High resolution seismic stratigraphic analysis

An integrated approach to the subsurface geology of the SE Persian Gulf

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Dissertation for the degree *philosophiae doctor* (Ph.D.)

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Contents

Preface

This dissertation constitutes the work that I have done for the degree of "Doctor of Philosophy" at the Department of Earth Science of the University of Bergen (UiB), located in Bergen, Norway. It is prepared in the format required by the University Board. The research work has been conducted in the Department of Earth Science and also, collaboratively, at the Research Centre of Norsk Hydro ASA. The study focuses mainly on a 300 km^2 area of the southeastern Persian Gulf. The Iranian Offshore Oil Company (IOOC) made available recently-acquired (2001) high-resolution seismic data, wireline logs, palaeontological logs and core descriptions from five vertical wells. Professor Kuvvet Atakan (UiB), Drs. David Hunt and Ian Sharp (Norsk Hydro) have been my advisors; Norsk Hydro has funded my studies. I began this academic work after 14 years working in the oil industry (NIOC) in different positions including wellsite geology, subsurface geology, well planning, sequence stratigraphy and seismic stratigraphy interpretation.

The dissertation comprises two separate and complementary parts. The first part introduces and summarizes the research, while the second part provides the main research details and record in the form of scientific articles for publication.

Part I is an introduction, summarizing the research. This part includes the regional geology, state-of-the-art of the problems, objectives of the study, my approach in the study as a step forward towards closing the gap between geology and geophysics in the study area, and, finally, the dataset on which the research is based. This dataset is one of the few datasets of its kind presented in the literature. The section numbers in Part I follow the Paper numbers in Part II.

Part II consists of four academic journal articles and a web-published extended abstract. Two of the articles have been published and two are accepted for publication. The extended abstract pertains to a web-published international lecture video. The complete list of papers ordered chronologically is given below. This reflects a research passage progressing from the basic well- and seismic-interpretation building blocks to an integration of advanced 2D and 3D problems.

My goal has been to approach the stratigraphic record using the relationship of high-resolution 3D seismic data to the geology of the subsurface in greater detail than previously thought possible in an oil field. The work concentrates on the geological context of complex sediment accumulations and dynamics in the context of time. This work also contributes to improved seismic interpretation methods, focusing on recognizing geological and petrophysical details, usually hidden, by applying multivariate analysis and seismic pattern-recognition techniques. In addition to this basic research, practical spin-offs include the development of extra geological information in the study area, leading

to low-risk exploration targets that would not have been identified (or even suspected) from conventionally-interpreted 3D seismic data.

The dataset used in this work is considered confidential by its owner, the IOOC. Pursuant to the confidentiality agreement between the University and the IOOC, exact geographical coordinates are not given. Page numbers in Part I and Part II are independent. Page numbers of the first two papers in Part II appear as assigned by the journals.

Pourdad Farzadi
April 2006
Bergen, Norway

Papers included in this dissertation:

Paper 1: Farzadi, P. 2006a. The development of Middle Cretaceous carbonate platforms, Persian Gulf, Iran: Constraints from seismic stratigraphy, well and biostratigraphy. *Petroleum Geoscience,* **12**, 59-68.

Paper 2: Farzadi, P. 2006b. Seismic facies analysis based on 3D multi-attribute volume classification, Dariyan Formation, SE Persian Gulf. *Journal of Petroleum Geology,***29/2**, 159-174.

Paper 3: Farzadi, P. & Hesthammer, J. (Submitted 2006). Diagnosis of the Upper Cretaceous paleokarst and turbidite systems from the Iranian Persian Gulf using volume-based multiple seismic attribute analysis and pattern recognition. *N.B.: Originally accepted for publication in the AAPG Bulletin, later rejected because the US government prohibits the publication of papers using Iranian government datasets. The manuscript has been re-submitted to Petroleum Geoscience.*

Paper 4: Farzadi, P. & Alaei, B. (Submitted 2006). Stratigraphic architecture of the Zagros Basin: towards an objective comparison of the Fold-Thrust Belt and Foreland provinces. *Submitted to the Journal of Petroleum Geology; under consideration for a thematic issue.*

Presentation (at international meeting and on web): Farzadi, P. 2005. Stratal geometries of the Cretaceous carbonate systems: application of multiple volumes attributes analysis to 3-D seismic data from the Persian Gulf. *At:* Middle to Far East Carbonate Reservoirs: Exploration, Development and Exploitation. PESGB Carbonate conference, 15th & 16th Nov. 2005 London.

Scientific environment

This research was conducted at 4 locations. The principal locations are UiB and Norsk Hydro; only minor work occurred in Iran.

Department of Earth Science, University of Bergen, Norway.

The majority of the research was conducted in the Department of Earth Science. My primary advisor, Professor Kuuvet Atakan, is located here. The main tools for the advanced attribute-based seismic interpretation, petro-acoustic modelling and visualization, Seisfacies NexModel and VoxelGeo supplied by Paradigm Geophysical, were located at the Department of Earth Sciences.

Research Centre, Norsk Hydro, Bergen, Norway

Some seismic interpretation, visualization, and consultation occurred in Norsk Hydro's Research Centre. My secondary advisors, Drs. David Hunt and Ian Sharp, work at the Research Centre. The main tool used for the seismic interpretation was the Charisma interpretation package within the Schlumberger Geoframes system.

Iranian Offshore Oil Company (IOOC)

IOOC involvement was mainly consultations about the nature of the data and availability of detailed reports, and presentations to keep IOOC informed of the research progress. These took place at the IOOC in Tehran.

National Iranian Oil Company (NIOC)

As part of the agreement to allow the use of the IOOC / NIOC data for my Ph.D. studies and publication, I kept NIOC informed of the research progress. Consultations about the nature and details of the data also occurred. These took place at the NIOC in Tehran.

Acknowledgements

To a large extent, this work is the product of the University of Bergen; it would not have come out the same if I had not been immersed its brilliant, motivating research environment. I am particularly grateful for the interaction with my supervisor Professor Kuvvet Atakan, my advisors David Hunt, Ian Sharp and Walter Wheeler to whom I express sincere thanks.

I would also like to extend my appreciation to Professors William Helland-Hansen, Michael Richard Talbot, and Wojtek Jozef Nemec who cheerfully welcomed my frequent interruptions, paused their own research to answer my inquiries. This doctoral work benefited from kind support of Professor Jens Havskov, Gro Haatvedt, Haakon Ostas, Stig-Morten Knudsen, Ridvan Karpuz, Reza Sedaghat, Ole Martinsen, Jens-Peter Kverstein, and Mohammed Mokhtari during planning, thanks go to them for their time and efforts.

This research project received generous financial support from Norsk Hydro, to whom I wish to express my gratitude. IOOC and NIOC are also thanked for allowing access to the unique seismic/well datasets and internal reports. I would also like to thank the many carbonate geoscientists at Petroleum Exploration Society of Great Britain (PESGB) who provided helpful comments and support when I delivered a lecture on my doctoral project at the international carbonate conference, 2005. Thanks are given to the many journal reviewers for their thorough and careful critique of my manuscripts. I thank the computer system administration team at the University of Bergen who dedicated extra system support while my CPU-intensive processes were crunching through huge seismic datasets. Paradigm Geophysical UK is gratefully acknowledged for providing their powerful software (Seisfacies, Stratimagic, NexModel and VoxelGeo).

Special thanks are due to my friend Behzad Alaei who never left me alone even in the hardest situations. I could not wish for a better friend and colleague.

Lastly, I would also like to acknowledge the patience, support and sufferings of my lovely wife Nasrin and our daughter Helia throughout my often overtime-working hours. Their generosity cannot be appreciated by words.

Abstract

The integration of seismic stratigraphy with depositional-sequence concepts has revolutionized the geologist's ability to predict subsurface stratigraphy. Describing sub-seismic-scale geometric and depositional cycle relationships within the larger, seismic-scale chronostratigraphic framework has given fascinating insights into carbonate platform evolution. Carbonates deposited on passive continental margins, such as on northeastern Arabian Platform which is the subject of this study, contain some of the major hydrocarbon accumulations of the world. As such, the study of their stratal geometric evolution has considerable relevance to hydrocarbon exploration. In the Persian Gulf, which lies on the northeastern margin of the Arabian Platform, most of the "easy oil" (oil contained in structural traps) has been discovered. The vital importance of a shift in exploration emphasis from simple structural traps to the more complex stratigraphic traps is obvious. The study of stratigraphic traps depends closely on recognizing the geometry of stratal surfaces. At first sight it is tempting to think that primary seismic reflections should follow subsurface stratal surfaces (time stratigraphic units) thus providing the basic elements of seismic/sequence analysis. However, primary seismic reflection events often do not follow time-stratigraphic surfaces, for example clinoforms. The ability to distinguish time-stratigraphic from time-transgressive surfaces depends on the seismic frequency content. Moreover, low impedance contrast between carbonate strata, lack of bedding in reefal complex, the potential for steep depositional slopes, and the chaotic nature of karsted terrains all can potentially diminish seismic quality. Consequently conventional horizon-based seismic interpretation approaches may not be appropriate for truly 3D interpretation of complex geological features. In addition, conventional seismic data include features of diverse origin and the interpreter of these data can rarely create a unique map of complex geological features in 3D space.

Well-based subsurface data represent only a small fraction of the reservoir volume. The choice of conceptual depositional models strongly influences the outcome of the stratigraphic interpretation. In the subsurface studies where horizons become difficult to follow laterally, even recently-developed automated seismic interpretation techniques require integrating information from the conceptual tools of sequence stratigraphy with subsurface data.

Efforts to efficiently use seismic/sequence stratigraphic concepts in carbonate settings, for example to identify genetically related stratal packages for the purpose of correlation, depends on improving seismic images of the unique aspects of carbonate stratigraphy. Improving seismic stratigraphy of carbonates is critical to any advances in volume and attributes interpretation.

The first stage of this study focuses on the Cenomanian Mishrif and Khatiyah Formations in SE Persian Gulf. Working with 40 Hz conventional 3D seismic data in the first stage illustrated that, in comparison with high-resolution outcrop-defined sequences in the literature, the third-order sequence

scale (composite sequence scale) within the Cenomanian Mishrif and Khatiyah Formations is seismically resolvable. The Mishrif Formation, a major oil producer in SE Persian Gulf is broken down into seismic sequences by application of sequence stratigraphic principles and the cycle framework interpreted from the five vertical wells. This study brings new insight into carbonate platform evolution from the interpretation of the Khatiyah Formation, which is known only as a regional source rock, leading to recognition of a very low-risk prospect reservoir. The new information gained from the successive stages of drowning and back-stepping of carbonate platforms has important implications for reservoir development and can serve as a reference for regional stratigraphy.

The seismic interpretation of the Aptian Dariyan Formation, a potential regional reservoir unit, illustrates that conventional seismic data are insufficient to reveal the internal heterogeneity. Outcrop examples of the laterally-equivalent Shu'aiba Formation, a prolific carbonate reservoir in the UAE, indicate the Dariyan Formation should have a complex internal architecture. However complex internal geometries are apparently not seismically resolvable in the Dariyan. The traditional surface-based seismic interpretation only gives insights into variability at the top and base of this formation and not from within it. To enhance internal stratigraphic relations a multivariate seismic analysis, combined with a data reduction algorithm, enabled interpretation in an integrated fashion to construct a sequence stratigraphic framework, within which multiple seismic attributes could be interpreted. Six seismic attribute volumes were used, and Principal Component Analysis (PCA) reduced noise and redundant data. Three eustatically-controlled depositional units are recognized in the Dariyan Formation from well data. By analogy with the Shu'aiba, isolated rudist-dominated build-ups in the middle fining-upward unit probably have the best reservoir potential.

The extent of platforms and shelf flooding such as the Mishrif and Dariyan reservoirs discussed in this study is generally greatest during sea-level highstands. The carbonate factory is most robust and carbonate sedimentation is greatest at such times. Platform shallowing occurs mainly due to in-situ aggradation of the sea floor, and progradation of the islands, shoals, build-ups, and the shoreline. The studied depositional processes result in a variety of stratal geometries, ranging from parallel platform-interior beds to gently- to steeply-dipping foreslope beds, and complex-massive- to chaotically-bedded platform margin facies. The shingled geometry of the reservoir intervals is expressed as a series of basinward inclined clinoforms.

Turonian subaerial exposure of massive carbonates of the Mishrif Formation led to extensive karst formation. Karstification disrupted the normal bedding patterns at the top of the Mishrif Formation making chaotic stratal patterns, and dissolution expanded and enhanced fractures. This provides opportunity for complex raypaths, dispersion of wavefronts, and multiple diffraction points causing a lowered seismic resolution. Distinctive chaotic seismic facies with circular sinkhole and collapse

features, discovered by integrated attribute analysis of the Mishrif Formation, clearly correlate with the production rates of existing wells.

Prograding highstand platform margins may oversteepen and fail, generating gravity flows that add to highstand clinoform slopes and toe-of-slope basin deposits. In the study area, large quantities of platform-derived fine-grained sediment were transported off-bank, in suspension, probably by tide, currents, and storm waves, and settle on slope and basin floor of the Santonian Ilam Formation. The Ilam Formation is known as a non-reservoir unit, although one of the wells in the study area shows non-commercial oil from within this formation. Using integrated attribute analysis, interpretive work can focus directly on geologic features in 3D space. This study also gives new insights into the internal variability of carbonate turbidite systems that are essential to estimation of reservoir volume, connectivity and variability. The only producing well in this non-reservoir unit has penetrated one of the abandoned channels of the above-mentioned turbidite system.

The lack of sufficiently high-resolution seismic imaging techniques has precluded the definition of reliable exploration models at both regional and field scales. Here, advanced imaging techniques applied to conventional 3D seismic data reveal the relations between major tectonic events and depositional processes in two distinct but related tectonic provinces within the northeastern Arabian plate. This work finally focuses on building regional and local stratigraphic evolution models to compare the interplay of Cretaceous and Tertiary deposition processes and deformation events. The final stage is based on comparative studies in hydrocarbon producing regions that today are tectonically quite different: the Dezful embayment in the Zagros Fold and Thrust Belt (ZFTB) and the southeastern Zagros Foreland Basin. Cretaceous reservoir facies in both areas predate the ZFTB and are the result of depositional processes largely controlled by eustatic sea level punctuated by relative sea level changes attributable to salt and distal tectonic effects.

Part I: Summary

1. Introduction

The subsurface stratigraphic record can be discerned through multidisciplinary technique called seismic stratigraphy. For well-structured seismic stratigraphic analysis, the complications of regional geology must be incorporated in the analysis. The situation becomes rather complicated if we are to demonstrate the oil-field-scale stratigraphy in a regional context. This Introduction is intended to provide some necessary background on geological setting, state-of-the-art of the problems, study objectives and the approaches applied to find the solutions.

1.1 Background

The stratigraphy of the Middle East, particularly the Arabian Plate (Fig. 1), has been intensively studied and much of the subsurface architecture has been described using mostly lithostratigraphic principles (e.g. Van Bellen *et al.* 1959; James & Wynd 1965; Dunnington 1967; Koop 1977; Murris 1980a,b; Koop & Stoneley 1982; Beydoun 1988, 1991; unpublished industry reports).
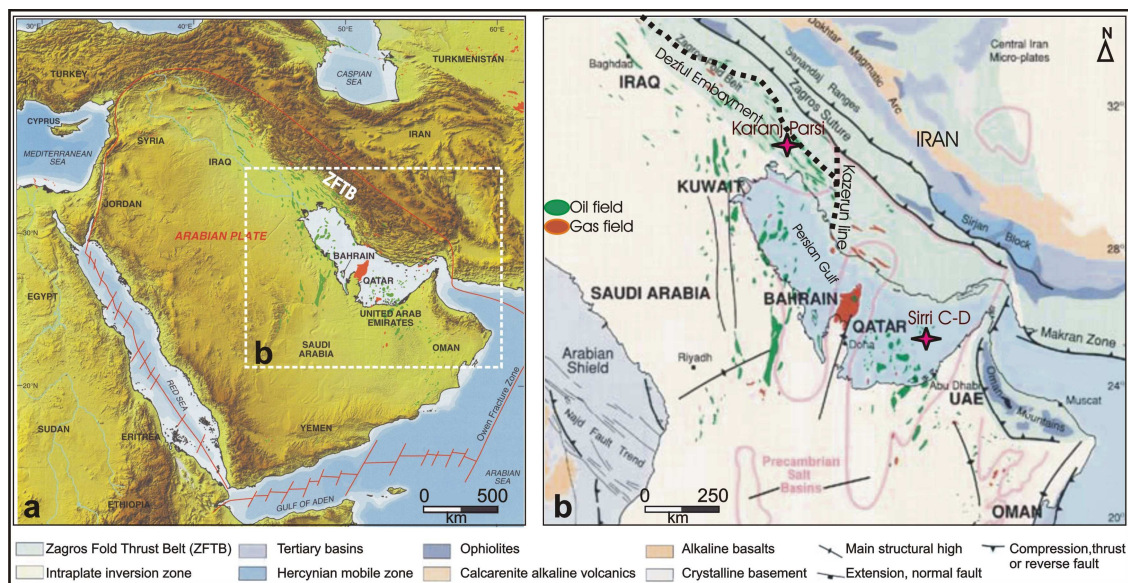
Figure 1: Regional map showing location of the oil fields studied in this dissertation (red stars). The Sirri C-D oil fields, which are the main focus of this study, lie in the southeastern Zagros Foreland basin (SE Persian Gulf). The Karanj-Parsi oil fields, used here for regional stratigraphic correlation, lie within the Zagros Fold and Thrust Belt in an area called the Dezful Embayment. Sirri has been chosen to highlight the subsurface geology in a less-deformed area; it is then compared with highly-deformed Karanj-Parsi area to better understand the regional factors controlling the stratigraphic architecture.

Many recent publications use sequence stratigraphic concepts, providing a more robust subsurface framework (e.g. Droste 1997; Wender *et al.* 1998; Alhajri *et al.* 1999; Sharland *et al.* 2001; Droste &

Steenwinkel 2004). A reason for such an enthusiasm for stratigraphic research among the petroleum geologists is that the Middle East contains around two-third of the world's remaining oil reserves and about a third of its remaining gas reserves (BP Amoco 2000). In contrast to this enthusiasm, new literature on the sequence stratigraphy of the Persian Gulf (Iranian sector) is scarce. The public-domain sequence-stratigraphy database of the Iranian sector is not detailed enough to allow existing interpretations and correlations to be refined using the advances made in other parts of the Arabian Plate.

1.2   Geological setting

Sediments have been deposited in various environments throughout the history of the Arabian platform. Various environments have occupied this spot on the face of the earth at varying times in its history. These sediments, today preserved as sequences of sedimentary rocks, provide a spectacular wealth of information concerning the geological evolution of the area. During most of the Palaeozoic the area was part of the stable passive margin of the Gondwanaland super continent, characterized by the deposition of shallow water sediments including the Infra-Cambrian Hormoz salt (Glennie 2000; Bahroudi and Koyi 2004; Sepehr and Cosgrov 2004). The Hormoz salt and its later movements have played an important role in deformation and structure generation (Koop 1977; Koop and Stoneley 1982; Beydoun *et al*. 1992).

The evolution of the Persian Gulf depositional basin has been a long and complex process since the Late Permian initiation of Neo-Tethys I and the Jurassic Neo-Tethys II (Smith *et al* 1994; Glennie 1995, 2000; Bordenave & Hegre 2005). During the Jurassic and Cretaceous, the Arabian platform in equatorial position was attached to the northern margin of Africa (Smith *et al*. 1994). Extensive Mesozoic carbonate platforms (Fig. 2) covered the NE edge of the Arabian Plate (Glennie 2000; Sharland *et al*. 2001) including the SE Persian Gulf. These carbonates overlie an angular unconformity. Alternating layers of sandstone and shale of Palaeozoic age underlie the unconformity. Mesozoic carbonate deposition was frequently interrupted by subaerial exposure (Fig. 2) and the influx of siliciclastics attributed to Arabian Shield tectonics and eustatic sea-level fluctuations (Sharland *et al*. 2001). Stratigraphic data can aid in our understanding of the dynamics of the area.

