STRUCTURAL KINEMATICS AND SALT EVOLUTION IN THE
“KUZAM” AREA; OFFSHORE SOUTHEAST GULF OF MEXICO:
IMPLICATIONS FOR PETROLEUM PROSPECTIVITY

by

Carlos Miguel Perez Gutierrez
A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Geology).

Golden, Colorado

Date _____________

Signed: ____________________________
Carlos Miguel Perez Gutierrez

Golden, Colorado

Date _____________

Signed: ____________________________
Dr. Bruce Trudgill
Thesis Advisor

Signed: ____________________________
Dr. Paul M. Santi
Professor and Head
Department of Geology and Geological Engineering
ABSTRACT

Seismic acquisition, seismic processing (PreSTM and PSDM), seismic interpretation, velocity modeling (for depth-to-time as well as time-to-depth conversion) and sequential restoration are all essential steps to illustrate the geometrical evolution of a very complex area located on the Mexican southeastern portion of Gulf of Mexico. This study uses all 5 approaches to improve the understanding of the tectonic evolution of the area as well as the implications for petroleum prospectivity in the area.

The study area presents a complex three-dimensional geometry, which is related to the complex evolution of the Gulf of Mexico, from a rifting stage during the Triassic to Middle Jurassic, the deposition of the Callovian salt, a passive margin stage during Late Jurassic to Late Cretaceous and a compressional stage from Late Cretaceous to Recent. In addition, salt withdrawal was related to the formation of important depocenters and gravitational movement of the Cenozoic deposits.

Sequential restoration resulted in valuable insights into: (1) The structural evolution of the salt and overburden; (2) Qualitative rates for several processes such as sedimentation rate, salt withdrawal as well as salt-rise; (3) Prediction of shape and depths of the seafloor paleogeography; (4) Position of several petroleum generating systems (such as the most important the Tithonian generating system) through the time (especially during the time of generation and expulsion of hydrocarbons); (5) Location of several reservoir rocks as well as seal rocks through the time; (6) Time of formation of traps at the different levels of the geologic column. (7) Timing and possible pathways for hydrocarbon migration (at least in 2D).
Limitations and errors during the entire workflow from seismic processing to section restoration arise. The most important are: (1) Errors during the PSDM seismic processing such as the use of the wrong velocity field, etc., (2) The seismic interpretation itself; (3) Errors during velocity model to depth-to-time conversion as well as time-to-depth conversion; (4) Cross-section orientation; (5) Assumption of plane-strain deformation, when actually there is movement out of the plane. (6) Errors calculating decompaction as well as isostatic corrections; (7) Wrong utilization of restoration algorithms to model actual rock deformation and faulting.

Regardless of all the listed limitations and errors, experience has shown that the errors are relatively minor. Therefore, restoration is a powerful tool even in salt basins. An analysis of the evolution of the area as well as its petroleum system implications was based on the restoration of a 2D regional cross-section (57 Km length). Important conclusions regarding to the structural evolution of the area as well as its implications for petroleum prospectivity are accomplished. First, Mesozoic traps have low risk of hydrocarbon charge since traps were already formed by the time of hydrocarbon generation and expulsion as well as its proximity with the Tithonian source rock. Second, Tertiary traps have higher risk than Mesozoic due to the important amount of salt that was sealing this stratigraphic level during part of the Miocene. However, as salt evacuated, and with the formation of a regional weld, the opportunities to charge these Tertiary traps increased. In addition, since migration is a three-dimensional phenomenon, lateral migration must occurred increasing significantly the chance for hydrocarbon charge. Finally, 3D restoration will help to understand such convoluted geometries, especially when there are several strain directions as well as complex salt movement in the area.
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ACKNOWLEDGEMENTS

A very special note of appreciation to my wife Dulce, and my two beautiful daughters Sofi and Angy, who provided invaluable encouragement, support, and love. To all my family as well as my wife’s family that support us during these two years in so many ways.

I want to thank to PEMEX-Exploration and Production, the Mexican Oil Company, for providing the data required for this thesis, but mostly for giving me the opportunity at this point of my professional life to pursue a challenging graduate program at one of the best universities in the world “Colorado School of Mines”. I am very grateful with CONACYT- SENER for providing me a scholarship.

My sincere thanks to the department of Geology and Geological Engineering at Colorado School of Mines. I want to extend thanks to my committee members, Dr. Bruce Trudgill, Dr. J. Fredrick Sarg, Dr. Thomas L. Davis, Dr. Mark Rowan, Dr. Charles Kluth and to all the professors of the department. I must to express my sincere gratitude to Dr. Charles Kluth, Dr. Mark Rowan and Dr. Michael Doe for all the time we spent having fun with seismic and during the restoration process, but most important for his friendship. It was a privilege and honor to work with all of you.


Also I want to thank all my friends at Colorado School of Mines: Long Wu, Alexander Betancur, Claudia Gutierrez, Thomas Arthur, Mohammad Naqi, Armagan Kaykun, Alyssa Franklin Dykes, Vivian Lin, and Martin C. Krueger.

Finally I would like to thank Schlumberger and Midland Valley for providing PETREL license software and 2D MOVE license software respectively, and especially thanks to Dave Phillips for the support of PETREL but mostly for his friendship.

Without all of you this study would have not been feasible. Thank you!!!
DEDICATION

A las personas más importantes de mi vida, mi amada esposa Dulce María y mis amadas hijas Brisa Sofía y María Angeline. Por todo el amor, comprensión, entendimiento, tolerancia, por este último año que hemos estado lejos mas no separados, por todos los viajes, juegos, alegrías y tristezas que hemos pasado juntos pero sobre todo por todas las cosas buenas y maravillosas que vienen en el futuro. Este trabajo está totalmente dedicado a ustedes con todo mi amor.

Con todo mi amor a mí querido México.

“Por Mi Raza Hablará el Espíritu”
CHAPTER 1
INTRODUCTION

The Gulf of Mexico (GOM) has been subject of exhaustive geologic and geophysical studies, mainly because it is one of the most prolific petroliferous basins in the world. Historically, Mexico has been one of the largest producers of oil in the world, with the majority of production from the Southeastern Basin provinces (Figure 1.1). At one time, Mexico’s production rate was second only to Saudi Arabia, but production from the super-giant Cantarell Field (Figure 1.2) has declined since 2004. Even though the biggest fields (Figure 1.3) in the most active exploration provinces of the Mexican portion of the GOM basin may already have been discovered (Cantarell, Sihil, Ku-Zaap- Maloob, Abkatun-Pol-Chuk, etc.), the Mexican Gulf of Mexico still has significant petroleum potential, both in shallow and deep waters.

To face the increasing demand for petroleum, exploration has begun in new frontiers and challenging areas, which in most cases are associated with a strong salt influence as well as high structural complexity. Seismic acquisition and conventional seismic processing in these complex areas does not always create a high quality seismic image, but advances in technology, such as Pre Stack Depth Migration processing (PSDM), can help to improve the seismic image.

In this study, seismic interpretation of both the PreSTM (Pre Stack Time Migration) and the PSDM seismic version are utilized, along with section restoration and recent salt evolution models to describe the geometry and the evolution of the area as well as allochthonous salt withdrawal and its effect on the petroleum system.

The improvement in imaging on the PSDM seismic version helps obtain a better and more reliable seismic structural interpretation. The description of the structural styles as well as
the stratigraphic evolution allows the definition of a 3D geological model of the area. A 2D restoration model increases the understanding of the evolution of the area as well as the salt movement and the elements of the petroleum system (source rock, reservoir rocks, trap integrity and timing).

1.1 Petroleum Significance

The Southeastern Basin (Figure 1.1) includes three Tertiary provinces formed within the Mesozoic basin: Salina del Istmo, Comalcalco (which includes the Mesozoic province of Chiapas-Tabasco), and Macuspana, as well as two offshore Mesozoic provinces: Sonda de Campeche and Litoral de Tabasco (E. Guzman and Marquez Dominguez, 2001).

![Southeastern Basin provinces](image)

**Figure 1.1** Southeastern Basin provinces (modified from E. Guzman and Marquez Dominguez, 2001).
The Sonda de Campeche petroleum province (Figure 1.1) was discovered in 1976 in waters less than 100 m deep. The Campeche shelf is considered an important oil-producing province. Most of the Sonda de Campeche (Figure 1.1) reservoirs are in Upper Cretaceous to Lower Paleocene talus breccias and Upper Jurassic oolitic sediments. The province covers 15,000 km\(^2\) and is by far Mexico’s most prolific area (E. Guzman and Marquez Dominguez, 2001). Discovery of the super-giant Cantarell Oil Field (Figure 1.2) in 1976 contributed to a huge increment in Mexican oil production, and also played a major role in Mexico-US oil trade. Located 80 kilometers offshore in the Bay of Campeche, the Cantarell Field or the Cantarell Complex is the world’s 12th largest oil field and a very important contributor to Mexican oil production. It was the world’s second largest oil field in terms of daily production after Ghawar in Saudi-Arabia, and in 2003, the production was 2.1 million barrels per day (source, PEMEX).

Figure 1.2  Detailed map of present day Southern Mexican Gulf of Mexico showing the Southern Basins, the Salt province, major structural features and Cantarell Oilfield (integration of Aranda, 1999; Jennette, et. al; Robles Nolasco, 2004, PEMEX).
The Litoral Tabasco petroleum province (Figure 1.1) covers approximately 7000 km² and was discovered in 1979. The most important reservoirs are Cretaceous to Paleocene breccias and Jurassic shelf facies on the east, and mostly basinal Jurassic to Cretaceous carbonates to the west. All are deformed by compressional and salt tectonics events. Recently, important discoveries have taken place in the Yaxche-Xanab area (Figure 1.3).

Most of Mexico’s oil production occurs in the Southeastern Basin (Figure 1.1), Cantarell and Ku-Maloob-Zaap (Figure 1.4) being the two main production centers in this area for many years (EIA, 2012). According to the report of Energy Information Administration (EIA), Mexico is the third largest oil producer in Western Hemisphere, seventh world-wide, and the state-owned “Petroleos Mexicanos” (PEMEX) is one of the largest oil companies of the world.
The oil sector (Figure 1.5) is an important part of Mexico’s economy: 14% of Mexico’s export earnings in 2010, although its relative impact on the general Mexican economy has been declining during recent years. Mexico’s government also relies upon earnings from the oil industry in Mexico, i.e. 32% of government revenues.

Mexico exported 1.3 million bbl/d of crude oil in 2010, 87.7% of which was (1.14 million bbl/d) exported into the United States. The United States, also imported 140,000 bbl/d of refined products, most residual fuel oil, naphtha, and other unfinished oils from Mexico (EIA, 2012).
1.2 Aims of Research Program

Based on seismic data, the primary aim of this study is to develop a consistent, structurally reasonable seismic interpretation in a very complex area affected by multiple tectonic events as well as salt tectonics. Second, based on the results obtained, develop a sequential evolution for “KUZAM” area (Figure 1.4) capable of explaining how tectonics and salt withdrawal affected the structural development of the area. Additionally, the interpreted tectonic evolution can be compared with the different models published in the literature. Finally, to define potential hydrocarbon traps, identify their integrity and give insights into the petroleum system that controls the hydrocarbon generation, migration, accumulation, and timing.

Figure 1.5 Map showing oil and gas bearing Basins of Mexico (modified from Talwani, 2011).
1.3  Location of Study Area

The KUZAM-3D seismic survey is located in the Mexican southeastern portion of Gulf of Mexico offshore, Tabasco State, in the shallow waters (Litoral Tabasco area) of the Campeche Bay between the isobaths 15 and 100m. The survey was acquired using streamer technique (bin size of 6.25 m X 25 m.) by CGGVeritas Company from December 23, 2009 to April 15, 2010 utilizing the SR/V Veritas Viking Vessel covering an area of 1009 km² (Figure 1.6).

Figure 1.6  Map showing the location of the KUZAM-3D seismic survey.
1.4 Database

PEMEX Exploration and Production, Southeastern Region at Ciudad del Carmen, Campeche, provided the research database for this project. The data set consists of 3D seismic data, 3D interval velocity cube (from depth migration), 2D seismic transects, 3 data sets of stacking velocities \( V_{stk} \), well data and unpublished reports for consultation. In addition, published literature has been studied as a part of this research and used to obtain geology background, petroleum system information of the area, etc.

1.4.1 Three-Dimensional Seismic Data

The 3D seismic database comprises three different seismic versions of the KUZAM-3D seismic survey. Figure 1.7 shows the geometry (irregular polygon) of the survey as well as the In-line and Cross-line directions. The numbering of the In-lines and Cross-lines are different in the PreSTM and PSDM versions.

![Figure 1.7 Basemap showing Kuzam-3D Seismic Survey (PSDM version).](image-url)
1.) Pre-Stack Time Migration (PreSTM) through Kirchhoff migration algorithm (Figure 1.8). This seismic processing was carried out by CGGVeritas during 2010 in Houston Texas, USA. The quality of the 3D-PSTM-seismic image in the upper part can be defined as good to adequate. Because of the structural complexities and the salt tectonics, from the middle to the deeper part of the survey the image can be classified as moderate to very poor.

![3D view from different angles of PreSTM version of Kuzam-3D seismic survey (no scale).](image)

2.) Pre-Stack Depth Migration (PSDM) via the BEAM migration methodology. Because the moderate to very poor seismic image in the deeper part of the seismic survey (especially because of salt tectonics), PEMEX decided to run PSDM seismic processing, with the aim of not only improving the image at the Tertiary level (where we have leads and prospects visualized already), but also (and more importantly) to improve the image at Mesozoic level and below,
since the main targets are located in the deepest part of the survey (Cretaceous and Jurassic).

Furthermore, this seismic processing will allow structural continuity to the Akal Horst structures (Figure 1.2).

The PSDM seismic processing was accomplished by ion-GX-Technology from August 2010 to December 2011 at Villahermosa Tabasco, Mexico (Figure 1.9).

Figure 1.9 Example of an In-Line and Cross-line from KUZAM-3D PSDM in depth seismic version.

3.) Pre-Stack Time Migration (PSDM-TWT) scaled to time (Figure 1.10). This seismic version is the time conversion of the PSDM seismic version in depth through the PSDM velocity model (Figure 1.11).
Figure 1.10  Example of an In-Line and Cross-line from KUZAM-3D PSDM scaled to time seismic version (same lines as Figure 1.9 to compare).

Figure 1.11  3D view from PSDM interval velocity model of KUZAM-3D Seismic Survey (no scale).
1.4.2 Two-Dimensional Seismic Data

The 2D seismic database includes thirteen 2D seismic transects (that come from several 3D-seismic surveys from the area). The geometry of the 2D-seismic transects is in general dictated by the location of 23 wells within an area of approximately 6000 Km$^2$.

The main purpose of these transects is on one hand, to help to provide a reliable seismic well tie for the seismic interpretation, whereas on the other hand, to help understand the regional structural framework as well as to comprehend the regional salt withdrawal through time, if possible. Figure 1.12 shows the location of the 3D-seismic survey (green) and the 2D seismic transects (red).

Figure 1.12 Basemap showing the location of the 2D Seismic Transects in red color.
1.4.3 Stacking Velocities

The velocity database embraces the KUZAM-3D, BOLOL-3D and MEGA-UNION-3D stacking velocity data set derived from seismic processing. These velocities are obtained by the processors at intervals along a section. They are fairly reliable in shallow parts of the section and pretty unreliable in the deeper parts (Coffeen, 1984). The use of these velocities as well as well data velocities available, allowed the construction of a velocity model whose purpose is the “time-to-depth” conversion of the 2D seismic interpretation (horizons and faults) as well as the seismic lines. Figure 1.13 shows the original stacking velocity data that almost cover the whole area of seismic transects.

Figure 1.13 Stacking Velocity data set from KUZAM-3D, BOLOL-3D and MEGA-UNION-3D seismic surveys.
1.4.4 Well Data

The well database consists of 23 wells, although only three of them, are located inside of the Kuzam-3D seismic survey. Figure 1.14 shows the location of the wells with respect to the KUZAM-3D seismic survey and the 2D seismic transects. In addition, the well database includes well logs, time to depth tables from ether check-shots or vertical seismic profiles (VSP’s), well tops and well reports, etc.

![Location of the wells with respect to the 2D and 2D seismic surveys.](image)

1.5 Research Methodology

This project is based on the structural interpretation of 3D and 2D seismic data. The first step consists of selecting the best seismic version (understanding “best” as superior and more reliable seismic image) of the 3D seismic volumes to perform the structural interpretation (PreSTM Vs PSDM). After a visual comparison of the whole seismic volumes, the assumption is that there is an improvement of the seismic image on the PSDM version; however, the expectations of the PSDM seismic processing were higher.
Second (as a consequence of the step one), structural seismic interpretation accomplished over the PSDM 3D seismic data in depth (Figure 1.9).

Third, time-to-depth conversion of the structural seismic interpretation through the PSDM velocity model (Figure 1.11). After the time conversion, make a quality control to verify if the reflections picked over the depth volume (PSDM-Z) are the same over the time volume (PSDM-TWT).

Fourth, transfer the time converted interpretation to chosen 2D seismic transects and extend the interpretation. The aim of extending the interpretation is to get a regional structural framework of the area as well to try to understand the salt withdrawal through the time in a regional context.

Fifth, build a velocity model to convert the 2D seismic extended time interpretation to depth by using well velocity data as well as seismic processing velocities (Vstk).

Finally, to execute the structural restoration. As a result of this process, acquire insights into the structural evolution of Kuzam area.

1.6 Software

The Department of Geology and Geological Engineering at Colorado School of Mines, has available professional software and a special computer laboratory for the accomplishment of all of the specific tasks required during this project.

1.) The seismic structural interpretation as well as all time-to-depth and depth-to-time conversions were completed using Schlumberger’s PETREL software.

2.) The structural restoration was done with the Midland Valley’s 2D Move software.
CHAPTER 2
REGIONAL TECTONIC AND GEOLOGIC FRAMEWORK OF SOUTHERN GULF OF MEXICO

2.1 The Gulf of Mexico

The present day Gulf of Mexico (GOM) is situated at the southeastern corner of North American Plate (with the Cocos Plate to the southwest and Caribbean Plate to the southeast) (Figure 2.1). The GOM is a roughly circular basin measuring approximately 1600 km from east to west and around 900 km from north to south; therefore, covering about 1,500,000 km² (www.epa.gov/gmpo/about/facts.html). The basin is filled with 10 – 15 km of sedimentary strata that range in age from Late Triassic to Recent (Ewing, 1991), with water depths of up to 4,350 m on the Sigsbee abyssal plain.

![Figure 2.1 Location of the Gulf of Mexico, Caribbean Plate and Cocos Plate.](image)
The GOM is bordered to the north by The United States of America (Florida, Alabama, Mississippi, Louisiana and Texas), to the West by Mexico (Tamaulipas, Veracruz, Tabasco, Campeche and Yucatan) and to the Southeast by the island of Cuba. The Gulf of Mexico is connected to the Atlantic Ocean by the Straits of Florida, and connected to the Caribbean Sea through the Yucatan Channel.

2.2 Tectonic and Geologic Framework

The Gulf of Mexico has had a complex evolution, reflecting regional as well as more localized tectonic events. Regional tectonic events are directly linked to the opening of the Gulf of Mexico. According to Padilla y Sanchez (2007), the first studies of Southeastern Gulf of Mexico were published in the first half of the twentieth century by Böse (1905, 1906), Villarello (1909), Burckhardt (1930), Gibson (1936a, 1936b), Alvarez (1949, 1951), Viniegra (1950) and Oñate (1950). After that, Castillo-Tejero (1955) and Contreras (1959) summarized the historic geology as well as the stratigraphy framework.

