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The Middle Cretaceous to Early Miocene Petroleum System in the Zagros Domain of Iran, and its Prospect Evaluation.

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ABSTRACT :

An impressive gathering of giant fields, located in the 50,000 sq km Dezful Embayment, produces from the Asmari limestone of Early Miocene and from the Cenomanian Sarvak limestone, and contains some 400 billion barrels of oil-in-place, or 7% of the oil global reserves.

Two excellent source rocks are associated with these reservoirs, the Kazhdumi Fm of Albian, and the Middle Eocene Pabdeh Fm. Kazhdumi was deposited in a depression corresponding to the present Dezful Embayment, and probably extending northeastwards, while Pabdeh accumulated in a NNW-SSE trough, from Shiraz to Lurestan.

Modeling showed that Kazhdumi and Pabdeh reached the onset of oil expulsion, 1 to 10 Ma, after the beginning of the Zagros folding. Therefore, migrations took place almost vertically and were facilitated by intense fracturing in high-relief anticlines. The distribution of source rocks, thickness, characteristics, and maturity were used to forecast if an undrilled structure is expected to be oil, gas or water-bearing, and what would be the order of magnitude of the oil-in-place.

In the Dezful Embayment, many low-relief Zagros anticlines, poorly defined by a poor quality early seismic, remained to be drilled, after seismic confirmation. However, their fracturing, critical for limestone permeability, is expected to be less developed. N-S oriented pre-Zagros salt-related elongated structures, also fed by Kazhdumi or deeper sources, are prospective, especially for Zubair and Burgan sandstones. In addition, large anticlines remained to be drilled to the Sarvak, north of the Mountain Front.

INTRODUCTION :

The Zagros Foothills, a system of large size whaleback assymetric anticlines, formed as the result of a Late Miocene to Pliocene orogeny, includes two uplifted areas, Lurestan to the north, where anticlines are deeply dissected, and Fars to the south. In between, a

50 000 sq km depressed area, known as the Dezful Embayment (Fig-1) corresponds to an impressive gathering of 45 oil fields, often associated with gas caps. Several of them are categorized as super giants as they contain 10 to 50 billions barrels of oil-in-place, i.e. Agha Jari, Ahwaz, Bibi Hakimeh, Gachsaran, Mansuri, Marun and Rag-e Safid.

About 98% of the oil-in-place, namely 250 billions barrels of oil and more than 200 Tcf of associated gas are trapped in two reservoirs (Fig-2), the 300 to 500 m thick Early Miocene high energy Asmari limestone, which is extremely porous almost everywhere in the study area and well sealed by the efficient Gachsaran evaporites, and the Sarvak limestone (Cenomanian and Early Turonian), very thick, up to 1000 m, but porous only for some of the high-energy platform facies, capped by the thick Gurpi/Pabdeh marls. In most of the fields, which correspond to high-relief, assymetric, often thrusted anticlines, the Asmari and Sarvak reservoirs are interconnected as the result of an intense fracturing of the Pabdeh-Gurpi marls in the crestal part of the anticlines.

SOURCE ROCK DISTRIBUTION AND CHARACTERISTICS :

Excellent type IIs source rocks were deposited in intracratonic depressions when anoxic conditions prevailed as the result of water stratification during the Middle Jurassic (Sargelu Fm), Valanginian (base of the Garau Fm), Albian (Kazhdumi Fm), and Middle/ Late Eocene (Pabdeh Fm). In the northern part of the Gulf, organic-rich layers were also deposited in the Ahmadi Mbr (Early Cenomanian) of the Sarvak Fm (Fig. 2). In addition, marginal source rocks were deposited during the Barremian (Gadvan Fm) and the Late Cretaceous (Gurpi Fm), but their contribution to the charge of the Iranian fields is negligible (Bordenave and Huc, 1995).

