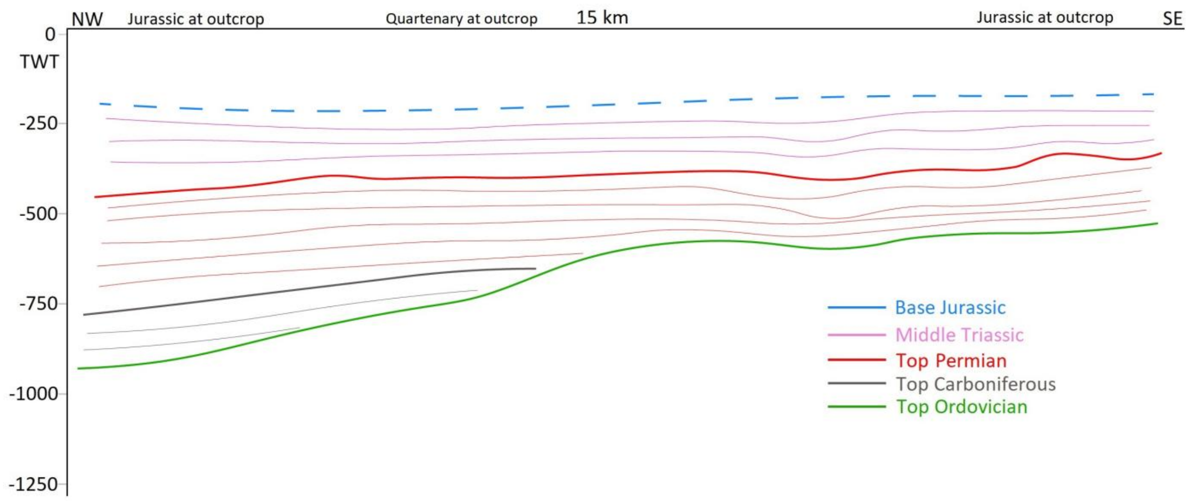

Figure A.20: Interpretation of Line-10.

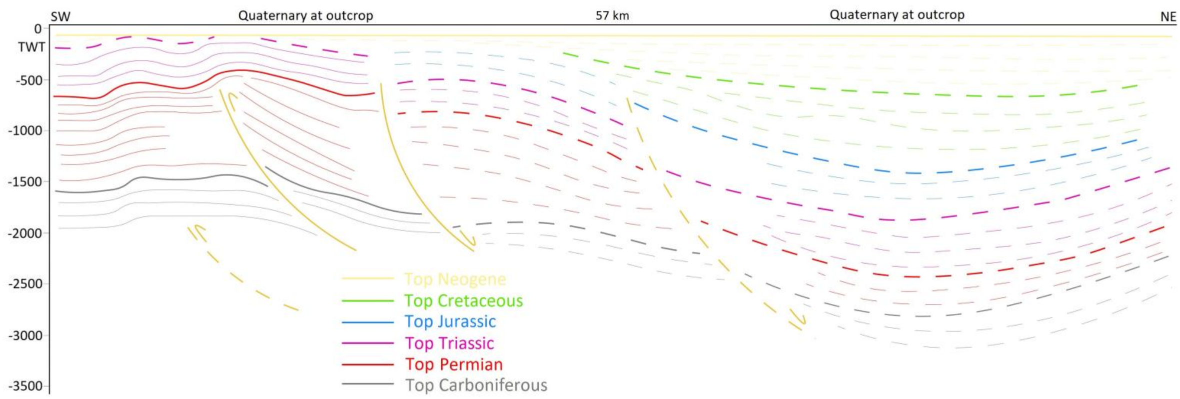

Figure A.21: Interpretation of Line-11.