Since the beginning of plate tectonic revolution, most of the efforts to understand the origin and early evolution of the Gulf of Mexico have been investigated from the point of view of plate tectonics, using a variety of methodologies (e.g., Ball and Harrison, 1969; Freeland and Dietz, 1971; Beall, 1973; Burgess, 1976; Pilger, 1978, 1981; Pindell and Dewey, 1982; Anderson and Schmidt, 1983; Klitgord et al, 1984; van Siclen, 1984; Pindell, 1985), geophysical surveys (e.g., Wilhelm and Ewing, 1972; Worzel and Watkins, 1973; Humphris, 1978; Buffler et,al, 1980,1981; Halletal, 1982), and also examined from the stratigraphic point of view based on the premise that is necessary to develop a stratigraphic framework to solve any geological problem (e.g., Salvador 1987).
Present plate tectonic interpretations suggest that at the end of the Paleozoic and beginning of the Mesozoic, the area that would become the Gulf of Mexico Basin was part of the western section of very large landmass (Salvador, 1987; Pindell & Dewey, 1982; Anderson & Smith, 1983; Pindell, 1985; Ross & Scotese, 1988; Pindell et al., 1988; Pindell, 1994; Pindell et al., 2000, Bird et al., 2005); the supercontinent Pangaea (Figure 2.2).

Figure 2.2  Diagram showing part of the break-up of the super continent Pangaea from Early Jurassic to Upper Jurassic (Iturralde-Vinent, 2003).
Regional tectonic events in southern Mexico for the Mesozoic and Cenozoic can be grouped into three main phases (Oviedo-Perez, 1996):

1.) A rifting stage during the Triassic to Middle Jurassic.

2.) A passive margin stage during the Late Jurassic to Late Cretaceous.

3.) A compression and/or transpression (Rowan, 2013, personal communication) stage from Late Cretaceous to Recent.

Present day, the Gulf of Mexico is generally recognized as a passive margin system (Pindell & Dewey, 1982; Pindell, 1985; Pindell et al., 1988; Salvador, 1987; Pindell, 1994; Pindell, et al., 2000; Bird et al. 2005), where differential sedimentary loading, gravity tectonics and salt tectonics dominate, in particular in the northern Gulf of Mexico (e.g., Wu et al., 1990; Weimer & Buffler 1992; Peel et al., 1995; Diegel, et al., 1995; Rowan et al., 1999; Trudgill, et al. 1999; Wu & Bally, 2000, Rowan et al., 2004).

2.2.1 Mesozoic

From the geological prospective, the Campeche marine region originated through the rifting and spreading phase of the Gulf of Mexico during the Mesozoic (Ortuno et al., 2009)

2.2.1.1 Late Triassic

The Gulf of Mexico began to form during two rifting episodes (Figure 2.3): The Late Triassic (represented by the Eagle Mills deposits in East Texas) and the Middle Jurassic (represented by half grabens in the deep Gulf of Mexico) (Weimer, et al., 1998).

Late Triassic was the time of initial fragmentation and separation (riifting) of Pangaea along extensive fracture zones (Salvador, 1987); the proto Gulf of Mexico was still part of a huge emergent area, dominated by tensional stress (Figure 2.2).
Pangaea began to rift along widespread, poorly defined zones of intercontinental block-faulting and dike emplacement (Pindell, 1985). Widespread mantle upwelling and crustal attenuation produced areas of thin and thick transitional crust (Buffler and Sawyer, 1985), and the North American Plate started to separate from South America and Africa Plates (Figure 2.4).
As a consequence of continent separation, development of extensive grabens continued, filled by nonmarine red beds and associated volcanics (Salvador, 1987). To the west, southeasterly tectonic transport of blocks within Mexico began at this time, along one or several shear zones (Pindell, 1985). The geometries were controlled by grabens with approximately parallel alignments to the present day shore line (Padilla y Sanchez, 2007).

Figure 2.5 shows the Upper Triassic paleography. Shoreline and borders of Mexico are shown as a reference.
2.2.1.2 Middle Jurassic to Late Jurassic

The tectonic process of separation prevailed until the end of the Middle Jurassic (Figure 2.6). Marine deposition was restricted to embayments of the Pacific Ocean in northwestern and central Mexico. These marine embayments persisted during early Middle Jurassic, but seawater did not ingress into the future Gulf of Mexico Basin until the Callovian.

The presence of marine fossils in the west-central and east-central Mexico suggests that for the first time seawater from an arm of the Pacific Ocean reached the incipient Gulf of Mexico and extended across the central part of the country (Salvador, 1987).
A decisive change from the predominant earlier conditions of the Gulf of Mexico took place at this time; at the beginning, the invasion of seawater was perhaps intermittent, typically during hurricanes or unusually high tides. The transgression of the Pacific waters finally reached the Gulf of Mexico and water accumulated in depressions on the floor of recently flooded land areas, creating shallow and wide hyper-saline water bodies. An arid climate resulted in extensive evaporation under restricted conditions of shallow salt water. Precipitation of evaporites, known as the Louann and Campeche Salt took place over large regions of the Gulf of Mexico (Figure 2.7). Halite predominated in the central parts whereas anhydrite formed most of the deposits of the periphery of the large hypersaline bodies (Salvador, 1987).
The original salt sequence at the end of evaporite deposition is estimated to have been 5.5 km thick at the center of the Gulf salt basin, and may have thickened to perhaps 7.5 km beneath the present-day shelf-slope break (Pindell, et. al. 2007), but was apparently much thinner or even absent in other areas, suggesting that during salt deposition, some areas subsided persistently, whereas others subsided less or more slowly (Salvador, 1987). Buffer and Sawyer, (1985), suggested that during the Callovian, different rates of subsidence between thin transitional crust and a thick transitional crust (Figure 2.8) may have produced the southwest tilting of the basement and the wedge like geometry of the salt.

Figure 2.7 Late Middle Jurassic (Callovian) paleography of the Gulf of Mexico region about 160 Ma. At this time Gulf-wide salt had been deposited (Pindell et al., 1985).

In regards to the exact age of the Middle Jurassic Salt, the issue has long been controversial because there are no reliable data to rigorously determine its age. However, the salt age might be established indirectly based on regional stratigraphic and paleographic reasoning.
Nevertheless, most of the authors (Humphris, 1979; Salvador, 1987, 1991c; Pindell 1985, etc.,) agree that the salt of the Gulf of Mexico was deposited during the Callovian (164.7 -161.2 Ma). Furthermore, deposition of Callovian salt across the basin was the most important event during the rifting, as salt played a critical role in hydrocarbon maturation, migration and entrapment at a later time.

![Map showing present distribution of crust in Gulf of Mexico basin based on seismic reflection data, refraction data, gravity, and magnetics. Taken form Buffer and Sawyer, 1985, (TTS=Total Tectonic Subsidence).](image)

Some geoscientists have long believed that the Gulf of Mexico salt was deposited as a single salt body during the continental break-up (Figure 2.9). Later, the evaporate basin was separated by oceanic spreading during Late Jurassic (Figures 2.6, 2.9 and 2.10).
According to Pindell and Dewey’s, (1982) plate tectonic reconstruction (Figure 2.6), during the Oxfordian-Kimmeridgian, the seafloor started to spread at the Gulf ridge system, separating the Yucatan and Florida Straits blocks from U.S. Gulf Coast margin and isolating the three main provinces. The Yucatan block progressively rotated 43 degrees counterclockwise away from the Texas-Louisiana margin around a pole in northern Florida (Figure 2.10).
The movement of the Yucatan Block southward was accommodated along the Tamaulipas-Golden Lane-Chiapas fault zone (Pindell, 1985). Many workers agreed that salt deposition might had ceased around Early Oxfordian when more open conditions prevailed (Pindell & Dewey, 1982; Anderson & Smith, 1983; Pindell, 1985; Pindell et al., 1988; Salvador, 1991; Pindell, 1994; Pindell et al., 2000; Bird et al., 2005).

Figure 2.10 Rotation stages of the Yucatan Block diagram (modified from Tectonic Analysis Report, PEMEX, 2002).
Subsequently (Kimmeridgian), while the marine water invasion progressed, the development of wide platform margins took place on the Gulf’s borders, with restricted water circulation and widespread oolitic banks that extended for hundreds of kilometers around the Gulf of Mexico (Figure 2.11).

![Figure 2.11 Paleogeography of the Early Kimmeridgian (modified from Padilla y Sanchez, 2007).](image)

According to Padilla y Sanchez (2007), during the Tithonian, development of wide shallow platforms took place creating optimal conditions for the deposition of huge volumes of carbonates (Figure 2.12). Mudstone, rich in organic matter, was deposited in the basin. These rocks, represent the most important source interval responsible for most of the immense
hydrocarbon volumes in the Gulf of Mexico, especially southeast. Thicknesses oscillate between 400 to 500 m.

Figure 2.12 Paleogeography of the Tithonian. The principal source rock in the Gulf of Mexico (modified from Padilla y Sanchez, 2007).

2.2.1.3 Cretaceous to Paleogene Boundary

By the Early Cretaceous, horizontal plate motions related to the opening of the Gulf of Mexico were completed (Pindell, 1985). North America pulled sufficiently far away from South America (Pindell, 2001) and the Yucatan block reached its present-day position (Figure 2.13). Southwestern Basin provinces (Figure 1.1) and the rest of Southeast Mexico were subject to crustal cooling (Angeles-Aquino et. al., 1994).
Tectonic stability persisted in the region during the Early Cretaceous. The area of the extensive carbonate platforms continued its development and thus, vast volumes of carbonates were deposited over most of Mexico. During the Early Cretaceous (Hauterivian – Barremian), wide rudists reefs were built on the platform edges (Figure 2.14). Evaporate sedimentation continued over wide zones of the platform in areas with restricted water circulation.

At the end of the Cretaceous, during the Campanian-Maastrichtian stage, a significant intensification of clastic sedimentation from the west took place while at the same time, the subsidence rate of the Gulf of Mexico increased in the east (Figure 2.15).

Figure 2.13  Early Cretaceous plate reconstruction (Pindell, 2001).
A definitive change in the pattern of sedimentation occurred, altering the depositional environment from carbonates to clastics. Thick layers of marls and shales were deposited during this period (Padilla y Sanches, 2007). In addition (by the Campanian), high oblique motion between Kuala Plate and Mexico, triggered initial northward migration of Baja California (Sedlock et al., 1993).

Another important change in the tectonic evolution of the Gulf of Mexico happened at the Cretaceous and Paleogene boundary (K-Pg). An exceptional meteorite impact, the Chicxulub event (Figure 2.16) on the northern part of the Yucatan Peninsula strongly influenced the sedimentary processes that occurred 65 Ma in the region (Figure 2.17).
Coincidentally, a widely distributed sedimentary succession (700 m thickness in some localities) consisting of a major graded carbonates debris flow breccia is located on the southern part of the Gulf of Mexico, which could be related to the impact. This breccia is denominated by PEMEX as the “Breccia K-T” and represents the most important reservoir rock for the biggest oilfields in Mexico (Figure 2.18).

![Paleogeography of the Turonian-Maastrictian](modified from Padilla y Sanchez, 2007).

However, the origin of this breccia is still debatable and has been explained in many different ways. The three of the most likely theories are:
1.) An impact of an extraterrestrial body in Chicxulub area implies that the grain size of the ejecta should decrease the farther away it is from the impact area (Grajales-Nishimura et al., 2000). This condition is not entirely supported.

2.) The breccia is a product of a submarine collapse of the carbonate fragments which lay over the slope of the Campeche escarpment when the Chicxulub impact occurred (Angeles-Aquino, et al., 1992). However, if this hypothesis is true, the shape and distribution of the breccia should adjust to an extended morphology parallel to the Campeche escarpment with a grain size variation from highest to lowest basinwards.

3.) The origin of the breccia is related to karstified conditions for sub-aerial exposition on wide areas. This could explain the territorial extension of the breccia, yet, the thickness requires a sudden subsidence movement of the order of 700m to justify the age (65 my).

Figure 2.16 Location of Chicxulub impact and its influence zone (Modified from J. M. Grajales-Nishimura, et al, 2000).
Figure 2.17 Paleogeography at the beginning of the Paleocene. Location of the Chicxulub crater impact is shown (modified from Padilla y Sanchez, 2007).

Figure 2.18 Samples from the Breccia K-T, source PEMEX-IMP.
2.2.2 Cenozoic

The Cenozoic period was initiated with an important regional tectonic event. The Laramide orogeny created the mountain belts located west of the Gulf of Mexico. This tectonic regime produced the optimal conditions for the formation and movement of huge amounts of clastic sediments after the end of the orogeny.

2.2.2.1 Eocene

According to Pindell & Dewey, (1982), by Late Paleocene – Middle Eocene, the old plate boundaries become inactive (Figure 2.19); new boundaries were formed (Northern Caribbean), the Caribbean plate moved very little with respect the North America Plate. Motion between the North and South America plates, although minor, was approximately strike-slip and probably occurred along northern South America borderland (Pindell, 1982).

![Figure 2.19](image-url)  
Middle Eocene Paleoreconstruction (Pindell, 1987).
Additionally, during the Eocene, thick layers of fine sand were deposited on the slopes of the western part of the Gulf of Mexico, and the finest sediments filled the deepest parts of the basin (Goldhammer, 1999). As a consequence of this massive introduction of sediment, the salt and shale started its remobilization forming rollers, diapirs, tongues and canopies. During the Late Eocene, important depocenters formed (Figure 2.20), that then started to fill with clastic sediments derived from the west (Jannette, et al 2003).

![Figure 2.20](image)

**Figure 2.20** Paleogeography of the Late Eocene (modified from Padilla y Sanchez, 2007).

### 2.2.2.2 Oligocene

The Caribbean plate continued its migration eastward (Pindell, 1982). Deposition of clastics continued over the southeast (Ambrose et al., 2003); however, over the Macuspana area (Figure 1.2) the development of a depocenter began and thicker packages of shale sequences
were deposited. At the same time, across the Chiapas-Reforma-Akal belt (Figure 1.2), thinner sands and shales were deposited. Additionally, at Comalcalco-Salina del Ismo area (Figures 1.1), huge volumes of salt started to move northward (Angeles Aquino et al., 1994).

### 2.2.2.3 Miocene to Pleistocene

The same sedimentation patterns continued until the early Miocene, yet, during the Middle Miocene (Serravallian), a high compressional deformation stage occurred. Sanches-Montes de Oca, (1980) named this orogenic stage as “The Chiapaneco event”, and it is responsible for the deformation of the Chiapas-Reforma-Akal belt (Figure 2.21).

In addition, according to Angeles Aquino et al., (1994), at the beginning of the middle Miocene the main regional tectonic events on the area contemporary to the “Chiapaneco” event were:

1.) The inception of left-lateral movements across the Polochic fault of Guatemala and Chiapas (Burkart, 1983).
2.) An episode of dynamic metamorphism along the Tonala-Motozintla fault that borders the southern margin of the Chiapas massif.
3.) The inception of left-lateral motion along the strike-slip faults of the Sierra de Chiapas (Sanchez-Montes de Oca, 1979; Meneses-Rocha, 1991).

In terms of regional tectonics (Figure 2.22), these three events, combined with subduction of the Cocos Plate beneath the North American Plate (southwestern Mexico), produced a northeast-oriented maximum horizontal compressive stress in southeast Mexico (Meneses-Rocha, 1991) (Figure 2.23).

At the end of the Miocene and overlapping the early stages of the Pliocene (after the compressive deformation) deep water shales and sandstones accumulated on an angular
unconformity (Angeles-Aquino et. al. 1994), meanwhile, the Chiapas-Reforma-Akal belt (Figures 1.2 and 2.19) started to tilt NNW as a response to the Callovian salt withdrawal (Padilla y Sanchez, 2007), which migrated northward through the time. The high contribution of sediments coming from the Chiapas Massif (Figures 1.2 and 2.21) caused the deposition of several kilometers of sediments. The excessive loading triggered the development of listric normal faults oriented NE-SW (Figure 2.24).

![Paleogeography of the Late Miocene](image.png)

Figure 2.21 Paleogeography of the Late Miocene (modified from Padilla y Sanchez, 2007).

Most of these normal faults formed within the Macuspana Basin (Figures 1.2 and 1.3) as well as the Comalcalco-Salina del Ismo Basin (Figures 1.2). Concurrently, thinner layers of sediments were deposited over the Chiapas-Reforma-Akal Belt (Figure 2.25).
One remarkable difference between these basins is the fact that while the Comalcalco-Salina del Ismo basin evacuated salt (Ricoy, 1989), the Macuspana Basin evacuated shale (Ambrose et al., 2003).

Figure 2.22 Early Miocene paleoreconstruction (Pindell, 1987).

The sequences deposited within the Macuspana Basin (Figures 1.2 and 1.3) were affected by the extensional regime from the Late Miocene to the Pleistocene; at this time, the tectonic regime changed, causing tectonic inversion and creating the anticline folds that constitute the structural traps of the reservoirs in this area (Ambrose et al., 2003).

A northwest-oriented cross section through Campeche Sound (Figure 2.26), demonstrates that during this time growth faulting and salt diapirism were the dominant styles of deformation in the northwestern region (Angeles-Aquino, et.al. 1994).
Figure 2.23  Generalized tectonic map of the Campeche Sound (Angeles-Aquino et. al, 1994).

Figure 2.24  Diagrammatic scheme of the Chiapas-Reforma-Akal belt which is tilted NNW. Macuspana and Comalcalco Basins are product of the gravitational sliding (Padilla y Sanchez, 2007).
Figure 2.25  Paleogeography of the Pleistocene (modified from Padilla y Sanchez, 2007).

Figure 2.27 shows the regional geologic sections illustrating the structures of the Comalcalco- Salina del Ismo Basin (Figures 1.2 and 1.4) and the Macuspana Basin (Figures 1.2 and 1.3) as well as the structures of the Chiapas-Reforma-Akal Belt (Figure 1.4).

Figure 2.26  Interpreted seismic section oriented northwest-southwest (B-B’ Figure 2.20). P-L-P, Pliocene-Pleistocene; UM, upper Miocene; MM, middle Miocene; LM, lower Miocene; O, Oligocene; E, Eocene; K, Cretaceous; Ki, Kimmeridgian-Tithonian; O, Oxfordian (Angeles-Aquino et. al, 1994).
2.2.2.4 Present Day

At the present time (Figure 2.28), the Cocos Plate is moving northeastward relative to the Caribbean Plate at a rate of approximately 8.5 to 10 cm per year (http://geology.fullerton.edu/whenderson/f2007201/tectoniccocos/volcanicarc.htm). The North American plate is moving to the west-southwest at about 2.3 cm per year (http://www.pnsn.org/outreach/about-earthquakes/plate-tectonics). The Mexican portion of the Gulf of Mexico Basin extends onshore into several oil and/or gas-producing basins (Figure 1.5).
2.3 Summary

According to Buffler and Sawyer (1985), a generally accepted model for the “early” evolution of the Gulf of Mexico Basin (Figure 2.29) includes:

1.) A starting point during Late Triassic to Middle Jurassic rift stage (where the sedimentary record began with red beds) and the formation of transitional crust. This stage culminated with widespread deposition of large volumes of evaporates (Figure 2.7).

2.) A brief Late Jurassic period of oceanic crust formation in the deep central Gulf of Mexico.

Figure 2.28 Map showing regional gravity anomaly and main tectonic elements of the present Gulf of Mexico. This figure shows good correlation between potential fields and Pindell and Kennan’s (2002) kinematic model. Taken from Roman Ramos J.R. et al., 2008.
3.) A Late Jurassic through Early Cretaceous period of cooling and subsidence of the crust and buildup of extensive carbonate platforms surrounding the deep basin.

4.) Terminated with a Middle Cretaceous (Middle-Cenomanian ?) period of erosion and non-deposition and the formation of a prominent basin-wide unconformity.

At the beginning of the Paleogene (Figure 2.29), an important turning point in the Gulf of Mexico history occurs (Padilla y Sanchez; 2007) when:

5.) The sedimentary regime changed to clastic when the Laramide Orogeny resulted in uplift formed the folds and faults of the Sierra Madre Oriental (Figure 1.2).

