GENERAL INTRODUCTION

Main objectives

The Zagros area is one of the most important hydrocarbon systems in the world containing 8.6% of the oil and 15% of the gas proven world reserves and its tremendous hydrocarbon potential has always been an attractive topic for geologists. Geological investigation in the Zagros goes back to the first oil discovery, approximately one century ago. The study area ranges from the Lurestan to Southern Fars onshore and to the Persian Gulf offshore wells related to Cambrian to Early Permian succestion. During the Precambrian and trough the Palaeozoic, the Zagros area was part of the Arabian platform (Beydon, 1993). The Arabian platform was an eastern extension of Gondwana. The Neoproterozoic recording the Panafrican tectonic phase was composed mainly of granites and organized in several basins (Stöcklin, 1968; Becker et al., 1973; Berberian and King, 1981; Davoudzadeh, 1997; Horton et al., 2008) infilled at the end of Neoproterozoic by a thick evaporitic succession named "Hormuz salt". The Zagros area and its sedimentary succession are clearly impacted by the deformation of ductile evaporites (Jahani, 2008). The Early Cambrian is characterized by massive post rift clastic continental sediments covered by marine carbonate deposits that expends throughout the Middle to Late Cambrian (Mila Formation). The Ordovician time is characterized by a siliciclastic succession deposited on a gently dipping, wide and stable marine shelf bordering the Paleo-Tethysan Ocean (Senalp et al., 2001). It is capped by "Hot- shales" deposits that expended throughout the Silurian. At the end of the Silurian, an uplift in the Middle East area was related to epeirogenic movements (Ala et al., 1980; Berberian and King, 1981; Al-Sharhan and Nairn, 1997) and associated with a major sea level drop (Al-Husseini, 1991, 1992; Sharland et al., 2001; Konert et al., 2001; Haq and Al-Qahtani, 2005). The resulting hiatus is recorded in Southeast Turkey, Syria, Iraq and Oman and probably corresponds to the "Pre Tawil Unconformity" in Saudi Arabia. The Late Silurian hiatus was followed by a Devonian transgression caused by a global sea level rise (Vail et al., 1977). During the Middle and Late Devonian, a major hiatus resulted from epeirogenic tectonic movements in many parts of the Arabian plate (Al-Husseini, 1991). The latest Silurian and Devonian periods are poorly recorded due to erosion associated with Hercynian tectonism (Konert et al., 2001).The Hercynian tectonic period corresponds to a hiatus induced coinciding with a huge sea-level drop (Konert et al., 2001; Sharland et al., 2001). During the Mississipian (Lower Carboniferous), a horst and graben system is observed displaying a N-S orientation (Sepehr & Cosgrove, 2004). Dercourt et al. (1986), Kazmin (1991), Stampfli et al. (1991), Golonka (2000), and Heydari (2008) proposed a Permian age for the Neo-Tethyan rifting resulting in the separation of the Arabian platform from Cimmerian Plate (Central Iran, Afghanistan, Tibet, Sanandaj-Sirjan). However, Berberian & King (1981), Glennie (2000), Sepehr & Cosgrove (2004) and Bordenave (2005) attribute an Upper Trias age to this structuration.

The Palaeozoic succession also records two periods of glacial events in Gondwana: Late Ordovician and Carboniferous. During the Late Ordovician, Gondwana was covered by an extended ice-cap (Vaslet, 1990; Scotese, 1999). This glaciation developed during the Hirnantian (Brenchley et al., 2003; Sutcliff et al., 2000). In the Zagros, Hirnantian glaciation is recorded at Kuh-e Faraghan in Bandar Abbas area (Ghavidel Syooki et al., 2011). During the Late Carboniferous and Early Permian the southern regions of Pangea (southern South America and southern Africa, Antarctica, India, southern India, and Australia) were covered by ice. Alternating cool and warm periods during the ensuing Carboniferous Ice Age coincided with cycles of glacier expansion and retreat.

The first objective of this study was to present the main facies evolution of the Palaeozoic, to discuss the depositional environment and will tend to propose new palaeogeographic maps of the Palaeozoic succession.

The second objective will focus on the hiatuses observed all along the Palaeozoic succession and the inducing factors.

Industrial interests

Since 1990's, the oil and gas exploration are evolving towards deeper and more complex objectives. In the Middle-East, this evolution was declined by shifting from the conventional carbonate oil bearing Mesozoic and gas bearing Upper Permian towards deeper, relatively tighter and stratigraphically more complex clastic Palaeozoic section.