The study area was a tectonically passive carbonate shelf from the Permian to about the Middle Cretaceous (Glennie 1995, 2000; Alsharhan and Scott 2000). The Tethys Sea began to close with Early Cretaceous subduction of oceanic crust beneath Central Iran. A major relative sea-level fall attributed to the onset of a compressional event in the Late Aptian is recognized as a regional unconformity (Fig. 2) across the entire Middle East (Harris *et al* 1984; Sharland *et al*. 2001). Salt-diapirism contemporaneous with the Late Aptian compression is observed in the SE Persian Gulf (Farzadi 2005, 2006b). The Late Cretaceous south-westerly obduction and continued shortening

associated with closing of Neo-Tethys resulted in intense faulting and thrusting along the Zagros Fold Thrust Belt and onset of folding in the Oman Mountains. A regional highly-karstified Turonian exposure surface is developed due to this compressional event (Alsharhan & Kendal 1991; Loucks & Sarg 1993; Pascoe *et al.* 1995; Montenat *et al.* 1999; Farzadi 2005, 2006a). This compression continued until the central Iranian Plate and the Arabian Peninsula collided in the Maastrichtian (Glennie, 1995, 2000). Ocean-floor sediments were rapidly thrust onto the north-eastern edge of the Arabian plate as a result of this collision. The Late Cretaceous represents a period of major change in the area of the modern Zagros Foreland basin. (Loutfi *et al.*, 1987; Burchette, 1993; Pasco *et al.*, 1995; Van Buchem *et al.*, 1996, 2000, 2002a; Alsharhan and Scott, 2000; Sharland *et al.*, 2001; Droste and Steenwinkel, 2004; Farzadi, 2005, 2006a). Regression at the end of the Cretaceous (Fig. 2) left most of the Arabian Plate emergent apart from basinal areas in the northern UAE and the Zagros basin. Subsequent transgression in the Paleogene led to development of shallow marine conditions over most of the Arabian Plate. Deep-water conditions prevailed in the Zagros and the Ras-Al-Khimah basin (Oman), which were separated by the slightly emergent Fars Arch (Kazerun line). Thus in the Palaeocene to Early Eocene, the Zagros basin became separated from Neo-Tethys for the first time. A rapid transgression in the Late Eocene marked a return to more open marine conditions. Then, during the Late Eocene/Oligocene regression, the Zagros basin, while not exposed, nearly disappeared as a distinctive depocenter. This eustatic sea level fall led to widespread emergence across the Arabian Plate. An early-mid Oligocene transgression is marked by open marine facies close to the base of the Asmari Formation (Fig. 2). The middle Oligocene global sea level fall again restricted marine deposition in the Zagros basin; this period is characterized by sabkhas and a thick deltaic wedge of coarse siliciclastic.

Rifting of the Afro-Arabian plate during the Oligocene initiated development of the Red Sea. Broad uplift of the Arabian shield provided an abundant source of coarse clastics for the Zagros basin from the southeast. A major Mid-Oligocene sea-level lowstand caused a reactivation of fluvial systems (Ahwaz Sandstone Member, Asmari Fm., Fig. 2) with a marked unconformity at the base. Asmari

EPOCH/ERA			Group	SE Zagros Foreland	ZFTB
TERTIARY		QUATERNARY	G	Bakhtiary	Bakhtiyary
		Pliocene		Aghajari	Aghajari
		Miocene		Mishan	Mishan
				Gachsaran	Gachsaran
		Oligocene		Asmari	Asmari Ah Kal*
		Eocene		Pabdeh	Jahrum
		Paleocene			Pabdeh
CRETACEOUS	UPPER	Maastrichtian	Bangestan	Gurpi	Gurpi
		Campanian			
		Santonian		Ilam	Ilam
	MIDDLE	Coniacian		Laffan	Laffan
		Turonian		Mishrif	Sarvak
		Cenomanian		Khatiyah	
		Albian		Mauddud	
		Aptian	Khami	Kazhdumi	Kazhdumi
				Dariyan	Dariyan
		Barremian		Gadvan Khalij	Gadvan Khalij
	LOWER	Hauterivian			
		Valanginian		Fahliyan	Fahliyan
		Berriasian			
				Hith	Hith

* Ah: Ahwaz sand member   Kal: Kalhur anhydrite

Figure 2: Stratigraphy and major erosional surfaces (red lines) mentioned in the text. Most of these correlate well between Zagros Fold Thrust Belt (ZFTB) and SE Zagros Foreland (main study area).

Formation shallow-marine carbonates dominated the Zagros basin during the Middle Oligocene. Rising sea level during the Early Miocene is recorded by the disappearance of the deltas and their replacement by shallow-marine carbonate systems. Marginal areas starved of clastic supply developed coastal sabkhas (Kalhur Member, Asmari Fm., Fig. 2). The compressional folding began during or soon after the deposition of the Oligo-Miocene Asmari formation. Interpretation of well and seismic data suggests that the evaporites of the Lower Miocene Gachsaran Formation were deposited mainly in the subsiding lows with thickness variation controlled by several factors including tectonics. During the Plio- Pleistocene, low-angle thrusting and associated folding generated the present-day structural configuration (Mapstone, 1978; Sepehr and Cosgrov, 2004). The contact boundary between the Upper Asmari Limestone and the Lower Gachsaran Evaporites is diachronous implying progradation of coastal sabkhas across shallow-marine carbonates as the basin filled, possibly related to the westward growth of the Zagros Fold-Thrust Belt (ZFTB). The halite sequences of the Gachsaran Evaporites indicate nearly closed conditions and almost complete evaporation of the basin waters.

1.3   State-of-the-art of the problems (needs and constraints)

Applying the conventional approaches of well-data correlation and geophysical interpretation to the carbonate-rich Persian Gulf subsurface stratigraphy exposes the interpreter to major difficulties. Well and seismic data are the main sources of information from the subsurface. A wellbore divided into depositionally- and petrophysically significant packages (cycles and their component lithofacies) is the end-product desired from a 1-D cycle analysis. The hierarchy of cycles will form the basis of a 2-D stratigraphic correlation framework. In most carbonate environments, the fine-grained component is minimal and the correlation between the wellbore gamma-ray log, grain size, and depositional environment, although useful, can be misleading. This is particularly true if organic-rich material is present within the interval of interest. Thus core-based lithofacies studies are necessary for a high-resolution seismic stratigraphic framework to be constructed.

The lithostratigraphic correlation (layer cake) of gamma ray logs provides a meaningless framework based only on log signature matching. The lithologic signature of logs and the cycle hierarchy must be understood in order to interpret the stratigraphic framework and incorporate it into the next successive phase.

Because a chronostratigraphically significant depositional unit, such as a prograding cycles set, crosses facies tracts as it is traced across the depositional profile, the gamma-ray signature of this package and its bounding surfaces may change character totally. Thus attempting to match gamma-ray signatures without a depositional model will generate a more layer-cake lithostratigraphic

correlation scheme that does not honour the actual reservoir layering. Log correlation in dip direction is not straightforward.

The fundamental motivations for sedimentological interest in seeking to recover stratigraphic information from qualitative analysis of seismic data are based on a simple assumption that can be misleading. The assumption is: seismic reflections from within a depositional sequence should be generated along stratal surfaces that have significant acoustic impedance contrasts. Stratal surfaces are assumed to be relict depositional surfaces or bedding planes that are formed almost instantaneously; the reflections are then assumed to be chronostratigraphically meaningful. The rigid assertion that primary seismic reflections are always time stratigraphic can lead to erroneous interpretation. For example, in the Aptian basin of SE Persian Gulf, a model of carbonate progradational sequences is composed of multicycle, clinoform deposits of shelf-crest/shelf-margin, and slope facies (Farzadi 2006b). In this model, as geologic-time units prograde basinward, seismic reflection events cut across depositional surfaces of geologic time lines.

Mapping of seismic sequences in the subsurface relies heavily on the mapping of common surfaces of onlap and downlap using reflector terminations that mimic stratal terminations. Results of detailed lithofacies analysis demonstrate that while the general Exxon "slug model" (Vail 1987) is useful, many complexities make it clear that stratal geometry interpreted from seismic alone does not necessarily lead to unique interpretations. We should keep in mind that variations in sediment supply and non-eustatically driven accommodation dramatically affect the slug model's geometric relationships. There is an ambiguity in cases where an upward-thinning cycles-set could be interpreted as a progradational- or highstand systems tract (HST) deposit when in fact the thinning trend can be associated with upward deepening and slower sedimentation rates in a transgressive cycle set that is not keeping pace with sea-level.

The traditional line-by-line, surface-based interpretation technique, even if replaced by techniques that operate throughout the seismic volume, can only provide insights into the variability at the top and base of intervals and not within them. A surface-based interpretation of a single seismic attribute cannot provide the interpreter with a truly 3D interpretation of complex geological features. "Single seismic attribute" here includes features of diverse origin and the interpreter can rarely create a unique map of geobodies in 3D space.

What can we do to improve the seismic stratigraphic interpretation and to demonstrate that the subsurface stratigraphic record can be approached on a rational basis? Answering this question is one of the main objectives of this study.

1.4 Dissertation Study Objectives

In concept this dissertation has its roots in the successful worldwide application of seismic sequence-stratigraphic techniques to resolve complex reservoir stratigraphy. Many aspects of the subsurface data analysis are considered within a dynamic context in order to fully appreciate and consider the range of stratigraphic geometries possible in the geologic record. The objectives of this study are:

1) To integrate a high-resolution, sequence-stratigraphic framework derived from wireline-log analysis with multiple seismic-attribute versions of the 3-D seismic data.

2) To catalog depositional cycle hierarchies, stratal geometries, the formations, and the biostratigraphic time framework where available.

3) To interpret time-stratigraphic units instead of time-transgressive units through high-resolution seismic data using sequence stratigraphic concepts.

4) To move away from a purely line-based, single seismic attribute data analysis approach to one that incorporates and uses multiple seismic volumes, each based on a different attribute.

5) To find the true dimensionality of the 3-D seismic data and provide a truly 3-D interpretation. The "true dimensionality" is that which relates to geologic patterns; this is always less than the theoretical dimensionality of the seismic data.

6) To provide for the Iranian Persian Gulf the first 3D realization of key reservoir-related geologic features such as Cretaceous carbonate build-ups, Turonian paleokarst and Santonian turbidite systems. Conventional interpretation fails to adequately discern these features.

7) To analyze in horizontal dimension the meaningful geologic patterns throughout the seismic volume.

8) To focus on building regional and local stratigraphic evolution models to compare the interplay of Cretaceous and Tertiary deposition processes and deformation events.

9) To determine the utility of regional stratal interval-velocity trends for providing a framework for future evaluation of lithologic and porosity trends.

10) To provide tectonostratigraphic interpretation and the first high-resolution comparison between the ZFTB and Foreland Basin. Modern conventional seismic processing and analysis were insufficient to resolve the stratigraphic relations and identify the reservoir facies necessary for such a comparison.

11) To contribute to filling the gap in the literature on the detailed geology of the Iranian side of the SE Persian Gulf and Zagros Foreland Basin

1.5   Approach

The academic and applied field of subsurface data analysis has evolved cyclically. Advances in seismic imaging techniques, seismic multivariate analysis and well log analysis have improved our understanding of subsurface stratigraphy. Stratigraphy itself has been moving systematically toward consideration of the kinetics by which its configurations were achieved. The years since development of seismic stratigraphic concepts (Payton 1977) have given us a new, dynamic framework within which to consider the stratigraphic record. This dissertation applies a set of well and seismic sequence-stratigraphic techniques, along with multivariate analysis of seismic data, to construct advanced stratigraphic reservoir models for the subsurface Iranian Persian Gulf.

1.5.1 Seismic sequence stratigraphy

From a historical perspective, modern sequence stratigraphy developed from the concepts of unconformity-bound stratigraphic units (Sloss 1963; second-order sequences) with some very important variations. A step forward was seismic stratigraphy (Payton 1977), which is a methodology for identifying unconformity-bound sequences using reflection seismic data. Seismic stratigraphy seeks to recover stratigraphic information from qualitative analysis of seismic reflection events. Seismic stratigraphy emphasizes the use of the geometry and termination patterns of seismic reflectors to divide a sedimentary section into unconformity-bound seismic sequences (Mitchum *et al*. 1977a, b). Vail *et al*. (1977a) introduced landward reflection terminations and coastal onlap leading to the derivation of eustatic sea-level curves. Biostratigraphic control (Vail *et al*. 1977b) established global correlation of seismic-stratigraphic sequences. The chronostratigraphic significance of seismic reflections (Vail *et al*. 1977c) was another key aspect of seismic stratigraphy research. Seismic chronostratigraphy shifted the focus from global correlation of unconformity-bound stratal packages to the internal architecture and reflection patterns of stratigraphic sequences, viewed them as genetically-significant depositional sequences. This paradigm shift enabled the transition from seismic stratigraphy to sequence stratigraphy (Vail 1987; Posamentier and Vail 1988; Van Wagoner *et al*. 1988): studying unconformity-bound units as genetic depositional cycles associated with global sea-level variations.

In sequence stratigraphy, depositional sequences contain predictable suites of systems tracts and lithofacies tracts related to, progressive sinusoidal global sea-level rise and fall. The definition of the sequence stratigraphic concepts and their formative background are rooted in siliciclastic stratigraphy. Carbonate and siliciclastic sedimentary systems differ in two principal ways: carbonates

are autochthonous in origin and susceptible to early diagenesis. Carbonate lowstand systems tracts in particular are not well developed because during sea-level fall, carbonate sediments become lithified whereas siliciclastic deposits are reworked downslope, hence carbonate lowstand systems tracts are only a minor component of the sequence model, and lowstand carbonates contain a higher proportion of lithoclastic grains.

1.5.2   1-D and 2-D sequence analysis

For reservoir characterization, it is beneficial to determine the regional stratigraphic context of the reservoir data-volume before beginning even 1-D (well-based) analysis. The regional context is determined from published literature, regional 2-D seismic data interpretation, and regional well logs and cores. The regional study will serve to address several important unknowns at an early stage of the project to orient the detailed log and core analysis to capture maximum variability within the reservoir volume. Once this has been accomplished, the more detail-oriented tasks can be carried out in the proper context, with the end result being improved understanding of the reservoir stratigraphy.

The aim of 1-D stratigraphic analysis is two-fold. The first is establishing an initial cycle framework from wellbore data. To interpret a cycle framework, lithofacies data are almost always required, and cores represent the only true source of lithofacies data. The second aim is to quantify, integrate, and analyze the wellbore data. Wireline logs, which represent the vast majority of the 1-D data in a reservoir, must be calibrated to lithology using quantified core data (Fig. 3), after which they can be used for 2-D stratigraphic framework interpretation and 3-D geologic models.

The main carbonate depositional environments are characterized by lithological assemblages. Examples include rock fabrics such as mud-rich packstones and wackestones with low primary porosity and a potential abundance of vugy porosity, grainstones with high interparticle porosity, and chalky limestones with abundant chalky porosity. Core-based quantitative and qualitative descriptions of depositional environments, rock fabrics and their petrophysical affinities (reservoir properties) are fundamental for stratigraphic framework construction from wireline log interpretation.

In summary, in 1-D analysis it is important to work from the individual cycles up to cycle sets, system tracts, high-frequency sequences, and composite sequences. The correlation procedure for building the 2-D framework from the 1-D sequence interpretations is the reverse. In the 2-D analysis correlation between wells starts with the longest-term (lowest order) cycles, usually the composite seismic sequence boundaries, and then builds downward through high-frequency sequence boundaries, maximum flooding surfaces, and cycle sets. Once these seismic surfaces are tied between the wells, it is possible to evaluate whether it is possible to tie individual cycles between wells. Here

the 3-D framework begins to be established. Utilizing the interpreted seismic surfaces, it is then possible to begin to construct isopach or isochor maps for evaluating lateral thickness variations.
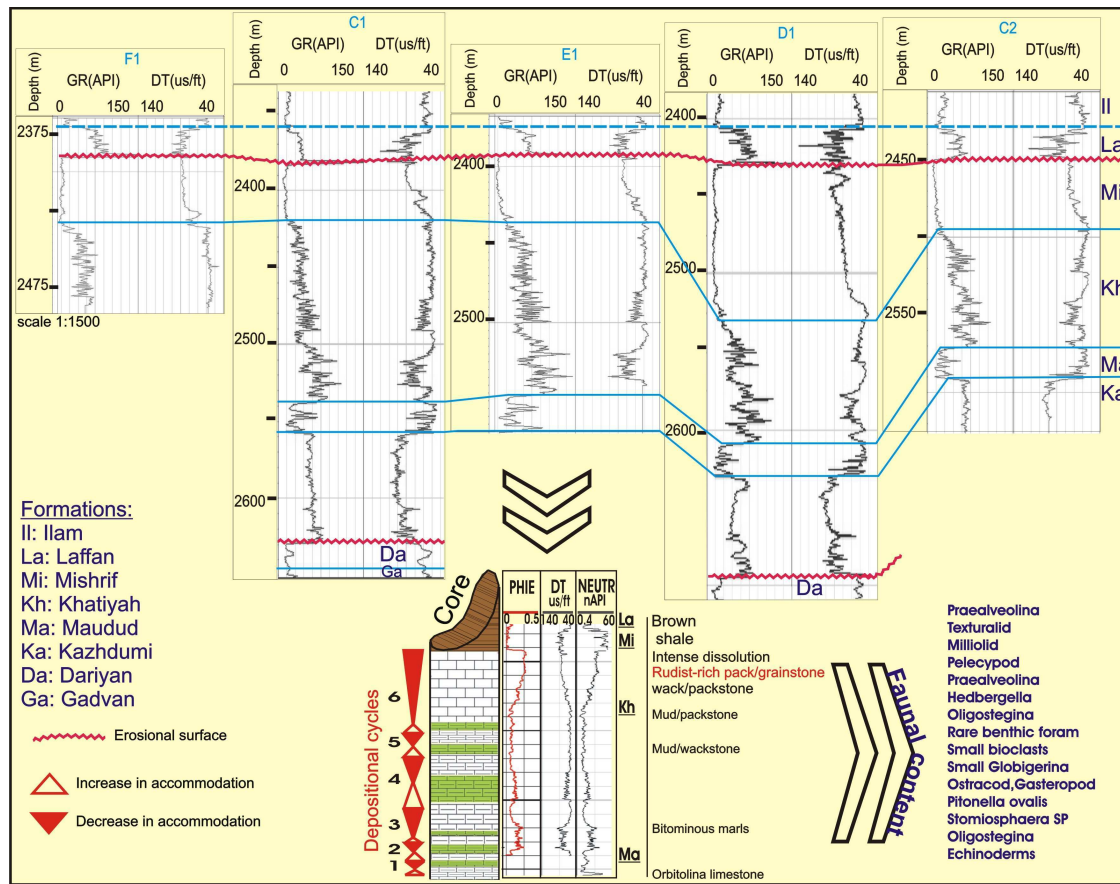

Figure 3: Gamma ray and Sonic log responses from 5 vertical wells used for 1D sequence analyses in the Sirri oil field. Blue and red lines show a preliminary layer-cake correlation. Wireline logs of well E1 Calibrated with lithology and faunal content of core data show the Mishrif (Mi) and Khatiyah (Kh) interval to comprise 6 depositional cycles (Farzadi 2005, 2006a).

1.5.3 2-D seismic isochor mapping

This study was carried out using time-seismic data. Seismic isochor maps of each stratigraphic interval can be examined for correlation busts, data entry errors, and to ensure that the depositional trend for each stratigraphic horizon was reasonable (Fig. 4). For example, if the origin of a particular map unit is a major flooding event, then the isochor map of this unit should appear as a sheet-like feature with a gentle landward taper. Any major discrepancies in thickness should be examined for data-entry errors, correlation busts, or seismic interpretation errors. In fact the thickness variation might be absolutely correct; this is simply a means of quality control. The successive younger clinoforms should show isochor thicknesses stepping progressively basinward if the system prograded and stepping landward if the system retrograded. If clinoform thicknesses vary

significantly along the depositional strike, the stratigraphic interpretation should be examined for integrity.
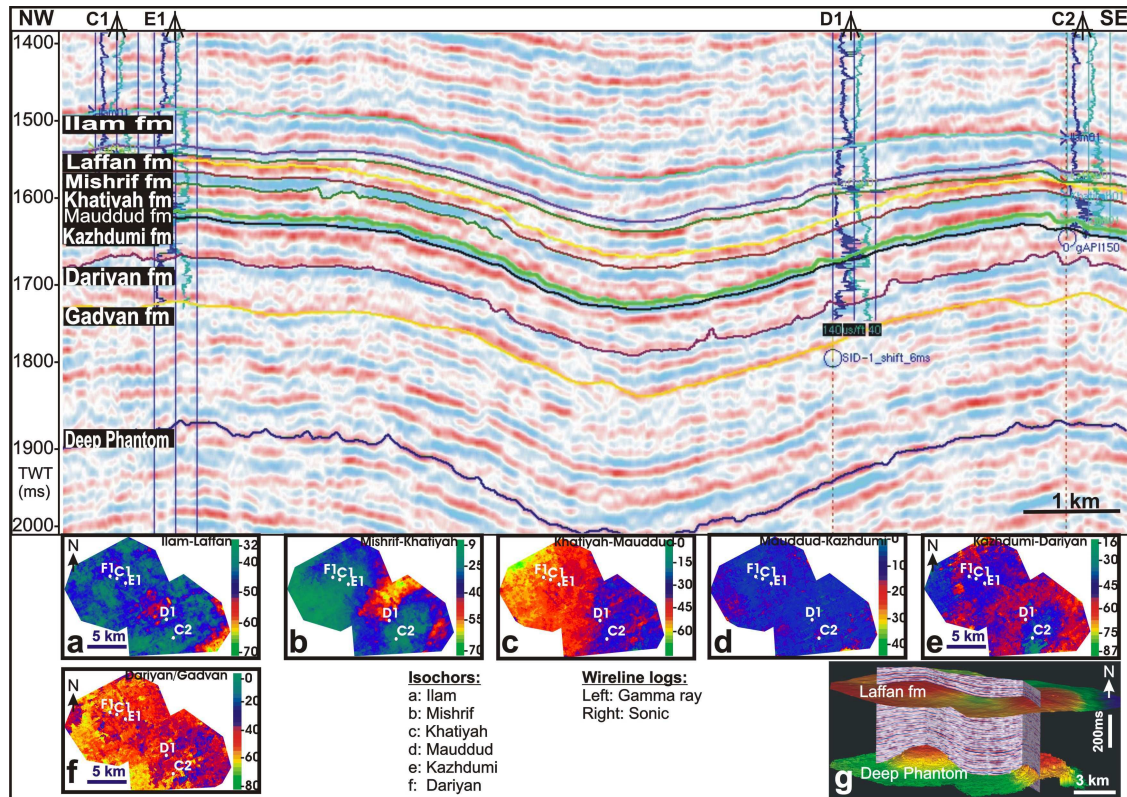

Figure: 4 Composite seismic profile through key wells in the study area. 8 continuous seismic events interpreted throughout the 3D seismic data provide a framework for recognizing surfacial variability at the top and base of the key horizons. Isochor maps (a-f) give insight to the general depositional trend and also can control the quality of the seismic interpretations. A 3-D view of 2 interpreted horizons (g) shows the geometries of the salt-cored structures (Sirri C-D) at two different depths.