6.) Clastic sedimentation (during the rest of Paleogene) in the southern and southwestern parts of the Gulf of Mexico where the Chiapas Massif (Figure 1.2) produced large volumes of sediment. Meanwhile, in the Yucatan block the deposition of shallow water carbonates continued.

7.) During the Middle Miocene (Serravallian), compressional stress resulting from the lateral movement of the Chortis Block and the subduction of the Cocos Plate against the southern of the North America Plate, formed the folds and faults of the Chiapas-Reforma-Akal Belt (Figure 1.2) over a decollement at the level of the salt. Later, the structures were tilted NNW when the salt was mobilized northward.

8.) Salt withdrawal caused the formation of new minibasins and depocenters controlled by faults with vergence toward the deepest part of the Gulf of Mexico and by regional antithetic faults, which limit the southeast basins. The gravitational movement of the Cenozoic deposits, finally caused tectonic inversion in the Neogene basins, from which the most evident is the Macuspana Basin (Figures 1.2 and 1.3).
Figure 2.29  Tectonic events occurred on the Mexican southeast of the Gulf of Mexico (modified from Padilla y Sanchez, 2007).
CHAPTER 3
STRATIGRAPHY AND PETROLEUM SYSTEM OF SOUTHERN GULF OF MEXICO

3.1 Regional Stratigraphy

A detailed regional stratigraphy of the Campeche marine region area over the whole stratigraphic column is described below:

3.1.1 Basement (Silurian-Permian to Triassic Stratigraphy)

No well has yet drilled to basement of the sedimentary sequence in the Campeche area. According to Sawyer et al., (1991), the basement in the study area consists of thin, transitional crust formed during the opening of the Gulf of Mexico. Basement rocks of the Campeche area, are thought to be granitic and/or metamorphic, similar in composition to rocks cut at the bottom of three wells, Cobo-301, Quintana Roo-1 and Yucatan-1, in the Yucatan platform, and rocks exposed in the Chiapas and Mixtequita Masiff (Angeles-Aquino et al., 1994). Isotopic data reveal that basement ranges in age from Late Silurian to Permian.

3.1.2 Red-Beds and the Isthmian Salt (Late Triassic to Middle Jurassic Stratigraphy)

The oldest sedimentary rocks in the Campeche area are the inferred siliciclastic sequence of continental origin known as the “red-beds” and the salt sequences identified as “Isthmian Salt” (Figure 3.1). These sequences represent the beginning of the Mesozoic marine transgression and have been generally dated based on their stratigraphic position. They are widely distributed in or around the Gulf of Mexico with ages ranging from Late Triassic to Middle Jurassic (Gaxiola R.J., 2009).

In regards to the salt, it is believed that the salt deposits were accumulated contemporaneously with the Louann Salt in the northern part of Gulf of Mexico during Callovian
time (Salvador, 1987) (Figure 2.7). For many years, these rocks represented the “economic basement” of the area. However, with the acquisition of deeper seismic as well as the improvement of seismic images, new petroleum systems may be found below them in the future.

![Figure 3.1 Present day Salt distribution in the Gulf of Mexico. Modified from Salvador, 1987.](image)

3.1.3 Upper Jurassic Stratigraphy

Based on data from 50 exploratory wells that have penetrated Jurassic rocks of the Campeche shelf, Gulf of Mexico, Angeles-Aquino and Cantu-Chapa (2001), formally proposed the names for the stratigraphy for the Upper Jurassic (Oxfordian-Tithonian) (Figure 3.2).
Eight lithofacies were defined and informally denominated as A, B, C, D, E, F, G, H (Figure 3.2). These lithofacies, were defined based on the analysis of 4500 samples of cuttings, and mechanical logs of the studied wells. Nevertheless, these units were not defined on the basis of their gamma-ray response and were only represented on lithofacies maps (Cantu-Chapa, 2009).
3.1.3.1 Ek-Balam Group

The Ek-Balam group (Figure 3.2 and 3.3) comprises numerous lithologically well-defined units of significant thickness consisting of (1) a lower member consisting of clayey and sandy wackestone to packstone with quartz cement and intercalated evaporites; (2) a middle member consisting of rhythmic alternations of calcareous sandstones, mudstones, and bentonitic shales; and (3) an uppermember characterized by sandy limestones grading into calcareous sandstone and anhydrite (Cantu-Chapa, 2009).

Figure 3.3  Distribution of the terrigenous lithofacies with continental influence from the Ek-Balam Group of the upper Oxfordian (A). The lithofacies grades into carbonates with a marine influence toward the western portion in the Campeche shelf (Modified from Angeles-Aquino and Cantu-Chapa, 2001).

3.1.3.2 Akimpech Formation

The Akimpech Formation (Figure 3.2) is widely distributed and mappable through the area (± 4500 km2). It consists of carbonates and terrigenous rocks characterized by oolitic and
partially dolomitized limestones, algal shales, and bentonitic mudstones (Angeles-Aquino and Cantu-Chapa, 2001). This formation was divided into four members; B, C, D and E.

3.1.3.2.1 Lower Terrigenous Member “B”

The Lower Terrigenous Member “B” (Figure 3.4) conformably overlies the Oxfordian Ek-Balam Group; its thickness varies from 75m to 408m. The member consists of mudstone and bentonitic sandy shales, sporadically and thinly interbedded with sandstones and bentonitic microdolomite with anhydrite (Angeles-Aquino and Cantu-Chapa, 2001).

![Diagram of the Gulf of Mexico showing the distribution of the lower terrigenous member “B” of the Akimpech Formation (lower Kimmeridgian), located in the eastern portion of the area. The member changes into carbonates toward the west of the Campeche shelf (Modified from Angeles-Aquino and Cantu-Chapa, 2001).](image-url)

Figure 3.4  Distribution of the lower terrigenous member “B” of the Akimpech Formation (lower Kimmeridgian), located in the eastern portion of the area. The member changes into carbonates toward the west of the Campeche shelf (Modified from Angeles-Aquino and Cantu-Chapa, 2001).
3.1.3.2.2 Lower Calcareous Member “C”

The Lower Calcareous Member “C” (Figure 3.5) overlies conformably the “B” member. It is mainly found in the central portion of the Campeche Shelf and its thickness varies from 37 to 267 m. The member consists of microcrystalline to mesocrystalline dolomites, packstone with incipient dolomitization, isolated interbeds of mudstone, and olive-gray sandy shales (Angeles-Aquino and Cantu-Chapa, 2001).

![Lithofacies distribution of lower carbonate member C of the Akimpech Formation (lower Kimmeridgian), located in the central portion of the Campeche shelf (Modified from Angeles-Aquino and Cantu-Chapa, 2001).]

3.1.3.2.3 Upper Terrigenous Member “D”

The Upper Terrigenous Member “D” (Figure 3.6) conformably overlies unit “C”. It is best developed in the eastern portion of the area and thickness varies from 23 m to 387 m. It
consists of claystones, mudstones, and sandy shales interbedded with carbonates and abundant algal material (Angeles-Aquino and Cantu-Chapa, 2001).

Figure 3.6 Distribution of upper terrigenous member D of the Akimpech Formation (lower Kimmeridgian), west of the Campeche shelf (Modified from Angeles-Aquino and Cantu-Chapa, 2001).

### 3.1.3.2.4 Upper Calcareous Member “E”

The Upper Calcareous Member “E” (Figure 3.7) overlies member “D” and underlies member “F” from the Tithonian, and its thickness varies from 52m to 255m. Member “E” extends throughout the studied area and its best development is in the western portion. It consists of mesocrystalline and microcrystalline dolomites. Petrographic studies carried out by Angeles-Aquino (1988-1996) indicate that the rocks are packstones, ooid and peloid grainstones,
and pelloid mudstones or wakestones, locally dolomitic (Angeles-Aquino and Cantu-Chapa, 2001).

Figure 3.7 Distribution of the upper calcareous member E of the Akimpech Formation (Kimmeridgian). Mesocrystalline (a) and microcrystalline dolomites (b). Evaporitic carbonate facies (c). Campeche shelf (Modified from Angeles-Aquino and Cantu-Chapa, 2001).

3.1.3.3 Edzna Formation

The Edzna Formation was divided in in three members F, G and H. The first of them was deposited irregularly over Kimmeridgian rocks (Akimpech formation, member “E”). The second member was deposited more uniformly and widely distributed. The last member is the most widely distributed of the three (Angeles-Aquino and Cantu-Chapa, 2001).

3.1.3.3.1 Lower Member “F”

The Lower Member “F” (Figure 3.8) is distributed uniformly in the Campeche Shelf; its thickness varies from 20m in the east to 110m in the west. It consist of clayey mudstone, light
gray to dark brown color, with abundant organic material and occasional thin intervals of dark-gray or black shale. The lithofacies of this carbonate unit, alternate with clayey carbonates and gradually become dolomitized eastward (Angeles-Aquino and Cantu-Chapa, 2001).

Figure 3.8 Distribution of the carbonated lithofacies of member F of the Edzna Formation (Tithonian). The central part of the area (a and b) is occupied by clayey carbonates that are dolomitized (c) and tend to become terrigenous toward the east because of the continental influence of the Campeche shelf (Modified from Angeles-Aquino and Cantu-Chapa, 2001).

3.1.3.3.2 Middle Member “G”

The Lower Member “G” (Figure 3.9), consists of sandy shales of dark gray to black predominate, interspersed with dark-colored clayey limestones. Its thickness varies from 39m to 171m. This member is thicker in the western portion than in the easter portion of the Campeche
Shelf (Angeles-Aquino and Cantu-Chapa, 2001). Member “G” is the main source rock unit in the Campeche Shelf.

Figure 3.9 Distribution of lithofacies terrigenous member G of the Edzna Formation (Tithonian). The lithofacies tends to be carbonated toward the east. This horizon is considered the principal generator rock for hydrocarbons in the Campeche shelf (Modified from Angeles-Aquino and Cantu-Chapa, 2001).

3.1.3.3.3 Upper Member “H”

The Upper Member “H” (Figure 3.10) consist mainly of clayey and bentonitic lime mudstones, with a chalky appearance and dolomitization toward the east. This member represents the top of the Upper Jurassic (Tithonian). It has wide and quite uniform lateral distribution. Its
thickness varies from 26m to 83m generally thinner eastward and thicker in the west (Angeles-Aquino and Cantu-Chapa, 2001).

Figure 3.10 Lithofacies plan of member H of the Edzna Formation (Tithonian): calcareous-clayey (a) and clayey dolomites (b) in the Campeche shelf (Modified from Angeles-Aquino and Cantu-Chapa, 2001).

3.1.4 Cretaceous-Paleocene Stratigraphy

The K-Pg boundary offshore Campeche has been studied particularly in oilfields located about 80 east of the study area, km such as Cantarell and other nearby oilfields and outcrops southeast Mexico. The stratigraphic architecture of the K-Pg boundary graded carbonate sequence generally suggests a single continuously graded fining-upward deposit (Grajales Nishimira, et al., 2009). The K-Pg boundary stratigraphic packages in the southeast region have been divided in three marine sequences based on their distinctive lithologies, ages, and relative
stratigraphic position: (1) The Maastrichtian pelagic limestone with 10cm, 15cm, and 20-cm thick beds. Overlying these limestones is (2) a graded detrital K-Pg boundary carbonate sequence consisting of coarse calcareous breccia, fine calcareous breccia, sandstone, and claystone.

Finally, above this carbonate sequence is (3) a basal Paleocene package of shaly limestones and marls (Figure 3.11) (Grajales Nishimira, et al., 2009).

Figure 3.11  Offshore Campeche Sound stratigraphic column showing the Cretaceous-Tertiary boundary modified from modified from Mitra et al. 2006 and Grajales Nishimira, et al., 2009.

3.1.4.1 Cretaceous

The Cretaceous stratigraphic units consist essentially of dolomites and shaly limestones in the lower and middle part, leaving the Upper Cretaceous breccia and dolomites the most prolific reservoirs in this region. The Campanian-Maestrichtian (Cantarell Formation) has been informally described as a breccia formed of calcareous or dolomitized fragments cemented by
micrite (Cantu-Chapa et al, 2001). The thickness of the Cretaceous sequences ranging from 600m to 100m depending on the area (Ortuño A.S., et al. 2009).

### 3.1.4.2 Paleocene

Pelagic limestone, marl, calcareous shale, and argillaceous limestone overlie the upper unit of the K-Pg boundary.

#### 3.1.4.2.1 Lower Paleocene

The Abkatun Formation (“god who holds the world” in Mayan dialect) took its name from the “Abkatun” oilfield. This formation is widely distributed on the Campeche Shelf and was formally described by Cantu-Chapa et al, (2001), as a 30m to 60m thick formation that consist of reddish-brown and beige sandy limestone that contain foraminifera. The boundary between the Lower and Upper Paleocene is conformable.

#### 3.1.4.2.2 Upper Paleocene

According to Cantu-Chapa et al, (2001), the Upper Paleocene sequence has a very distinctive lithostratigraphy and chronostratigraphy represented by 50m to 450m of bentonitic, soft to semi-arid, laminated and locally calcareous greenish-gray shale that contain foraminifera.

### 3.1.5 Eocene to Pleistocene

Tertiary successions of Southeastern Basins of Mexico consist of “siliciclastic” Paleogene and Neogene sequences. The geometry and thickness of these sequences change depending of the area and they are deeply related with the tectonosedimentary evolution of the area (compression, extension and salt tectonic). The Miocene-Pliocene “Chiapaneco” orogeny event redeformed the previous structures generating large volumes of detritus. Consequently, clastic shelf facies prograded rapidly. The paleoenvironments became aggradational-deltaic in nature from the Early Pliocene onward; major gravity slide triggered the separation of the
Comalcalco and Macuspana sub-basins (Chavez V.V. et al., 2009). Depositional sub-basins that formed during Neogene (mainly in the Miocene) were a response to halokinetic processes (Ortuño A.S., et al. 2004).

During Paleocene to Middle Miocene, deep-water organic-rich shales were deposited at the Reforma-Comalcalco area (Figure 1.2) whereas debris flows and breccias were deposited on a slope derived of exhumed Cretaceous Platform (Chavez V.V. et al., 2009). In general the average thickness of the Paleogene is about 700m, and about 4500m for the Neogene (Angeles-Aquino; Ortuño et al., 2004).

3.1.5.1 Comalcalco Sub-basin

The sub-basin is a depocenter filled with thick delta front sands that were deposited in the vicinity of a late Miocene-Pliocene Platform. This sub-basin is associated with a system of normal faults dipping north-northwest and counter-regional faults related to salt evacuation (Chavez V.V. et al., 2009).

3.1.5.2 Macuspana Sub-basin

According to Chavez V.V. et al., 2009, the Macuspana sub-basin, owes its origin to the interaction of three important events: (1) a huge amount of incoming sediments, (2) gravity sliding, and (3) deformation and mobilization of shale masses. The sedimentary facies from southwest to northeast change from fluvio-deltaic to transitional marine and turbidite deposition. The central part of the sub-basin develops shale ridges, salt diapirs and argillaceous domes.

3.1.6 Summary

A representative Mesozoic-Cenozoic sedimentary column of the Campeche Sound is shown in Figure 3.12.
3.2 Petroleum System

The Southeastern Basins (Figure 1.1) is the greatest petroleum province in Mexico. The area hosts important oil and gas reservoirs either in carbonate and siliciclastic sequences. These reservoirs are widely distributed on different stratigraphic levels from Mesozoic to Tertiary ages. The elements of the petroleum system are intimately related with the evolution of the Gulf of Mexico, from initial extension, two compressive phases followed by an extensional episode and of course salt tectonics.
3.2.1 **Source Rocks**

Three main regional generative systems have been recognized on the Campeche area: (1) shaly limestones of Tithonian age, (2) Cretaceous limestones and evaporates, and (3) Miocene arguillaceus terrigenous deposits (Holguin, 1998; Guzman et al., 1995, PEMEX-Chevron, 1995), (Chavez Vlois et al., 2009).

These sedimentary units are confined between autochthonous salt horizons, allochthonous walls and intrusive bodies of salt. Salt is, therefore, a critical factor in the maturation of organic material (kerogen) in these strata. Salt-bounded subbasins are identified in which hydrocarbons were generated. The proximity to the basement and the high thermal conductivity of the salt have generated liquid hydrocarbons from these source rocks (Ortuño A.S., et al. 2004).

### 3.2.1.1 Upper Jurassic Generating System

Four generating systems have been identified within the Upper Jurassic sequences buried to depths of between 400 and 7500m in the Campeche marine region. The Oxfordian generating system, the Kimmeridgian generating system and the Tithonian generating system. The typical average thickness of the Oxfordian and Kimmeridgian sequences on the Campeche Sound (Figure 1.1) is about 600m, whereas, the Tithonian sequence average around 200m (Ortuño A.S., et al. 2009).

The Oxfordian facies in the marine region has TOC contents ranging from very low to very high within a relatively small area; e.g., they are quite variable and spatially discontinuous (Romero et al., 2001). These source rocks charge the Oxfordian and Kimmeridgian reservoirs with 20° to 35° API oils. Organic material within the Kimmeridgian is of good quality derived from algae (kerogen type II) with TOC values from 0.5 to 3.0% (Angeles-Aquino, 1996).
The Tithonian facies has the greatest significance in the region as a source rock. It is widely and continuous distributed over the area, is rich in type II organic matter with TOC values of 4% to 15% where immature, and with a residual richness of 1% to 3% TOC (Figure 3.13).

Figure 3.13  Map of Upper Jurassic (Tithonian) geochemical parameters. TOC, total organic carbon; S2, potential hidrocarbon; HI, hydrogen index; TMax, maximum temperature; R0, vitrinite reflectance. Modified from Clara Valdes, et al., 2009.

These rocks represent the principal component of the petroleum system in the area since they are responsible for the generation of nearly all the hydrocarbons produced from plays in several stratigraphic levels such as Kimmeridgian, Tithonian, Cretaceous, Eocene, Miocene and Pliocene with fluids ranging from 10° to 58° API (Clara Valdes, et al., 2009) (Figure 3.14).
3.2.1.2 Lower Cretaceous Generating System

The Lower Cretaceous generating system consists of a carbonate-evaporite sequence. TOC values vary from 0.6% to 1%, with poor to fair generating potential (0.5 -6 mg HC/g of rock). Type II kerogen which is an oil and gas prone source is related to algal material with a relative abundance of bacterial and algal-amorphous organic matter. Based on the maximum pyrolysis temperatures of 430°-437°C, these rocks are considered as thermally mature (Clara Valdes, et al., 2009).

3.2.1.3 Lower Miocene Generating System

The Lower Miocene generating system has been recognized only on the Macuspana Basin (Figure 1.2) (although the Lower Miocene is widely distributed over the Tertiary southeastern basins). Much of the organic matter of these rocks is derived from higher plants mixed with algal material in aqueous environments. TOC values vary from 1% to 2% with a good hydrocarbon potential (2 to > 5 mg HC/g of rock). The kerogen is primarily type II/III with
the capacity of generates oil and gas depending of the local maturity level (Clara Valdes, et al., 2009).

3.2.1.4 Summary of Generating System

Several sours rocks on the Campeche Shelf basins have been identified based on organic richness, quality, distribution, optical studies, cuttings, core samples, etc. Maturity of these rocks has been obtained from pyrolysis studies (TOC, S1, S2, Tmax, HI, OI, PI, etc.). From all the source rocks in the area, the Jurassic (Oxfordian) is defined as the major source rock. These rocks are responsible for the generation of most of the hydrocarbons in the region and capable to charge several stratigraphic sequences not only on the Mesozoic but also in Tertiary levels. Figure 3.15 shows the geochemical signatures of the most important source rocks of the Campeche Shelf.