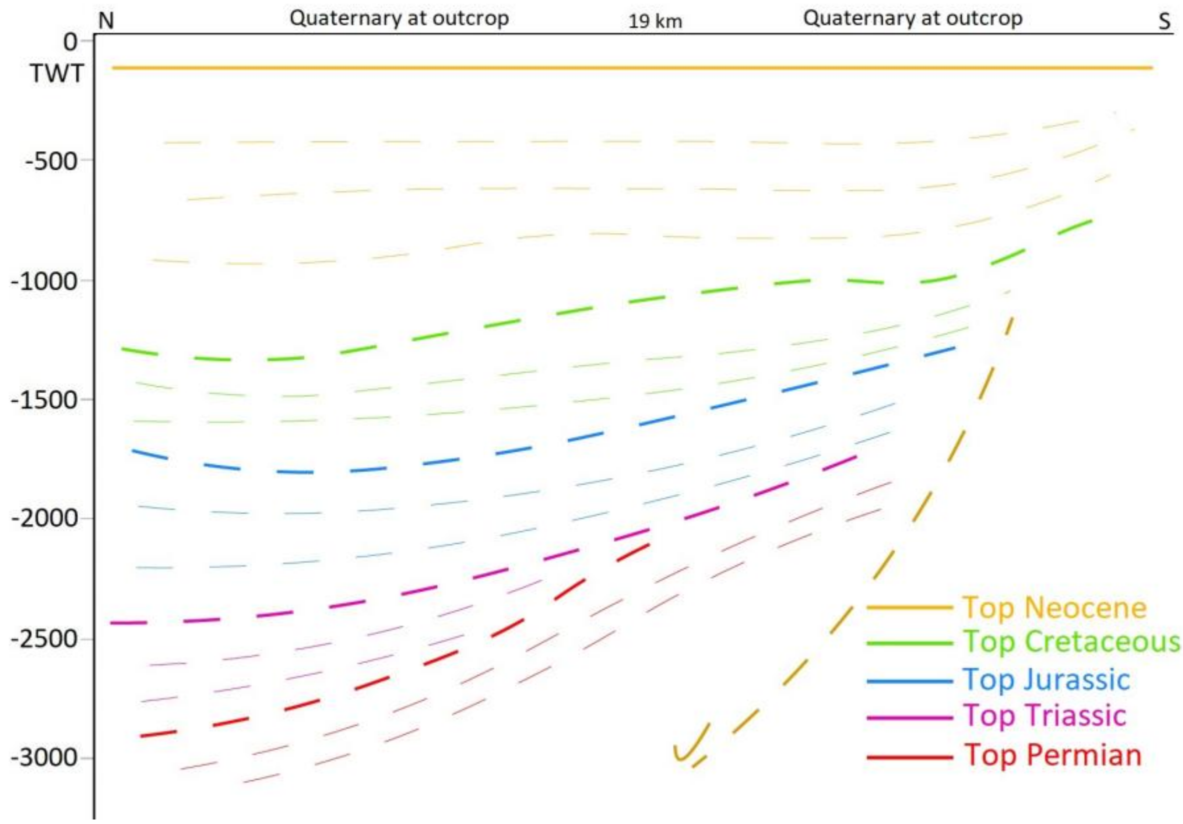

Figure A.22: Interpretation of Line-12.