This exploration began in Oman and Saudi Arabia, where these Formations are shallower, and resulted in the discovery followed by production of several fields. The reserves discovered are situated mainly in the Devonian and Early Permian sections (Konert et al., 2001). The remaining potential is considered to be high as the exploration remained marginal in the other countries of the Persian Gulf.

As other international companies, NIOC are considering the exploration of these deeper targets, and the knowledge of the Palaeozoic succession and its depositional environment has a direct interest for the Groups. The Companies are involved in several licences in Middle East, in which the Devonian and Early Permian levels present a high potential. Moreover, the deeper levels of

the Ordovician and Silurian, although they are not a direct target for today's exploration in the area, have a major importance as they are lateral analogues of the "Hot Shale" source rock and of the reservoirs of fields situated in Algeria and Libya.

The goal of this Ph.D is to answer to several uncertainties concerning Palaeozoic succession. The Lower Permian succession (called Unayzah/Haushi in Arabian Countries, Al Khlata/Gharif in Oman and Faraghan in Zagros) are a complex stacked pattern of continental clastics, varying from braided stream, flood plain, lacustrine deposits and Aeolian deposits that can fill paleoglacial valleys. The depositional sequence evolves while going further east, passing into more distal succession. However, the lateral evolution and the palaeogeography of this succession are badly understood. This weak knowledge is even truer for the older levels of Carboniferous or Devonian, Silurian and Ordovician.

The stratigraphical study of this succession in Iran will allow obtaining distal control points to fit the palaeogeographical interpretation of the area. This will help to better prognoses and assess the prospectively of the area. In addition, identifying hiatuses and regional markers will allow understanding the tectonic and sedimentary phases of this area.

The Ph.D is in coordination with NIOC that will assume the logistic for the outcrop observations.

The first objective will tend to determine the stratigraphic architecture throughout the pre-Khuff deposits. This approach will be based on facies and palaeolog datas.

The second is to constrain and compare at a reservoir scale the dimension and distribution of sand deposits during different geologic periods.

Methodology and scientific organization

The approaches applied in this study are listed below:

1- Identification of the regional stratigraphic framework of the Paleozoic Pre-Khuff series in Zagros area based on outcrops data and subsurface data (well logs, cores, cuttings, and paleologs).

2- Identification and dating of the major sequences and markers based on palynologic studies

3- Sedimentary facies analysis and depositional environments

4-Correlations of the depositional sequences and stratigraphic distribution through time in order to approach correlation at the Iranian platform scale and Arabian plate.

5- Reconstruction of palaeogeographic maps

All these initial objectives will be addressed in this Ph.D thesis. This study focused on the Palaeozoic deposits cropping out in the Bandar Abbas and Fars area (Eastern Zagros). Surface data collected during the Ph.D have been complemented and compared with numerous sub-surface sections. The study of sub-surface sections has been carried out in an earlier stage and now is available from the NIOC archive.

Main topics

This Ph.D thesis is arranged in six Chapters.

Chapter 1, as a general part, introduced the geology and geography of the study area based on previous carried out investigations.

Chapter 2 shows the different methods used for facies analysis, X-ray diffraction, gamma ray, sequence stratigraphy, lithostratigraphy and palynology in the Zagros area. At the end of this chapter some of the outcrop sections are described based on the stratigraphic studies such as lithostratigraphy and biostratigraphy.

Chapter 3 focused on litho-stratigraphy of Palaeozoic succession in the Zagros area including litho-stratigraphic sections, overview photos and geological maps.

Chapter 4 concentrates on depositional environments, regional sequence stratigraphy and paleogeography of the Pre-Khuff succession (Ordovician, Silurian, Devonian and Permian) in Fars, Bandar Abbas and Persian Gulf.

Chapter 5 described unconformities and major erosional surfaces, depositional environments, sequence stratigraphy and palaeogeographic distribution through time in order to approach correlation at the Zagros scale and Arabian plate. Various paleogeographic maps for the area are presented and discussed in detail through time.

Chapter 6 summarizes the conclusions.

States of the art

The limited Palaeozoic outcrops in the Zagros are insufficient to enable the geological evolution of this part of the Arabian Plate during this period to be determined. Many studies have been carried out in the Zagros area since 1929, and all proposed different structural classifications for

this area. Several numbers of stratigraphical and palynological studies have been published, although many other unpublished reports are still available in the NIOC archives.