![Geochemical signatures of the petroleum system in Campeche Shelf](image)

Figure 3.15  Geochemical signatures of the petroleum system in Campeche Shelf (Clara Valdes, et al., 2009).
3.2.2 Reservoir Rocks

Production of the southeast basins of Gulf of Mexico comes from large segments of the stratigraphic column (Figure 3.12). The southeast basins produce heavy oil, light oil, volatile oil, super-light oil, condensate, wet gas, and dry gas (Clara Valdes, et al., 2009) (Figure 3.14). The known plays so far are: Kimmeridgian, Lower Cretaceous, Middle Cretaceous, Upper Cretaceous and Tertiary.

3.2.2.1 Kimmeridgian Reservoir Rocks

Kimmeridgian reservoir rocks consist of ooid packstone-grainstone with intraclasts and bioclasts that change laterally to mudstone-wackestones with peloids and intraclasts. The oil densities produced from these rocks varies from 28° to 45° API (Clara Valdes, et al., 2009).

3.2.2.2 Tithonian Reservoir Rocks

Tithonian reservoir rocks are characterized of arguillaceous mudstones-wackestones. The produced oils have densities of 38° – 44° API (Clara Valdes, et al., 2009).

3.2.2.3 Lower Cretaceous Reservoir Rocks

Two facies have been identified at Lower Cretaceous reservoir rocks. The first facies is represented by dolomitized flow breccias with sub-rounded casts in a calcareous-argillaceous matrix. These rocks present fractures with vugular cavities partially filled with dolomite and residual oil. The second facies is denoted by dark gray microdolomite (argillaceous mudstone-wackestone) with black chert nodules, abundant fractures and microfractures. The oil densities of the oils produced from these rocks has ranges from 25° to 54° API (Clara Valdes, et al., 2009).

3.2.2.4 Middle Cretaceous Reservoir Rocks

The most important play in this sequence are exemplified by patch reef facies (intraclasts and bioclasts packstone-grainstone), lagoonal facies (miliolid packstone-grainstone), slope facies
(dark gray, dolomitized breccias), and basinal facies (argillaceous mudstones). All of them are dolomitized with abundant fractures. The produced oils have densities ranging from 26° to 53° API (Clara Valdes, et al., 2009).

### 3.2.2.5 Upper Cretaceous Reservoir Rocks

Upper Cretaceous reservoir rocks are illustrated platform patch reefs, slope calcareous flow breccias, and basinal arguillaceous mudstones-wackestones highly fractured and with chert banding. The oil densities produced from these rocks varies from 30° to 53° API (Clara Valdes, et al., 2009).

### 3.2.2.6 Tertiary Reservoir Rocks

Important siliciclastic reservoirs can be found at Lower to Middle Eocene levels. These reservoir rocks comprise carbonated debris flows surrounded by argillaceous matrix. The oil gravities vary from 43° to 53° API. Other important reservoir sequences can be found within the Middle Miocene section typified by deep-water turbidity sands associated with slope and basin-floor fans. Most of these fields reports good production with oil densities fluctuating from 24° to 44° API. In addition, Upper Miocene and Lower Pliocene, display a shallower depositional environment configuration. Deltaic and fluviodeltaic reservoirs consisting of isolated or stacked shallow-water bar-sands represent these sequences. The oil densities produced on these intervals fluctuate between 17° and 60° API (Clara Valdes, et al., 2009).

### 3.2.3 Trap

Trap formation as well as its integrity and quality in the area are closely related with the tectonic and sedimentary evolution of the whole basin. Structural controls for trap formation are considered mainly as a result of:
1.) A compressive “Laramide” phase responsible for the formation of wide regional fold belt.

2.) The compressive Miocene-Pliocene “Chiapaneco event” phase re-deforming the pre-existing structures and forming the folds and faults of the Chiapas-Reforma-Akal Belt (Figure 1.2).

3.) Salt tectonic processes (halokinesis) followed by an important extensional phase associated with gravity sliding during Pliocene-Pleistocene.

4.) Diagenetic processes of compactation, cementation, dissolution and fracturing that modify textures, sedimentary structures and produce adequate porosity and permeability. The kinds of traps that can be found in the area depending on the structural phase extensional or compressive) as well as depositional system (carbonates or siliciclastic) are: Anticlines with natural closure, monoclines with closure towards fault, turtle structures, rotated blocks, thrust imbricate structure, roll overs anticlines associated to growth strata and listric faults, wedge out against salt and welds, stratigraphic traps associated to fluvial systems and deep-water turbidity systems as well as combined traps (structural-stratigraphic traps).

3.2.4 Seal

Seal rocks are widely distributed at the different stratigraphic levels of the Campeche Shelf column working for the different plays in the area. The area can be separated in two main stratigraphic levels regarding to the oil production importance: (1) Mesozoic level where carbonate rocks provide most of the hydrocarbons on the area and (2) Tertiary rocks that consist of siliciclastic rocks. In addition, salt tectonics in the area created good conditions for salt-related traps formation on several stratigraphic levels.
3.2.4.1 Mesozoic Seal Rocks

Tithonian seal rocks are characterized by clay-mudstones and shale whereas in the Cretaceous are represented by clay-mudstones, pelagic marl and calcareous shale. A good example of the Mesozoic’s seal rocks is typified in The Akal Horst at the Cantarell oilfield (Figure 1.2), where overlying the oil producing breccia, there is an impermeable seal about 30m thick (Figure 3.16). This layer that also has been dolomitized is made up of fine grained impact ejecta, including shocked quartz and feldspar, and clay minerals interpreted as alteration products of impact glass. (Mitra et. al., 2006).

Figure 3.16 Representative Cantarell’s stratigraphic K-Pg boundary column. Petroleum system elements and petrophysical properties are shown. Notice the Paleocene seal rock for Cretaceous reservoirs. Modified from J.M. Grajales-Nishimura et. al. 2003.
3.2.4.2 Tertiary Seal Rooks (Kuzam Area)

Identification of the possible regional seal rocks over Kuzam area and surroundings was performed by PEMEX during 2010 (Integracion y Actualizacion de Plays Terciarios). This study was based on data collected from 30 wells over 9 stratigraphic sections (Figure 3.17-A) and the interpretation of well logs (Figure 3.17-B). According to this study, several regional seal rocks are present over the Tertiary column widely distributed all over the place.

![Figure 3.17](image.png)

Figure 3.17  (A) Location KUZAM-3D seismic survey, wells and Stratigraphic sections. (B) Example of possible seal sequences based on well logs interpretation. Modified from “Integracion y Actualizacion de Plays Terciarios, PEMEX 2010”.

The most important regional seal rocks are located at Middle Miocene, Upper Miocene, Lower Pliocene, and Middle Miocene levels. Two main facies were identified: (1) Sandy shale
facies with mudstone traces and (2) light calcareous shale facies distributed on several stratigraphic levels. Figure 3.18 shows two stratigraphic sections near KUZAM-3D seismic survey.

Figure 3.18 Stratigraphic sections (red lines) near KUZAM-3D seismic survey showing the correlation of several reseal rocks sequences over the area at different Tertiary stratigraphic levels. Modified from “Integracion y Actualizacion de Plays Terciarios, PEMEX 2010”.
Thicknesses of each sequence vary depending on the area. Calculation of isochore maps (Figure 3.19) constructed on basis of well tops for each sequence establish that all sequences tend to increase its thickness southward as prevailing trend. Thicknesses for “Middle Pliocene” fluctuate approximately from 100m to 500m (Figure 3.19-A), the “Lower Pliocene” oscillate from 100m to 900m (Figure 3.19-B), the “Upper Miocene” vary from 100m to 800m (Figure 3.19-C), and the “Lower Miocene” thicknesses shows the smallest variations ranging from 50m to 200m (Figure 3.19-D).

Figure 3.19 Regional seal isochore maps Kuzam area and surroundings. Modified from “Integracion y Actualizacion de Plays Terciarios, PEMEX 2010”.

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In addition, this study integrated the calculation of petrophysical properties such as effective porosity to determine the seal efficiency based on the “play fairway methodology”. According to the results of this study, the risk for the presence and effectiveness of these seal rocks in general vary from “medium” to “low”, in other words, the regional seal on this area may be good to very good. However, fault systems may modify seal condition of the area acting either as a hydrocarbon migration pathways or seals. “Allen diagrams” methodology and calculation of petrophysical properties over the fault plane may help to understand the whole seal integrity.

3.2.5 Migration and Timing

According to geochemical studies conducted by PEMX-Becip-Franlab during 2007 and 2009 over the study area, had been occurred on different ways and processes.

3.2.5.1 Jurassic Plays

The hydrocarbon migration efficiency to charge Jurassic reservoirs is considered high to very high since Jurassic reservoir rocks are directly in contact to Jurassic source rocks. In addition, the efficiency has been verified on near productive oilfields on Jurassic rocks.

3.2.5.2 Cretaceous

According to this study, the first hydrocarbon accumulations on Cretaceous reservoir rocks on this area took place about 4 to 3.5 million years ago.

Migration effectiveness for Cretaceous reservoir rocks in general depend on capacity of connect the source rocks to the Cretaceous highs reservoir rocks trough fault systems. This efficiency varies depending on the geometry and petrophysical properties of the faults (shear zone) as well as the distance from the source rock respect to the reservoir rock and trap. However, hydrocarbon migrations to Cretaceous reservoir rocks have been confirmed on several oilfields near KUZAM-3D with significant accumulations.
3.2.5.3 Neogene Plays

Migration efficacy for Neogene reservoir rocks is determined by the ability to move hydrocarbon from the source rock (mainly Tithonian) through:

First, the Paleogene regional seal across huge normal faults systems to the sandy Neogene Plays (there are few deep faults that connect the Tertiary sequence to the deepest levels of the Mesozoic). In addition, migration through the Paleogene seal cannot be significant without an extraordinary hydrocarbon charge at the Cretaceous level. However, part of the hydrocarbons escape through the Paleogene seal from the Cretaceous accumulations using as a pathway faults with low permeability properties.

Second, migration ability also rests on vertical migration processes as well as the lateral migration capability that are the result of the adjacent connectivity between sandy bodies. Migration of hydrocarbons from the Tithonian source rocks has been confirmed on several Tertiary oilfields in the area.

3.2.6 Timing

According to a geochemical study for the Tithonian-Kimmeridgian and Tithonian-Cretaceous petroleum systems performed by PEMEX during 2012 over the Kuzam area, the events of the petroleum system are considered synchronous.

The age of hydrocarbon generation fluctuates between 10 to 5 My and the age of the hydrocarbon expulsion ranges from 5 to 3 My until recent. Figure 3.20 shows graphically the timing of the essential key factors of the petroleum system (source rock, reservoir rock, seal rock and trap formation) as well as the processes of generation, migration and accumulation of hydrocarbons.
Figure 3.20  Chart showing the timing of the essential elements of the Tithonian-Kimmeridgian and Tithonian-Cretaceous petroleum system for KUZAM area. PEMEX 2012.
CHAPTER 4
SEISMIC ACQUISITION AND PROCESSING

Knowledge from the history of a seismic survey can be a key factor during subsequent interpretation. The basic knowledge from seismic acquisition to seismic processing of a seismic data set provides information regarding the final seismic image. Thus, interpreters should use this knowledge to get a better understanding of the wavelet, seismic reflections, velocity issues, etc., to improve their seismic interpretation.

4.1 Seismic acquisition

KUZAM-3D seismic survey was acquired by CGGVeritas with the streamer technique from December 2009 to April 2010 utilizing the SR/V Veritas Viking Vessel (Figure 4.1) covering an area of 1009 km².

Figure 4.1 CGG SR/V Veritas Viking Vessel (Taken from field operation report, VERITAS-PEMEX, 2010).
Figure 4.2, shows the plan view of the seismic acquisition geometry of KUZAM-3D seismic survey.

There were several challenges during the acquisition of the seismic data such as very hard climate conditions during the winter season, shallow waters (15-60m, deep), two permanent buoys just in the limits of the full fold area, intense fishing activities with small boats, active petroleum vessel operations and people diving around the buoys. All of these factors influence the seismic acquisition process, impacting the final seismic image. The acquisition parameters of the survey are shown in Table 4.1.
Table 4.1  Seismic acquisition parameters.

<table>
<thead>
<tr>
<th>Source</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessels</td>
<td>R/V Veritas Viking</td>
</tr>
<tr>
<td>Source type</td>
<td>Air gun</td>
</tr>
<tr>
<td>Number of sources</td>
<td>2</td>
</tr>
<tr>
<td>Source separation</td>
<td>50 m</td>
</tr>
<tr>
<td>Operation Pressure</td>
<td>2000 psi</td>
</tr>
<tr>
<td>Volume (per source)</td>
<td>4450 cu.in.</td>
</tr>
<tr>
<td>No of sub arrays (per source)</td>
<td>3</td>
</tr>
<tr>
<td>Sub array separation</td>
<td>8m</td>
</tr>
<tr>
<td>Source depth</td>
<td>6m</td>
</tr>
<tr>
<td>Shot point interval</td>
<td>25m (50m unique CMP)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Streamer</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of streamers</td>
<td>6</td>
</tr>
<tr>
<td>Streamer separation</td>
<td>1000m</td>
</tr>
<tr>
<td>Streamer length (per streamer)</td>
<td>6000m</td>
</tr>
<tr>
<td>Number of groups (per streamer)</td>
<td>480</td>
</tr>
<tr>
<td>Group length</td>
<td>12.5 m</td>
</tr>
<tr>
<td>Streamer depth</td>
<td>8m</td>
</tr>
<tr>
<td>Inline offset (centre source/centre near trace)</td>
<td>150</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Recording</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Recording System</td>
<td>Sercel</td>
</tr>
<tr>
<td>Recording length (after T0)</td>
<td>8 sec</td>
</tr>
<tr>
<td>Sample rate</td>
<td>2ms</td>
</tr>
<tr>
<td>Recording filter - Low cut/slope</td>
<td>3.0 Hz @ 370 dB/Oct</td>
</tr>
<tr>
<td>Recording filter -High cut/slope</td>
<td>200 Hz @370 dB/Oct, linear ph.</td>
</tr>
<tr>
<td>Tape format</td>
<td>SEG-D, 8058</td>
</tr>
<tr>
<td>Tape media</td>
<td>3592</td>
</tr>
</tbody>
</table>

4.2  Seismic Processing

The seismic processing phase was divided into two separate stages. The first stage concentrated on the Pre Stack Time Migration processing (PreSTM). Because of the structural complexity, as well as the tectonics influencing in the area, the second stage was focused on improving the seismic image by means of the Pre Stack Depth Migration technique (PSDM).
4.2.1 Pre Stack Time Migration

The Pre-Stack Time Migration (PreSTM) was performed by CGGVeritas Company during 2010. The methodology used for this seismic processing was that of a Kirchhoff migration algorithm.

There were numerous challenges during this seismic processing process. The first challenge was the variety of noise that needed to be eliminated, which included swell noise, ground roll and external noise sources. However, noise was successfully eliminated using a combination of FXEDIT XRLIN and a Tau-p mute. Figure 4.3, shows an example of the removal of the swell noise by applying the FX filtering. Figure 4.3-A shows the gathers affected by swell noise (highlighted with black arrows), Figure 4.3-B shows the same gathers after applied the filters, and Figure 4.3-C shows the noise eliminated from the gathers.

Figure 4.3 Swell noise removal (A) Gathers with noise, (B) Gathers without noise, and (C) noise removed.
The second challenge was the removal of multiple energy, which was performed using a combination of Tau-p deconvolution and radon demultiple, which work well in this area. The complete processing sequence for the PreSTM seismic processing is shown in Table 4.2.

Table 4.2  PSTM processing sequence

<table>
<thead>
<tr>
<th>Processing Sequence</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Read in data from SEG-D field tapes</td>
</tr>
<tr>
<td>2</td>
<td>Save in TANGO internal format</td>
</tr>
<tr>
<td>3</td>
<td>Apply trace edits</td>
</tr>
<tr>
<td>4</td>
<td>Apply 3Hz high pass filter</td>
</tr>
<tr>
<td>5</td>
<td>Apply deterministic source de-signature to zero phase, designed using supplied far field signature, including cable ghost</td>
</tr>
<tr>
<td>6</td>
<td>Apply anti-alias filter</td>
</tr>
<tr>
<td>7</td>
<td>Reduce to 4ms sample rate</td>
</tr>
<tr>
<td>8</td>
<td>Apply t2 divergence correction</td>
</tr>
<tr>
<td>9</td>
<td>Interpolate to temporarily fill trace edits</td>
</tr>
<tr>
<td>10</td>
<td>Scale down amplitudes on front 29 traces, -12dB on channel 1 sloping to 0dB on channel 30</td>
</tr>
<tr>
<td>11</td>
<td>Apply FXEDIT swell noise attenuation in shot domain, targeting 0-10Hz with a tolerance ratio of 2.6</td>
</tr>
<tr>
<td>12</td>
<td>Apply FXEDIT swell noise attenuation in shot domain, targeting 0-110Hz with a tolerance ratio of 1.5</td>
</tr>
<tr>
<td>13</td>
<td>Apply FXEDIT swell noise attenuation in receiver domain, targeting 0-10Hz with a tolerance ratio of 1.5</td>
</tr>
<tr>
<td>14</td>
<td>Reverse scaling of front 29 traces.</td>
</tr>
<tr>
<td>15</td>
<td>Pick first round of velocities on a 2km x 2km grid.</td>
</tr>
<tr>
<td>16</td>
<td>Apply AGC wrap with 200ms gate length.</td>
</tr>
<tr>
<td>17</td>
<td>Apply spatial low cut filter targeting wave numbers above 0.75 Nyquist.</td>
</tr>
<tr>
<td>18</td>
<td>Apply spatial low cut filter targeting wave numbers above 0.5 Nyquist.</td>
</tr>
<tr>
<td>19</td>
<td>Remove AGC wrap.</td>
</tr>
<tr>
<td>20</td>
<td>Apply linear move-out (LMO) wrap using a velocity of 2750m/s.</td>
</tr>
<tr>
<td>21</td>
<td>Apply AGC wrap with 200ms gate length.</td>
</tr>
<tr>
<td>22</td>
<td>Apply coherent noise attenuation using XRLIN high resolution linear radon transform. Target 3-120 Hz.</td>
</tr>
<tr>
<td>23</td>
<td>All data characterised by dips in the range -1400 to 600 microseconds per meter of offset.</td>
</tr>
<tr>
<td>24</td>
<td>True signal characterised by dips in the range -800 to 125.</td>
</tr>
<tr>
<td>25</td>
<td>Remove AGC wrap</td>
</tr>
<tr>
<td>26</td>
<td>Reverse 1500ms shift</td>
</tr>
<tr>
<td>27</td>
<td>Revert trace length to 10000ms</td>
</tr>
<tr>
<td>28</td>
<td>Pick second round of velocities on a 1km x 1km grid.</td>
</tr>
<tr>
<td>29</td>
<td>Apply Tau-P domain inner trace mute</td>
</tr>
<tr>
<td>30</td>
<td>Transform data to x-t domain</td>
</tr>
<tr>
<td>31</td>
<td>Reverse 1500ms shift</td>
</tr>
<tr>
<td>32</td>
<td>Auto correlations computed over 1500ms to 6500ms (0ms to 5000ms taking into account 1500ms shift above)</td>
</tr>
<tr>
<td>33</td>
<td>Apply normal move-out (NMO) correction using 1km velocity field.</td>
</tr>
<tr>
<td>34</td>
<td>Apply AGC wrap using 200ms gate length.</td>
</tr>
<tr>
<td>35</td>
<td>Apply XRMULT extra high resolution radon transform multiple attenuation, allowing frequencies between 6 and 90Hz and move outs of -600 to 4000 microseconds per meter. Primaries are defined as having a move-outs of between -600 and 600 at a time of 0ms , -600 and 300 at 5000ms and -600 and 200 by 8000 ms.</td>
</tr>
</tbody>
</table>
Table 4.2  PSTM processing sequence (cont.)