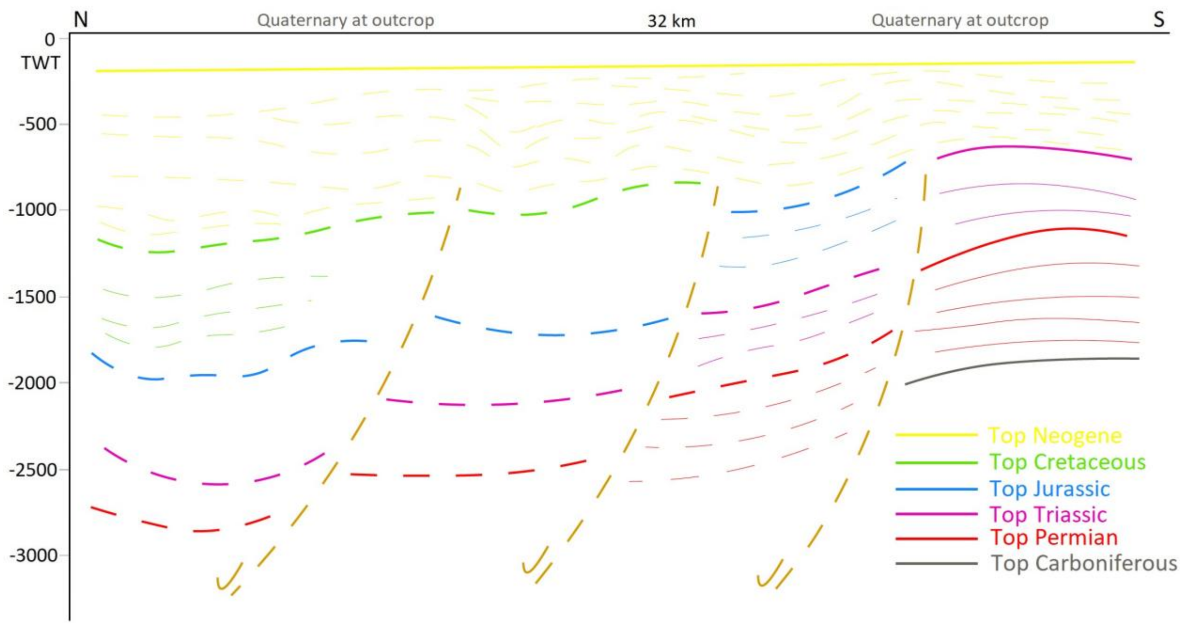

Figure A.23: Interpretation of Line-13 and Line-14.

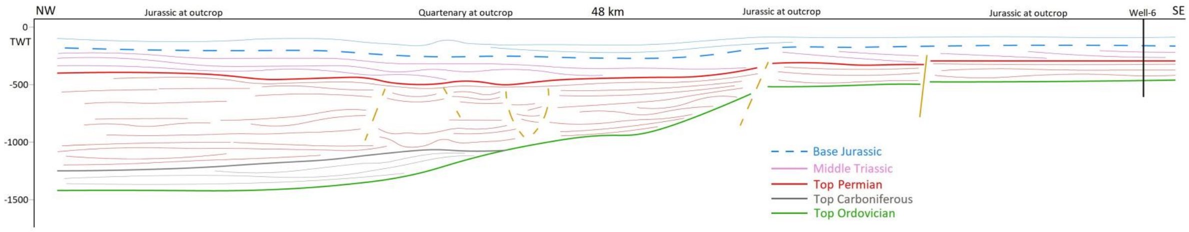

Figure A.24: Interpretation of Line-15.

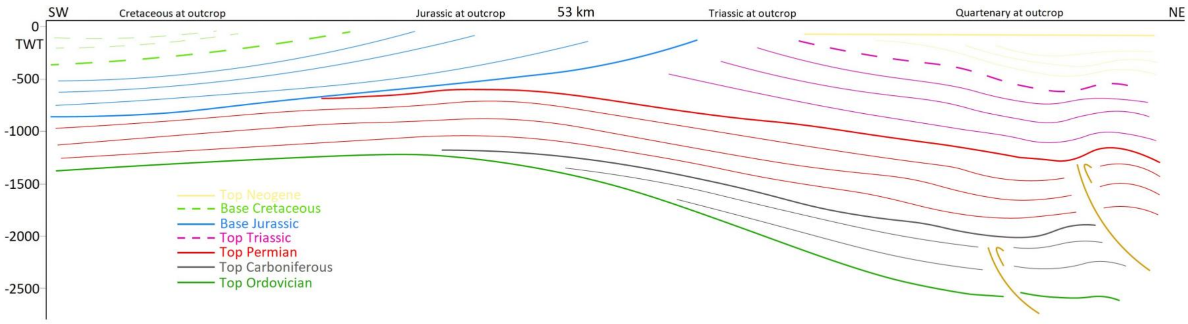

Figure A.25: Interpretation of Line-16.

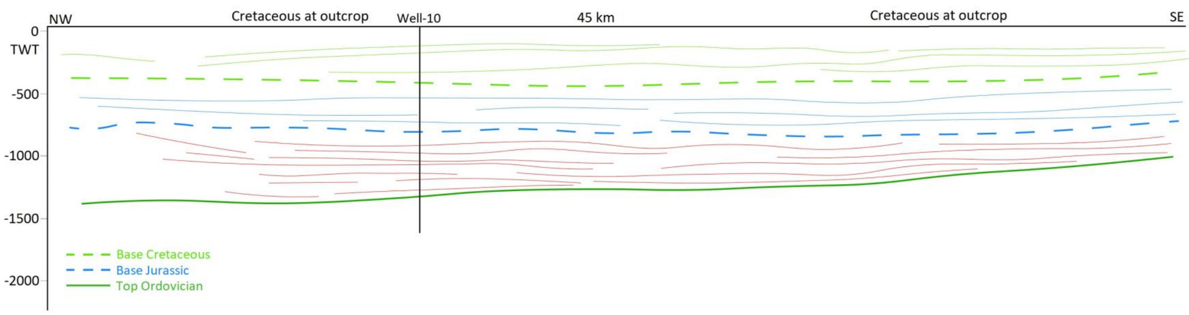

Figure A.26: Interpretation of Line-17.