A summary of the main publications of the Zagros area is given below:

Boeck, Lees and Richardson (1929) addressed the entire Zagros area, extending from Iraq in the north to the Strait of Hormuz in the south, bounded by Makran zone located east of the Strait of Hormuz. These authors have mentioned different tectonic zones between the Mesopotamian depression (foreland) and the northeastern part of the Arabian Plate (Zagros allochthon): 1- Foreland autochthon and parautochthonous zone which is simply folded. 2- Fold and thrust units involving the Palaeozoic and Mesozoic platfonn senes of the fonner Arabian passive margin. 3- Far traveled radiolaritic and ophiolitic units. 4- Allochthonous Cretaceous carbonates units. 5- Allochthonous Palaeozoic metamorphic units.

Schroeder (1944) described the tectonics and architecture of the Zagros (Iran), and presented from the southwest to the northeast the following zones: 1- The Arabian foreland 2- The folded Zagros 3- The far travelled Palaeozoic thrust sheets 4- The radiolarite and ophiolite zones (basinal and paleo-oceanic units). He evidenced the similarities between the sedimentary contents of the Arabian plate and the more distal portions of the passive margin, which are currently thrusted in the Zagros Mountains.

Falcon (1958) published a paper called "oil fields in Iranian Zagros" focusing on stratigraphy. This paper dealed mainly with the gently folded parautochthonous successions of the outer Zagros (Sananndai-Sirjan ranges) (Fig. I.1), which thickness ranges from 6 to 12 km.

Stocklin (1968) has carried out a structural analysis in Iran. He considered that the main Zagros Thrust was a fundamental limit separating the Inner Zagros (Zagros area) from the Outer Zagros (Sanandai-Sirjan ranges) (Fig. I.1). He distinguished a folded parautochthonous sector in the Outer Zagros and a thrust zone in its inner part with Palaeozoic thrust units, including radiolarites and ophiolite units.

Setudehnia (1975) carried out the earliest work on the Palaeozoic strata in the High Zagros and indicated that the sequence comprised Cambrian clastics and carbonates deposits overlain disconfornably by Early Permian sandstones which in turn were overlain by Middle- Late Permian carbonates. Late Ordovician to Devonian rocks was not recorded. Three sections have been re-measured and re-sampled at Kuh e Dena and one at Zard Kuh. As a result of this work a 1050 m-thick Middle and Upper Cambrian and Ordovician succession has been identified at Zard Kuh whilst a 900 m-thick Early Cambrian is obsereved at Kuh e Dena. The Ordovician deposits are absent at Kuh e Dena.

Berberian and king (1981) reviewed the geological evolution of the Iranian region since late Precambrian time. The large Silurian-Carboniferous sedimentary gap in the Zagros (following the Ordovician and (or) Early Silurian deposits) is correlated to epeirogenic movements, which

led to a regional regression and general emergence of the region. Most of the Zagros basin, which emerged during Late Ordovician- Early Silurian, remained above sea level and underwent erosion until the end of the late Palaeozoic (Hercynian) movements. Following this large middle Palaeozoic (Silurian-Carboniferous) sedimentary gap, the regional shallow marine transgression of Permian sea with basal coastal clastics (Faraghan Formation), overlies with a low-angle unconformity the Ordovician and (or) Silurian rocks. The unconformity observed in the High Zagros indicated the earliest known activity of the High Zagros belt along its northern (Main Zagros) and the southern (High Zagros) fault.

Ghavidel Syooki (1996) worked on acritarch biostratigraphy of the Palaeozoic units in the Zagros basin. He proposed eleven acritarch assemblage zones for the Palaeozoic succession (zone C1 for the Middle - Late Cambrian, zone C2 for the Cambrian- Ordovician, zones O1 to O6 for the Early- Late Ordovician, zones S1 to S2 for the Early Silurian, zone D1 for late Devonian (Frasnian) and zone P1 the Early Permian.

Ghavidel Syooki (2003) introduced the Zakeen Formation (Devonian) by palynological study in Kuh e Faraghan (Zagros basin). The 65 palynomorphs have been arranged into 7 spore and pollen assemblage zones. Zones I-VI are presented in Zakeen Formation suggesting an Early Devonian (Lochklovian) to Late Devonian (Frasnian) age whereas zone VII suggests an Early Permian age (Faraghan Formation). As main result of this study, the Devonian Zakeen Formation is recorded for the first time in the Zagros basin.