<table>
<thead>
<tr>
<th>Processing Sequence</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>36 Remove AGC wrap</td>
<td></td>
</tr>
<tr>
<td>37 Remove NMO correction</td>
<td></td>
</tr>
<tr>
<td>38 Output to SEGY</td>
<td></td>
</tr>
<tr>
<td>39 Apply outer mute</td>
<td></td>
</tr>
<tr>
<td>40 Apply inner mute</td>
<td></td>
</tr>
<tr>
<td>41 3D DMO</td>
<td></td>
</tr>
<tr>
<td>42 3D stack</td>
<td></td>
</tr>
<tr>
<td>43 Interpolation to 6.25x12.5m grid</td>
<td></td>
</tr>
<tr>
<td>44 Preparation of Migration Velocity Field</td>
<td></td>
</tr>
<tr>
<td>45 Kirchhoff Pre Stack Migration – bin size 6.25x12.5m</td>
<td></td>
</tr>
<tr>
<td>46 Output to SEGY - RAW MIGRATION</td>
<td></td>
</tr>
<tr>
<td>47 Residual Noise Attenuation</td>
<td></td>
</tr>
<tr>
<td>48 Time Variant Filter</td>
<td></td>
</tr>
<tr>
<td>49 Signal Enhancement</td>
<td></td>
</tr>
<tr>
<td>50 AGC (3000ms gate length)</td>
<td></td>
</tr>
<tr>
<td>51 Output to SEGY – FINAL MIGRATION</td>
<td></td>
</tr>
</tbody>
</table>

4.2.2 Pre Stack Depth Migration

The second processing stage was the Pre Stack Depth Migration (PSDM). The PSDM seismic processing was accomplished by ion-GX-Technology Company from August 2010 to December 2011 through the BEAM migration methodology. This methodology consisted of three important steps: decomposition, migration, and reconstruction. As a result of the structural complexities of the area (Figure 4.4), the “Beam” algorithm, was expected to provide a better definition for the Tertiary leads and prospects already visualized on the area. However, the most important aim of this seismic processing is to improve the image at the Mesozoic level, where there are no leads visualized yet.

The petroleum potential in this area is considered high since the 3D seismic survey is located over the continuation of a huge and important trend: the “Akal Horst” (Figure 1.3), with important production fields, such as Yaxche and Xanab to the west, and the oolitic banks fields Xux and Tsimin to the East.
Figure 4.4    Seismic line in two way time from the KUZAM-3D seismic survey (PreSTM) showing the structural complexities in the area.

The complex velocity fields (Figure 4.5) characterized by an extensional system, thrust imbricates and salt tectonics, and other geologic scenarios generate illumination problems especially for deep-seated sub-thrust targets that can be handled by multi-arrival imaging algorithms, such as shot-domain Beam pre-stack depth migration (B-PSDM).

The angle-domain implementation of B-PSDM together with hit-count trace equalization enable a number of amplitude-friendly processes for the image gathers. B-PSDM can also handle complex anisotropy.

With the improvement of the seismic image through the PSDM seismic processing, geological and geophysical interpretation should increase the understanding of the area with the purpose of:

- Defining the 3D structural framework and structural evolution;
- Reducing the risk of the petroleum system elements;
- Allowing the reservoir characterization and improving the hydrocarbon volume calculations;
• Allowing the identification of new exploratory leads in already proved plays of low risk;

• Increasing the value of the project by increasing the hydrocarbon reserves.

Figure 4.5  Arbitrary line between wells Kuz-1 and Yaab-1 showing the complexities of the velocity model created for structural complexities as well as salt tectonics. Horizon in green is the possible top Cretaceous (seismic in TWT). Taken from PEMEX.

4.3 Pre Stack Time Migration Vs Pre Stack Depth Migration

To compare the quality of the images between the different seismic processes (PreSTM Vs PSDM) a visual inspection of the whole seismic data was performed. To be able to compare these images, the process was based on the comparison between the PreSTM (TWT) and the PSDM scaled to time (TWT) versions. The aim of this process was to identify which seismic version has the best seismic image and, therefore, accomplish the seismic interpretation over that seismic version.

Figures 4.6 is an example of the quality control performed over two “In-lines” in time domain (TWT). The upper line (A) belongs to the PreSTM seismic version whereas the lower
line (B) corresponds to the PSDM scaled to time version. Both lines are located in the same position. First, the image at the upper part of the seismic lines can be defined as a good in both versions. However, in the PSDM seismic line, the processing seems to slightly improve the image, making it cleaner and defining the normal fault planes a little bit better.

Second, the structural complexities (thrust imbricates structure) in the middle part of the seismic lines (Figure 4.6) make it hard for Kirchhoff migration algorithm to resolve the image (Figure 4.6-A). Here, the seismic image can be classified as moderate to very poor. PSDM seismic processing in this middle part of the seismic line (Figure 4.6-B), shows an improvement of the seismic image particularly at the right side of the line. Nevertheless, at the left side of the line the image is really poor on both seismic versions.

Finally, the deepest part of the seismic line of the PreSTM seismic version (Figure 4.6-A) could be classified as moderate to poor or very poor in some areas. Fortunately, the PSDM seismic processing displays a moderate to good improvement depending on the area to define the possible top and base of the salt bodies, give better continuity of the reflections of the possible Cretaceous and Jurassic, and define better the possible top and base of the “mother salt”. This improvement is very important since the most important targets are located at the deepest part of the survey (Mesozoic).

Similarly, the same analysis was applied to the whole seismic survey. Figure 4.7 is another example of two X-lines where the quality control was achieved. The seismic image in the upper part of the seismic lines can be defined as a respectable in both versions. Yet, the PSDM seismic version (Figure 4.7-A) appears to be cleaner. Regarding the middle to deepest zone of the seismic line, the PSDM seismic version (Figure 4.7-B) in contrast to the PreSTM seismic version, seems to be enhanced by the seismic processing.
Figure 4.6 Comparison of two In-lines in the same position from different seismic processing. (A) In-line of PreSTM seismic version; (B) In-line of PSDM seismic version scaled to time.

In general, the PSDM seismic version shows an improvement of the seismic image. Based on this comparison, the final decision was to use the PSDM (in depth) seismic version to develop the seismic interpretation. In addition, besides the seismic image improvement, another
advantage of implement the interpretation over the “depth” version is that velocity issues such as “pull-ups” shouldn’t be present over this version allowing seeing the “real” shape of the structures.

Figure 4.7  Comparison of two In-lines in the same position from different seismic processing. (A) In-line on PreSTM seismic version; (B) In-line on PSDM seismic version scaled to time.
Additionally, the PSDM seismic processing does not provide real depths and actually is more focused on the improvement of the seismic image for the structural interpretation. For that reason, after finishing the seismic interpretation of the PSDM seismic version, the seismic interpretation should be re-scaled to the time domain. Then, a velocity model based on the well data (time-to-depth curves) either from the vertical seismic profiles (VPS) or checkshots, combined with seismic processing velocities, such as stack velocities or root-mean-square velocities (Vrms), should be used to create a velocity model for depth conversion, prior to structural restoration.
CHAPTER 5
SEISMIC INTERPRETATION

The strategy for seismic interpretation is based on recognition within the seismic data of a series of key features, both structural and stratigraphic. The structural interpretation follows a simple workflow that includes picking and mapping faults, seismic horizons, salt bodies, etc. The structural seismic interpretation provides insights into the structural history of the area and the tectonic episodes to which it was subjected such as extensional, compressional, strike-slip and salt tectonics systems. The recognition of stratigraphic features such as seismic stratigraphic surfaces (that separate and define depositional packages) and sedimentary deposits/rocks between those surfaces is helpful in the process of choosing the horizons to interpret. Distinctive reflection patterns and terminations (Figure 5.1), such as onlaps, downlaps, toplaps, truncations, concordances (Mitchum et al., 1977), apparent truncations, and faults terminations (Emery and Meyer., 1996), can be used to define stratigraphic bodies.

![Figure 5.1 Relations of strata and boundaries of depositional sequences (modified from Mitchum et al., 1977).]
Figure 5.2 shows some of these important features in the KUZAM-3D seismic survey.

The age of the sequences as well as the seismic-well-tie is also another important aspect of this process. Considering the final structural restoration; important unconformities were chosen for seismic interpretation. The identification of key seismic horizons over the Tertiary section was based on the recognition of these stratigraphic relationships. The reason for selecting the key horizons in this way instead for its age is to try to get a better understanding of the
geologic events occurred during the evolution of the area. Another important part during the seismic interpretation process was the fault interpretation as well as salt interpretation (autochthonous and allochthonous top salt, base salt, welds, feeders, etc.)

5.1 Synthetic Seismograms

One of the first steps during the seismic interpretation process is to establish the relationship between seismic reflections and stratigraphy through synthetic seismograms. According to Barcon et al., (2007), for structural mapping, it may be sufficient to establish an approximate relationship (e.g. reflection “X” is near Base Cretaceous); however, for seismic attributes, reservoir characterization, etc., a more detailed and precise well-seismic-tie is required. For the aim of this project a well-seismic tie is important because: (1) Formations cannot be identified directly from seismic section. (2) Formations identified previously in wells are measured in depth, whereas points in seismic section are measured in time (3) Synthetic seismograms provide reliable time-to depth relationship and help to improve depth conversion. (4) Assign the correct “Formation name and age” to the correct seismic reflection is important to improve the understanding of the evolution of the area and its implications associated with the petroleum system. KUZAM-3D seismic survey has only three wells, Teek-1 (Tertiary well), Kuz-1 (Mesozoic well) and Yaab-1 (Mesozoic well). Figure 5.3 shows an arbitrary seismic line and the location of those three wells over the PSDM seismic version scaled to time. To calculate the synthetic seismograms, it was necessary to accomplish the procedure using the PSDM seismic version scaled to time (PSDM-TWT). The aim of this step of the process was to identify seismic reflections of interest in this version, after that, recognize them on the PSDM seismic version in depth (PSDM-Z), where the seismic interpretation finally was performed.
Figure 5.3  Arbitrary line between wells over the PSDM seismic version scaled to time showing the well tops on the wells.
The first step for calculation of the synthetic seismogram was to implement a quality control of the time-to-depth chart (that comes from the VSP and or Check Shots) to calculate the interval velocities and verify if the interval velocities seems geologically reasonable. The second step was to execute a quality control for the well logs required to calculate the synthetic seismograms (sonic log (DT) and the density log (RHOB)).

One way to make a quality control of the sonic log is to convert the DT values to velocities and verify if the velocities are geologically realistic. Also, the velocity values must be similar to the interval velocities calculated using the time-to depth charts. Nevertheless, the velocity values from the sonic log (DT) and from the VSP or Check Shot do not have to be exactly the same since they come from different methodologies and tools that have different resolutions. For that reason during the synthetic seismogram calculation it is necessary to perform a sonic calibration. In normal conditions, to complete the quality control of the DT log it may be enough to eliminate the spikes. Yet, if anomalous velocity values arise, a detailed analysis will be needed to determine either if the anomalous velocities are real and related with the geology of the area or the anomalous velocities are wrong and may be related to an error during its acquisition or processing (e.g., tool problem, human error, etc.).

With regard to the density log (RHOB) a visual inspection looking for anomalous values of density may be enough. In many cases, when the lithology is unknown, it is hard to see if the density values are correct. However, in most of the circumstances, it may be enough to eliminate spikes from the well log. In addition, for the calculation of the acoustic impedance values (Acoustic Impedance= Density X Velocity), the velocity variations have more “weight” than the densities. In other words, problems in velocities will affect the calculation of the acoustic impedance more than problems in densities.
Figure 5.4 shows some average densities and velocity values that must be considered during the quality control of the sonic log DT as well as the density log RHOB to calculate more reliable synthetic seismograms.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Average Density [g/cm³]</th>
<th>Average Interval Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shale</td>
<td>2.5</td>
<td>2200-3000</td>
</tr>
<tr>
<td>Sand</td>
<td>2.65</td>
<td>3200-4500</td>
</tr>
<tr>
<td>Limestone</td>
<td>2.75</td>
<td>5000-5700</td>
</tr>
<tr>
<td>Dolomite</td>
<td>2.83</td>
<td>5800 (6400 max)</td>
</tr>
<tr>
<td>Anhydrite</td>
<td>2.99</td>
<td>3000-6000</td>
</tr>
<tr>
<td>Salt</td>
<td>2.1</td>
<td>4500-6500</td>
</tr>
</tbody>
</table>

- Average water velocity = 1500 (m/s)
- $DT = \frac{1}{V}$
- $V (\text{m/s}) = \frac{304800}{DT}$

Figure 5.4  Density and velocity values considered to calculate synthetic seismograms.

5.1.1 Teek-1 Synthetic Seismogram

Figure 5.5-A shows a seismic section (PSDM-TWT) and the Tertiary well Teek-1. The seismic character on this section can be divided in two. The upper part from 0 [ms] to around 1400 [ms] shows a combination of continuous reflections mixed with some less continuous intervals that are a little bit chaotic. In contrast, the lower part of the seismic section from approximately 1400 [s] to near 2200 [s] shows more continuous reflections but with a change of frequency content (loss of high frequencies). This kind of situation may be important during the wavelet extraction making the extracted wavelet not appropriate for a specific zone. Despite this change in frequency, the synthetic seismogram for the whole well was calculated in one single
operation. Additionally, there are no structural complexities or salt bodies in this seismic section making the calculation of the synthetic seismogram easier.

Figure 5.5-B shows three tracks, the first one display the interval velocity calculated from the time-to-depth chart (from VSP or Checkshot). The velocities calculated seem to be geologically realistic and show an increasing main trend as depth increases.

No anomalies such as velocity reversal or highest or lowest velocities can be observed in this well. The second track shows the original sonic log DT in black color and the corrected (despike) DT in red color.

Finally, the last track shows the original density log RHOB in black color and the corrected (despike) RHOB in blue color. The corrected logs were used to calculate the acoustic impedance reflectivity series.

The next steps for the generation of the synthetic seismogram was the sonic calibration, calculation of the acoustic impedance reflectivity series, wavelet extraction and finally the convolution of the extracted wavelet with the reflectivity series to get the synthetics seismogram.

Figure 5.6-A shows the extracted wavelet which has a phase of -83°, the power spectrum where is possible to observe that the central frequency is around 25 Hz, and the parameters used during the wavelet extraction procedure.

The synthetic seismogram for the Teek-1 well (Figure 5.6-B) in general shows very good to excellent well to seismic tie for the whole column. However, the aim of this synthetic seismogram was to identify the “Middle Pliocene” seismic reflection in the lowest part of the well. The zoom- in of the synthetic seismogram (Figure 5.6-B) demonstrates that an excellent well-seismic-tie was achieved, making easy identification of the “Middle Pliocene” seismic reflection in this well.
Figure 5.5  A) Seismic section on Teek-1 well location. (B) Interval velocities, sonic logs (DT) and density logs (RHOB) respectively. Seismic in TWT.
Figure 5.6  Teek-1 Synthetic seismogram showing excellent well-seismic-tie. Seismic in TWT.

5.1.2  Kuz-1 Synthetic Seismogram

Figure 5.7-A shows a seismic section (PSDM-TWT) of Kuz-1 well location with the well tops of interest, whereas Figure 5.7-B shows three tracks containing interval velocity, original sonic log (in black) corrected sonic log (in red) as well as original density log (in black) and
corrected density log (in blue). In addition, the upper part of the density log was calculated based on the sonic log.

Figure 5.7 Seismic section on Kuz-1 well location. (B) Interval velocities, sonic logs (DT) and density logs (RHOB) respectively. Seismic in TWT.

To accomplish Kuz-1 synthetics seismogram it was necessary to divide the process in two parts based on seismic character as well as geologic complexities. The first part, from 0[ms] to around 2000 [ms] where is it possible to observe continuous and high amplitudes reflections with low angle dips (Figure 5.7-A). Figure 5.8-A shows the extracted wavelet (10.1° phase), the power spectrum (around 20 Hz as central frequency) and the wavelet extraction parameters.
Figure 5.8  Kuz-1 Part 1 of 2 of the synthetic seismogram. Seismic in TWT.

The upper part of the synthetic seismogram (Figure 5.8-B) shows a good correlation making it possible to identify the “Upper Miocene” seismic reflection. However, this situation changes downward (from around 1700 [msl]) with the change in frequency content (loss of high frequencies) as well as the increase of dip angles, making evident the need to extract a new wavelet for the next zone and the calculation of the second part of the Kuz-1 synthetic seismogram (Figure 5.9).
Figure 5.9  Kuz-1 Part 2 of 2 of the synthetic seismogram. Seismic in TWT.

Figure 5.9-A shows the extracted wavelet (which shows a degraded shape that may be related with the lack of high frequencies as well as the high angle dips), the power spectrum (with a central frequency of approximately 10 Hz), and the wave extraction parameters. The calculated synthetic seismogram shows a regular to may be good correlation until “Top salt”, making possible the identification of the seismic reflections of “Middle Miocene”, “Lower Miocene,” and Top Salt. The subsalt targets well picks (Mesozoic), shows an anomaly since the Jurassic Tithonian overlies the Early Cretaceous (Figure 5.9-B). In addition, this condition is observed just beneath of the salt base where the seismic image is not good. Nevertheless, the synthetic seismogram shows a regular correlation for the Mesozoic.
5.1.3 Yaab-1 Synthetic Seismogram

Figure 5.10-A shows a seismic section (PSDM-TWT) that crosses over the location of well Yaab-1 (showing the well markers of interest for the aim of this project). The seismic character on this section could be divided in three different zones. The first zone, in the upper part of the section (from 0[ms] to around 1800[ms]), consists of packages of continuous reflections with mostly high amplitudes. In contrast, the second zone (from around 1800[ms] to 3300 [ms]), is characterized by a package of weak amplitudes and a visual change of frequency content. The lowest part of this zone (from around 2700 [ms] to 3300[ms]) is characterized by chaotic reflections that overlie a salt body. The last zone, is composed of a salt body (that shows internal reflections) and underlying it, a zone of weak reflections where the Mesozoic well markers can be observed.

Figure 5.10-B in track one shows the interval velocities calculated from the time-to-depth chart (from VSP or Checkshots), original sonic log (DT) in color black and corrected “DT” in color red (track two) and the original density log (RHOB) in black color as well as the corrected “RHOB” log in blue color. The corrected logs were used to calculate the synthetic seismograms for this well. Due to the geological and geophysical complexities on this well, the synthetic seismogram was divided in three parts. The first window from 0[ms] to 2200[ms], the second window from 2200[ms] to around 3300 [ms] (or top salt) and finally the last window the subsalt targets (Mesozoic).

Figure 5.11-A shows the extracted wavelet (25.5° phase), the power spectrum (central frequency around 25 Hz) and the wavelet extraction parameters for the first zone. The synthetic seismogram (Figure 5.11-B) shows a good to excellent correlation allowing the easy identification of the “Upper Miocene seismic reflection”. Furthermore, around 1900 [ms] where
there is a change on amplitudes as well as frequency content, this synthetics seismogram become useless making evident the need to generate a new synthetic seismogram for the next zone.

Figure 5.10  (A) Seismic section on Yaab-1 well location. (B) Interval velocities, sonic logs (DT) and density logs (RHOB) respectively. Seismic in TWT.
Figure 5.12-A shows the extracted wavelet (-17° phase), the spectrum power (central frequency near to 10 Hz), and the wavelet extracted parameters for the second zone. The extraction of a new wavelet with its new characteristic may help to obtain a better and more reliable synthetic seismogram in this zone where the geological complexities are different than in the upper part.

This second part of the synthetic seismogram (Figure 5.12-B) shows a good to medium correlation that make possible the identification of the “Middle Miocene”, “Lower Miocene” and “Top Salt” seismic reflections. However, the subsalt targets (Mesozoic), need a new synthetic seismogram for the last zone.
Figure 5.12   Yaab-1 Part 2 of 3 of the synthetic seismogram. Seismic in TWT.