1.5.4 3-D conceptual model for Quality Control

Conceptual, idealized 3-D depositional models should be created for the transgressive systems tracts and highstand systems tracts. These maps show the ideal vertical lithofacies successions and illustrate spatial lithofacies positions and water-depth associations. Comparison of these models to the actual isochor maps helps recognize perturbations from the idealized progression; major changes in the vertical progression are candidates for sequence boundaries. Ambiguities in interpreting temporal deepening or shallowing trends should be reduced using well data, by selecting indicator facies that constrain water depth and energy regime, and that also have distinct wireline log signatures. Key indicator facies in carbonate shelf settings could be common deepest-water lithofacies, build-up facies, and slope breccias. The interpretation of lateral deepening and shallowing trends is similar.

1.5.5 Multivariate analysis of seismic data

The aim of multivariate analysis in this work is to expand the information content and to reveal seismic patterns which are geologically meaningful. This is accomplished through integrating the sequence-stratigraphic study with a multiple-volume seismic attribute study. This requires several attribute volumes to be generated from the original post-stack migrated seismic data. These attribute volumes can be generated by standard numerical calculations. Once the meaningful seismic patterns are recognized, a classification process focuses on their organization and the true dimensionality of seismic data. There are several techniques for analyzing multivariate data, including linear regression, cluster analysis, and neural network (Davis, 1986). This study illustrates that using multi-dimensional (here "n-dimensional") cross plots of the attribute-volume correlation matrix to classify the seismic facies maximizes the resolution of seismic data. This in turn enhances the stratigraphic interpretation fidelity.

Prior to reviewing a version of the multivariate analysis, it is noteworthy to emphasize a few obstructions: 1) Seismic response to geology is always imperfect. 2) Seismic data and calculated seismic attributes contain a large amount of redundancy and noise. Noise tends to obscure the meaningful seismic patterns. 3) Most geologic data violate the assumption of independence. 4) The uncertainty inherent in subsurface geologic data is large, hence the errors in predictions based on these uncertain data are also (very) large. 5) We are not mathematicians.

With those obstructions in mind the process can be outlined: **1)** Generate seismic attribute volumes to expand the information content of the multivariate data set. **2)** Create a correlation matrix that includes the dependent variables (patterns to be recognized) and independent variables (e.g. noise or redundant data). A correlation matrix (Fig. 5) shows the amount of correlation between input attribute volumes in a range -1 +1. **3)** Create n-dimensional cross plots of the variables. **4)** Eliminate the variables that do not significantly correlate to the dependent variables (Fig. 6).

Correlation Matrix		Attribute 1	Attribute 2	Attribute 3
1	Attribute 1	1.000000	-0.153419	-0.001053
2	Attribute 2	-0.153419	1.000000	-0.000247
3	Attribute 3	-0.001053	-0.000247	1.000000

Figure 5: Example of a correlation Matrix of three input attribute volumes

Principal Component Analysis (PCA) is a technique that can analyse multiple variables at the same time. The method computes linear relationships and reduces the dimension-space required to project these relationships by strongly reducing redundant and noisy data while only minimally reducing the information.

The main scope of PCA is the representation of large sets of data in a new vector space with a smaller dimension than the original. This method is a powerful data-driven tool that describes the relationships between multiple variables and their classification as homogenous sets (Fig. 6; cf. Fig. 18, Sections 5.2 and 6.4). The coordinates of the variables in a generated vectorial space represent their contribution to the new components.
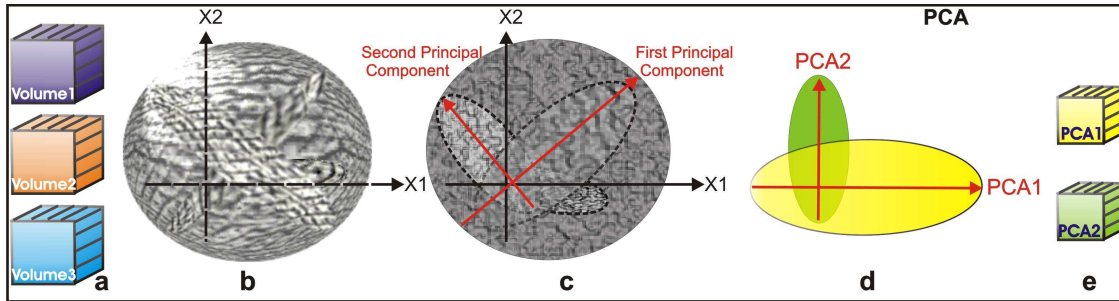

*Figure: 6 Schematic diagram of PCA analysis showing 3-D crossplot of three data volumes (standardized seismic attributes, **a**) that are reduced to two PCA components (**e**). Integrated attribute volume (correlation matrix) is decomposed into a summation of Eigen vectors and Eigen values in a decreasing order. Orthogonal rotations of the coordinate system (**b**, **c**) give distinct discrimination as maximum variance along one of the axis (**d**). Redundant data and noise which do not contribute to the maximum spread of the data clouds are eliminated here.*

The procedure treats information globally rather than by adding together independently-analysed data-matrix subsets, thus avoiding reproduction of the complex relationships among variables. Data objects may be standardized prior to use in PCA to ensure that the all attributes have a similar numerical range, preventing one attribute having a greater significance than another. First, a correlation matrix (Fig. 5) is calculated for the input attribute volumes, and then the eigenvalues are calculated directly from the correlation matrix, representing the variance from the optimal linear transform. This means that the correlation matrix is decomposed (singular value decomposition, Mari *et al*. 1999) into a summation of eigenvalues and eigenvectors (Fig.7). Because the input attributes have been standardized, the variance of each object is 1 and the mean value 0.

EigenVectors		Attribute 1	Attribute 2	Attribute 3
1	eigenvector-1	0.707108	-0.707105	-0.000902
2	eigenvector-2	-0.001611	-0.002887	0.999995
3	eigenvector-3	-0.707104	-0.707102	-0.003180

Figure7: an example of the display of normalized Eigen Vectors.

When the eigenvector table (Fig. 7) is analyzed, the sum of the variances (eigenvalues) will equal the total number of input attributes (Fig. 8). In order to describe the data more effectively, the coordinate system is rotated so that the new X-axis lies along the maximum variance resulting in a distinct discrimination along the axis (Fig. 6). Eigenvalue 1 (component 1) will be aligned along the longest axes of the n-dimensional pattern with maximum variance; subsequent eigenvalues will be orthogonal to each other and of smaller magnitude. In the example of Figure 8 the sum of the values in the eigenvalue column is 3

(1.153421+1.000003+0.846576). The magnitude of the variances of each component is similar and therefore the contributions from each component are of the same magnitude. The cumulated inertia values (Fig. 8) give a guide to the contribution of the selected components to the maximum spread of the data. Component values are calculated by multiplying the eigenvector by the square root of the eigenvalue. This ensures that the components represent the weighting of the original eigenvalues. This table gives an indication of the contribution of each block to the PCA components. PCA identifies the main elongation directions within a multiattribute crossplot and enables a change of input space (where the principal axes are orthogonal to each other) via N-dimensional rotation (Coléou *et al.* 2003).

EigenValues and Cumulated inertia		EigenValues	Contributions	Cumulated	Components-variables correlation		Attribute1	Attribute2	Attribute3
1	component-1	1.153421	38.447364	38.447364	1	component-1	0.759415	-0.759412	-0.000969
2	component-2	1.000003	33.333446	71.780811	2	component-2	-0.001611	-0.002887	0.999995
3	component-3	0.846576	28.219189	100.000000	3	component-3	-0.650605	-0.650603	-0.002926

Figure 8: an example of eigenvalues, the contribution from each component, cumulated inertia (left) and components-variables correlations (right) which give a guide to how many PCA components should be included.

Data reduction is achieved by dropping the dimensions with the lowest variability. The output of this procedure is a set of new 3D volumes called PCA components (Fig. 6). The PCA components are ranked according to their contribution to data variability. The least important PCA components contain noise and redundant information and are usually removed (Linari *et al*. 2003). The remaining components are then projected onto the principal axes, having reduced volume, noise and redundancy for the classification process. The main trends of the crossplots are identified. These principal directions represent the heterogeneity of the multi-dimensional clouds. Finally, a hierarchical classification procedure builds a model of classes or clusters of similar points and compares them to the original seismic data values of the entire cube. Each data value is then assigned the cluster to which it best correlates. The resulting seismic-classification volume

Figure: 9 Hierarchical classification of the seismic data assigns each value of the original data to the cluster to which it best correlates.

synthesizes the many input attributes (Fig. 9). Using this classification volume for the interpretation gives new insights into the internal variability that are essential to enhance our high-resolution seismic stratigraphic analysis.
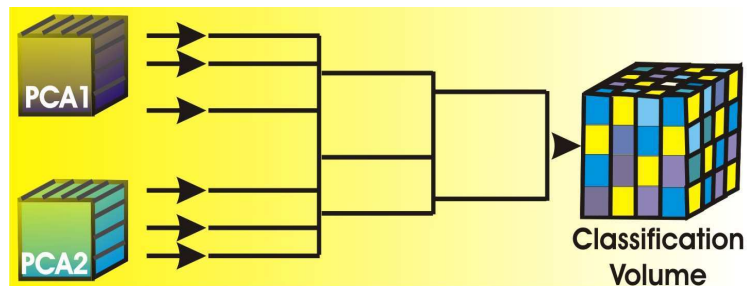
1.5.6 Closing the sequence frequency gap

In some complex environments, such as prograding carbonates with inclined time stratigraphic units, or outer slope and basin floor carbonates where chaotic reflections of turbidite lobes and channel systems dominate, the real geology and seismic response correlate poorly. In addition, limited frequency bandwidth makes it difficult to tie seismic surfaces to log lithology. Other difficulties include the lack of good seismic-facies indicators, discontinuous hard to trace seismic events, and the inability of seismic profiles to resolve high frequency sequence stratigraphic surfaces. This study illustrates that, for accurate correlation of time-equivalent seismic horizons, and to close the gap between high-frequency sequences derived from well data and those interpreted from seismic data, volume-based approaches may currently be a better choice. The advantages of 3-D seismic data are that a truer positioning of discrete reflection points can be calculated in 3-D space and that the data volume created by these reflection points can be inspected along any surfaces that are convenient for interpretational purposes. Subsurface geobodies and structural and stratigraphic detail that appear when a 3-D seismic data volume is sliced along horizontal planes or interpreted surfaces are especially important in understanding why some seismic anomalies exist and how such anomalies should be geologically interpreted. However, picking seismic events and facies on vertical sections and then interpreting their seismic sequence-stratigraphic context in plan view is an approach that can be inefficient and misleading. Many high-frequency sequences are detected, but not fully resolved, on seismic profiles. A more efficient approach is to first interpret the plan-view depositional-system images, then study their seismic sequence-stratigraphic context in vertical slices and 3-D views. Stratal (proportional) slices (Fig. 10) provide an initial view of how depositional systems developed laterally and were preserved in the high-frequency sequence framework. 3-D mapping of sequences and systems tracts can be done more accurately using stratal slices. For an integrated seismic facies

Figure: 10 Stratal Slices (bottom) are proportionally distributed between two reference surfaces and are in conformity with both of the surfaces. Here, they are compared to Time Slices (top), which tend to cross dipping reference time surfaces, and Horizon Slices (middle), which are in conformity near one of the two reference surfaces, but, if there is lateral thickness variation, tend to cross the other reference surface. After Zeng & Hentz (2004).

classification volume, a geobody can be resolved in plan view, even if it can be detected only in vertical section, or not be detected at all in conventional seismic data. This approach contrasts with that used in wire-line-log and outcrop studies, in which the vertical characteristics of a high-frequency sequence are much more useful.
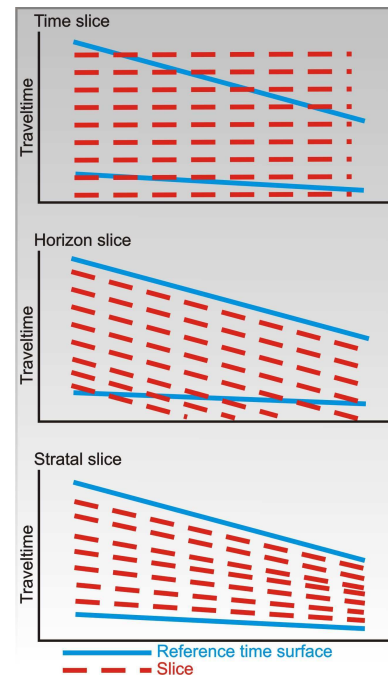
2.   Data

The dataset used in this work includes: Wireline logs of 5 vertical wells, limited core description reports (unpublished NIOC reports), Paleologs including faunal content, a seismic cube covering 300 sq. km. (Processing completed on 14 October 2002). Available well data are referred to in detail throughout the dissertation and 3-D seismic data have following parameters. Pursuant to confidentiality agreements geographic coordinates are not shown.

2.1   3D Seismic Data

The 3D reflection seismic data volume used in this study was acquired in late 2001 by Fugro GeoTeam; processing, through time migration, was completed in late 2002. Details are contained in an Appendix; the relevant information is summarized here.

Acquisition was by two vessels, one recording and shooting and a second under-shooting. Each vessel deployed two ca. 1500 cu.in. sleeve gun source arrays at 4 m depth and 25 m separation; the shot interval was 18.75 m. The recording vessel towed six 240-group streamers at a nominal spacing of 100 m and at 7 m depth. The streamers consisted of 240 12.5-m-long groups with a 12.5 m group centre spacing. The source to near-trace inline offset was 140 m. The geometry resulted in 40-fold and a 6.25 m CDP spacing. The data were recorded in SEG D format, in 6.114 second records at 500 Hz, with a 4 Hz, 18dB/octave low-cut filter and a 206 Hz, 264 dB/octave high-cut filter.

The most important processing aspects are that the data are pre-stack time migrated, processed largely in 12.5 x 25 m bins but later resampled to a 12.5 x 12.5 m grid, and early NMO and migration was based on velocities picked on a 1000 m grid, whereas later NMO and migration used velocities picked on a 500 m grid. The filtering passband in the stratigraphic interval studied here is 12-60 Hz at 1800 ms and 10-45 Hz at 2600 ms.

2.2   Quality control

One of the most important aspects to the ultimate success of stratigraphic interpretation and reservoir characterization is the quality of the data. In the interpretation process, data quality must be examined. Although it is impossible to locate all of the errors in a data set, systematic examination can identify many, for example out of range values or spikes within the logs; these must be eliminated. For those that can not be easily found, such as seismic noise and redundant data, the best we can do is attempt to reduce them.

Surface seismic data can be checked for artifacts by comparing it to synthetic seismic traces generated from well data. The synthetic traces are generated through petro-acoustic modelling. Here,

Paradigm's NexModel software was used to model two key wells to confirm that seismic trace shape could be used as a stratal thickness indicator within the Cenomanian Khatiyah and Mishrif Formations (main reservoir unit). This quality control showed that the seismic image does not contain misleading artifacts.

Synthetic seismic traces were generated from sonic and density logs at wells E1 and D1. The acoustic impedance logs were blocked for the seismic modelling taking care that all the main interfaces were represented by impedance changes (Fig. 11).
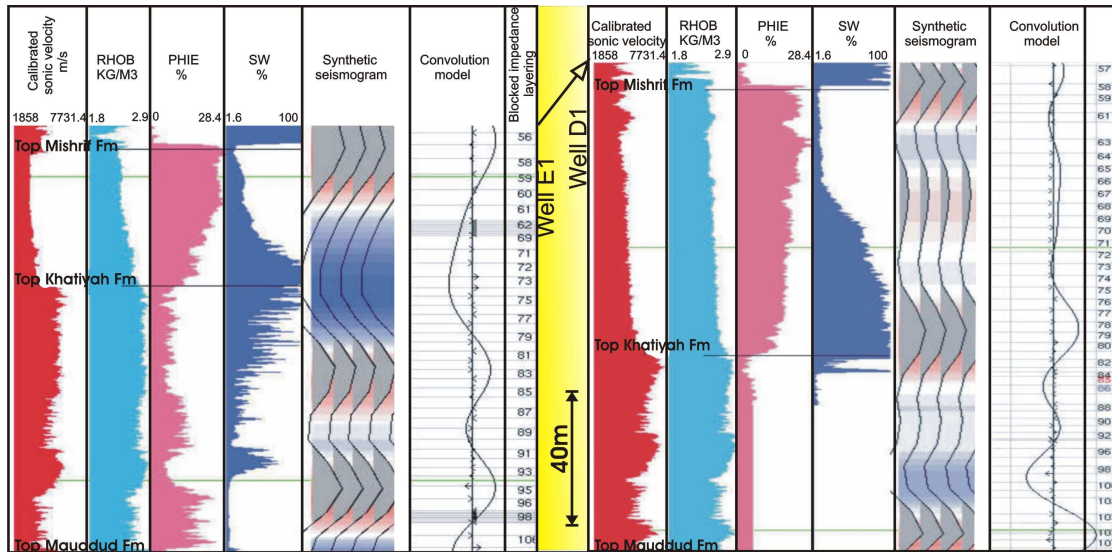

Figure: 11 The wireline logs used for Petroacoustic modelling at the wells E1 (left) and D1 (right) are calibrated velocity from sonic, density, porosity and water saturation. The synthetic seismograms are generated from sonic and density log. A convolution operator produced the convolution model using blocked acoustic impedance layers. The correlation coefficient between synthetic seismogram and convolution model is 0.98 for both wells.

A convolution operator generated model traces at both well locations, using petrophysical logs (porosity, density and water saturation). Iterative testing determined the number of blocked impedance layers required for the correlation coefficient between model convolution and synthetic seismograms to reach 0.99 at the well locations. A seismic sensitivity analysis showed that layer thickness greatly affects the seismic signal shape. It was also determined that amplitude changes were influenced by tuning effect. Changes in bed thickness and porosity along a horizon manifest themselves as changes in seismic trace shape, even for beds that are considerably below tuning thickness. Variations in porosity are detectable: an increase in porosity causes an increase in amplitude at the base of the porous interval and an increase in the travel time. The variation in fluid content is not seismically detectable.

The petrophysical properties of the blocked impedance layers are known at the well locations. Using an actual seismic trace at a distance from the well (a "prospect location"), the modelling

system calculated new properties (porosity, density and water saturation) through an iterative process in search for the best fit between the model trace and actual seismic trace. At each iteration the system calculated a cross correlation between calculated model trace and seismic. The properties of the iteration that produced the best fit were applied to the model. The difference in stratal thickness between the well and prospect affected the model trace shape, and the initial correlation coefficient between model trace and seismic trace reached 0.96. Slight manual changes of the porosity affected the relative amplitude of the main peaks and increased the correlation coefficient to 0.98. This procedure constrained the end points for the two wedge models created for the interwell area (Fig. 12). The wedge models, based on linear interpolation, satisfy the actual seismic data. Well C2 was used for a blind test to evaluate the physical property calculations by forward modelling (Fig. 12).
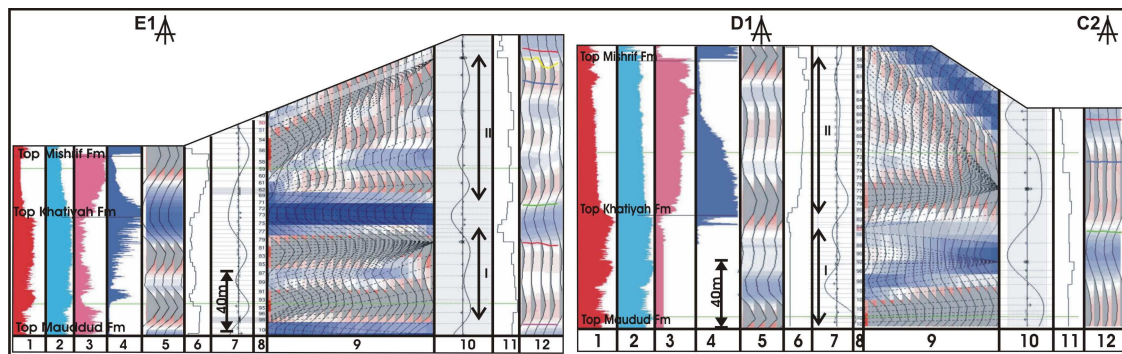

Figure: 12 Petroacoustic modelling at the wells E1 and D1 revealed two wedge models. This figure illustrates: wireline logs used for the modelling (1-4, see Fig.11for details), the synthetic seismograms (5), blocked porosity used for the modelling (6), convolution models at well locations (7), blocked acoustic impedance layering (8), wedge model generated through an interpolation between model trace at well and prospect locations (9), model trace at prospect location (10), blocked porosity predicted for prospect locations (11) and actual surface seismic traces at prospect locations near wells (12).