In spite of their excellent characteristics (initial TOC values in the 5-15% range, high Hydrogen Index (HI) varying from 500 to 700 g HC/kg C, and thickness from 100 to 300 m), the contribution of each source rock to the charge of the Zagros oil fields was extremely variable. This contribution, based on source rock maturity, association of mature source rocks with reservoirs and traps, was verified by oil-to-source rock and oil-to-oil correlations using stable isotopes ($\delta^{13}C$ and $\delta^{34}S$) and biomarkers (Bordenave and Burwood, 1990). Two source rocks, Sargelu and Garau, are not associated with reservoirs, being limited above and below by basinal facies, either massive evaporites or thick marls and tight argillaceous limestone. Their contribution to the oil accumulated in the Dezful Embayment is limited to 1 or 2%. Only the two source rocks, which play an important role in the charge of the Dezful Embayment oil reserves, the Kazhdumi and the Pabdeh, are considered in this paper.

THE KAZHDUMI FORMATION :

At the end of Aptian, a major regression, which caused the shallow water Aptian carbonates to become emergent, was followed by a low amplitude transgression marked by a sudden influx of clastics. Most of Saudi Arabia, Kuwait and Iraq, west of the Euphrates river, were covered by alluvial plain facies, while deltaic sediments rapidly prograded in the Safaniya-Burgan area. The more distal part of the basin was

the locus for the deposition of the Kazhdumi Fm, dated as Albian. A depression was limited to the SE by the Fars Platform, where the deposition of shallow-water thin oxic marls was interrupted by temporary emergences. To the north, it was limited by the EW Bala Rud carbonate shoal, which separated the Kazhdumi depression centered on the present day Dezful Embayment from the Lurestan depression. To the east, the depression was bordered by a sill, on which anoxic and oxic facies fluctuated according to sea level changes (Fig 3), however little information is available on a possible eastern extension.

Up to 300 m of dark grey marls and subordinate argillaceous limestone, containing a pelagic fauna of globigerina, globotruncana and radiolaria, were deposited in strictly euxinic conditions. The organic matter is of algal origin. Kazhdumi TOC values vary from 1 to 11% with average values in the 5% range in the center of the depression. The potential S_2 may reach 50 to 60 g HC/kg rock and HI reaches values as high as 500 to 700 g HC/kg C. The source Potential Index (SPI) may be in excess of 25 tonnes/m^2, classifying the Kazhdumi as one of the richest source rocks. The Kazhdumi organic matter contains up to 5 to 7% per weight of sulfur, this fact explains the high sulfur content of the oil generated.

During the Albian, the Arabian Platform was close to the Equator, according to plate tectonic reconstruction, and under a humid climate as shown by the large amount of fresh water which flowed into the Dezful Depression through a system of rivers (Bordenave and Burwood, 1995). This fluviatile water, outwash from the Arabo-Nubian land mass, was nutrient rich (nitrates and phosphates). Ideal conditions were realized for a high plankton productivity in the shallow low-density oxygenated fresh water. Density stratification and the fall of organic matter in the oxygen-deprived zone is a classical mechanism for anoxic conditions. Sulfate reducing bacteria were extremely active as demonstrated by the sulfur incorporated in the Kazhdumi organic matter.

THE PABDEH FORMATION :

As a consequence of the aggradation of the former Radiolarite Trough to the Arabian Platform, during the Campanian, the direct access of the Arabian Platform to the South Tethys ceased, and a thick sequence of flysch, made for a large part of radiolarite debris, accumulated in front of the newly emergent area, which was actively eroded. A well individualized NW-SE trending depression, parallel to the Zagros Suture, extended from Fars to Lurestan, during the Paleocene-Eocene and even Oligocene in Lurestan (Fig-4). It was bordered to the SW by platform carbonates covering most of the Arabo-Persian Gulf. To the SE, the depression was limited by the Fars Platform, where the shallow water dolomitic limestone of the Jahrum Fm surrounded a subsident Sebkha (Sachun Fm). A monotonous and thick (200 to 1000 m) sequence of grey marls, containing a rich planktonic fauna of Globorotalia and Globigerina were deposited. Euxinic conditions prevailed in the central part of the depression during Middle/Late Eocene and even Early Oligocene in Lurestan. 150 to 200 m of organic-rich marls contain up to 11.5% organic carbon, the average TOC values varying from 3% in Fars to 7.5% in Lurestan (Fig.4). The organic matter is mostly algal (Tasmanacea), with HI