Figure 5.13-A shows the extracted wavelet (showing some degradation may be related to the loss of signal associated with subsalt targets with phase of -34.7°), the power spectrum (central frequency nearby to 10 Hz), and the wavelet extraction parameters.

The synthetic seismogram (Figure 5.13-B) shows a good to regular correlation making possible to recognize the “Upper Cretaceous” (KS), “Middle Cretaceous” (KM) and the “Jurassic Tithonian” (JST) seismic reflections.
Based on the results of all the synthetic seismograms of the three wells, as well the identification and interpretation of the interest horizons over the PSDM seismic version in depth, an age was assigned to the Tertiary interpreted horizons (which interpretation was based on important stratigraphic relationships) (Figure 5.14).

Concerning to the Mesozoic horizons, the synthetic seismogram from the Yaab-1 well, helped to recognize the “Upper Cretaceous”, “Middle Cretaceous” and the possible “Jurassic Kimmeridgian” (the next positive reflection from Tithonian Jurassic) (Figure 5.14).
Figure 5.14  Arbitrary line between wells Teek-1, Kuz-1, and Yaab-1 showing interpreted horizons over PSDM-Z version and the names assigned based on synthetic seismograms.
5.2 Seismic interpretation

The structural framework of the study area within KUZAM-3D survey can be divided in three main zones according structural style as well salt levels. According to the different salt levels, from the deepest part to the shallower part of the seismic sections:

1) The autochthonous salt level or “Mother Salt” (Figure 5.15-A and B).
2) An allochthonous salt level (Figure 5.15-A).
3) An important regional weld that connects salt bodies of the allochthonous salt levels.

With respect to structural phases, three main phases can be differentiated. From the deepest to the shallower part of the seismic sections (Figure 5.15-A and B):

1) An older compressional stage characterized by compressive structures between the autochthonous “Top Salt” and the regional “salt weld”. Deformation of this structural stage is directly related with the compression of the “Chiapaneco event”
2) A lenticular (and anomalous because is only present in this area) compressional stage level between the regional weld and the regional unconformity characterized by a beautiful set of thrust imbricates that detach at the salt weld level.
3) A younger extensional stage characterized by extensional structures such as normal faults, listric faults, horst, rollover anticlines, antithetic and synthetic fault systems, turtle structures, relay ramps, etc.

In general, the tectonic evolution of the area based on observations of seismic sections (Figure 5.15) roughly corresponds with a phase of compressional deformation followed by a phase of halokinesis, a phase of deposition and subsequent basin fill during Tertiary.
Figure 5.15  Seismic sections showing the three main structural phases (extensional and compressional) as well as the two different salt levels (deep, and upper).
5.2.1 Structural maps

Seafloor was acquired using eco sounding technique by the SR/V Veritas Viking Vessel (Figure 4.1) during the seismic acquisition process. This operation allows the acquisition of a reliable structural map in depth since it is pretty shallow and as a consequence hard to be mapped by seismic. Depths vary from around 17 [m] to 60 [m], increasing in depth very gently in a basinward direction. Figure 5.16 shows the structural map corresponding to the seafloor.

![Structural map of the Seafloor in depth acquired by eco sound technique](image)

The deformation style of the youngest structural stage (Figure 5.15) is predominantly characterized by extensional structures. The system would be associated with gravity sliding or gravity spreading (during Pliocene-Pleistocene). Predominant structural styles include: normal faults systems, listric faults with associated rollover anticlines, growth faults linked to salt diapirs, synthetic-antithetic listric faults, horst blocks, relay ramps, evacuated salt minibasins,
etc. Figure 5.17 shows some examples of the most common structures that can be identified within this structural stage.

![Common structures and stratigraphic features identified within the extensional structural stage.](image)

Additionally, syndepositional sequences deposited during the compressional event responsible for the formation of the thrust imbricates structure can be identified within this structural stage.
Since the only wells within KUZAM-3D seismic survey are located at the southern part of the survey, there is no well control for the seismic correlation toward the north part of the survey. This condition represented a challenge during the seismic interpretation process due to the structural complexity in this stage that includes variable fault displacements over the whole area. A key factor (over most part of the extensional stage) to obtain a more reliable seismic correlation was the identification of relay Ramps (Figure 5.18). Relay ramps allowed the correlation of continuous reflector packages to the northern and deepest part of the survey with more confidence.

Figure 5.18  Seismic correlation of the Upper Pliocene horizon showing the relay ramps that allowed correlating the northern and deeper part of the seismic survey.

Figures 5.19 to 5.22 shows a 3D view of the seismic structural maps corresponding to the horizons of the denominated extensional stage.
Figure 5.19 3D view of structural maps on the extensional stage. (A) “02 Upper Pliocene”. (B) “Horizon 03”.

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Figure 5.20 3D view of structural maps on the extensional stage. (A) “Horizon 04”. (B) “Horizon 05”.

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Figure 5.21 3D view of structural maps on the extensional stage. (A) “06 Middle Pliocene”. (B) “07 Upper Miocene”.

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Figure 5.22  3D view of structural maps on the extensional stage. (A) “Horizon 08”.  
(B)“Horizon 09”.

The Middle Miocene “Regional Unconformity” (Figure 5.23) marks an important change of structural style separating the youngest extensional stage from the older compressional phases. Change in thicknesses related to salt movement and extension can be observed over the whole extensional stage. However, an important change in thicknesses (growth strata) can be identified between “Horizon 09” and the “Regional Unconformity” revealing the possible age (during Upper Miocene) of initial formation of the thrust imbricates structure (Figure 5.24) which is contained between the “Regional Unconformity” and the “Regional weld” (which is used as a detachment). Three horizons were interpreted within this compressional stage where seismic image was good enough to achieve this. Figure 5.25 and Figure 5.26 shows a 3D view of the structural maps corresponding to this structural stage.

![3D view of structural map of the “Middle Miocene” Regional Unconformity.](image)
Figure 5.24  Seismic section showing syndepositional sequences within the extensional phase deposited during the compressional event linked to the creation of the thrust imbricates structure.
Figure 5.25  3D view of structural maps on the younger compressional stage. (A) “Horizon 11”. (B) “12 Lower Miocene”.

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The thrust imbricate structure (Figure 5.24) is an anomalous feature of the area, which is located locally inside a lenticular structure formed between the “regional unconformity” and the “regional weld”. An important characteristic to note is that when those regional horizons get close together, the thrust imbricates structure ends. However, there are areas where those horizons are separated, containing between them, in most cases rotated minibasins. The hypothesis for the formation of this thrust imbricates structure is that it formed due to gravity sliding in an area that may had an important amount of salt (in contrast to the surrounding areas) that modified the detachment strength. It is believed that this structure was not formed due to the Chiapaneco Event specifically due to its orientation as well as its age of possible formation (during Upper Miocene).
Thus, salt tectonics is an active factor for the whole study area since all of these structural phases are influenced by salt tectonics creating and modifying structures. Large volumes of pre-Oxfordian salt were evacuated and emplaced in upper levels of the sedimentary column (from Mesozoic to Tertiary), where the allochthonous salt level is connected by a regional weld that can be recognized over the whole study area (Figure 5.15).

Figure 5.27 shows a 3D view of the structural map corresponding to the “Regional Weld” merged with the “Allochthonous Base Salt”. Figure 5.28-A and B shows a 3D view of the structural maps corresponding to the allochthonous Top Salt and the allochthonous Base Salt respectively.

![14 Regional Weld & Base Allochthonous Salt](image)

Figure 5.27 3D view of structural map of the Regional Weld.
Figure 5.28 3D view of structural maps of: (A) “15 Top Salt (allochthonous)” and (B) “16 Base Salt (allochthonous)”.
The structural configuration of the Mesozoic is the result of both compression and salt movement (halokinesis).

Regionally, the onset of compressive deformation was during the Eocene (Laramide Orogeny), subsequently reactivated in the Middle Miocene (The Chiapaneco Event) forming the present structural style of the area.

The structural style of this zone is characterized mainly by salt evacuated minibasins, followed by folding and reverse faults (Figure 5.29). Most of the greatest oilfields of the area are encountered at this stratigraphic level, making it the most attractive level for petroleum exploration.

Figure 5.30-A and B shows a 3D view of the structural maps corresponding to the Upper Cretaceous and Middle Cretaceous respectively. Figure 5.31 shows a 3D view of the structural map corresponding to the Jurassic Kimmeridgian.

Salt withdrawal and shortening are responsible for the formation of depocenters and localized depressions over the whole area.

Different volumes of salt were mobilized in different zones at different times, influencing the dimensions and position of the depocenters and their sedimentary fill.

Figure 5.32-A and B shows a 3D view of the seismic structural maps corresponding to the autochthonous Top Salt, and the autochthonous Base Salt respectively.

A series of highs associated with salt pillows, salt roller, feeders, pedestals, etc., as well a series of lows associated to minibasins and welds can be recognized on these maps.
Figure 5.29  Seismic section showing the compressional structural style at the Mesozoic level.
Figure 5.30  3D view of structural maps on the older compressional stage. (A) “17 Upper Cretaceous”. (B) “18 Middle Cretaceous”.

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Figure 5.31 3D view of structural map on the older compressional stage of the “19 Jurassic Kimmeridgian”.

5.3 Isochores Maps

Isochore maps records paleo-highs and paleo-lows that reveal considerable information about tectonic history through the mapped time interval (measuring vertical thicknesses). The strategy used here to obtain the isochores is based in the recognition of big scale features (interval 1, interval 2, interval 3 and interval 4) as well to obtain small scale features within zones of interest (interval 1 and interval 3). Figure 5.33 shows the main divisions over the whole stratigraphic column used during isochores calculation. In addition, the isochores maps are not corrected for the effects of compaction.
Figure 5.32  3D view of structural maps of the: “20 Top Salt (autochthonous)”. (B) “21 Base Salt (autochthonous)”. 
5.3.1 **Interval 1 (extensional phase)**

Figure 5.34 shows the isochore between the Seafloor and the Regional Unconformity (large scale features). The isochore reveals dramatic thickness variations from around 1200 [m] to 7200 [m] that starts to reveal part of the tectonic history of the area. In general terms, three main regional regions can be differentiated: (1) Thinner areas around 1200 [m] to 3500 [m], especially at the southern part of the seismic survey may be related to paleohighs (e.g., thrust imbricates structure and/or smallest amounts of salt withdrawal (considering a constant sediment supply) where accommodation was limited. (2) A thicker area nearly to the center part of the seismic survey showing variations from around 3500 [m] to 5000 [m] that may be related with important amounts of salt withdrawal creating important accommodation. (3) The thickest area at the northern part of the survey showing variations from around 5000 [m] to around 7200 [m] may be related to large amounts of salt withdrawal and extension.

Figure 5.35, 5.36 and 5.37 shows the isochores calculated from the horizons interpreted between the Seafloor and the regional Unconformity allowing thickness changes to be observed at smallest scale. The same general regional trend can be recognized on these isochores (Figure 5.35, 5.36 and 5.37-A and B).

The southern part of the seismic survey is characterized by thinner thicknesses, increasing northward to the center of the survey and finally showing the biggest increase of thicknesses in the northern part of the survey. At the center part of the survey, depocenters created by salt movement migrate with time between stratigraphic packages (also this situation can be easy seen on seismic on Figure 5.29 extensional stage).
Figure 5.33  Seismic sections showing zone divisions used to differentiate areas of interest to calculate isochores.
Figure 5.34 Isochore between “01 Seafloor” and “10 Regional Unconformity”.

The southern part of the survey displays the most important changes in thicknesses revealing the area of most important salt withdrawal and extension. In addition, the regional fault system seems, in some way to separate these three main regions. Furthermore, growth strata linked with growth listric faults can be recognized.

In contrast to the regional pattern observed overlying Horizon09 (Figure 5.37-C) important changes of thicknesses forming localized minibasins that overlay the thrust imbricates structure (Figure 5.24) can be documented. The formation of this pattern (growth strata) is interpreted to be related to the formation of the thrust imbricate structure. Sediments deposited between Horizon 09 and the regional Unconformity were deposited while the thrust imbricate structure was active. However, salt withdrawal also continued over this time period influencing indirectly this area at this time.
Figure 5.35  Isochore between: (A) “01 Seafloor” and “02 Upper Pliocene”, (B) “02 Upper Pliocene” and “Horizon 03”, and (C) “Horizon 03” and “Horizon 04”.

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Figure 5.36  Isochore between: (A) “Horizon 04” and “Horizon 05”, (B) “Horizon 05” and “06 Middle Pliocene”, and (C) “06 Middle Pliocene” and “07 Upper Miocene”.
Figure 5.37 Isochore between: (A) “Horizon 07” and “Horizon 08”, (B) “Horizon 08” and “Horizon 09”, and (C) “Horizon 09” and “Regional Unconformity”.

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5.3.2 Interval 2 (thrust imbricates structure, compressional phase)

Another important isochore calculated between the regional Unconformity and the regional Weld is shown on Figure 5.38. Some of the most important characteristics that can be recognized in this map are:

1) The most significant thicknesses at the southern part of the survey that may expose the extension of the thrust imbricate structure (white dashed lines),

2) Areas with almost zero thicknesses that in some cases are related with the presence of allochthonous salt bodies and in some cases related with big minibasins or both (Figure 5.33).

3) The occurrence of important isolated minibasins that in some case are rotated (Figures 5.15 and 5.33).

Figure 5.38 Isochore between “10 Regional Unconformity” and “11 Regional Weld”.

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5.3.3 Interval 3 (compressional phase)

Figure 5.39, shows the isochore between the regional Weld and allochthonous Top Salt. This isochore is really hard to interpret since on one hand, the regional Weld (Figure 5.27) presents an extraordinary irregular shape, whereas in the other hand, the autochthonous Top Salt (Figure 5.32-A) is composed by a series of highs (salt pillows, feeders, pedestals, etc..) and lows (minibasins and welds). However, important changes in thicknesses can be observed within this interval revealing the available accommodation created by salt withdrawal at this time period. In addition an interesting feature can be recognized at the northeast corner of the survey where thickness tends to zero revealing the position of an important Tertiary minibasin which is welded with a huge pedestal (Figure 5.33).

Figure 5.39  Isochore between “11 Regional Weld” and “18 Top Salt (autochthonous)”.

Figure 5.40-A and B shows the isochore between “Upper and Middle Cretaceous” as well as “Middle Cretaceous and Jurassic Kimmeridgian” respectively. In general terms, these
Isochores demonstrate that the movement of the salt started at a very early stage right after its deposition. Changes in thicknesses can be observed, however, the rate of salt withdrawal in contrast with the upper levels should be considerable low. Additionally, knowledge of the thicknesses of these intervals is very important since most petroleum targets of the area may be located at Mesozoic level.

Figure 5.40 Isochore between: (A) “15 Upper Cretaceous” and “16 Middle Cretaceous”, and (B) “16 Middle Cretaceous” and “17 Jurassic Kimmeridgian”.
5.3.4 Interval 4 (Autochthonous Salt)

Finally, Figure 5.41 shows the isochore between autochthonous Top Salt and Base Salt revealing the thickness variations on this interval from around 0 [m] to 2500 [m]. In general terms, autochthonous salt in the area still presents a thickness of around 800 [m] to 500 [m] showing few areas welded. Consequently, the future evolution of the area will be influenced by “salt movement” while it response to factors such as overload, extension or compression.

5.4 Time Conversion and 2D Regional Seismic Interpretation

As a part of an effort to acquire better understanding of the structural evolution of the area, regional seismic interpretation was performed on 4 regional lines chosen from the 13 original transects. Since the regional transects are composed for different seismic surveys (included the original PreSTM KUZAM seismic version) all of them in time domain (TWT), it was necessary to convert the interpretation performed over the PSDM-Z version to time. Time
conversion was performed utilizing the PSDM depth migration velocity model (Figure 1.11). After that, a quality control of the time conversion was performed over the PSDM-TWT version to ensure that the same reflections interpreted in depth are the same reflection obtained after the time conversion. Some difficulties were identified during this process showing the necessity of a velocity model calibration. Nevertheless, those problems were solved on the interest lines and the regional seismic interpretation was performed on the 2D transects. Figure 5.42 shows the workflow followed to get the regional seismic interpretation.

![Workflow followed to take seismic interpretation in depth from the PSDM 3D seismic survey to the PreSTM 2D regional transects in two way time.](image)

Figure 5.42  Workflow followed to take seismic interpretation in depth from the PSDM 3D seismic survey to the PreSTM 2D regional transects in two way time.

Figure 5.43, 5.45 and 5.47 shows respectively for Line 5, Line 7A and B and Line-11: (A) original seismic interpretation performed over the PSDM-Z seismic vision at the same position of the regional transect and (B) original seismic interpretation converted to time and corrected over the PSDM-TWT that fit at the same reflection events than in the depth version. Figures 5.44, 5.46 and 5.48 shows (A) time converted and corrected interpretation over the PreSTM regional transect, and (B) extended interpretation over the whole regional transects respectively for transects Line 5, Line 7A and B and Line-11.
Figure 5.43 Depth to time conversion of the seismic interpretation (Line-5).
Figure 5.44  Extended regional interpretation over transect 5.
Figure 5.45  Depth to time conversion of the seismic interpretation (Lines-7A and 7B).
Figure 5.46 Extended regional interpretation over transects 7A and 7B.
Figure 5.47  Depth to time conversion of the seismic interpretation (Line-11).
Figure 5.48  Extended regional interpretation over transect 11.
A 3D view from different angles of the final interpretation is shown on Figure 5.49 to observe the regional structural framework and its complexities which is an important issue for time to depth conversion as well as restoration process.

![3D view from different angles of the final interpretation](image)

Figure 5.49  3D view of final regional interpretation in TWT (not scale).

5.5 Time to Depth Conversion

Conversion of seismic data from time to depth involves appropriate velocity functions to generate a velocity model. The velocity model used here for depth conversion of the 2D regional lines is based on both, well data velocities and seismic processing velocities.

5.5.1 Velocity Model

The velocity model relies on the calculation of interval velocities derived from the staking velocities (Figure 1.13) through Dix equation as well as interval velocities from VSP and or check shots. Interval velocities calculated from staking velocities are only reliable for shallow areas; for that reason, they were used only on the Tertiary sequence (Figure 5.50-A). Interval
velocities derived from available wells over the 2D lines (Bol-1, Xul-1, Teek-1, Xan-1 and Kuch-1) were included on the model allowing to calculate velocities for the Mesozoic sequence as well as to calibrate the model (Figure 5.50-B).

Figure 5.50 Interval velocity data set used to generate an interval velocity volume for depth conversion. (A) 3D view of the interval velocities calculated from stacking velocities. (B) 3D representation of the interval velocities from the wells logs.

To build a reliable velocity model, it is necessary to create a 3D grid that honors the structural complexities of the area and represents as close as possible the real structural geology. Several challenges such as salt bodies as well as huge listric faults, etc., arise during the 3D velocity modeling process. Figure 5.51 shows the final 3D grid that represents the actual
Structural complexities of the area and includes the autochthonous and allochthonous salt bodies (purple color).

Figure 5.51 View of the 3D grid surrounding the 2D transacts built to create the velocity model.

Population of the 3D grid with the interval velocities is another important step. Choosing the best mathematical algorithm to interpolate velocities is key and depend on the velocity data available and the knowledge of the area. Sedimentary models will be very usefully as an interpolation trends when they are available. The Kriging interpolation method was chosen to populate the 3D model in a smoothly way. Figure 5.52 shows a 3D view of the final interval 3D velocity volume, (A) whole 3D grid and (B) only overlapping seismic lines.
The resultant interval velocity volume, honors the structural complexities of the area such as normal faults, listric faults, salt bodies, velocity contras between Tertiary siliciclastics and Mesozoic carbonates, etc. Figure 5.53, shows detailed 3D view of each 2D seismic line with the interval velocities on 50% opacity of the lines 05, 07, and 11 respectively.