3.   High-resolution seismic stratigraphy of the Middle Cretaceous carbonate platforms, Persian Gulf.

This section focuses on basic stratigraphic evolution and seismic interpretation of the Middle Cretaceous carbonate platforms in the Sirri C and D study area. It summarizes information contained in Paper 1 (Farzadi, P. 2006a). The structure of this section generally follows the paper (Part II).

3.1   Sequence concept

During Albian to Turonian times, a basin-wide, transgressive, shallow-water carbonate system developed on the NE Arabian Platform, including the present Persian Gulf and ZFTB. This carbonate system includes of one of the most prolific regional reservoir units, the Mishrif Formation and its lateral equivalents. The stratigraphy and development of this carbonate system has been intensively studied on the Arabian Peninsula (e.g. Burchette 1993; Pasco *et al.* 1995; Van Buchem *et al.* 1996,

2002a). Such is not the case in the Iranian sector of the Persian Gulf, where sequence concepts using subsurface data have not been applied. Thus in the Iranian Persian Gulf the field-scale definition of this important reservoir has been precluded.

In this study a standard suite of lithofacies tracts associated with transgressive and highstand systems tracts (TST and HST, respectively) is used to predict the development of reservoir, source and seal facies in the Sirri C and D oil fields. Sequence stratigraphy made a step forward through application of sequence concepts using wireline logs and core description (High resolution sequence stratigraphy) to interpret an additional level of sequences within seismically resolvable depositional sequences. Analyses of the seismic character revealed the response of the carbonate sediments to sea-level rise. Rising sea level causes a higher rate of sediment production (keep-up) forming isolated build-ups and thick cycles (Fig. 13). In contrast, transgressive clastic systems are characterized by updip trapping of sediment supply.

3.2 Establishing a 1-D cycle hierarchy

Depositional cycles and their component lithofacies interpreted from well data are fundamental for establishing a 1-D cycle hierarchy. Core description available from industry consists of qualitative description as visual estimates of various core properties, typically including lithofacies (texture, lithology, grain components, sedimentary structures, pore types) and general comments. This information is used to qualify the properties that will be used to calibrate wireline logs for input into a 3-D reservoir model. Calibrating the log to the visual core description establishes the geological meaning of the log signature for critical lithofacies types, cycles, and key surfaces recognized in core.

Dramatic shifts in depositional environment documented in core may represent the most important well log correlation ties in the data set. Carbonate reservoir systems are dominated either by physical sedimentary processes or by reef-building and similar biologically dominated processes. The log-core calibration allows the interpreter to recognize the log-signatures of significant variations in depositional energy. Otherwise the dramatic depositional-environment shifts, so important to sequence stratigraphic models, might be missed. In this study, the marked tops of the depositional environments led to candidates for potential sequence boundaries and maximum flooding surfaces.
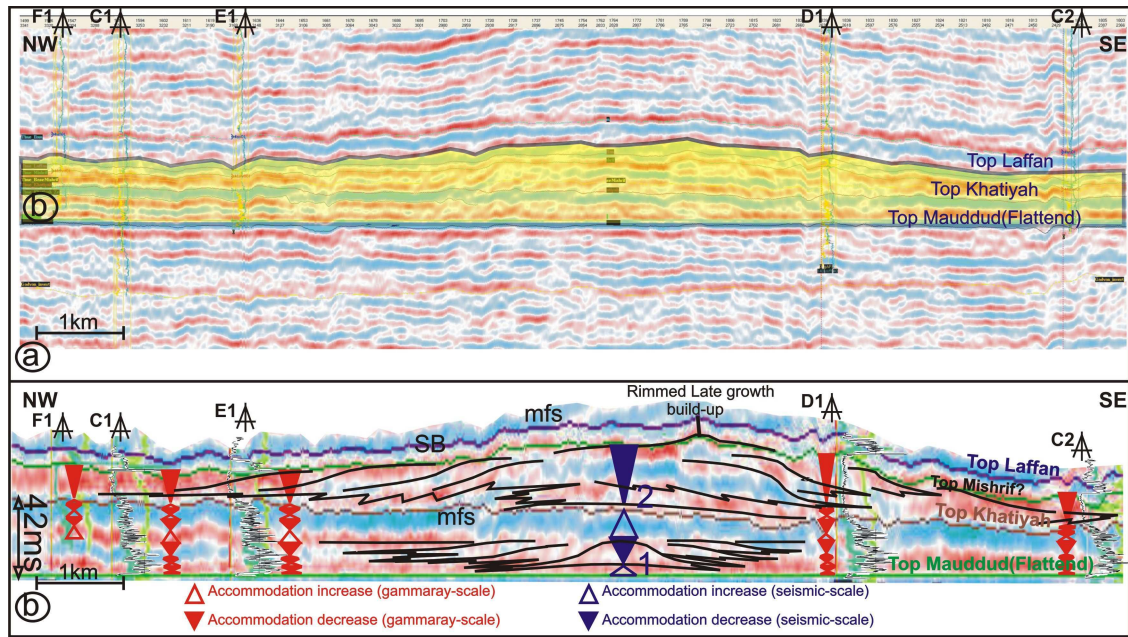
Figure: 13 a seismic section cutting through all wells (a) flattened on the interpreted top Maudud Formation, a well-developed orbitolina-rich limestone. In the area between wells, two superimposed clinoform geometries are developed within the Khatiyah (1) and Mishrif (2) Formations (b, vertically exaggerated). A combination of the geometric control from the seismic data with the lithological and facies control from the wells gives insight into more accurate interpretation of seismic events (Farzadi 2006 a). Note the late-growth build-up geometry at the top of the upper platform. This geobody was generated during back-stepping of this platform due to a northwest tilting of the basin prior to the Turonian emergence.

3.3   Correlation procedure

In calibrating wireline logs and then building a subsurface geologic model it is essential to describe in detailed the vertical lithofacies succession referred to as cyclicity. The initial interpretation of the vertical cycles provides a template for identifying stratigraphic trends and higher-order surfaces. Only through correlation with adjacent wells will it be determined which vertical lithofacies successions mark significant cycles and sequence boundaries, as opposed to local variations. The cycle framework is evaluated based on trends in accommodation (stacking patterns) corresponding with the major flooding or exposure surfaces.

For example, in the Sirri C-D area upper Cenomanian platform shoreface deposits are occupied by rudist shoals and bioherms and their flanking bioclastic grainstone deposits, reworked into bedforms in which their size depends on shoreline orientation and basin physiography. Shoreline-parallel and offshore-directed transport directions are recorded in these grainstones. This lithofacies is preserved as a highstand deposit because of early beach-rock lithification of the foreshore sediments. Cycle-thickness variations and six packages of upward-thickening and upward-thinning trends indicate potential transgressive and highstand systems tracts. The clear stratal geometries interpreted from seismic data provide an understanding of accommodation trends (Fig. 13). Dividing every

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depositional cycle observed in the 1-D data into transgression and regression portions leads to describing the cycle symmetry. The first five depositional sequences lie in the Khatiyah Formation and are interpreted to indicate the progressive development of an intrashelf basin, on the basis of abundant small globigerina, Favusella washitensis (Hedbergella in core reports) and Oligostegina at the top. An isolated carbonate platform developed within the Khatiyah intrashelf basin and is resolved by the high-resolution seismic interpretation techniques described above. This isolated platform is a potential reservoir. High concentrations of organic matter in intrashelf basins, associated with shoaling upward successions, can create source and reservoir within the same depositional system. Prediction of the location of the isolated carbonate platforms is a real challenge because they can be initiated on subtle palaeogeographic highs, not necessarily interpretable from conventional isopach analysis. It is obvious that neither seismic nor well data can alone explain the development of these isolated geobodies.

3.4   Cycle symmetry and thickness variation

The analysis of cycle symmetry provides an important context for paleotopographic studies. This is usually combined with stacking pattern analysis that is, documenting systematic upward changes in cycle thickness. For slow sea-level change, cycle thickness provides a proxy for accommodation and upward-thickening and upward-thinning trends define potential transgressive and highstand systems tracts, respectively. Figure 13 illustrates this for the studied interval. If sea-level fluctuations are sufficiently rapid that cycle thickness is limited by the sediment production rate, cycle thickness trends, while useful, is not a proxy for accommodation. Thickness alone may not lead to a unique solution, and thickness-based stacking pattern analysis must be combined with analysis of lithofacies proportions and stratal geometries to interpret accommodation trends and changes in lithofacies evolution. At the top of the succession the final stage of relative sea-level rise and overlying Turonian erosional surface indicate trends in creation and loss of accommodation and resultant lithofacies changes.

3.5   Isochor maps and horizon flattening

Isochor maps of each stratigraphic interval have been examined to ensure that a reasonable depositional trend has been correlated for each interpreted stratigraphic horizon (Fig. 4 a-f). For example the Khatiyah Fm. isochor map (Fig. 4c) shows a sheet-like feature tapering gradually to the SE. This is consistent with wireline log and core interpretations which show deepening upward ending up with a major flooding event and differential subsidence increasing towards the northwest. In general, major thickness changes should be examined for data entry errors, correlation busts, and seismic interpretation and isochor errors.

Isochor maps of the Sirri C-D carbonate platforms illustrate that the higher rate of platform aggradation was followed by northwest tilting of the basin. This tilting formed an isolated late-growth build-up as the platform stepped back towards the southeast. The growth of this centrally located bank, with an elevated rim at the top of the platform (Fig. 13), kept pace only over a local shoal area. This build-up was the last phase of drowning and backstepping of the platforms before Turonian emergence. The isochors show no significant along-strike variation in clinoform thicknesses, confirming the integrity of the stratigraphic interpretation. Both the isochor maps and horizon flattening on the Mauddud, Khatiyah and Laffan seismic markers shows no evidence of significant syn-depositional folding, faulting or salt diapirism. The relatively slightly greater subsidence of the Khatiyah Formation towards the northwest is recognizable both on the isochor and flattened seismic section (Figs. 4 and 13 a-b).

3.6   Diachronic nature of clinoforms

Carbonate platform margins have inclined geometries, which results in diachronous lithological units. This has important implications for reservoir characterization, because it is these diachronous lithological surfaces that are imaged in seismic reflection data. Building even the best geological model without considering sequence-stratigraphic correlation will leave important aspects of reservoir architecture poorly understood. Recognition of transgressive and regressive cycles is essential for correlating the diachronous seismic surfaces. Analysis of the hierarchy of cyclical variations using biostratigraphy, lithostratigrahy and wireline logs, integrated with sequence stratigraphic principles, resulted here in a detailed geological model. This model is of great value for understanding and predicting Mishrif Reservoir heterogeneities and provides an opportunity for evaluation of the Khatiyah Formation.

4.   Interpretation of carbonate platforms in horizontal dimension using supervised Neural Network

This section focuses on unsupervised and supervised predictive methods to determine reservoir properties at distances from wells. Although in manuscript form, it has not been submitted for publication and, because of its applied exploration nature, is not included in Part II of the Dissertation.

4.1   Reservoir prognosis in plan view

The construction of a solid 3-D model starts with the conversion of 1-D data into 2-D panels of interpreted lithologies, petrophysical properties and seismic mapped surfaces. This 2-D interpretation stage is a fundamental conceptual step that forms the skeleton that is subsequently expanded into 3-D

space using a variety of deterministic and/or geostatistical techniques. This is also the critical stage that differentiates a good model, having predictive potential, from a fancy but rather useless 3-D geocellular model. The 2-D environment represents common ground for geologists, with their background in construction of maps and cross sections that form the basis of our collective frame of reference (Kerans & Tinker 1997).

In the Sirri structures, SE Iranian Persian Gulf, the reservoir quality in the Upper Cenomanian Mishrif carbonate reservoir and prospective Albian-Cenomanian Khatiyah carbonates is considered to be mainly controlled by primary depositional facies variability linked to a paleokarst overprint. The presence of two vertically-stacked carbonate platforms overlain by an isolated bank, all lying between two domal structures, was identified in the first stage of the study (Farzadi 2006a). The geological model, based on seismic sequence stratigraphy and well data analysis, suggests significant hydrocarbon potential in the virtually-unexplored area between the two producing domal structures. Key interpretation difficulties associated with developing these undocumented reservoirs were the limited lateral extent of the rudist build-up margins, the isolated build-ups in the platform interior, and the lack of amplitude response of the internal heterogeneities. Delineating these geobodies in plan view using conventional amplitude stacks is challenging (Hunt *et al*. 2003). In cases where reservoir continuity is greater than the well spacing, traditional, deterministic approaches to well correlation and extrapolation may be utilized, with the sequence concept used to generate a single, most realistic interpretation. However, where reservoir bodies are narrower than well spacing, as in Sirri, or where marked heterogeneity exists, as in Sirri, then stochastic (or probabilistic) methods are employed to complete the interwell volume (Kerans & Tinker 1997). The Sirri plays are not apparent in amplitude seismic. As an alternative to conventional amplitude-based analysis, seismic-trace-shape analysis, implemented as neural-network seismic facies classification, is an extremely useful technique.

4.2   Unsupervised neural-network facies classification map

An unsupervised neural-network (Lawrence 1994; Gurney 1997) seismic facies classification (Coléou *et al*. 2003; Dowd & pardo- lgúzqiza 2005) was used to map seismic facies in several stratigraphic intervals. This unsupervised seismic facies classification is a data driven process (Linari *et al*. 2003; Poupon *et al*. 2004) used to assess the spatial distribution of seismic trace shapes. Based on the initial Sirri seismic sequence-stratigraphic model, seismic data in 40 ms time windows, referenced to the top Platform 1 and top Platform 2 horizons, were used to characterize the main platforms over the entire 3D survey (Figs 13 a & b). A self-organized neural network (Gurney 1997; Rainer 2002) identified the trace shapes in the window and generated a series of synthetic traces representing shape variation within the interval. Ten synthetic trace models were sufficient to

describe Platform 1; 9 were sufficient for Platform 2. These synthetic trace models are displayed in Figure 14, sorted in a panel below the platform maps. Based on correlation maxima between actual and model trace shapes, each seismic trace is assigned a model trace and its colour. These data are used to generate seismic facies maps which show the similarity between the seismic traces and model traces. Consequently, the main platform bodies are confirmed (Fig. 14). The quality of the result is evaluated using two additional maps: a correlation map showing the correlation between actual seismic traces and synthetic model traces, and a discrimination map representing the difference between the correlation map and the second best possible correlation. Higher values on the correlation map and lower values on the discrimination map indicate a discriminant and unique result (Fig. 15).
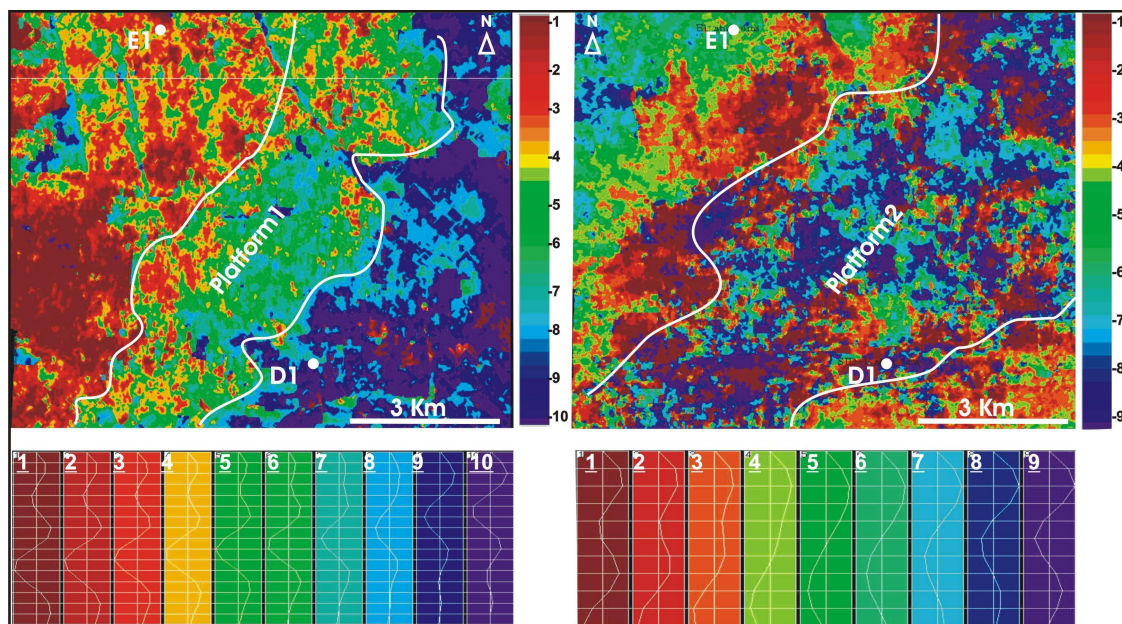
Figure: 14 Unsupervised facies classification maps of platform 1 (left) and platform 2 (right) show the distribution of seismic trace shape similarity. The panels of the model traces generated by a self-organized neural network are shown below each map. These models represent the diversity of seismic signal shapes over 40 ms of the 3-D seismic interval. Colour codes in both maps do not have the same geological meaning. However, the trace shape analysis can delineate two isolated geobodies.

4.3   Petroacoustic modelling

Integrated petroacoustic modelling (Poupon *et al*. 2004) optimizes the definition of the marginal wedge of the upper carbonate platform, where the build-up geometries are developed. Focusing on the margin of the platform is better to classify trace-shape variations and use the results to supervise the facies classification in this prospect area. The procedure was also discussed in Section 2.2 and Figures 11 and 12.

The modelling is based on a well, where the acoustic, lithological and petrophysical properties are known. It proceeds by modelling a prospect point near the well, modifying first the thickness of the layers (i.e. blocked impedance layers) and then porosity. A convolution operator propagates these physical properties and generates a model trace for the unknown area. The modelling is a 1D iterative process in search of the best fit between the convolution model trace and the seismic trace at the prospect location (Fig. 12). A convolution model with a correlation coefficient of 0.99 has petrophysical meaning, such as porosity, density and water saturation for each blocked impedance layer. Thus, for carbonate platforms with seismic trace shapes that can be modelled from petrophysical logs, the seismic facies maps can be calibrated to platform thickness and petrophysical properties.

Performing this modelling procedure and an interpolation between the generated model traces at well locations and prospect locations generated two wedge models at the NW and SE margins of the carbonate platform
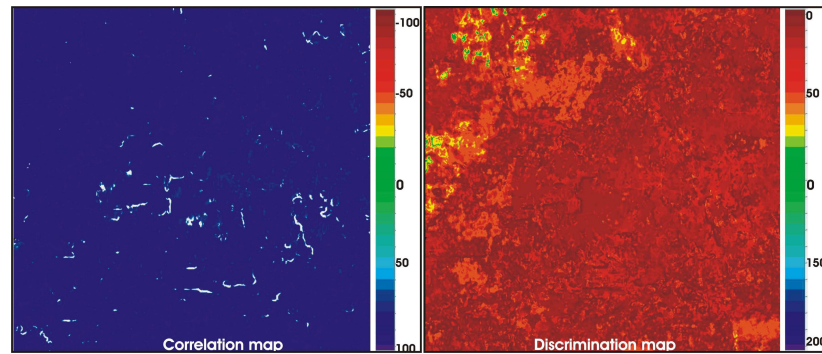
Figure: 15 Quality control maps. Left map shows the correlation between each seismic and model trace for Platform 2. The correlation threshold is set to 80%, thus all cells with less than 80% correlation are painted white. Right map shows the difference between the correlation and the next best possible correlation. Low values indicate a strong discriminant and unique model.

(Fig. 12). The resulting wedge models best represent the signal shape variations at the platform margins and can be used as training sets for neural-network classification of seismic trace shapes. In general, this quantitative forward modelling can be calibrated against known basins and provide valuable learning sets by testing the impact of differing porosity and lithology combinations on the resulting stratigraphic models.

4.4   Supervised classification of seismic data

The interwell uncertainty of reservoir properties can be significantly reduced if a valid relationship can be established between the seismic trace and petrophysical properties at wells (Pramanik *et al*., 2004). Here, an estimation of the physical relationship between log properties and the surface seismic trace (Coléou *et al*. 2003) is established using a single seismic attribute: trace shape.

Model traces, generated in the wedge models, can be used in classification, keeping in mind that this time the model traces have petrophysical meanings linked to their shapes. The forward modelling

performed over a limited area (platform margin around well location), therefore using the generated model traces for the classification, results in generating facies maps, which are more informative around the well with potential errors increasing away from the well. These maps proved to be useful because they could uniquely reveal the internal heterogeneity nature of the platform margin as well as their accurate external morphology around the well (Fig. 16). Due to lack of petrophysical logs from the lower sections of the wells D and C2, supervised map of Platform 1 cannot be generated.

4.5   Exploring subtle build-up geometries

A clear differentiation between the platform margins and basin facies is essential to delineate the development of the Mishrif carbonate platform. Amplitude interpretation typically does not clearly differentiate the spatial facies heterogeneity because of amplitude anomalies resulting from tuning effects.

Predicting the geology from seismic response is challenging. There is commonly not a unique solution to the relationships between seismic attributes and petrophysical properties. The relationship between changes in these properties and attributes may be established by petroacoustic forward modelling where the geology is documented. Modelling makes it possible to narrow down the range of possible solutions and gives geologic meaning to seismic attributes. In this study subtle changes in seismic response are interpreted to result from variations in lithofacies, and reservoir parameters can be defined by seismic trace shape with greater detail than in time and amplitude mapping.