up to500/650 g HC/kg C, however terrestrial influences are visible in the vicinity of the NE shoreline.

THE PETROLEUM SYSTEM :

The Main Fields area corresponds almost exactly to the depression where the Kazhdumi source rocks were deposited. Moreover, oil-to-oil and oil-to-source rocks correlations, based upon carbon and sulfur isotopes and biomarkers composition, have shown that most of the oil accumulated in the main fields in the Asmari/Sarvak reservoirs is originated from the Kazhdumi, while only the oil of the NE Dezful fields (Lab-e Safid, Par-e Siah, Lali, Qaleh Nar and Karun) comes from the Pabdeh (Bordenave and Burwood, 1990 and 1995).

Except perhaps in the Pazanan field, no interference was observed between the Asmari/Sarvak reservoirs and source rocks deeper than the Kazhdumi. This was explained by the high pore pressures developed in mature Kazdumi source rocks, which formed a barrier for the oil and gas from deeper origin. Only limited amounts of Kazhdumi oil have reached the tight generally basinal Khami Fm. Therefore, the Middle Cretaceous to Early Miocene Petroleum System, limited on its lower part by the base Kazhdumi and on its upper part by the Gachsaran evaporites, includes two source rocks, Kazhdumi and Gurpi, and two main reservoirs, the Sarvak and the Asmari.

The IFP Genex software was used to model the thermal evolution of the Kazhdumi and the Pabdeh source rocks and to determine the onset of the oil expulsion. Kinetic parameters were measured on source rock samples by using the IFP Optkin program of pyrolysis. Because of the stability of the platform and its almost constant subsidence through time, the application of a constant heatflow was considered as reasonable. A value of 36mW/m^2 was choosen as it gives a best fit between the observed and the calculated values of the thermal indicators such as the vitrinite reflectance, the Rock-Eval T_{max} and the Hydrogen Index. The onset of oil expulsion was assumed to happen for a 30% oil saturation of the source rock pore space. It means that the onset of oil expulsion was reached earlier for rich source rocks.

Modeling was performed for selected wells in almost each field of the Dezful Embayment, and for virtual wells located on the flank of the anticlines, by adding slices of 1000 ft (304.8m) down to the synclinal axes. The thickness of the eroded sediments has been evaluated from a set of formation isopachs. One of the critical point remains, namely the thickness estimate of the Gachsaran evaporites, as the Gachsaran and the overlying beds are unconformably folded and thrusted over the Asmari .

If Karanj and Paris are excepted, the onset of oil expulsion from the Kazhdumi was reached, when its base was burried to 3900 to 5000m, according to places, between 8 and 1Ma, in synclines as well as in anticlines. In Karanj and Paris, oil began to be expelled 16Ma ago. For the Pabdeh, the oil expulsion has not commenced yet on the Mansuri trend, even in the synclines. Elsewhere, it was not reached on the top of the

Main Field anticlines, even at Karanj and Paris, but it was reached in the deeper part of some synclines, from present to 4.5Ma.

On the NE edge of the Platform, Burdigalian sediments (16 and 20Ma) were deposited before the Zagros folding (Ricou, 1974). In the Dezful Embayment, the main phase of Zagros folding apparently began after the deposition of the Mishan Fm (Middle Miocene), and was witnessed by the deposition of the Agha Jari molasse, some 10Ma.