Depth conversion using PETREL software is based on average velocity volumes. Therefore, before running a depth conversion calculation, it was necessary to calculate the average velocity volume derived from the interval velocity volume. Figure 5.54 show the workflow followed to calculate the average velocity volume from the interval velocity. The final interval velocity volume was used as an input data for the generation of the velocity model and depth conversion.
Figure 5.53  
3D view of 2D regional transects 05, 07 and 11 displaying interval velocities (no scale and seismic in TWT).
5.5.2 Depth Conversion

Depth conversion is the final process of seismic interpretation that allows seeing the data in the space domain. In addition if velocities are accurate enough, depth images allow us to see the real geometry of the subsurface since velocity artifacts (such as pull ups, etc.) were removed by the time to depth process. Figure 5.55, 5.56 and 5.57 shows the regional seismic transects, horizons and faults converted to depth of the lines 05, 07 and 11 respectively.
Figure 5.55  Regional seismic transects-05 horizons and faults in depth.

Figure 5.56  Regional seismic transects-07 horizons and faults in depth.
Figure 5.57  Regional seismic transects-11 horizons and faults in depth
CHAPTER 6

RESTORATION

Cross-section restoration and balancing has its roots in an old methodology used to calculate the depth of detachment during shortening (Chamberlain, 1910; Bucher, 1933; Gougel, 1962).

Cross-section restoration starts with the present deformed state of the stratigraphic boundaries and transforms them into an earlier or less deformed state. Much of the concern in cross-section restoration, especially for hydrocarbon exploration, originates from geometric constraints such as a paleostructure and its evolution through the time relative to hydrocarbon generation and migration.

Any restoration technique is based on some assumptions associated with the undeformed configuration (boundary conditions). Assumptions such as the original horizontality of the upper layer or linear or nonlinear transformation model cannot be geologically precise. Additionally, restoration results are very sensitive to an initial incorrect interpretation of the cross-section.

Working in two dimensions is also problematic since fault displacements as well as salt withdrawal rarely occur in the same plane as the cross-section. If these violations are important, the final restoration will not be reliable even if the original cross-section looks reasonable (Figure 6.1).

For the aim of this project, one cross-section was selected for restoration, following as closely as possible the methodologies described by Rowan (1993). This technique calculates and removes the effects of decompaction, isostasy, faulting, folding and salt movement. Nevertheless, errors such as velocities used during the PSDM seismic process, seismic
interpretation, depth-to-time and time-to-depth conversion (in this particular case), calculation of isostatic subsidence, decompactation and, the incorrect application of a restoration algorithm, etc., may arise.

Figure 6.1 A cross-sections from interpreted seismic line in the North Sea. Note that the intersecting faults can be restored, but the gap in the lowest layer suggests that the interpretation may be erroneous, or that the movement of material out of the plane has occurred. (Wickham, et al; 1997).
The presence of salt over “Kuzam” area brings about special problems due to the nature of salt’s mobility and poorly constrained deformation kinematics. One of the most important assumptions during section restoration is that the cross-sectional area of each sequence is maintained during deformation (Rowan, 1993). However, this is not valid for salt because of its complex three-dimensional flow.

The key to determining the changes in salt thickness and area through time is to calculate independently the evolution of the sub-salt and supra-salt sequences; the resulting space between the restored base- and top-salt at any stage defines the salt geometry at that time (Rowan, 1993). The final restored cross-section from an exploration and production point of view will provide insights into:

1) Timing of structural trap formation and geometry evolution through time.
2) Salt evolution and its relationship to sequence stratigraphy and trap formation.
3) A framework for evaluating hydrocarbon migration pathways and timing.

Figure 6.2 exemplifies the uncertainty in determining how salt moves through the time. Depending on whether allochthonous or autochthonous salt provided accommodation for the shallow minibasins (in this case), diverse restored scenarios are geologically possible.

The 3D nature of salt movement and considerations regarding to its movement during the restoration process will result in one of the possible solutions, but, different considerations will give a different solution. More importantly, each solution will have its own implications regarding the petroleum system. These considerations can be the difference on whether to drill a successful or a dry well.
Figure 6.2 Restorations illustrating ambiguity in determining whether allochthonous or autochthonous salt provided accommodation for the shallow minibasin (modified from Rowan and Inman, in press): (A) PrSDM seismic profile in deepwater of northern Gulf of Mexico, courtesy of WesternGeco, copyright 2011; (B) sequential restoration assuming evacuation only of the shallow salt; (C) sequential restoration assuming evacuation only of the deep salt; and (D) sequential restoration showing an arbitrary mixture of both shallow and deep evacuation. Salt in blue outline (A) or in black (B, C, or D), welds indicated by pairs of dots, no vertical exaggeration. Restorations carried out in LithoTect_ using vertical-simple shear and method of Rowan (1993). Taken from Rowan and Ratliff, (2012).
6.1 Restoration Methodology

It is widely agreed that cross-section restoration is a potentially powerful tool for structural analysis. In this study, a seismic profile (seismic line-11) and its interpretation after depth conversion (Figure 5.47) was chosen for sequential restoration.

Before starting the restoration process, a review of the interpretation was accomplished with the aim to correct, as well as to simplify the section (from very complex structures and faults with small displacement to focus the larger scale structures).

Figure 6.3-A shows the seismic line in depth and Figure 6.3-B shows the seismic line with the final and simplified interpretation. Also, the line was cropped, cutting the very left part of the section due to the uncertainties in interpretation associated with poor seismic imaging and ambiguous data in that area. However, the area of KUZAM-3D seismic survey is completed covered by the line.

The objective of restoration process is to unfold and unfault actual geologic data starting with the present state of deformation. The total deformation of a sequence can be described as the sum of deformation due to folding, faulting and compaction; therefore, all effects should be considered if we want to restore profiles rigorously (Novoa et al, 2000).

The methodology used for restoration in this study combines structural and backstripping techniques and consists of 3 major steps:

The first step consists of restoring faults and folds (using proper algorithm available in 2D Move). Conceptually, a correct restoration moves points from their present position (X,Y) to the position that they occupied before folding and/or faulting (X0,Y0) (Novoa et al, 2000).
Figure 6.3  (A) Depth seismic line-11 loaded in 2D move. (B) Seismic Line-11 with final and simplified interpretation ready to be restored.
Even though natural deformation is substantially more complex than any algorithm available, the choice of a “correct” algorithm is “key” factor during restoration since different algorithms frequently produce noticeably different restored geometries. In this study, to unfault a section, “Fault Parallel Flow” and “Inclined Shear” algorithms were chosen depending on fault geometry as well as bed thickness variation.

The Inclined Shear algorithm, geometrically models the relationship between fault geometry and hangingwall deformation features. This algorithm is more applicable to extensional tectonics regimes, where anticlinal rollovers develop over a non-planar normal faults and on the presence of growth faults, where thickness of beds may vary (2D Move Tutorial). Figure 6.4 explains how the Inclined Shear algorithm works. The angles used in this work to apply the Inclined Shear algorithm (Figure 6.6-A), varies from 60°-85° depending of the results obtained (try and error process).

![How the Inclined Shear algorithm works?](image)

**Figure 6.4** Graphic representation of how does “Inclined Shear” algorithm works? Taken from 2D Move Tutorial.
The Fault Parallel algorithm, is used to model hangingwall deformation, resulting from movement along fault plane. Fault parallel flow allows hangingwall surfaces to be moved across faults in such a way that the hangingwall vertices move parallel to the fault segment over which they are flowing (2D Move Tutorial).

Fault Parallel Flow algorithm was used to unfault planar normal Faults (Figure 6.6-A). In addition, to unfold, in this study the “Flexural Unfolding” algorithm was utilized since it can be applied to thrust folds or folding within supra-salt stratigraphy while it maintains cross-section area and line length.

The second step is decompaction. Decompaction is a technique used to remove the progressive effect of rock volume change (loss of porosity) with increasing the depth of burial through geological time (Allen & Allen, 1990).

Decompaction can be achieved applying the methodology proposed by Sclater and Cristie (1980). This approach is based on the following equation:

\[
 f(z) = f_0 e^{-cz}
 \]

Where:

\( (z) \): is the present-day porosity of a lithology at depth “z”

\( f_0 \): is the porosity of that lithology at surface

\( c \): is the depth coefficient related to a specific lithology.
Using an exponential decay of porosity with depth model, the remaining layers, after the uppermost layer has been removed, can be decompacted by moving each layer up the appropriate porosity depth curve. Different curves are used for different lithologies. This enables the new thickness of the layer and hence depth to base of each layer to be calculated (Williams et. al, 1996). Due to the lack of a petrophysical database, decompaction was performed in this study utilizing the default values in 2D Move for the gross rock composition (sands, shales, salt, etc.) of each layer).

Figure 6.5-A represents the initial present state of deformation and shows the respective algorithms used to restore each fault. Figure 6.5-B shows an example of decompaction process applied to the Recent Pleistocene sequence. Notice the thickness of the Upper Pliocene (in red color) before decompaction (Figure 6.5-A) and after decompaction (Figure 6.5-B).

The last step is the isostatic adjustment. The entire crust needs to be adjusted isostatically in response to subsidence as a result to sedimentary loading that may also include either uplift or subsidence due to faulting and or salt movement (Rowan, 1993). On the one hand, “Airy Isostatic” modeling is very sensitive to massive thickness variations (such as variations shown in line-11), whereas on the other hand, “Flexural Isostatic” modeling is mostly applied under constant thickness conditions that cover hundreds of kilometers. Table #3 shows the values of the isostatic adjustment applied.

Table 6.1 Isostatic adjustment applied per sequence

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Isostatic adjustment [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Miocene to Middle Miocene</td>
<td>501</td>
</tr>
<tr>
<td>Oligocene</td>
<td>196</td>
</tr>
<tr>
<td>Eocene to Paleocene</td>
<td>214</td>
</tr>
<tr>
<td>Upper Cretaceous</td>
<td>311</td>
</tr>
<tr>
<td>Tithonian to Middle Cretaceous</td>
<td>155</td>
</tr>
<tr>
<td>Kimmeridgian</td>
<td>172</td>
</tr>
<tr>
<td>Autochthonous Salt</td>
<td>525</td>
</tr>
</tbody>
</table>
Figure 6.5  (A) Initial Present deformation structure and algorithm chosen to unfault. (B) Upper Pliocene decompacted.
6.2 Restoration Considerations

A truly sequential restoration consist of many such stages, starting with the present state of deformation geometry in depth (Figure 6.5-A): the top layer is the layer stripped off and the result of the effects listed above are calculated and removed, resulting in the restored geometry at the time of the base of the removed layer (Rowan, 1993). This sequential methodology described above has been used to restore the interpreted profile (Line-11).

This profile can be divided in three main zones according structural style (Figure 6.5-B). From the deepest to the shallowest part of the profile: (1) The older compressional stage between the “Top Autochthonous Salt” and the “Regional Weld” (Top Oligocene?) characterized by folds and a reverse fault. (2) A middle level between the “Regional Weld” and the “Regional Unconformity” (Middle Miocene) characterized on one hand to the southeast by the “thrust imbricates structure” which on this line is intersected almost perpendicular, whereas on the other hand, is characterized for minibasins to the northeast. (3) The younger extensional stage characterized by normal faults with the most important fault being a huge listric fault with its associated rollover structure and growth strata. In addition, two salt levels are present in this profile: (1) The autochthonous salt level and (2) The allochthonous salt level with a regional salt weld that connects the different salt bodies.

An important consideration that is fundamental to any section restoration in two dimensions is: “the cross-section must be drawn perpendicular to an axis of no finite strain” (Williams., et al., 1996). However, in some cases this can be difficult due to a number of different reasons. In this particular case, the extensional stage is the only phase that closely fulfills this “rule”. As a consequence, any calculation of shortening on this section will not be accurate. However, a reliable approximation of the extension can be measured.
Even though the restoration process was carried out going back in time, an easier way to present, understand and discuss the results, is by describing the forward evolution of the area. For that reason, the restoration process is presented in this way in this study. In addition, the section was restored in approximately 170 steps. Yet, here only the last restored geometries of the most important steps are presented.

6.3 Cross-Section Restoration

It’s widely agreed for most workers (Humphris, 1979; Salvador, 1987, Pindell 1985, etc.,) that the evaporites of the Gulf of Mexico were deposited during the Callovian (164.7-161.2 Ma) and this was the most important event during the rifting. According to Pindell, et. al. (2007), it is estimated that the original thickness of the evaporites in the Gulf of Mexico vary from 5.5 km (at central part of the basin) to perhaps 7.5 km. Figure 6.6 shows “one” possible scenarios for restoration of “Top Autochthonous Salt” where thickness of the original salt deposition on this area vary from approximately 1.2 km to around 4km, depending on the geometry of the basement which may have been defined by horst and graben blocks.

Figure 6.6 Restored Geometry at the time of Callovian Salt deposition (164.7-161.2 Ma).

According to Padilla y Sanchez (2007), salt deposition conclude by about Early Jurassic (Oxfordian). Following the Jurassic Oxfordian (161.2 Ma), during the Kimmeridgian (150 Ma), wide platforms were developed on the Gulf’s border (oolitic banks extended for kilometers around the Gulf of Mexico).
Figure 6.7, shows the restoration of “Top Kimmeridgian”, where it is possible to observe important changes of thickness on this sequence that demonstrate that salt started to move since a very early stage. Thickness of both Oxfordian and Kimmeridgian sequences together varies from around 800m to 2.6 km on this area. An important feature that can be observed on this section is a passive diapir growing near to seafloor triggered by differential loading.

![Image](image.png)

Figure 6.7  Restored Geometry at the time of Top Jurassic Kimmeridgian deposition (150 Ma).

By early Cretaceous, the Yucatan Block reached its present-day position. Tectonic stability continued in the region and wide carbonate platforms continued to develop. During Middle Cretaceous, periods of erosion and non-deposition occurred (Padilla y Sanches, 2007).

Figure 6.8 shows the restored “Top Middle Cretaceous” (100 Ma) where the salt withdrawal continues, but may be at a slower rate in contrast to the Jurassic. The evidence for this is that although the Middle Cretaceous shows thickness variations (from around 400m to approximately 900m in this area); they are not as significant as the Jurassic variations.

![Image](image.png)

Figure 6.8  Restored Geometry at the time of Top Middle Cretaceous deposition (100 Ma).
The Upper Cretaceous was deposited during the afore mentioned tectonic stability regime as part of extensive carbonate platform (66.5 Ma). Figure 6.9 shows the restored “Top Cretaceous”, where salt movement persisted at this time evidenced by the thickness variations (from around 200m to 400m) in this sequence. In addition, the development of the passive diapir continues as a function of the interplay between salt-rise-rate and sedimentation (Figures 6.7, 6.8 and 6.9). Salt rises as sediments are deposited around the diapir (downbuilding process). The shape of the passive diapir is governed by the relative rates of diapir rise and sedimentation. If sedimentation is slower than salt rise, the diapir will widen upward and salt will extrude over the sediments, conversely, if sedimentation is faster than salt rise, the diapir will narrow upward. In this case, it seems to remain a kind of equilibrium between salt rise and sedimentation ratio since the diapir appears to grow almost vertically (at least at this scale).

![Image of restored geometry](Image)

**Figure 6.9** Restored Geometry at the time of Top Upper Cretaceous deposition (66.5 Ma).

At the end of the Cretaceous, the impact of Chicxulub meteorite, intensely influenced the sedimentary pattern processes occurred 65 Ma in the region. Additionally, as a consequence of the “Laramide Orogeny” during the Eocene a massive introduction of clastic sedimentation took place from the west. Regionally, salt movement started to produce rollers, diapirs, tongues and canopies. Figure 6.10 shows the possible “Eocene and/or Paleocene” sequence restored. Important changes of thicknesses related with salt withdrawal can be observed varying from around 400m to 1600m on this area. In addition, the relative rate of sedimentation and salt rise
had been changed. As a consequence salt started to extrude over the Paleocene-Eocene sediments toward the southeast.

![Figure 6.10](image1.png) **Figure 6.10** Restored Geometry at the time of Eocene-Paleocene deposition.

During the Oligocene (25 Ma), huge volumes of salt started to move in Comalcalco-Salina del Ismo area (Figure 1.2). Figure 6.11, shows the restoration of the possible “Top Oligocene”. In this section it is possible to observe thickness variations from around 400m to 1800m associated with salt withdrawal. Furthermore, the diapir continued its extrusion over the Oligocene sediments.

![Figure 6.11](image2.png) **Figure 6.11** Restored Geometry at the time of possible Top Oligocene deposition (25 Ma).

According to this restoration, the extrusion of the salt over the Oligocene sediments produced a large salt canopy (Figure 6.12). Moreover, the base salt was ultimately folded during this time. In addition, a thin siliciclastic roof (maybe a couple of hundreds of meters thick) prevented this salt from dissolution. However, this roof may be beyond the resolution of this restoration, reason for which is not shown in Figure 6.12.
Regionally, clastic sedimentation prevailed until Early Miocene. Figure 6.13 shows the restoration of “Top Lower Miocene” (16.4 Ma), the transition from the previous Cretaceous-Paleocene-Oligocene to the development of Middle Miocene secondary minibasin is intimately related to the collapse of the salt canopy. Once more, the interplay between salt rise and sedimentation ratio as well as differential loading plays an important role at this time. Furthermore, the evolution of the autochthonous salt is also important since this is the source of all the salt that can move laterally and to upper levels. Notice that at the southeast of the pedestal (Figure 6.13), there is a small amount of salt left available; consequently, an autochthonous weld may be formed and no more salt would be able to move from this area.

Regionally, during the Middle Miocene, an increase in deformation occurred: The “Chiapaneco Event” (responsible for the deformation of the Chiapas-Reforma- Akal belt, Figure 2.21), salt withdrawal caused the formation of new minibasins and salt depocenters (active stage or rejuvenation stage due compression). Figure 6.14 shows the restoration geometry at the time...
of the “Top Middle Miocene” (11.7 Ma). Notice the evolution of both autochthonous salt and allochthonous salt.

During the Upper Miocene the development of a Thrust Imbricate structure occurred (Figure 6.15). The formation of this structure is an anomalous feature of the area, located locally inside a lenticular structure formed between the “regional unconformity” and the “regional weld”.

As mentioned previously, the formation of this structure could be related to gravity sliding (roughly from southwest to northeast) using the allochthonous salt as a decollement. Figure 6.15 shows the restoration geometry sometime during the “Upper Miocene”. The deformation strain of this structure is almost perpendicular to the section; therefore, there is “out of the plane” movement and as a consequence balancing problems. Nevertheless, a simplified restoration was carried out for this structure (Figure 6.14).

In addition, the amount of shortening shown in that section is apparent. Notice the evolution of the allochthonous salt beneath the thrust imbricate structure (Figure 6.15). Salt movement may be mostly “out of the plane” leaving almost no salt left and development of a weld. Likewise, at the southeast side of the pedestal, the formation of an autochthonous weld took place at this time. One of the most important implications of the formation of this primary weld is that no more salt can feed the canopy at least from the southeast side.
In addition, on the southeast side of the section, the autochthonous salt is getting thinner and thinner with time.

Figure 6.15  Restored Geometry somewhere during Upper Miocene deposition.

Regionally, at the end of the Miocene, beginning of the Pliocene, a high contribution of sediments from the Chiapas Massif (Figure 1.2 and Figure 2.21) caused the deposition of several kilometers of overburden. The excessive overloading triggered the development of large listric faults within the Macuspana and Comalcalco-Salina del Ismo Basin (Figure 1.2 and Figure 1.4). Thinner layers of sediments were deposited over the Akal Horst (Figure 1.2 and Figure 1.4).

Figures 6.15 through Figure 6.23 shows the restoration steps from “Top Upper Miocene” to the present deformation stage “Recent Pleistocene”. As the huge amount of sediments reach the basin, salt reacts to the loading creating accommodation (extensional conditions). Notice the evolution of both, autochthonous salt as well as allochthonous salt and the migration through the time of the secondary minibasin.