In unsupervised classification, the respective similarity of individual traces is used for the analysis. Supervised
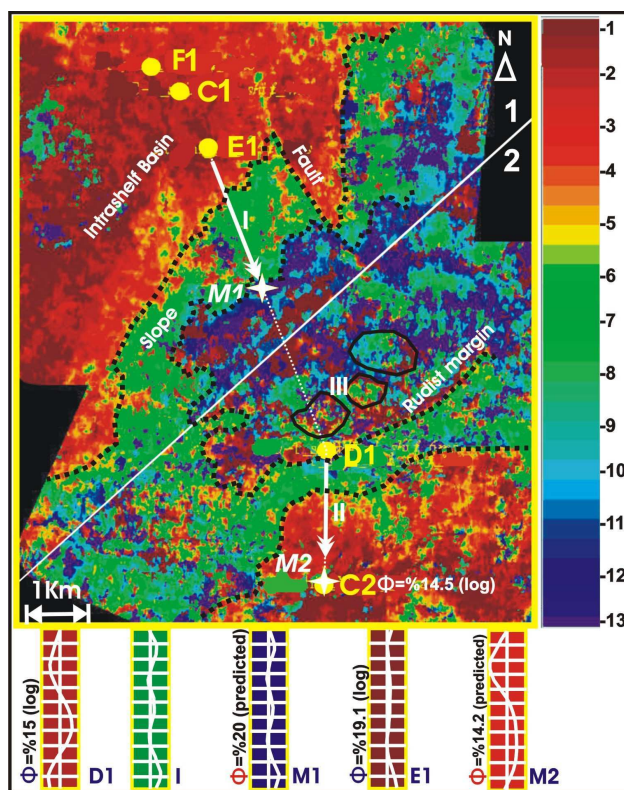

Figure: 16 Supervised seismic facies classification map of Platform 2, generated based on the trace shapes derived from petroacoustic modelling. This map is more informative around the well locations at the platform margins. Upper part of the map (1) is generated from the modelling at the well E1 (I) and the lower part of the map (2) at the well D1 (II). I and II and associated arrows are the directions of petroacoustic modelling at the Platform 2 margins. M1 and M2 are the modelling targets away from the well locations. Isolated build-ups (III) in the Platform 2 interior and the boundaries between different parts of the platform are differentiated on this map. Trace shapes at key positions on the map (D1, I, M1, E1 and M2) are shown with their log or predicted porosity values. Well C2 (white star) is used for the blind test. The predicted (14.2%) and actual porosity (14.5%) values at well C2 location show reliability of the modelling around wells.

classification makes it possible to impart geologic meaning to the trace shape analysis; however it is valid only for prospect locations near a calibration well. It may be possible to use petroacoustic modelling to predict the signal shape response of subtle geological features of interest in undrilled areas. A supervised trace shape analysis could be used to explore subtle build-up geometries and predict their petrophysical properties within small areas near a well. Figure 16 illustrates in plan view the isolated late-growth build-ups explained in 3.5, but here resolved by supervised seismic classification.

5. Sequence analysis in 3-D space using seismic volume attributes, Dariyan Formation, a prospect reservoir in the SE Persian Gulf

This section uses advanced volume-based interpretation of seismic attributes to interpret the development of potential build-up geometries within the Aptian Dariyan Fm., in the Sirri area. The techniques used address high resolution seismic sequence stratigraphic analysis. It summarizes information contained in Paper 2 (Farzadi, P. 2006b). The structure of this section generally follows the paper (Part II).

5.1 Complex geology, adding details to the subsurface interpretation skeleton

The Aptian Dariyan Formation correlates with the lower and middle Shu'aiba Formation, a prolific reservoir in the UAE (Calavan *et al.* 1992; Terken *et al.* 2001; Fisher *et al.* 1997; Duffy Russell *et al*. 2002; Van Buchem *et al*. 2002b). It is a laterally extensive, shallow-marine carbonate platform consisting of mainly mud-supported and some grain-supported limestones with rudist debris. The overall regional setting during deposition of the Dariyan Formation was a shelf-to-shallow basin complex, resulting in progradational mounds. The time equivalent deposition based on the literature corresponds to a 3rd order sea-level highstand (Sharland *et al.* 2001). The best quality reservoirs are anticipated in build-up facies. Seismic response within the interval includes discontinuous reflection and chaotic events, which are difficult to trace laterally (Fig. 17).
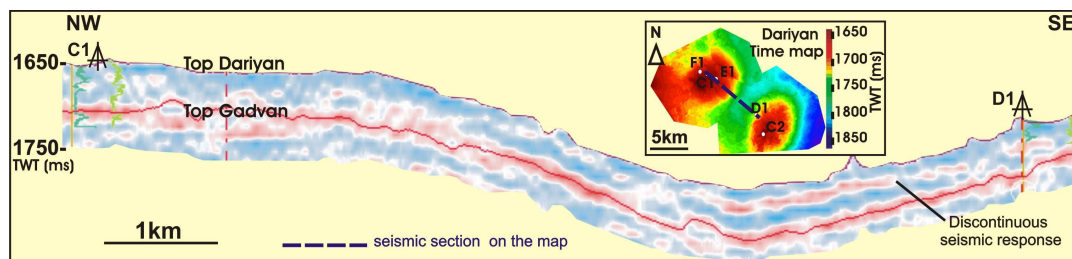

Figure: 17 A section through the conventional seismic data with a NW-SE orientation (figure inset) illustrates discontinuous and chaotic seismic response within the Dariyan Formation in the Sirri C-D oil fields.

An interval-based single-attribute facies classification (for example trace shape analysis) is not a reliable solution when seismic response within the interval is discontinuous. A range of seismic reflection and attribute patterns characterizes the internal heterogeneity of the build-ups. A synthesis of different 3-D attribute volumes can be used to reveal meaningful variability within the seismic data from the Dariyan Formation by adding details to the information content.

5.2 Expanding the information content by data reduction

Multiple post-stack seismic attribute volumes, if integrated, can expand the information content for seismic facies classification. Processing the huge number of multi-dimensional data samples within the data volumes, however, is demanding. Although integrated 3-D attribute volumes consist of significant information, it is a challenge to capture the geologic and sequence stratigraphic patterns inherent in the data. Increasing the number of input data volumes dramatically increases the data redundancy.

Multi-variable seismic data include noise and redundant data as components with the least contribution to the data variability but great contribution to blurring and obscuring geological patterns. N-dimensional cross-plots of the data show the main elongation trends as a limited number of subclouds (clusters), indicating that the true dimensionality of the data is much lower than the large number of samples would suggest.

Principal Component Analysis (PCA) examines the cross-plotted patterns and finds the principal directions of variances within the multi-dimensional data. These were discussed previously in Section 1.5.5. PCA compresses the bulk of the variance in data into a few vector components (Eigen vectors) by orthogonal rotations of the coordinate system. The essential information about the dataset is contained in the first few principal components, which will be used for a hierarchical facies classification (Fig. 18). Reducing noise and redundancy enables the classification process to capture seismic stratigraphic patterns hidden in the data volumes.

Performing the data reduction procedure on six post-stack attribute volumes within an interval of 70 ms from the top Dariyan Formation resulted in recognition of 4 principal components (out of 6) (Fig. 18). These components with 93.4% contribution to the dataset are projected onto the principal axis and the actual attribute values associated with each volume are replaced by the projected values. Meaningful population subsets represented by a class for each subset characterize the data volume. Examining the 2-D cross-plots of different components and modifying the number of classes to achieve minimal overlap between them, determines the appropriate number of classes. Two classes may appear right next to each other in one cross-plot, but may actually be some distance apart when viewed on another cross-plot.
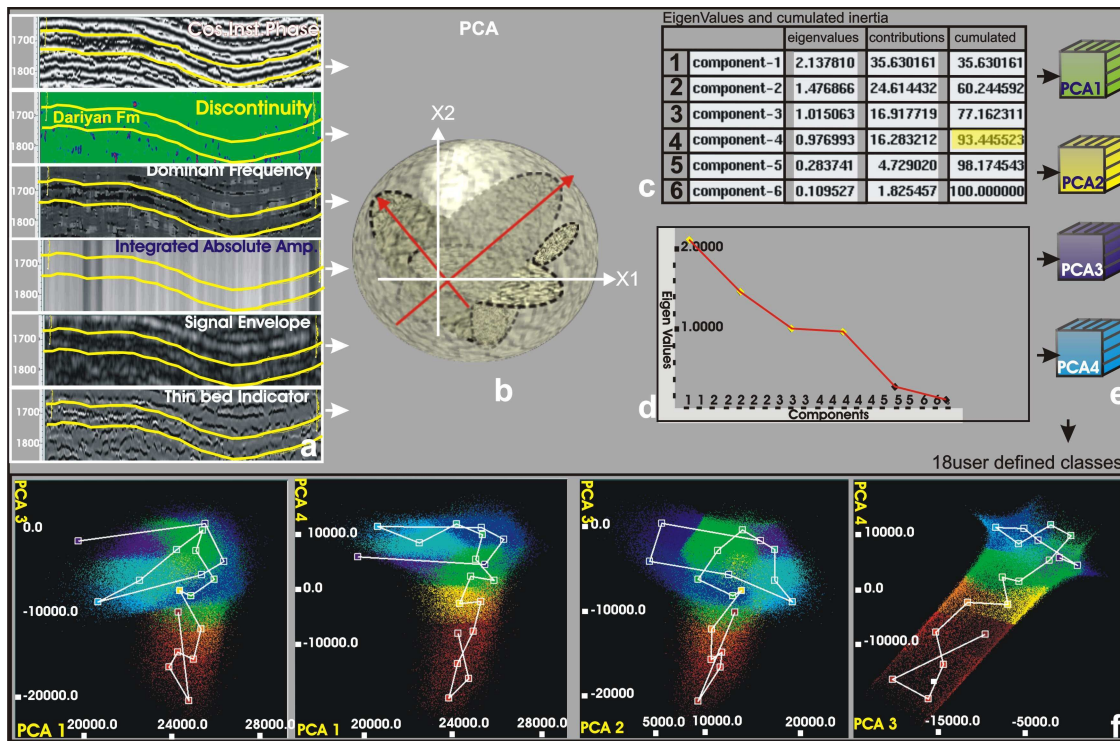
Figure: 18 Multiple attribute volume analysis of complex internal features of the Dariyan Formation in the Sirri C-D structures. Six seismic attribute volumes (a) extracted from the study interval (70 ms) are integrated and redundant data are reduced by PCA (b) in a vectorial space. PCA explains the maximum variance of the data cloud by number of Eigen vectors and values in a decreasing order (c, d). Four new volumes are generated (e) that contain the most important information from all input volumes. Classification of the original seismic data based on the maximum elongation trends (patterns or clusters) recognized here generates a single volume (Fig. 9). Cross plots of the classification data (f) show the heterogeneity of the data.

5.3   The first truly 3-D interpretation of the Dariyan Formation in the SE Persian Gulf.

A hierarchical seismic facies classification applied to the entire dataset within the Dariyan interval assigns original data points to the appropriate facies class (subset) based on Euclidean distance. The classification generates a single classification volume with information inherited from all input attribute volumes.

A combination of wireline logs and core descriptions revealed three depositional cycles as coarsening and fining upward successions developed during the deposition of the Dariyan Formation (Fig. 19). The Dariyan isochor map shows a little thickness differentiation suggesting an eustatic origin for the depositional cycles. The lower cycle consists of calcareous shale with rudist debris. The classification volume resolves a transported-sediment geometry corresponding with the lower depositional cycles, probably correlating with tempestite deposition within the Lower Shu'aiba in northern Oman (Pittet *et al*. 2002). Application of stratal slices allows delineation of this geometry in

plan view (Fig. 20). Neither conventional seismic data nor gamma ray layer-cake lithostratigraphic correlation can show the distribution of this geobody.

A vertical lithofacies progression produced by aggradation of the lower Dariyan succession contains mudstone passing upwards into wackestone and grainstone (Fig. 19). However, microbreccia lithofacies and very shallow-water Bacinella lithofacies are found resting directly on the aggradational inner platform lithofacies; this would indicate a key lithofacies tract offset, in this case a downward shift in coastal onlap. In conjunction with limited core information, lithology and porosity data from wireline logs are used to distinguish carbonate lithofacies types and carbonate cycles. Therefore, lithology and porosity data are very important petrophysical parameters for stratigraphic interpretation (Fig. 19).
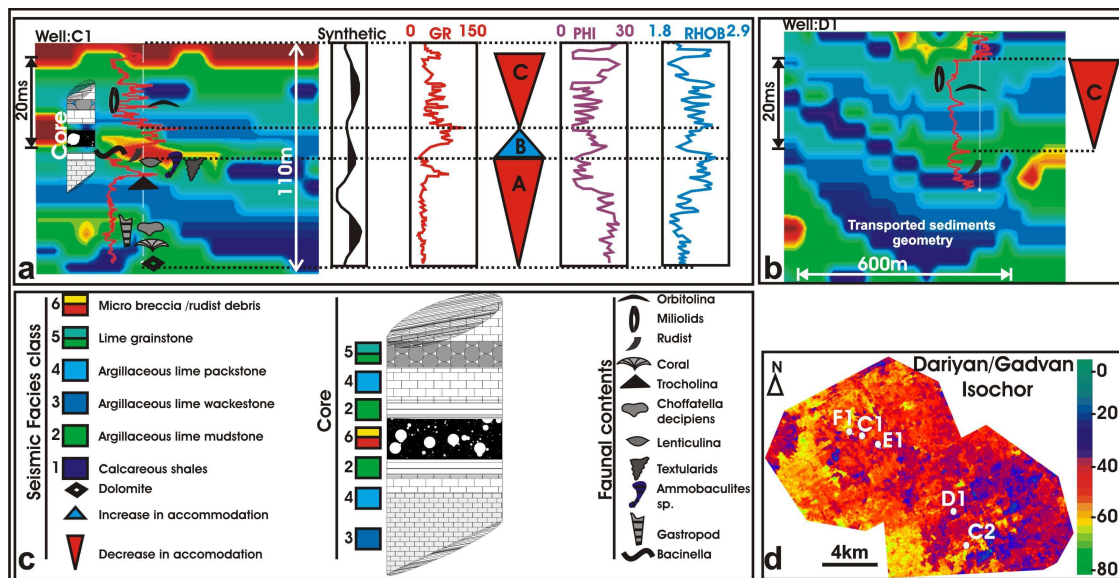
Figure: 19 Well calibration within the Dariyan interval in wells C1 and D1(a and b): three fining and coarsening-upward successions corresponding to a 3rd order highstand relative sea level are interpreted from wireline logs and lithology, faunal content from core descriptions (a and c). A comparison between synthetic seismogram, GR, PHI, RHOB at Well C1 (a) and classification data (a and b) shows that the latter is more diagnostic. Fossils from core descriptions (c) are projected over the classification data at well location (a). Six facies classes are recognized (c); their 3-D distribution is discussed in the text and in Farzadi 2006b (this volume). The Dariyan isochor map (d) shows a little thickness differentiation indicating less influence of deformation during the deposition of the Dariyan Formation.

The middle transgressive part (B, blue in Fig. 19) is characterized by a basinward-tapering cycle that steps progressively landward or, in later stages of the TST, stacks vertically. In settings with high carbonate productivity, TST deposits may be represented as purely-aggradational stacks of margin growth followed by more rapidly prograding highstand strata.

Depending on the magnitude of eustatic fluctuations associated with the unit, TST carbonates can include important build-ups. This is because the rapid addition of accommodation during sea-level rise permits the unhindered upward growth of high-productivity reef settings and concomitant

drowning of other lower-productivity surrounding lithofacies. The Aptian middle Dariyan Formation of the Sirri oil field contains rudist build-ups on the platform top that record high accommodation during base-level rise associated with TST deposition (Farzadi 2006b). Rudist mounds in the TST are positive build-ups with local relief, whereas rudist facies in the highstand are low-relief shoals (upper Mishrif).
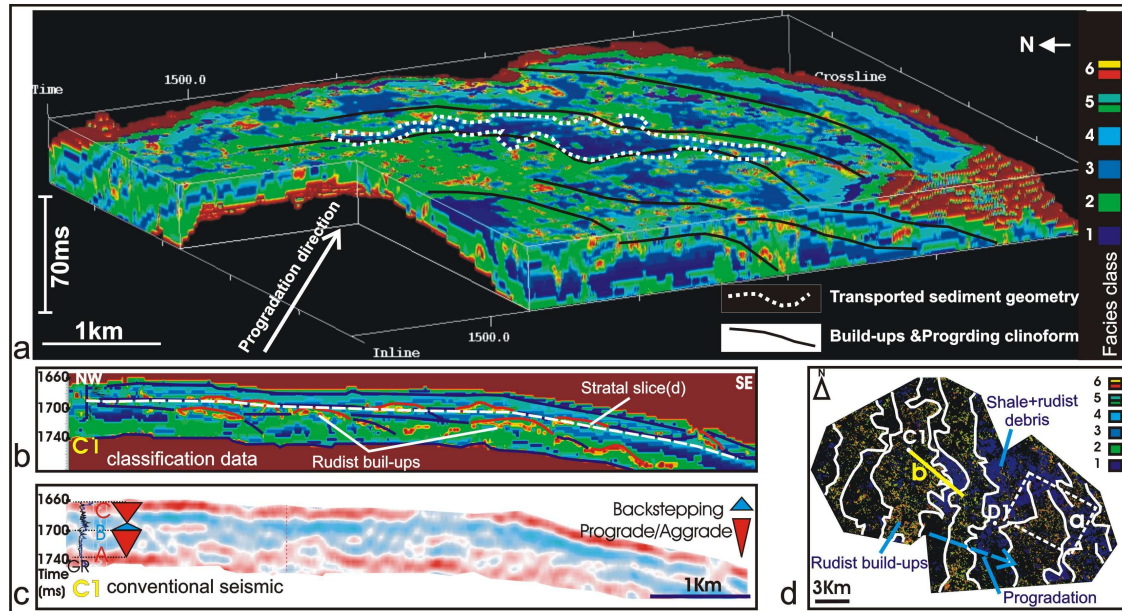
Figure: 20 3-D view of the classification data (a) and sections through it (b) and the conventional amplitude stack (c) show the development of rudist build-ups and corresponding depositional cycles (c). A stratal slice (d) through the classification volume (dashed-line in b) shows the distribution of the build-ups in plan view. Location of the 2-D sections is shown in d.

Stratal slicing through the classification volume made it possible to generate the plan view of the lateral distribution and progradation direction of the rudist build-ups developed within the middle Dariyan formation. The upper Dariyan is an upward-thinning and shallowing unit that represents the record of progradation at the shelf margin. Progradation distance is a function of space to be filled by each depositional event, such that for a given sediment volume produced, a shallow dipping carbonate ramp may prograde 1 km where a steep margin may prograde a few meters (Harris 1991).

5.4   Reservoir architecture

Seismic facies analysis based on seismic/sequence stratigraphic concepts integrates subsurface data and provides a framework for 3D reservoir simulation studies. A multiple attribute volume classification provides a truly 3-D interpretation of build-up geometries within the Aptian Dariyan Formation in SE Persian Gulf. The importance of stratal geometry in any given subsurface data set depends on the accommodation setting, which is in turn controlled by pre-existing topography, syndepositional tectonics, and eustatic fluctuations. Many carbonate reservoirs are in shallow shelf settings that have near-flat-lying stratigraphy and the reservoir model consists of a series of thin, sub-

seismic layers. Carbonate fields exhibit exceedingly complex local reef topography, shelf margin complexes, and rapidly prograding shelf margins. Seismic geometry particularly as displayed on higher quality seismic classification data volumes can be the key to resolving the stratigraphic architecture of the field and is a useful first step where data are available.

Three depositional units (two coarsening- and one fining-upward) recognized from well data were resolved by seismic facies classification. Depositional styles and resulting reservoir architecture change systematically in conjunction with varying accommodation conditions associated with the LST, TST, and HST portions of a high-frequency sequence, or across several high-frequency sequences in a composite sequence. No lowstand deposition can be expected within the middle Dariyan Formation. The transition in the late highstand from more sigmoidal clinoforms (preserved platform top section) to oblique toplap-truncated clinoforms (little or no preserved platform top record of clinoform) as a common signal of the transition to lowstand deposition (forced regressive systems tracts) is not observable here.

Where individual cycles can be mapped continuously across the platform lithofacies tract in both highstand and transgressive systems tracts, a distinct difference in the grainstone presence in each cycle shows a preferential development of grainstone in the highstand cycles. This suggests that no single Walther's-Law model, developed on the basis of one or two cored intervals, will yield a predictive model of reservoir distribution and lithofacies architecture that is representative of the whole. It is essential to move away from a surface-based single-seismic attribute-interpretation method to one that incorporates multiple attribute volumes to enable a dynamic approach. The dynamic model approach does provide enhanced predictive capabilities if integrated with a high-frequency sequence framework. An understanding of reservoir window in the longer and shorter-term sequence stacking pattern will assist in correlation and in evaluating existing models.

6.   The complications and significance of the prognosis of paleokarst and carbonate turbidite systems using seismic data.

This section uses largely the same methods as the previous section, but focuses on paleokarst and carbonate turbidites. Of interest, the turbidite study documents potential reservoir facies in a unit otherwise considered to have no reservoir potential. It summarizes information contained in Paper 3 (Farzadi, P. & Hesthammer, J. _Submitted 2006). The structure of this section generally follows the paper (Part II).