Alavi (2004) has studied regional stratigraphy and its proforeland evolution of the Zagros area. He proposed for the Latest Neoproterozoic through Phanerozoic strata (7 – 12 km thick) four groups of rocks in different tectonosedimentary environments of the Zagros area: *(i)* Neoproterozoic to Devonian Pull-apart and Epicontinental Platform, *(ii)* Permian to Triassic Epi-Pangean Platform, *(iii)* Jurassic to Upper Cretaceous Neo-Tethyan Continental Shelf, and *(iv)* Latest Turonian to Recent foreland Basin. These groups include 11 megasequences. The lowest megasequence (I) represented deposits of pull-apart basins genetically related to Najd strike-slip tectonism of latest Neoproterozoic to Early Cambrian time. This megasequence is overlain by megasequence (II), which comprised the transgressive deposits of a shallow epicontinental platform that covered the region during tectonic quiescence in Middle and Late Cambrian time. Overlying the second megasequence, megasequences (III and IV) contains Ordovician, Silurian, and Devonian siliciclastic strata deposited in a warm shallow sea transgressiv over a platform along the margin of Gondwanan landmass during Permian and Triassic time.

Heydari (2008) worked on tectonics versus eustatic controls on 12 supersequences of the Zagros. They are: (1) Late Precambrian- Cambrian, (2) Ordovician, (3) Silurian, (4) Devonian, (5) Mississippian- Pennsylvanian, (6) Permian- Triassic, (7) Jurassic, (8) Early Cretaceous, (9) Late Cretaceous, (10) Paleocene- Oligocene, (11) Oligocene- Miocene, and (12) Miocene- Pleistocene supersequences. This study reconstructed the relative sea-level history of the Zagros region based on lithofacies characteristics and depositional environments. He confirmed that, the

relative sea-level curve for the Zagros Mountains mimicted perfectly the second-order eustatic sea-level curve of Vail et al. (1977).

Zamanzadeh (2008 and 2009a,b) studied the petrography, sedimentary environment, diagenetic alterations and sequence stratigraphy of the Zakeen (Devonian) and Faraghan (Permian) Formations in Kuh e Faraghan and Kuh e Gahkum. Kuh e Gahkum comprises different conglomerates, sandstones, siltstones, shales, dolomites and limestones, meanwhile in Kuh-e Faraghan the main lithologies corresponded to sandstones, siltstones and shales for clastics and some dolomite layers and limestones. The Zakeen Formation presented a progradational (shallowing upward) stacking pattern, indicating a fall in relative sea-level during Middle to Late Devonian and the Faraghan Formation represented a retrogradational (deepening upward) stacking pattern which resulted from the rise in relative sea-level that continued up to late Permian.

Jahani (2008) mainly worked on the halokinesis in the eastern Fars Arc and adjacent area. He studied the activation of Late pre-Cambrian to Early Cambrian Hormuz salt Formation during and before Zagros Orogeny and showed that pre-existing diapirs controlled the localization of Late Cenozoic folding.

Ghavidel Syooki (2011) has studied the stratigraphic evidence for the Hirnantian (latest Ordovician) glaciation in the Zagros Mountains. He noticed that the effects of the Hirnantian glaciation has been recognised in Kuh e Faraghan and Kuh e Gahkum sections of the Zagros Mountains. The glaciogenic strata have been grouped in the Dargaz Formation, a new lithostratigraphic unit that comprises three progradational/retrogradational sedimentary cycles (bounded by two glacial erosive surfaces), each potentially controlled by the regional advance and retreat of the Hirnantian ice sheet.

Tavakoli (2012) focused on tectonic and thermal evolution during the Palaeozoic in the High Zagros. The most significant geological elements corresponded to large scale faulted detachment folds, associated with a complex system of thrust faults segmented by strike-slip faults. His work suggested that the existence of active Ordovician and/or Silurian “décollements” led to the development of duplex structures which are confined in the core of the anticlines. He also suggested an important heat flow during the Devonian and the erosion of ~3900m of the sedimentary pile prior to the deposition of Permian sequence. This outcome reinforced interpretation of a thermal uplift scenario responsible for pre-Permian vertical movements.