Figure 6.16 shows the restoration geometry at some point during the “Upper Miocene”.

Figure 6.16  Restored Geometry still somewhere during Upper Miocene deposition.
Since the allochthonous salt is welded beneath the thrust imbricate structure, the same sedimentation pattern continues at this time, the salt canopy only can evacuate “outside the plane” allowing the secondary minibasins to “sink” quickly. During this time period, the sedimentation rate is high relative to salt-rise only in the extensional rollovers because that is where accommodation is created. The salt canopy is finally buried (Figure 6.16) since there is not enough salt feeding it.

Figure 6.17 is the restored geometry at the time of “Upper Pliocene” deposition (5.73 Ma), important variations of thickness can be observed here from close to 100m (on landward direction near Akal Horst) to around 1600 m (basinward direction). In addition, a pattern can be recognized since thickness tends to increase toward the basin. Additionally, as a consequence of salt withdrawal in response of differential loading, an extensional regime developed allowing the formation of normal faults (Figures 6.16 and 6.17). Notice the formation of a normal fault at the pinnacle of the canopy (Figure 6.16).

Figure 6.17    Restored Geometry at the time of Top Upper Miocene deposition (5.73 Ma).

Figure 6.18 is the restored geometry at the time of “Middle Pliocene” deposition (2.55 Ma). The same sedimentation pattern continues at this time.

Notice that there is a small amount of allochthonous salt left below the secondary minibasin. For that reason, huge volumes of salt from the northwest side of the canopy move (mainly out of the plane) in response to the differential loading creating accommodation for
sediments and allowing the progress of the mentioned normal fault and growth strata near to the summit of the salt canopy (Figures 6.18). Besides, the amount of autochthonous salt to the southeast side of the section is decreasing with the time. Thickness of the Middle Pliocene sequence varies from around 100m to close to 2600m.

![Figure 6.18 Restored Geometry at the time of Top Middle Pliocene deposition (2.55 Ma).](image)

During the “Upper Pliocene” Figure 6.19 the development of a listric fault and a rollover structure with its associated growth strata continued. The secondary minibasins is close to reaching its final position since almost all the salt beneath it has evacuated. The thickness variation on this sequence fluctuates from approximately 70m to around 2400m.

![Figure 6.19 Restored Geometry somewhere during the Upper Pliocene deposition.](image)

“During Upper Pliocene” (Figure 6.20), a weld was finally developed underneath the secondary minibasin. The secondary minibasins is now separated by two different salt bodies. The thickness of this sequence fluctuates from around 50m to nearly 2200m.
Later, still during the “Upper Pliocene” (Figure 6.21), the same sedimentation pattern prevailed. The listric fault continued its development while salt evacuated.

The canopy beneath the growth strata is getting thinner. In addition, at the very southeast part of the section, just beneath the thrust imbricates structure, the area is completely welded. The thickness of this “inside” Upper Pliocene sequence oscillates from about 40m to nearly 4000m.

Figure 6.22 is the restored geometry of the “Top Upper Pliocene” (1.56 Ma). The northwest side of the autochthonous salt is finally welded. There is not much salt left to move (outside the plane) on the pedestal.

Thicknesses of this sequence vary from around 100m to near 6600m. This high sedimentation rate is due to the high contribution of sediments coming from the Chiapas Massif (Figure 1.2). However, extension (in first place), salt withdrawal as well as paleo-highs and
paleo-lows controlled the accommodation. As a result, important variations of thickness can be documented on the area.

![Figure 6.22](image)

**Figure 6.22** Restored Geometry at the time of Top Upper Pliocene deposition (1.56 Ma).

Finally, Figure 6.23 shows the present state of deformation geometry “Recent Pleistocene” (described above).

As mention before, due to the line orientation, the total amount of compression cannot be a trusted measurement. However, a reliable approximation of the total amount of extension can be measured. According to this restoration, the total amount of extension is roughly 20.75km which represents 36.48% of the length of the cross section (56.875km).

![Figure 6.23](image)

**Figure 6.23** Restored Geometry at the time of Top Recent Pleistocene deposition.

The complete restoration steps are shown in Figure 6.24, from the Callovian salt deposition to the present structural distribution.
Figure 6.24  Complete restoration steps, from the Callovian salt deposition to the present structural distribution
CHAPTER 7
DISCUSSION AND CONCLUSIONS

7.1 Discussion

The research presented in this thesis covers a wide workflow that incorporates seismic data acquisition, seismic processing (PreSTM to PSDM seismic migration data), 3D seismic interpretation in depth, depth-to-time conversion, 2D regional seismic interpretation in two-way-time, time-to-depth conversion and finally sequential restoration. All of the above were examined with the aim of understanding the structural evolution of a very complex area affected by different tectonic events as well as salt tectonics. Important implications for the petroleum system can be determined with this work for KUZAM area.

The system has a complex three dimensional geometry (Figure 5.15), which is directly associated with the complex evolution of the Gulf of Mexico (orogenic shortening, salt tectonics and passive-margin failure). This geometric complexity and especially the presence the allochthonous salt level make it hard to obtain a good image of the subsurface by conventional seismic processing (Figure 5.15) (e.g., Pre-Stack Time Migration). Consequently, Pre-Stack Depth Migration processing was performed to improve the image especially for deeper targets and of course beneath the salt bodies. Besides the PSDM seismic processing by itself (that depend of the final velocity model as well as the migration algorithm), errors during picking “key horizons” as well as interpreting “top salt” and “base salt” have important consequences for the final image obtained and, therefore, for this project.

Seismic interpretation over KUZAM-3D survey is also a “key” factor for this project. The first important challenge (in the upper extensional stage) was to extrapolate the seismic
interpretation from the southern part of the survey to the north. Relay ramps played an important role during this phase of the project allowing correlating continuous reflectors to the north with more confidence. However, there are some areas where there are no neither relay ramps nor well data to make a reliable seismic-tie. Despite these difficulties, correlation in these complex areas, between different blocks is based on geological knowledge, but, they represent “the best guess” since there is no other reasonable option. The accuracy of these “best guesses” was tested during the restoration process by try and error. The second challenge was the interpretation of the two compressional deeper levels, the thrust imbricates structure and the Mesozoic level as well as Top and Base of the autochthonous salt. Seismic interpretation at these levels was difficult to perform due to the quality of the seismic image at those levels, even though the seismic was already processed to improve the image (Figures 4.6 and 4.7).

Depth-to-time conversion using the PSDM velocity model demonstrated the necessity of a velocity calibration. Errors during this phase of the process came about. In this case in particular, it was quite easy to solve those problems for specific 2D lines manually. However, to convert appropriately the whole 3D seismic survey, special calculations will be needed.

The 2D regional interpretation of this project is challenging not only because the complexity of the area but also because the quality of the seismic image. Moreover, salt bodies and reflections out of the plane as well as uncertainties between well data and seismic image make this difficult. Errors in this regional interpretation may be the most important for the aim of this project since this interpretation represents the present structural geometry of the region and it is the input data for the restoration process.

Time-to-depth conversion has important implications. The use of the wrong velocity field can create false structures or destroy real structures as well as locating seismic reflections at the
wrong depths. The availability of velocity data is imperative during this phase. In this case, stacking velocities covered almost the entire area (Figure 1.13). An important consideration is that these stacking velocities are only reliable for shallower levels (the complete Tertiary). Well velocity data from five wells were added to the velocity model allowing calibrating successfully the Tertiary column. However, the calculation of the velocity model in the Mesozoic is based only on these five wells over the whole area (Figure 5.44). This situation represents a limitation for the velocity model since the area is too big to be modeled with this small amount of data. Additionally, the interpretation of salt bodies is “key” factor for the velocity modeling process. Furthermore, since salt bodies are around two times faster than the surrounding siliciclastic sediments (in the Tertiary column), to add or eliminate salt velocity bodies will have important significances for the final depth image. Thus, velocity modeling and time-to-depth conversion is a serious issue in this work, and during the exploration process making the difference on either to find a hydrocarbon trap or not or calculate a wrong volume of hydrocarbons.

In regard to the restoration process, a methodology for restoration of salt structures described by Rowan, 1993 (Figure 6.2) was followed as closely as possible. The technique systematically calculates and removes the effects of sedimentation, compaction, isostatic adjustments, thermal subsidence (if present), faulting, folding, and salt withdrawal/diapirism.

Due to the complexity of the line choose for restoration (Figure 6.5-A) important concerns must be considered:

First, the conservation of the area in two-dimensional section is usually treated by preserving the length of layers (and/or) the area between these interfaces before and after deformation (Hossak, 1979; Mugnier and Vialon, 1986). However, plane strain conditions cannot be present on the restored cross-section since there is significant lateral movement of
sediments (i.e., extensional or compressional faulting). In fact, the only phase that may closely fulfill this condition is the upper extensional stage. For that reason, rock volume, or area may need to be added or removed from the section during the restoration process. On the other hand, due to the complex and three-dimensional salt’s mobility in response to sediment loading and deformation, lateral movement of salt is not a problem because the restoration method does not require that salt area be maintained (Rowan, 1993). However, determining the changes in salt thickness and area through the time of both autochthonous and allochthonous salt separately is a key factor during the restoration process.

Second, several errors may arise from a number of different sources such as seismic acquisition and processing, PSDM seismic processing (in this case), velocities used during depth-to-time as well as time-to-depth conversion, the seismic interpretation by itself, inaccurate decompaction process, invalid isostatic correction, restoration to an incorrect seafloor-template (in this case lack of paleoseafloor data), and finally improper application of the different restoration algorithms (that affect restored and bedding geometries). However and more importantly, besides this list of possible errors, experience has shown that these errors are relatively minor (Rowan, 1993). Furthermore, section restoration is a useful and powerful tool for structural analysis that academic geologists and some geophysicists use to validate cross-sections and determinate the original position and dip of structures, the amount of rate of deformation, the timing of basin formation and evolution, and the kinematic evolution of deformed sedimentary basins (Bunles., et, al., 1999).

In industry, the restoration technique is used to investigate the hydrocarbon and mineral prospectivity of deformed sedimentary basins. In the oil and gas industry, this technique is particularly used to test the position of source rock, the validity of migration routes, and the
timing of generation, expulsion and migration of hydrocarbons; to analyse the geometry and formation of structural traps; and determine the timing of trap formation and/or destruction (Buchanan, 1996). Thus, based on the restored sections presented in Chapter 6 and with regard to the petroleum system, the following geological history can be reconstructed:

The first important event during the rifting, was the deposition of evaporites (Figure 6.6). Salt is a chemical precipitate. Several factors are required for a large scale precipitation, the most important may be: (1) high temperatures or arid climate for rapid evaporation, (2) restricted circulation of water, to allow for supersaturation of dissolved material. Most salt tectonic literature use “salt” for all rocks composed mostly of halite, however, salt bodies may contain varying amounts of other evaporates especially anhydrite, or its hydrated form, gypsum (Hudec, et. al., 2007). The principal interest of salt tectonics originates from the oil industry since many of the important hydrocarbon provinces in the world lie in salt basins (e.g., Gulf of Mexico, Persian Gulf, North Sea, Campos Basin, Lower Congo, etc.,). Salt tectonics play an important role since salt flow creates structural, stratigraphic and combined traps, influences reservoir distribution, works as a seal to fluid migration, works as effective thermal conductor elevating the thermal maturity of rocks above salt structure and cooling rocks that lie below or adjacent bodies (Hudec, et. al., 2007). Thus the understanding of salt tectonics in this area is critical for the successful exploration for oil and gas in the region.

During the Upper Jurassic, Oxfordian Oolitic banks as well as carbonates were deposited that form reservoir rocks present day (Figure 6.7). In addition, the hydrocarbon generating systems (mostly shaly limestones), Oxfordian, Kimmeridgian and the Tithonian were deposited; the most important over the whole region is the Tithonian hydrocarbon generating system (Figures 6.7 and 6.8).
During the Cretaceous, deposition of the most important reservoir rocks in the region consisting of carbonates took place (Figures 6.8 and 6.9). Then, during the Paleocene (Figure 6.10) deposition of shaly limestones formed a regional seal. In addition, during the Paleocene, carbonates were deposited in some areas forming the Paleocene reservoir rocks.

From the Eocene to Middle Miocene salt tectonics increased in activity as a response of the huge amount of siliciclastic sediments that reached the basin (differential loading) (Figures 6.10, 6.11, and 6.13). Formation of stratigraphic traps such as wedges against salt formed at this time. In addition, salt withdrawal allowed the formation of some anticlines (structural traps) and synclines especially at deeper levels (Mesozoic) (Figures 6.10, 6.11, and 6.13). However, these are mostly due to shortening.

Regionally, during the Middle Miocene (Figure 6.14), the compressional “Chiapaneco event” occurred and most of the important structural traps were formed at this time by folding and faulting along the Chapas-Reforma-Akal belt (Figure 1.4). Another younger and localized compressional event took place during the Upper Miocene (Figure 6.15). As mention, this event may be due to gravitational sliding using an upper allochthonous salt level as a decollement forming Tertiary structural traps in an imbricated structure.

The same siliciclastic sedimentation continues delivering huge amount of sediments to the basin. Tertiary reservoir rocks as well as Tertiary seals were formed (Figure 3.17, and 3.18). In addition, salt withdrawal caused the formation of new minibasins and depocenters. In other words, salt movement continued, allowing the formation of traps as well as seals on the Tertiary column. (Figures 6.15 to 6.22).

According to a geochemical study performed by PEMEX during 2012, the age of hydrocarbon generation fluctuates between 10 to 5 My (during Middle Miocene to around Upper
Miocene). Figures 6.14 to 6.17, show the position of the Tithonian generating system. Depths of the generating system vary from around 5000m to 7200m allowing the rocks to enter the oil as well as gas window depending on the area (Figure 3.13). On the other hand, expulsion of hydrocarbons started since 5 to 3 My (Upper Miocene to Lower Pliocene) Figures 6.15 to 6.18. However migration of hydrocarbons still continues present day. Figures 6.15 to 6.23 show the structural configuration of the area through the time of the expulsion of hydrocarbons.

Some important implications for oil and gas exploration are: (1) All the structural and stratigraphic traps within the Mesozoic were already formed at the time of generation and expulsion. Therefore, the risk for the charge for this plays is very low. However, a 3D analysis of migration paths may be needed. (2) Important thicknesses of allochthonous salt were present from the Upper Miocene to may be Middle Pliocene (south side of the section) (Figures 6.15 to 6.18). The presence of salt in this area must inhibit the migration of hydrocarbons to the upper and already formed structural and stratigraphic traps during this time (e.g., secondary minibasins and thrust imbricate structure). However, the formation of a wide regional weld during the Upper Pliocene as well as salt withdrawal in the area (Figures 6.19 to 6.22) increased the possibility of subsequently charging those traps. Furthermore, since migration of hydrocarbons still continues, the risk for charge of these traps may be medium to low. In addition, this analysis was performed using a 2D line but lateral migration of hydrocarbons must be considered since it actually is a three-dimensional phenomenon. (3) Another implication for exploration is that the seismic data are, inadequate for good subsalt imaging. What is needed is wide-azimuth, long-offset acquisition and RTM rather than Beam migration.
7.2 Conclusions and Recommendations

The geology and petroleum aspects of the area are controlled by the complex evolution of the Gulf of Mexico. The most important events are: (1) Late Triassic to Middle Jurassic Rift stage. (2) The Callovian Salt deposition. (3) Salt canopy emplacement during the Eocene. (4) The Laramide Orogeny during the Eocene. (5) The compressional Chiapaneco Event during Middle Miocene forming folds and faults and responsible to the deformation of the Chiapas-Reforma-Akal belt. (6) Salt withdrawal that caused the formation of important depocenters as well as minibasins during the Miocene. (7) Gravitational sliding of the Cenozoic deposits.

The different tectonic events occurred in the area had different strain orientations. Hence, following the first deformation event, another deformation event with different strain direction took place and so on. Salt history can be described as follow: 1) Salt deflatin and inflation, leading to diapir initiation, began in Late Jurassic, but has unknown cause; 2) Ongoing passive diapirism; 3) Diapir squeezing, allochthonous emplacement begins during Eocene, continues to end Oligocene; 4) Canopy evacuation and secondary diapirism early-mid Miocene; 5) Brief, local episode of gravity-driven shortening earliest late Miocene; 6) Extensional failure late Miocene to present.

Within the KUZAM area, three different structural phases are recognized: (1) The oldest compressional stage (Mesozoic to Eocene-Paleocene-Oligocene). (2) An older compressional stage constituted by the thrust imbricate structure (Lower Miocene-Middle Miocene). (3) A younger extensional stage (from Middle Miocene to Pleistocene). Also, two salt levels were documented: (1) The deeper autochthonous salt level (or “Mother Salt”), (2) The allochthonous salt level. In addition, an important salt weld connects the autochthonous salt level, while also separating the oldest compressional stage from the youngest compressional stage. In addition, a
regional unconformity separates the youngest compressional stage from the younger extensional stage.

There are several limitations and errors that can be carried through the restoration process. Errors during seismic processing, velocities used for depth-to-time and time-to-depth conversion, the seismic interpretation by itself, errors calculating decompaction and/or isostatic corrections, the wrong use of a determined algorithm to unfault or unfold, and even the experience of the interpreter. However, despite all this limitations and errors, reliable restorations can be performed since experience had demonstrated that they are relatively minor making section restoration process a powerful tool even in salt basins. One other major possible source of error is the bias of the person - what he or she thinks happened in an area influences how a section is restored.

The restoration methodology performed in this thesis successfully illustrated the geometric evolution of the area. The methodology used here worked very well, even though some limitations arise such as the lack of paleobathimetry data, and especially, limitations to calculate decompaction as well the isostatic correction. Despite these limitations, a complete history of the structural evolution from the moment of salt deposition to the present structural configuration was carried out.

Due to the cross-line orientation, the total amount of compression cannot be reliably measured. However, a reliable approximation of the total amount of extension can be measured. According to the restoration, the total amount of extension is approximately 20.75 Km, representing 36.48% of the total length of the cross-section (56.875 Km).

From the exploration point of view, this restoration provides information of: (1) the timing of structural (as well some stratigraphic) formation. In this case all the traps formed in the
area were formed before the time of expulsion of hydrocarbons. Therefore, there is low risk for trap formation on the petroleum system in the area. (2) The position of the most important Tithonian generating system can be followed through the time on this restoration. According to previous petroleum system study done by PEMEX 2012, the age of hydrocarbon generation for the Tithonian generating system fluctuates from 10 to 5 My, whereas the age of expulsion of hydrocarbons fluctuates from 5 to 3 My. Thus, based on the restored section, the Mesozoic (carbonate) traps have low risk of charge since these rocks are close to the source rock. In addition, the formation of a regional Paleocene seal, make this stratigraphic level very attractive. With regard to the Tertiary traps, based on the restored section, this stratigraphic level shows more risk for charge in the first place because during part of the Miocene there was a huge amount of salt sealing the upper levels. However, as salt evacuated from the area and created the regional weld, the probability to charge these traps increased. Another important factor to consider is the formation of different regional seals during the Miocene-Pleistocene that may inhibit the migration of hydrocarbons to upper levels. However, since migration is a 3D phenomenon there may be still good chances to charge those traps.

One of the most important lessons learned during this work is that cross-section restoration process creates increased awareness of the seismic interpretation process. This is because by going through the restoration process, the interpreter (geologist or geophysicist) is forced to think analytically (and even to work with mental restoration during the process) about his or her interpretation. As a result of this way of thinking during seismic interpretation, interpreters challenge their own interpretations increasing the accuracy of the interpretation, and more importantly, increasing the understanding of the area allowing to reducing the risk of hydrocarbon exploration and therefore potentially saving millions of dollars.
Finally, due to the complexity of the area as well as the natural salt mobility property it is recommended for future research, to work with 3D restoration that will help to improve the understanding of the area, and, therefore, decrease the risk during hydrocarbon exploration.
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