6.1   Stratal preservation

The presence and distribution of erosion and truncation surfaces and abrupt lithofacies transitions should be noted where observed. The distribution of erosion surfaces, when plotted alongside other criteria, can yield an additional independent indicator of trends in creation or loss of accommodation, and resultant lithofacies changes. Monitoring the presence or absence of exposure surfaces is a method for calibrating the time represented by missing rock. The recognition of these surfaces is of prime importance in stratigraphic work. These surfaces must bound the major rock units and time-rock units within the study area. In seismic stratigraphy, recognition of offlap and onlap relationships associated with major unconformities is often a primary key to unravelling stratigraphic complexities. Major regressions and transgressions that produce intervening unconformity surfaces are usually gradual and pulsating events. Erosion surfaces may be discernible on the material beneath the unconformity.

6.2   Turonian Paleokarst prognosis

Long periods of subaerial exposure typically produce unconformities with associated features like paleokarst. These may be seismically detectable. Paleokarsts may have a controlling effect on reservoir quality. In oil exploration work, it is useful to use seismic stratigraphy to produce a range of products, but producing maps showing geologic features that are not stratigraphically controlled, including diagenetic products, poses a real challenge to the interpreter of seismic data.

The Turonian karsts cut into rudist-rich limestones of the top Mishrif reservoir (Fig. 2) as revealed by core description data from SE Persian Gulf. These limestones are fractured with extensive development of vugy porosity. The wells that encountered karsts show significantly higher oil production rates. The heterogeneous nature of karstified limestones resulting from the dual controls of depositional facies variability and karst distribution makes it critical to map these features in 3D. As a consequence of the heterogeneity and lateral thickness variations, the karstified surface is not uniquely mapped by a single seismic attribute. Even if a unique map of this surface was available, it could not provide insight to the variability of paleokarst bodies in 3D within the data volume.

In the study area, as in most other karst-modified carbonates, a traditional approach to mapping the paleokarst essentially limits the interpretation to surficial features visible on 2-D maps (Hunt *et al*. 2003). This constraint leaves the interpreter with a large gap between the possibly detailed picture of surficial paleokarst realized on a horizon map, and the 3-D volume population required for reservoir prognosis and well planning. In this work, the top Mishrif reservoir was not the primary source of information for the paleokarst prognosis. Instead seismic pattern recognition analysis was used, relying on a combination of 6 different seismic attributes within an interval of 80 ms. Figure 21 illustrates the distribution of karst as isolated features at the top Mishrif reservoir.
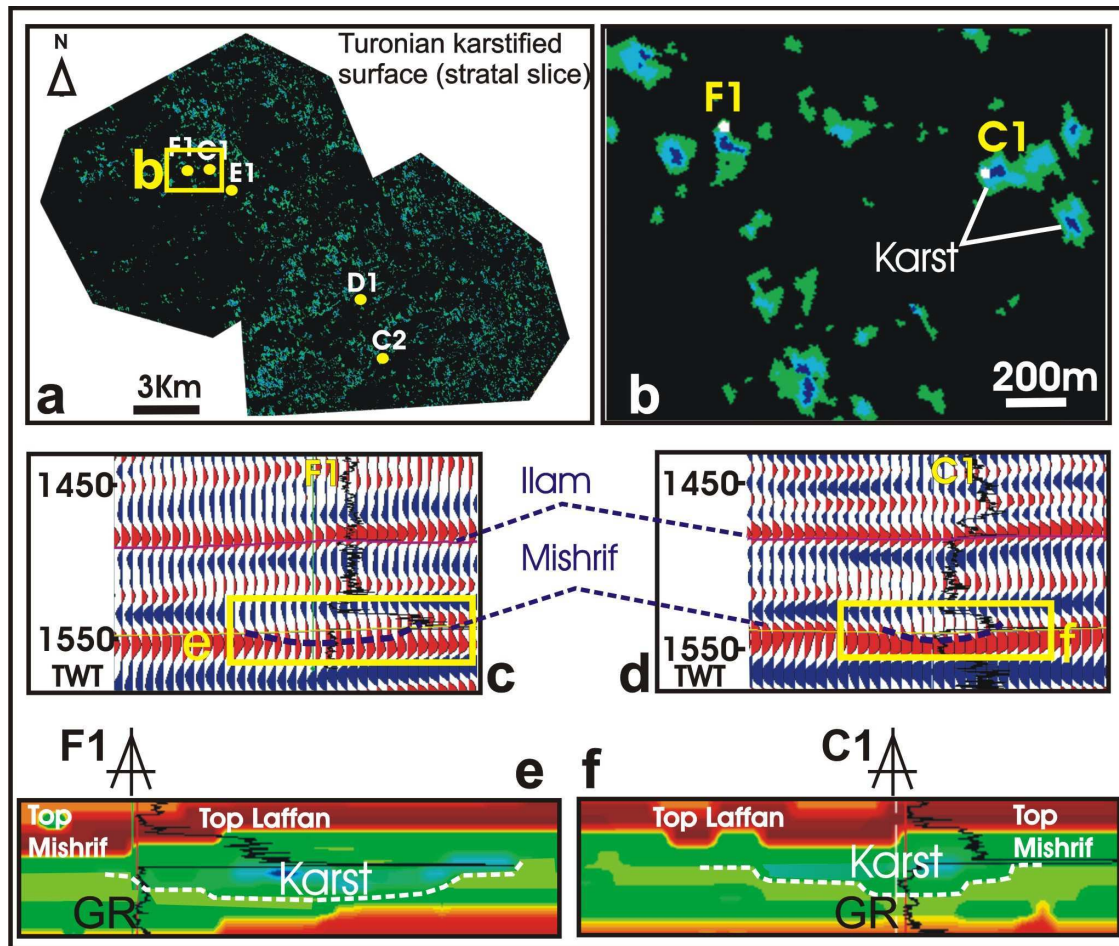
Figure: 21 Stratal slicing provided the plan view of the development of the Turonian paleokarst system (a). Classification data made it possible to explain why the oil production rate of well C1 (b and d) is almost twice the production rate of well F1 (b and c). 2-D sections through the classification data (e and f) at well locations reveal that Well C1 penetrates the middle of a karst collapse breccia while well F1 penetrates the margin of another karst collapse area. Original seismic wiggle traces (c and d) are compared with the classification data at well locations (e and f).

6.3   Santonian Carbonate turbidite

In response to thrusting of the Oman nappes and the development of the convergent margin (Robertson 1987; Burchette 1993) the Turonian erosional surface subsided and was covered by pelagic deposits and marly turbidites. Plate flexure and subsidence enhanced by eustasy continued and the Laffan marls, which directly overly the Turonian unconformity, passed up into the argillaceous neritic-to-pelagic limestones of the Santonian Ilam Formation (Fig. 2). This study, through multiple attribute-volume analysis, reveals a turbidite system that developed within the deep marine Ilam carbonates (Fig. 22). Resolving an otherwise seismically-hidden carbonate geobody led to better definition of the depositional mechanism of the Ilam Formation.

Figure: 22 The channeling systems of a carbonate turbidite within the middle part of the Santonian Ilam Formation are recognized on a stratal slice (a) through the classification volume (dashed-line in b). Three random lines b, c and d (location in a) through the data volume show the geometry of the different parts of this channeling systems and the terminal lobes. Seismic classification data at well E1 (the only well that shows oil in Ilam) is associated with depositional cycles derived from GR log. These high frequency coarsening/fining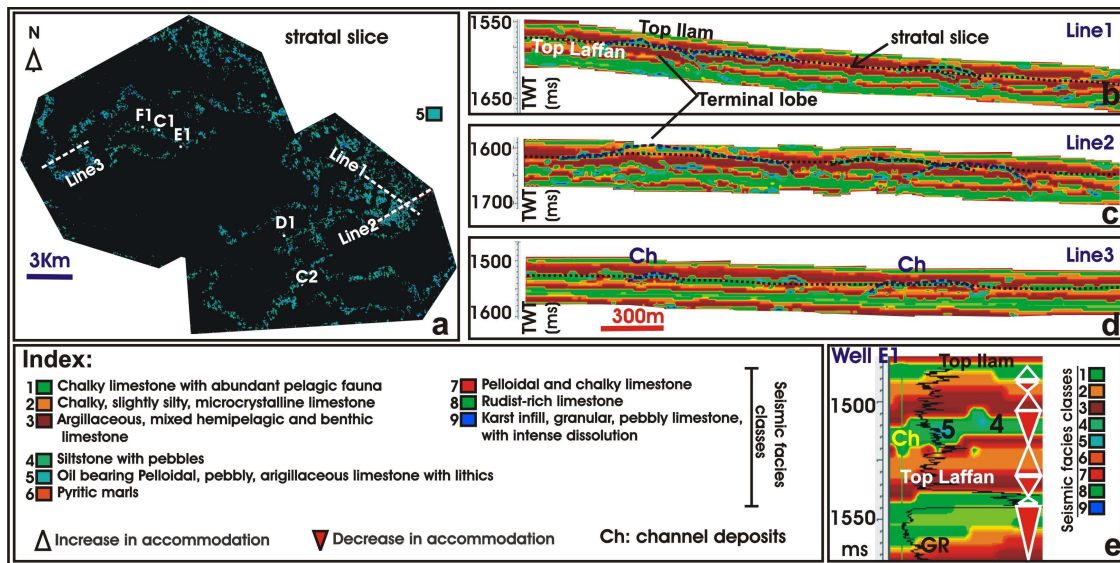 upward depositional sequences are superimposed on a general 3rd order increase in accommodation space. Seismic facies classes recognized in the classification process are numbered sequentially and are shown associated with their related lithologies.

A flooding event corresponding to MFS-K160 of Sharland *et al*. (2001) occurred near the base of the Ilam Formation (Fig. 2). A 3rd order stratigraphic sequence which drowned the preceding karstified surface is interpreted as a succession driven by a combination of eustasy and subsidence resulting from structural loading of the Arabian plate margin (Sharland *et al*. 2001). The area subsided and flooded during this period resulting in the establishment of marls and basinal carbonates in a rapidly sinking basin. Carbonate sedimentation dominates during relative sea-level highstands and rises, while turbidite sedimentation dominates during lowstands when carbonate sedimentation is largely shut down (Reading 1996). Occurrence of a turbidite system in this drowning situation suggests that other processes, including tectonic events and changes in oceanographic conditions with no clear relationship to relative sea-level stand, have introduced large quantities of turbidity currents into the basin otherwise dominated by quiet carbonate deposition condition.

6.4   Statistical properties

The spatial arrangement of geobodies through which a seismic wavefront passes affects the amplitude, phase, frequency, and propagation velocity of the wavefront (Hardage 1987). Consequently, any numerical parameter calculated from seismic data which measures a behavioural trait of any of these four seismic attributes in data windows that span a particular lithology, facies, or stratigraphic sequence is a potential parameter for identifying the lithological distributions imaged by

those seismic data. The behaviour which we should expect is that for any statistical property of a seismic parameter, there will be numerical ranges of that property where the values calculated for two or more lithologies, or for two or more depositional facies, will overlap. In such a case, an interpreter has to have the capability of examining several different statistical measures, calculated from the same seismic data window as was the first statistical measure, so that various combinations of the statistical properties of the seismic reflection signal can be tested for lithological and facies sensitivity. The statistical algorithm used in this work (PCA) integrates and handles all input attribute volumes at the same time and focuses on their true dimensionality and organization using n-dimensional cross plots. PCA was also discussed in Sections 5.2 and 1.5.5.

6.5 Seismic stratigraphy in 3-D space

In seismic stratigraphy it is essential to preserve depositional information, geomorphologic information, and the connectivity of geobodies. Small-scale variability observed in wireline logs represents variation in depositional energy associated with high-frequency cyclicity of thin beds that is difficult to map laterally. Interpretation of seismically thin, deep carbonate channelling systems or karstified carbonates within continuous seismic events is not repeatable without geomorphologic information from the horizontal dimension. Seismic polarity and amplitude of thin layers are neither good indicators of lithology nor reliable references of lithofacies location and geometry (Zeng & Hentz 2004). This is true for the present study, where single horizon-based interpretations are unable to map out the paleokarst networks and deep-marine carbonate turbidites in 3D space.

7. Geologically constrained seismic velocity variations

This section established the regional stratal interval-velocity framework used in Section 8. It is based on interval velocities from the tectonically-quiescent Sirri area, the highly deformed Karanj-Parsi area, and intervening wells. It summarizes information contained in the beginning of Paper 4 (Farzadi, P. & Alaei, B. -Submitted 2006). The structure of this section generally follows the paper (Part II).

7.1 Introduction

Improvements in the tools, interpretation techniques and types of data employed, most notably seismic and well data, have provided an insight into the 3-D organization of sedimentary rocks at basins and reservoir scales. Furthermore, much of the data collected by oil companies during hydrocarbon exploration and development have provided research opportunities that have improved the understanding of depositional processes, basin evolution and diagenesis. Exploration scale 3-D seismic data not only provide dramatic improvements to the understanding of distribution of those

intervals of immediate economic interest but also to the full stratigraphy of the basin under investigation. Efforts to significantly improve seismic imaging of carbonate sequences, including depth conversion, are critical to developments in our understanding of regional seismic velocity variations. Advancements will have to accommodate the unique properties of carbonate rocks.

In this study a unique regional comparison of the interval velocities within the carbonate units provides valuable information about the internal heterogeneity of the depositional sequences. Interval velocity is important in both the seismic data analysis (prestack depth imaging) and depth conversion of interpreted seismic data. Understanding geologically-constrained spatial velocity variations of rock units in the Zagros Foreland and ZFTB will help to improve seismic image qualities and depth conversion results. A northward general velocity-increasing trend combined with more structural complexities shows that carbonate sequences provide more imaging challenges in ZFTB than Foreland area. The velocity information provided in figure 23 is essential for future geologically constrained seismic imaging in this area.

EPOCH/ERA				Group	SE Zagros Foreland	Interval velocity m/s	Zagros FTB	Remarks
TERTIARY			QUATERNARY	Group	Bakhtiary Aghajari	2200..........................4000	Bakhtiyary Aghajari	Ahwaz(Ah) sand-3500m/s Kalhur Anhydrite (Kal)-5000m/s Salt-4450
			Pliocene					
			Miocene		Mishan	4450	Mishan	
					Gachsaran		Gachsaran	
			Oligocene		Asmari	4000.....................5750	Asmari Ah Kal*	
			Eocene		Pabdeh	4000..........................4750	Jahrum Pabdeh	
			Paleocene					
CRETACEOUS	UPPER		Masstrichtian	Bangestan	Gurpi		Gurpi	
			Campanian					
			Santonian		Ilam		Ilam	Interval velocities generally lower than sarvak
	MIDDLE		Coniacian Turonian		Laffan		Laffan	
			Cenomanian		Mishrif	5500..........................6000	Sarvak	Uniform velocity variation with depth
					Khatiyah			Kazhdumi/Sarvak boundary is an important regional velocity inversion
			Albian		Mauddud			
					Kazhdumi	3500..........................4000	Kazhdumi	Negative velocity gradient can be attributed to over pressure zones
			Aptian	Khami	Dariyan	5000..........................6000	Dariyan	No strong regional velocity trend. Velocity is controlledby depositional/post-depositional factors
			Barremian		Gadvan Khalij	4100..........................6000 3750..........................4300	Gadvan Khalij	Khalij limestone does not show depth-dependent velocity variation
	LOWER		Hauterivian					
			Valanginian		Fahliyan		Fahliyan	
			Berriasian					
					Hith		Hith	

Figure: 23 Velocity information derived from a regional study of the available sonic logs reveals a general velocity-increasing trend from SE Persian Gulf towards ZFTB. These information are used for the imaging of the 3-D seismic data of Karanj-Parsi oil fields and are of great importance for future geologically constrained seismic imaging in this area.

Regional interval velocity study and its usefulness in seismic depth imaging provided a large amount of detailed stratigraphic and structural information not available from conventional seismic processing techniques. Data derived from prestack depth imaging in the highly deformed ZFTB offers a basis on which to predict the stratal geometries. The interval velocities are derived from well data. These data made it possible to study the regional stratigraphic evolution of the Zagros basin by a comparison between ZFTB and foreland area.

8. Stratigraphic evolution of the Zagros basin: comparative study in regions that are tectonically quite different

This section builds on the regional stratal interval-velocity framework established in Section 7 to evaluate tectono-stratigraphic relationships within the Zagros Basin. This includes depositional environment, basin evolution and plate-scale deformation.. It summarizes information contained in Paper 4 (Farzadi, P. & Alaei, B. -Submitted 2006). The structure of this section generally follows the paper (Part II).

The advanced geologically-constrained, prestack depth imaging used in the ZFTB Karanj-Parsi study, and the PCA interpretation techniques applied in the SE Zagros Foreland Sirri study, each revealed geological detail that had not been achieved by conventional seismic analysis. On this basis, key aspects of the stratigraphic and tectonic history are correlated, forming the groundwork for future prospect evaluation. The regional stratigraphic trends presented below add sub-basin-scale details to present models of Zagros basin evolution. Aspects are seen in regional stratal interval-velocity trends, providing a framework for evaluating lithologic and porosity trends.

8.1 The Zagros Fold Thrust Belt and Foreland basins: a stratigraphic correlation between two different tectonic provinces

Many physical events in the depositional history of the Zagros basin have left us with hints of stratigraphic correlation. These hints can help us understand the precise history of the basin. Some of the geological events are global in scope; others are of a basin-wide or an extremely local nature. Whereas a basin-wide correlation may sound conceptually simple, it has been in fact a gigantic undertaking. Lack of a genuinely demonstrated precise correlation between the ZFTB and Foreland in the literature is mainly because it largely depends on the resolution of the imaged subsurface geology. In highly deformed terraces such as Karanj-Parsi (Fig. 1) it is necessary to rely on structural styles for seismic interpretation of structure and stratigraphy because the quality of the seismic images will be poor (Bally, 1983; Lingrey, 1991; Mitra and Fisher, 1992; Alaei, 2005a). Structural complexities include the steep dip of beds, overturned beds; complex thrust fault geometry (slip surfaces both along bedding-parallel and cross-cutting), multiple detachment levels and thrust vergence, repeated intervals, and asymmetric folds associated with thrusts. The Sirri area, in southeastern Zagros Foreland Basin, is undeformed and tectonically quiet. In the Sirri C and D oil fields it is the stratal geometries that are complex. This complexity is attributed to deposition during a period of profound sea level change.

The search for the best stratigraphic correlation across the Zagros basin is unending. We use the predictive capability of the seismic stratigraphic concepts but still cannot be absolutely certain that

we have events worked out correctly. We must bring as many lines of evidence as possible to bear on our correlation problems. If several lines of evidence begin to agree, we can develop a real confidence in our correlations.

8.2 The interplay of the Cretaceous deposition processes and the deformation events

The Cretaceous carbonate platform of the Zagros basin shows a complex internal architecture, rather than a "layer-cake" configuration. Recognition of these stratal geometries and correlation with their lateral equivalents has important implications for prospective hydrocarbon discovery and development in these sequences. The depositional processes were largely controlled by eustatic sea level punctuated by local, relative sea level changes generally attributable to salt and regional tectonics. The main deformation events occurred in the Aptian, Turonian, Santonian/Coniacian and Late Miocene-Pliocene (Fig. 24). By comparing the fold-thrust belt and foreland areas, this study shows that each contains a stratigraphy that is related to the other. The differences, sometimes subtle, place constraints on the regional basin evolution useful in regional exploration. Geology-guided PSDM seismic processing in the ZFTB and seismic attribute analysis in the Zagros Foreland reveal that Cretaceous depositional systems have similar features. Tectonic events also correlate. Examples of the regional velocity relations and basin-evolution inferences follow.

The NW progradation of the Barremian Gadvan Formation in the ZFTB (Fig. 25), in contrast to the SE progradation in the Foreland area, is interpreted as development of independent intrashelf basins. The NW thickening of the upper Gadvan Formation in the ZFTB, in contrast to constant thickness observed in the Foreland indicates NW tilting and a higher rate of subsidence in the ZFTB. The development of the Zubair deltaic sandstones NW of the Foreland basin (Sharland *et al*. 2001; Motiei 1993, 1995) is attributed to this subsidence (Fig. 24). This delta, however, did not reach the Karanj-Parsi study area in the ZFTB.

The progradation direction of the Gadvan Formation in both areas suggests that a subsidence area with NW-SE orientation developed perpendicular to the spreading trend of Neo-Tethys. Subsidence continued from the Barremian to the Aptian resulting in a similar progradation direction associated with rudist build-up development with the Dariyan Formation (Fig. 20). However, thinning of the Dariyan Formation from 110m in Sirri to 40m in Karanj-Parsi may cause an interpretation bias. Onlapping Kazhdumi strata over the Aptian unconformity at the top Dariyan Formation in both areas (Figs. 26 & 27) indicate regional development of this erosional surface. Nodular thinning of the Kazhdumi Formation over the crests of the Sirri C-D domal structures revealed by the isochor map (Fig. 27) and absence of growth strata indicate local salt diapirism before deposition of this formation. Salt diapirism is interpreted as a result of a regional foreland basin tectonic event possibly

related to subduction. Transgressive-regressive cycles in the Cenomanian Khatiyah and Mishrif Formation (Ahmadi and Sarvak in ZFTB) created isolated and vertically-stacked platform-to-intrashelf topographies (Fig. 13b) documented in Sirri (Farzadi, 2006a). The transgressive, platform-initiating part of each cycle probably correlates with a major regional flooding event.
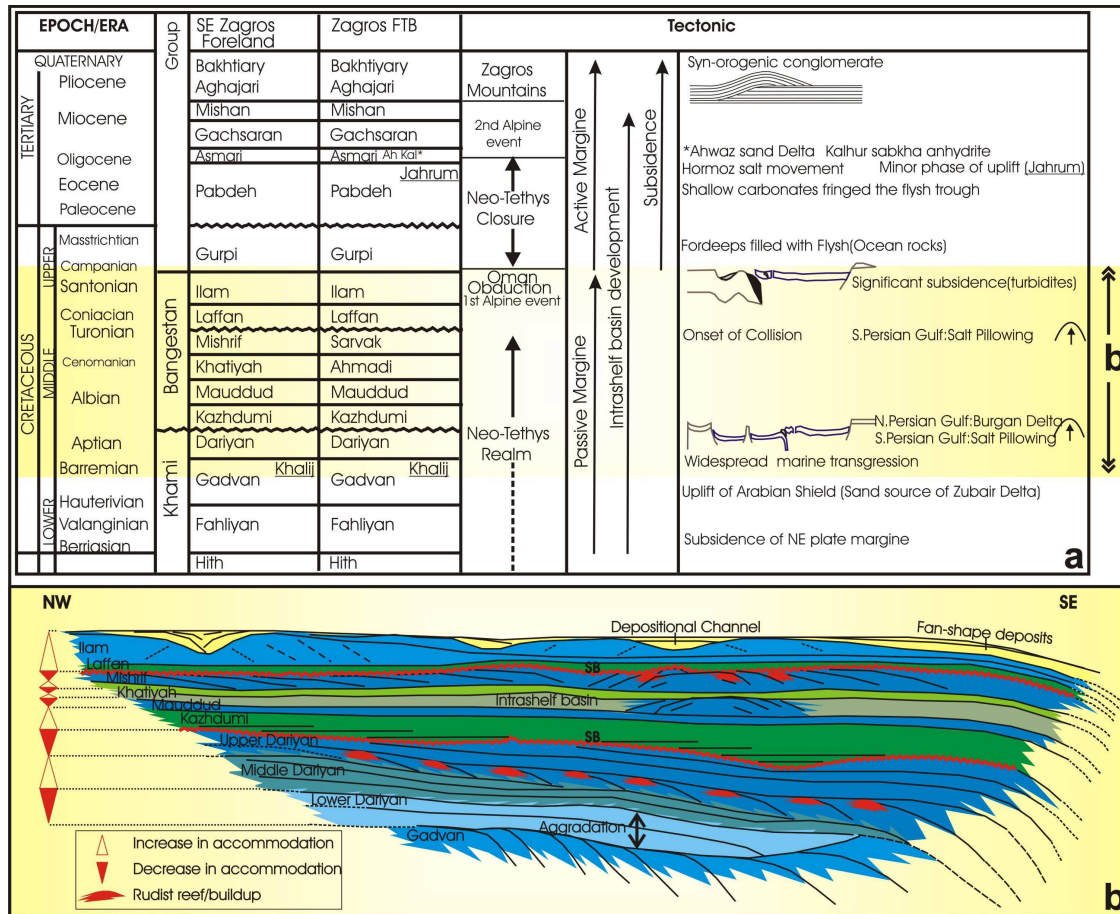
Figure: 24 The main deformation events in the ZFTB and the Zagros Foreland (a) in particular SE Persian Gulf are generally correlatable with different intensities in each area (discussed in the text). These deformations are shown in relation with the stratigraphy on a time chart (a). A conceptual geological model (b) indicates the internal architecture of the cretaceous strata in the SE Persian Gulf. The similarities of these patterns with their lateral equivalents in the ZFTB are discussed in the following text.

In the Karanj-Parsi area the narrow NW-SE-trending lower Sarvak Formation basin marginal mixed-facies deposits (basin/platform or Oligostegina/rudist debris) is well documented (e.g. T'Hart, 1970). The NW-SE-trending build up in the northern flank of Parsi also confirms the basin trend as well as the proximity of the Parsi field to the shelf.
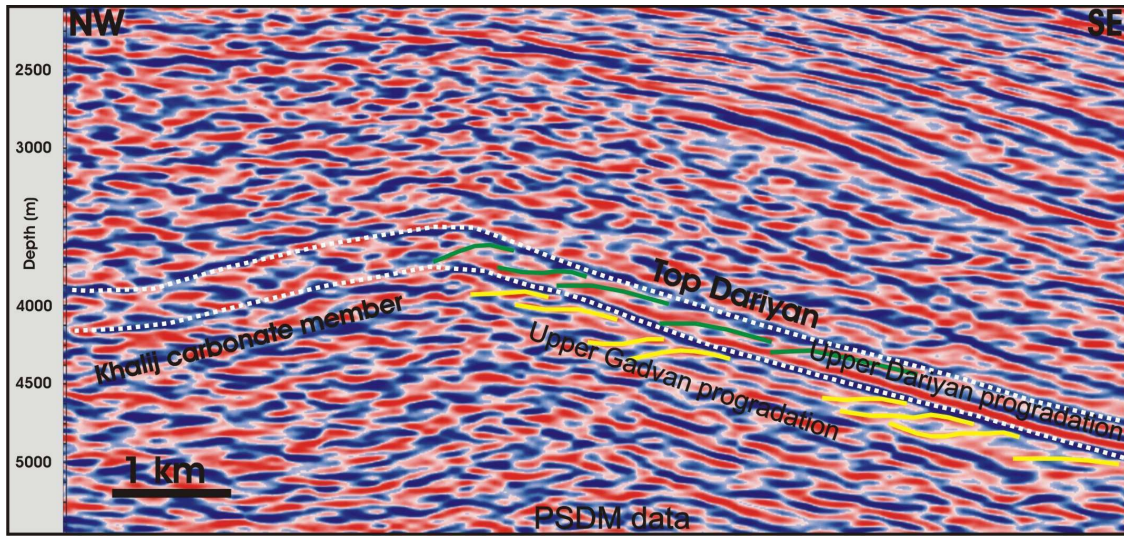
Figure: 25 A profile from the Prestack Depth Migrated (PSDM) 3-D seismic reflection data along the strike of the Karanj structure (Fig. 1) shows NW prograding clinoforms within the upper part of the Barremian Gadvan and the Aptian Dariyan Formations. Note that the thickness of upper Gadvan increases towards NW.
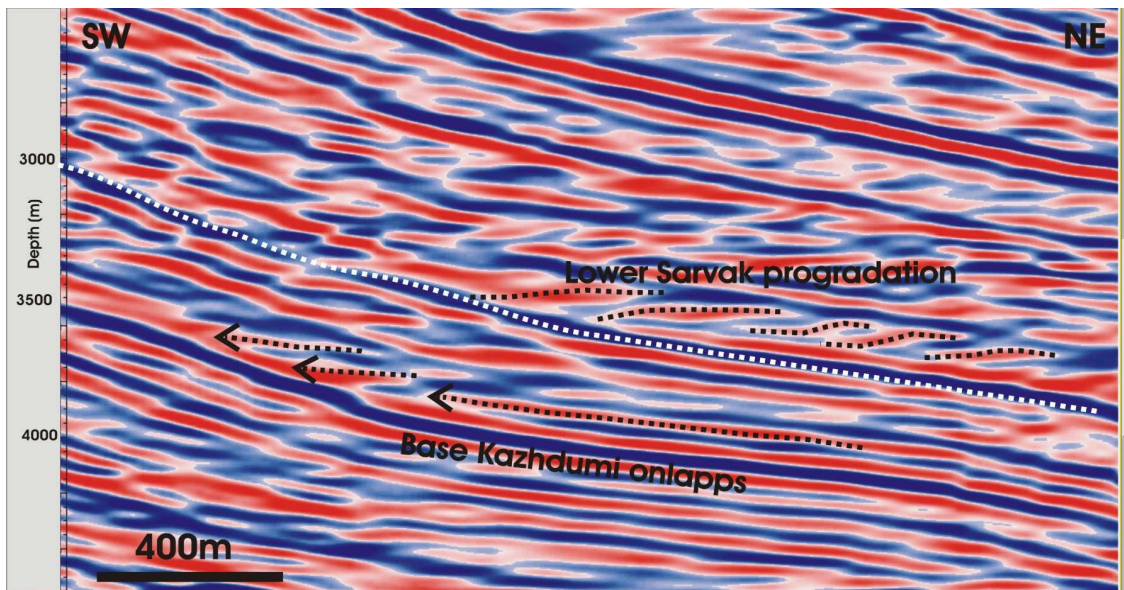
Figure: 26 Interpreted PSDM profile normal to the strike of Parsi structure shows reflection terminations within the lower Kazhdumi Formation that onlap the Aptian unconformity (top Dariyan). Lower Sarvak strata prograde towards a nearby intrashelf basin located in the southwest.
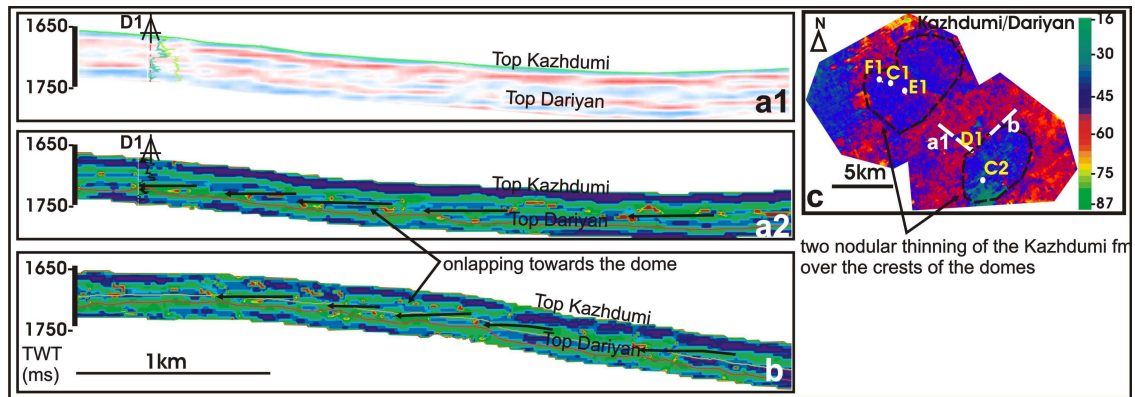
Figure: 27 A random line through the conventional amplitude stack (a1) is compared with a random line with the same position through the classification data (a2) within the Kazhdumi Formation. The lower Kazhdumi strata lap out over the top Aptian unconformity (top Dariyan). Observation of strata onlapping towards the crests of the Sirri domal structures (a2 and b) can explain the presence two nodular thinning on the Kazhdumi isochor over the crests of the structures (c). This rounded-shape thinning indicates a major tectonic event as salt movements occurred before the deposition of the Kazhdumi Formation. Positions of the profiles are shown in c.

A few million years of emergence (Scott, 1990) related to the initial phase of the collision between Eurasia and the Arabian margin (O'Conner and Patton, 1986; Warburton *et al.*, 1990) formed a faulted, truncated, karstified surface at the top of the equivalent Mishrif Formation (Alsharhan and Narin, 1988; Alsharhan and Kendall, 1991; Pasco *et al.*, 1995; Philip *et al.*, 1995; Montenat *et al.*, 1999; Sharland *et al.*, 2001). The deeper-water setting of the Turonian unconformity in the Karanj-Parsi area probably prevents its clear imaging.

The channel-like feature observed at the uppermost part of the Sarvak Formation in the Parsi field (Fig. 28) could be an indication of the Turonian tectonic setting. In the SE foreland basin the Ilam Formation is considered not to be a reservoir unit (Motiei, 1993, 1995). However the Ilam Formation carbonate turbidite channel system (Fig. 22) documented in this study (Sirri C-D) indicates the potential for stratigraphic traps. Thus, imaging the lateral extent of this system is of fundamental exploration importance. The Late Turonian regional transgression started with the deposition of Surgah shales in the Karanj-Parsi followed by the deposition of the Ilam Formation carbonates.
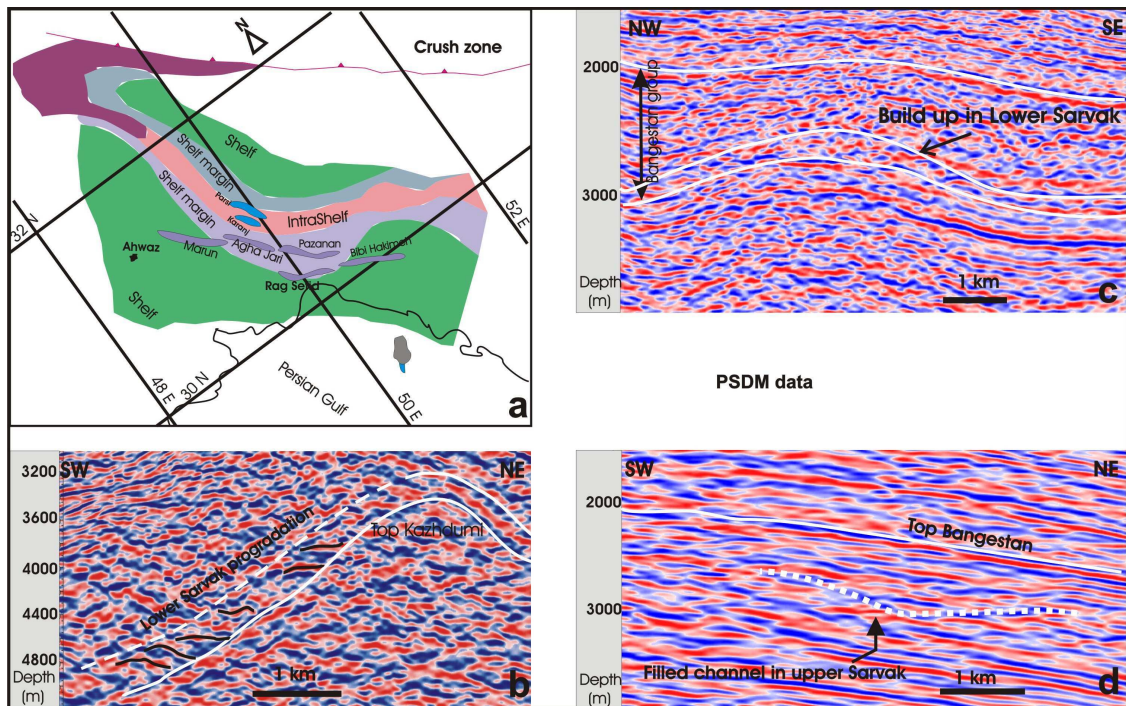
Figure: 28 Paleogeographic reconstruction of the lower Sarvak Formation (a) shows the mixed shelf-intrashelf facies expected in the Dezful embayment (Fig. 1). Interpreted PSDM section from Karanj structure (b) illustrates a NE progradation of the lower Sarvak Formation. This progradation direction and the SW progradation of the lower Sarvak in Parsi (Fig. 26) are consistent with the Paleogeographic map. NW-SE trending build-up at the northern flank of Parsi structure (c) confirms the proximity of this structure to the shelf margin. A subtle channel-like feature (d) near the top of the Sarvak Formation at the NE flank of Parsi probably indicates the Turonian unconformity.

9.   Conclusions

The integration of the concepts developed by seismic stratigraphy and sequence stratigraphy provides a more realistic framework for subsurface interpretation of carbonate systems in 3-D space. Seismic data, especially 3-D provide the best source of spatial information in the subsurface, which can assist two important aspects of carbonate reservoir characterization: stratigraphic correlation and volume attribute distribution. 3-D seismic stratigraphic correlation using sequence concepts is a topic of high interest and utility in subsurface geology, because seismic provides an areal picture with lateral detail necessary for correlation. Seismic volume attribute integration at the field scale is a rapidly evolving discipline. Any numerical parameter calculated from seismic data has a potential for expanding the information content of the data set. Seismic facies classification of the integrated volume attributes calibrated with well data is a potential source for high-resolution seismic stratigraphy. Maps, cross sections and slices created from an integrated classification volume are far superior to those created from conventional 3-D seismic data.

The process of interpreting the reservoir volume should proceed from interpretation of 1-D well data (wireline logs, core, paleologs and production data); to 2-D cross section and map construction,

correlation of high-frequency sequences and analysis; breaking down the study interval into seismic sequences using well ties; and finally reproducible 3-D mapping of seismic facies geobodies. The cycle and sequence hierarchical framework derived from wireline logs and core description is the basis for identifying and ranking key surfaces for correlation. Vertical stacking of the cycles, their symmetry and facies-tract offset are important tools for the 1-D interpretation step. The tools of 2-D stratigraphic analysis, including structural mapping, isochor mapping, cross-sections and 2-D stacking patterns, can be used to tie together the isolated well data into a sequence model. Sequence concepts can help to elucidate stratal geometry from seismic, geographic shift in accommodation and 2-D facies-tract offset to identify additional key surfaces not identified by the traditional well-to-well approach. Critically, the skills and experience of the interpreter play an important role in both controlling the classification and the interpretation phase. The interpreter is able to evaluate the data reduction by PCA in both a qualitative fashion and by quantitative measures to free the hidden isolated geobodies from redundant data. The patterns identified from cross plots of the integrated attribute volume are used in a classification step to produce the seismic classification volume, and these patterns with information inherited from all input attributes come together with confidence measures for each seismic facies. This approach frees the interpreter from the limitation of a traditional surface-based interpretation to one that utilizes the entire data volume and then displays the results as a 3-D volume. This approach to 3-D mapping can provide important new geological information and detail reflecting the external form, connectivity and internal heterogeneity of the main features of interest, as has been shown in this work for carbonate build-ups, paleokarst and turbidite.

The interpreter is best able to analyze the 3-D classification results in 3-D space using sequential stratal slicing to progressively move through the data. Stratal slices help to reveal new 3-D stratigraphic patterns from the seismic data that are captured by the multi-attribute analysis. Seismic facies mapping applied to the Persian Gulf provides new insights to the internal heterogeneity of the carbonate build-ups. It has also provided the first 3-D realization of the paleokarst system, providing new information concerning the connectivity and scale of the karstification. In the case of discrete objects, such as carbonate build-ups or paleokarst, where lateral distribution is hard to predict even with stochastic approaches, the multiple attribute analysis provides detailed 3-D geometrical information. The mapping of stratal geometries from the SE Persian Gulf in a structurally-quiet area can serve as a reference for better understanding the structurally complex area of the Zagros Fold Thrust Belt, where quality of conventional seismic data is usually poor. A comparison between stratal geometries in the SE Persian Gulf and that derived from interpretation of an advanced PSDM data from the ZFTB provides new insights to the regional geology of the Zagros basin.

References

ALAEI, B., 2005. Seismic forward modeling of two fault-related folds from the Dezful embayment of the Iranian Zagros Mountains. *Journal of Seismic Exploration*, **14/1**, 13-30.

AL-HAJRI, S.A., FILATOFF, J., WENDER, L.E., NORTON, A.K. 1999. Stratigraphy and operational palynology of the Devonian system in Saudi Arabia. *GeoArabia*, **4/1**, 53-68.

ALSHARHAN, A.S., and NARIN, A.E.M., 1988. A review of the Cretaceous formations in the Arabian Peninsula and Gulf, Part II. Mid Cretaceous (Wasia Group) stratigraphy and paleogeography. *Journal of Petroleum Geology*, **11**, 89–112.

ALSHARHAN, A.S., and KENDALL, C.G.St.C., 1991. Cretaceous chronostratigraphy, unconformities and eustatic sea-level changes in the sediments of Abu Dhabi U.A.E. *Cretaceous Research,* **12**, 379–401.

ALSHARHAN, A.S., and SCOTT, R.W., 2000. Hydrocarbon potential of Mesozoic carbonate platform-basin systems, U.A.E. In: Alsharhan, A.S. & Scott, R.W. (Eds) Middle East models of Jurassic/Cretaceous carbonate systems*. Society of Economic Paleontologists and Mineralogists Spec. Publ., **69**, 335–358.

BAHROUDI, A., and KOYI, H.A., 2004. Tectono-sedimentary framework of the Gachsaran Formation in the Zagros foreland basin. *Marine and Petroleum Geology*, **21**, 1295-1310.

BALLY, A.W., 1983. Seismic expression of structural styles. Vol. 3 - Tectonics of Compressional provinces/strike slip tectonics. AAPG Studies in Geology Series, No. 15.

BEYDON, Z.R. 1988. The Middle East: Regional geology and petroleum resources. Scientific Press Limited, Beaconsfield, U.K., 292.

BEYDON, Z.R. 1991. Arabian plate hydrocarbon, geology and potential- A plate tectonic approach. AAPG, Studies in Geology **33**, 77.

BEYDOUN, Z.R., HUGHES CLARK, M.W., and STONELY, R., 1992. Petroleum in the Zagros Basin: A Late Tertiary Foreland Basin Overprinted onto the Outer Edge of a Vast Hydrocarbon-Rich Palaeozoic-Mesozoic Passive Margin Shelf. In: MACQUEEN, R. and LECKIE, D. (Eds), Foreland Basins and Foldbelts. AAPG, Mem. **55**, 309-339.

BORDENAVE, M.L., and HEGRE, J.A., 2005. The influence of tectonics on the entrapment of oil in the Dezful Embayment, Zagros FoldBelt, Iran. *Journal of Petroleum Geology*, **28/4**, 339-368.

BP AMOCO, 2000. BP Amoco statistical review of world energy June 2000. BP Amoco, London, 43p.

BURCHETTE, T.P., 1993. Mishrif Formation (Cenomanian–Turonian), southern Arabian Gulf: Carbonate platform growth along a cratonic basin margin. In: SIMO, J.A.T., SCOTT, R.W. and MASSE, J.P. (Eds) Cretaceous carbonate platforms. AAPG, Mem, **56**, 185–199.

CALAVAN, C.W., HAGERTY, R.M., MITCHELL, J.C., and SCHUTTER, S.R., 1992. Integrated reservoir study and modeling of the Shu´aiba Reservoir, Bu Hasa Field, Abu Dhabi, United Arab Emirates. ADNOC/SPE Proceedings, SPE 24509, 299-312.

COLÉOU T., POUPON, M. and AZBEL, K., 2003. Unsupervised seismic facies classification: A review and comparison of techniques and implementation. Interpreter's corner, *The Leading Edge*, October 2003, 942-953.

DAVIS, J. C., 1986. Statistics and Data Analysis in Geology: 2nd edition, New York, John Wiley and Sons, 646.

DOWD, P.A. and PARDO-LGÚZQUIZA, E. 2005. Estimating the boundary surface between geologic formations from 3D seismic data using neural networks and geostatistics. *Geophysics*, **70/1**, 1-11.

DROSTE, H.H.J. 1997. Stratigraphy of the Lower Paleozoic Haima supergroup of Oman. *GeoArabia*, **2/4**, 419-472.

DROSTE, H., and VAN STEENWINKEL, M., 2004. Stratal geometries and patterns of platform Carbonates: The Cretaceous of Oman. In: Seismic imaging of carbonate reservoirs and systems. AAPG Memoir, **81**, 185-206.

DUFFY RUSSELL, S., AKBAR, M., VISSAPRAGADA, B., and WALKDEN, G.M., 2002. Rock types and permeability prediction from dipmeter and image logs: Shu´aiba reservoir (Aptian), Abu Dhabi. AAPG Bull. **86/10**, 1709-1732.

DUNNINGTON, H.V. 1967. Stratigraphical distribution of oilfields in the Iraq-Iran_Arabia basin. *Journal of the Institute of Petroleum*, **53**, 129-161.

FARZADI, P., 2005. Stratal geometries of the Cretaceous carbonate systems- Application of multiple volume attribute analysis to 3D seismic data from the Persian Gulf. Middle East to Far East Carbonate Reservoirs: Exploration, Development and Exploitation, Petroleum Exploration Society of Great Britain, Carbonate Conference, London, 15th and 16th November 2005.

FARZADI, P., 2006a. The development of Middle Cretaceous carbonate platforms, Persian Gulf, Iran: Constraints from seismic stratigraphy, well and biostratigraphy. *Petroleum Geoscience*, **12**, 59-68.

FARZADI, P., 2006b. Seismic facies analysis based on 3D multi-attribute volume classification, Dariyan Formation, SE Persian Gulf. *Journal of Petroleum Geology*, **29/2**, 159-174.

FISCHER, K.C., MOELLER, U., and MARSCHALL, R., 1997. Development of an exploration concept for the Shu´aiba Formation (Thamama Group) using seismic sequence and facies analysis in combination with forward modeling. In: I. Palaz and K.J. Marfurt (Eds.), Carbonate Seismology. Geophysical Developments Series 6, Society of Exploration Geophysicists, 407-416.

GLENNIE, K.W., 1995. The Geology of the Oman Mountains: An Outline of their Origin. Scientific Press, Beaconsfield, UK.

GLENNIE, K.W., 2000. Cretaceous tectonic evolution of Arabia's eastern plate margin: A tale of two oceans. In: Alsharhan, A.S. and R.W. Scott, (Eds.) Middle East models of Jurassic/Cretaceous carbonate systems. SEPM, Spec. publ., **69**, 9-20.

GURNEY, K. 1997, An Introduction to Neural Network: London, UCL press, 234p.

HARDAGE, B. A., 1987. Seismic Stratigraphy. In: HELBIG, K. and TREITEL, S., (eds.), Handbook of Geophysical Exploration, Section I, Seismic Exploration.**9**. 432.

HARRIS, P.M., FROST, S.H., SEIGLIE, G.A. and SCHENEIDERMANN, N., 1984. Regional unconformities and depositional cycles, Cretaceous of the Arabian Peninsula. In: J.S. Schlee (Ed.), Interregional unconformities and hydrocarbon accumulation. AAPG Memoir, **36**, 67-80.

HARRIS, M. T., 1991. Carbonate progradation geometry and the significance of sediment accumulation patterns and syndepositional relief: Comparison of modelling results with outcrop data In: FRANSEEN, E. K., WATNEY, W. L., KENDALL, C. G. St. C., and ROSS, W., (eds.). Sedimentary modelling: computer simulations and methods for improved parameter definition: *Kansas Geological Survey Bulletin* 233, 509-518.

HUNT, D., ELVEBAKK, G. RAFAELSEN, B., PAJCHEL, J., HOGSTAD, K., ROBAK, H., and RANDEN, T. 2003. Paleokarst recognition and 3D distribution: new insights from the upper Paleozoic, Loppa High, Barent sea. European Association of Geoscientists and engineers, 65th conference and Exhibition, Stavanger, Norway, Extended Abstracts. EAGE, Netherlands, 00-01.

JAMES, G.A. and WYND, J.G., 1965. Stratigraphic Nomenclature of the Iranian Oil Consortium Agreement Area. AAPG Bull, **49**, 2182-2245.

KOOP, W. J., 1977. The paleostructural history of SW Iran and its effect on hydrocarbon generation and entrapment. Oil Service Company of Iran (OSCO), internal report number 1292.

KOOP, W. J., and STONELEY, R., 1982. Subsidence History of the Middle East Zagros Basin, Permian to recent. In: KENT, P., BOTT, M.H.P., McKENZIE and WILLIAMS, C.A., (Eds), The evolution of Sedimentary Basins, Philosophical Transactions of the Royal Society of London, Part A, **305**, 149–168.

KERANS, C., and TINKER, S. W. 1997. Sequence stratigraphy and characterization of carbonate reservoirs. SEPM Short course notes 40, 130.

LAWRENCE, J. 1994. Introduction to Neural Networks: Design, theory and applications. California Scientific Software Press.

LINARI, V., SANTIAGO, M., PASTORE, C., AZBEL, K. and POUPON, M., 2003. Seismic facies analysis based on 3D multi-attribute volume classification, La Palma field, Maracaibo, Venezuela. *The Leading Edge*, January 2003, 32-36.

LINGREY, S., 1991. Seismic modelling of an Imbricate Thrust Structure from the Foothills of the Canadian Rocky Mountains. in Fagin, S.W., ed., Seismic Modelling of Geologic Structures Applications to exploration Problems, Geophysical Development, no.**2**, Society of Exploration Geophysicists, 11-125.

LOUCKS, R.G. and SARG, J.F., 1993. Carbonate sequence stratigraphy, recent development and applications. AAPG, Mem., **57**, 3–41.

LOUTFI, G., BASLAIB, S.M. and ABU HAMD, M. 1987. Cenomanian stratigraphic traps in western Abu Dhabi, U.A.E. Paper SPE 15684, presented at the 5th Middle East Oil Show, Bahrain, Society of Petroleum Engineers, 1–8.

MAPSTONE, N. B., 1978. Structural geology of structures of Dezful (north) Embayment. Oil Service Company of Iran (OSCO), internal report, Technical note 13/1978.

MARI, J.L., GLANGEAUD, F. and COPPENS, F. 1999. Signal Processing for Geologists and Geophysicists. *Institut francais du pétrole*, 458.

MITCHUM, R. M., JR., VAIL, P. R., and THOMPSON, S., III, 1977a. Seismic stratigraphy and global changes of sea level, part2: The depositional sequence as a basic unit for stratigraphic analysis In: PAYTON, C.E., (ed.), Seismic stratigraphy- application to hydrocarbon exploration: AAPG, Memoir **26**, 53-62.

MITCHUM, R. M., JR., VAIL, P. R., and SANGREE, J.B. 1977b. seismic stratigraphy and global changes of sea level, Part Six: Stratigraphic interpretations of seismic reflection patterns in depositional sequences, In: PAYTON, C. E., (ed.). Seismic stratigraphy- application to hydrocarbon exploration: AAPG, Tulsa, OK. 117-133.

MITRA, S. and FISHER, G.W., 1992. Structural Geology of Fold and Thrust Belts. The John Hopkins University Press, Baltimore, 254 pp.

MONTENAT, C., SOUDET, H.-J., BARRIER, P. and CHEREAU, A., 1999. Karstification and tectonic evolution of the Jabal Madar (Adam Foothills, Arabian Platform) during the Upper Cretaceous. Bulletin Centre Recherché Elf Exploration Production., **22**, 161–183.

MOTIEI, H., 1993. Geology of Iran: Stratigraphy of Zagros. Geological Survey of Iran (in Farsi).

MOTIEI, H, 1995. Petroleum Geology of Zagros-1. Geological Survey of Iran (in Farsi), 589pp.

MURRIS, R.J., 1980a. The Middle East: Stratigraphic evolution and Oil habitat. AAPG Bulletin, **64**, 597–618.

MURRIS, R.J. 1980b. Hydrocarbon habitat of the Middle East. In: Miall, A.D. (ed.) Facts and principles of world petroleum occurrence, *Canadian Society of Petroleum Geologists* Memoir **6**, 765-800.

O'CONNER, S.J. and PATTON, T.L., 1986. Middle Cretaceous carbonate reservoirs, Fahud field and northwestern Oman, Discussion. AAPG Bulletin, **70**, 1799–1801.

PASCOE, R.P., EVANS, N.P. and HARLAND, T.L., 1995. The generation of unconformities within the Mishrif and Laffan formations of Dubai and adjacent areas: applications to exploration and production. In: Husseini, M.I. (ed.) Middle East Petroleum Geosciences, Geo' 94, **2**. Gulf PetroLink, Bahrain, 749–760.

PAYTON, C. E., (ed.), 1977. Seismic stratigraphic application to hydrocarbon exploration: AAPG, Memoir **26**, 516.

PHILIP, J., BORGOMANO, J. and AL-MASKIRY, S., 1995. Cenomanian–Early Turonian carbonate platform of northern Oman: Stratigraphy and Palaeoenvironments. *Palaeogeography, Palaeoclimatology, Palaeoceology,* **119**, 77–92.

PITTET, B., VAN BUCHEM, F.S.P., HILLGÄRTNER, H., RAZIN, P., GROTSH, J. and DROSTE, H., 2002. Ecological succession, paleoenvironmental change and depositional sequences of the Barrremian-Aptian shallow water carbonates in northern Oman. *Sedimentology*, **49** (3), 555-581.

POUPON, M., GIL, J., VANNAXAY, D. and CORTIULA, B., 2004. Trackin Tertiary delta sands (Urdaneta West, Lake Maracaibo, Venezuela): An integrated seismic facies classification workflow. *The Leading Edge*, 909-912.

POSAMENTIER, H. W., and VAIL, P. R. 1988. Eustatic controls on clastic deposition II- sequence and systems tract models, In: WILGUS, C. K., HASTINGS, B. J., POSAMENTIER, H. VAN WAGONER, J. C., ROSS, C. A., and KENDAL, C.G.St. C., (eds.), Sea-level change: An integrated approach, Society of Economic Paleontologists and Mineralogists Special Publication **42**, 125-154.

PRAMANIK, A. G., SINGH, V., RAJIV, V., SRIVASTAVA, A. K., TIWARY, D. N., 2004. Estimation of effective porosity using geostatistics and multiattribute transforms, *Geophysics*, **69/2**, 352-372.

RAINER, T. 2002. Neural network seismic reservoir characterization in a heavy oil reservoir. *The Leading Edge*. 20, 309-312.

READING, H. G., 1996. Sedimentary environments: Processes, Facies and Stratigraphy. 3rd Edition. London, Blackwell Science Ltd. 688.

ROBERTSON, A. H. F., 1987. Upper Cretaceous Muti Formation- Transition of a Mesozoic carbonate platform to a foreland basin in the Oman Mountains, *Sedimentology*, 4, 1123-1142.

SCOTT, R. W. 1990. Chronostratigraphy of the Cretaceous carbonate shelf, Southeastern Arabia. In: ROBERTSON, A. H. F., SWALE, M. P. and RIES, A. C., (eds.). The geology and tectonics of the Oman region, Geological Society of London, Special Publication, **49**, 89-108.

SEPEHR, M., and COSGROV, J. W., 2004. Structural framework of the Zagros Fold-Thrust belt, Iran. *Marine and Petroleum geology*, **21**, 829-843.

SHARLAND P. R., ARCHER R., CASEY S.M., DAVIS R.B., HALL S.H., HEWARD A.P., HORBURY A.D., and SIMMONS M.D., 2001. Arabian plate sequence stratigraphy. *GeoArabia*, Spec. Publ., **2**, 261-278.

SLOSS, L. L., 1963. Sequences in the cratonic interior of North America; *Geological Society of America Bulletin*, **74**, 93-114.

SMITH, A.G., SMITH, D.G. and FUNNELL, B.M., 1994. Atlas of Mesozoic and Cenozoic coastlines. Cambridge University Press, Cambridge.

TERKEN, J.M.J., FREWIN, N.L., and INDRELID, S.L., 2001. Petroleum systems of Oman: Charge timing and risks. AAPG Bull. **85/10**, 1817-1845.

T'HART, B.B., 1970. Upper Cretaceous Palaeogeography, Structural history and prospects of Khuzestan Province Iran. Iranian Oil Operating Companies (IOOC), Geological and Exploration division, Internal Report No. 1172.

VAIL, P.R., MITCHUM, R.M. and THOMPSON, S.III 1977a. Seismic stratigraphy and global changes of sea level, Part 3: relative changes of sea level from coastal onlap; In: PAYTON, C.E., (ed.) Seismic stratigraphic application to hydrocarbon exploration: AAPG, Memoir **26**, 63-82.

VAIL, P.R., MITCHUM, R.M. and THOMPSON, S.III 1977b. Seismic stratigraphy and global changes of sea level, Part 4: global cycles of relative changes of sea level; In: PAYTON, C.E., (ed.), Seismic stratigraphic application to hydrocarbon exploration: AAPG, Memoir **26**, 83-98.

VAIL, P. R., TODD, R. G., and SANGREE, J. B. 1977c. Seismic stratigraphy and global changes of sea level, Part 5: Chronostratigraphic significance of seismic reflections; In: PAYTON, C. W., (ed.), Seismic stratitigraphic application to hydrocarbon exploration: AAPG, Memoir **26**, 99-116.

VAIL, P.R. 1987. Seismic stratigraphy interpretation using sequence stratigraphy in Bally, A.W., (ed.), Atlas of seismic stratigraphy; AAPG, Studies in Geology 27, **1**, 1-10.

VAN WAGONER, J. C., POSAMENTIER, H. W., MITCHUM, R. M., VEIL, P. R., SARG, J. F., LOUTIT, T. S., and HARDENBOL, J., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions, In: WILGUS, C. K., HASTINGS, B. J., POSAMENTIER, H., VAN WAGONER, J. C., ROSS,

C. A., and KENDALL, C. G. St. C. (eds.), Sea level change: An integrated approach, Society of Economic Paleontologists and Mineralogists Special Publication **42**, 39-46.

VAN BELLEN, R.C., DUNNINGTON, WETZEL, R. and MORTON, D.M. 1959. Iraq Lexique Stratigraphique Internationale, III, Asie, **10a**, 333.

VAN BUCHEM, F.S.P., RAZIN, P. HOMEWOOD, P.W. *et al.* 1996. High-resolution sequence stratigraphy of the Natih formation (Cenomanian/Turonian) in northern Oman: Distribution of source rocks and reservoir facies. *GeoArabia,* **1/1**, 65–91.

VAN BUCHEM, F.S.P., DANIEL, J.M., MENGUS, J.M., HOMEWOOD, P. and DROSTE, H., 2000. The Natih carbonate petroleum system (Cenomanian/Turonian; N. Oman) – an integrated study of reservoir facies, source rocks and fracture patterns in a high resolution sequence stratigraphic framework. AAPG, Field Seminar Guidebook.

VAN BUCHEM, F.S.P., RAZIN, P., HOMEWOOD, W., OTERDOOM, H. and PHILIP, J., 2002*a*. Stratigraphic organization of carbonate ramps and organic-rich intrashelf basins: Natih Formation (middle Cretaceous) of northern Oman. AAPG Bulletin, **86**, 21–54.

VAN BUCHEM F.S.P., PITTET, B., HILLGÄRTNER, H., GRÖTSCH, J., AL MANSOURI, A.I., BILLING, I.M., DROSTE, H.H.J., OTERDOOM, W.H., and VAN STEENWINKEL, M., 2002b. High-resolution Sequence Stratigraphic Architecture of Barrremian/Aptian Carbonate Systems in Northern Oman and the United Arab Emirates (Kharaib and Shu´aiba Formations). *GeoArabia*, **7/3**, 461-500.

WARBURTON, J., BURNHILL, T.J., GRAHAM, R.H., and ISSAC, K.P., 1990. The evolution of the Oman Mountains foreland basin. In: Robertson, A.H.F., Searle, M.P. & Ries, A.C. (Eds) The Geology and Tectonics of the Oman Region. Geological Society, London, Spec. Publ., **49**, 419–427.

WENDER, L.E., BRYANT, J.W., DICKENS, M.F., NEVILLE, A.S. and AL-MOQBEL 1998. Paleozoic (pre-Khuff) hydrocarbon geology of the Ghawar Area, Eastern Saudi Arabia. *Geo Arabia,* **3/2**, 273-302.

ZENG, H., and HENTZ, T.F., 2004. High-frequency sequence stratigraphy from seismic sedimentology: Applied to Miocene, Vermilion Block 50, Tiger shoal area, offshore Louisiana. AAPG, Bulletin, **88/2**, 153-174.

Appendix: 3D seismic acquisition parameters

Recorded by	:	Fugro-Geoteam AS
Date	:	29.11.01 to 28.12.01
Recording vessel	:	R/V Geo Pacific
Undershoot source vessel	:	R/V Geo Baltic

SOURCE

Number of Sources	:	2
Type	:	Sleeve Gun
Shot Interval	:	18.75m
Array Capacity	:	2x1500 cu/in (conventional)
		2x1420 cu/in (undershoot)
Pressure	:	2000psi
Depth	:	4m
Fold of Coverage	:	40 fold at 6.25m CMP interval

STREAMER

Number of Streamers	:	6
Type	:	
Hydrophones	:	
Hydrophones per Group	:	
Sensitivity	:	
Group Length	:	12.5m
Group Interval	:	12.5m
Number of Groups	:	240 per streamer
Depth	:	7m

RECORDING SYSTEM

Type	:	I/O MSX	
Format	:	SEG-D 8058	
Media	:	3590 cartridge tape	
Density	:		
Record Length	:	6144ms	
Sample Interval	:	2ms	
Filters	:	Low Cut	4Hz 18dB/octave
	:	High Cut	206Hz 264dB/octave

Polarity	:	SEG Standard

POSITIONING

Primary	:	STARFIX plus VBS
Secondary	:	STARFIX/SEADIFF

NOMINAL OFFSETS

Streamer Separation	:	+/-100m
Source Separation	:	+/-25m
Inline Offset: Source-Near Trace	:	148m

Final Processed UKOOA P1/90 Data Received:

Units	:	Metres
Spheroid	:	International
Projection	:	Universal Transverse Mercator
Central Meridian	:	Zone 40
False Easting	:	500000
False Northing	:	0.0
Scale Factor	:	0.9996

Processing Grid for 3D Migrated Data:

Line number at origin	:	2000 (bin centre)
CDP number at origin	:	800 (bin centre)
Easting co-ordinate at origin (m)	:	219803.215
Northing co-ordinate at origin (m)	:	2831547.143
Line bearing	:	62.0 Degrees
Grid dimensions (in-line) (m)	:	12.5
Grid dimensions (cross-line) (m)	:	12.5
Actual Line range	:	2041 to 3650 (increment 1)
Actual CDP range	:	955 to 2502 (increment 1)

Processing

The 500 Hz field data were put through a standard process of demultiplexing, signature decon and debubble to zero phase output, scaling, de-noise and de-spike before resampling to 250 Hz and filtering. Velocities were picked on a 1000 m grid before Tau-P deconvolution incorporating a coherent dipping noise mute. Velocities were used for NMO on the full stack, after which alternate traces were dropped resulting in 12.5 m CDP bins, followed by Radon demultiple and 3D DMO, NMO removal and pre-stack time KKF migration. Velocities re-picked on a 500 m grid were then used for NMO and the stack volumes produced. Only the full-fold volume was available for this study, equalized in a single window with amplitude compensation 1/rootN. This was followed by de-

migration for K filtering, deconvolution, interpolation from 12.5 x 25 m to 12.5 x 12.5 m grid, 3D 65-degree migration, bandpass filtering and amplitude correction. The passband in the stratigraphic interval studied here is 12-60 Hz at 1800 ms and 10-45 Hz at 2600 ms.

Part II: Papers