Excepted for the Karanj and Paris fields, the oil expulsion, either on the anticlinal tops or in the deeper parts of the synclines, commenced later than 8Ma, i.e., after the beginning of the Zagros folding. It is likely that the fracturing of the Sarvak to Asmari interval in the anticlinal part of the high-relief structures facilitated the oil expulsion and its upward migration to the first cap rock encountered, the Gachsaran Fm. The source rocks are expected to have been more easily drained in the anticlinal than in the synclinal part, which were in strong compression.

As the oil expulsion from the source rocks happened when the Zagros folds were already individualized, oil migrated almost vertically to the reservoirs of the neighbouring anticline. A concept of "Area of Drainage" could be applied for each anticline, and a tentative estimate of the oil trapped could be made, assuming a sufficient knowledge of the Kazhdumi and Pabdeh source rock characteristics (TOC, HI, TR, thickness), and of their geometry .

The geometry of the areas of drainage was deduced from early seismic data, at the top of the Asmari, which is a well defined marker. Each area of drainage was cut into slices every 1000 feet. The surface of each slice was measured by planimetry. A burial profile was established for each slice to calculate, for both the Kazhdumi and the Pabdeh, the evolution of their transformation ratio (TR) through time, the present day TR, the amont of oil generated and the amount expelled. The number of slices varied from 3 to 5 for the anticlines located on the SW Mansuri trend, to up to19 in high-relief anticlines, such as Naft-e Safid. Modeling was applied to 21 fields of the Dezful Emvbayment, which contain 86.5% of the oil-in-place found in the Zagros Domain. All together, 195 burial profiles were used.

The initial oil-in-place (IOIP) of each fields was compared to the oil expelled from the source rocks, according to the model. As a large proportion of the fields are full to the spill point, the anticlines were grouped into trends, to take care of secondary migrations. To make a long story short, the IOIP of the groups of fields of the Dezful Embayment corresponds to only between 12 and 21% of the oil calculated to have been expelled from the source rocks in their areas of drainage. The main contributor, the Kazhdumi Fm, would have generated some 95% of the oil generated in Zagros Foothills.

PROSPECTS :

As oil migrated vertically from the Kazhdumi and the Pabdeh source rocks to the Sarvak and the Asmari reservoirs of the Zagros structures, the distribution and the

maturity of these two source rocks provides a good definition of the potentially prospective areas, at least for the Middle Cretaceous to Early Miocene Petroleum System.

In Lurestan, the Kazhdumi is not a source rock anymore and the Pabdeh is not mature, moreover the Asmari reservoir is breached, and the Sarvak is having almost everywhere a tight basinal facies. In Fars, the Kazhdumi is generally oxic, and the Pabdeh immature. In the Shiraz area, however, the origin of the Sarvestan oil and of several noticeable seepages is not completely understood, but might come from an eastern development of the Kazhdumi source rocks. A few large anticlines are prospective for the Sarvak, and perhaps for the Upper Khami, in the Shiraz area. Some large anticlines in Khuzestan, east and northeast of the Mountain front are also prospective.

In the Dezful Embayment, all the large high-relief anticlines were drilled to the Sarvak and deeper. A few anticlines of smaller size remain to be drilled to the Sarvak. Several tenth of low-relief prospects, evidenced by the early seismic, remained to be tested for the Asmari reservoir, however, they need a detailed mapping from new seimic data. It should be noted that even if its reservoir characteristics are generally good, the fracturing in low-relief anticlines is expected to be less developed, and the reservoir productivity to be lower.

In addition, in the south of the Dezful Embayment, in areas not influenced by the Zagros folding, salt-related large N-S elongated very low-relief structures, formed sometimes as early as the beginning of the Jurassic, are prospective for the Sarvak and the Asmari limestone/Ahwaz sands and for the Burgan and the Zubair sands. Again a good quality seismic is needed in this vast area. Some stratigraphic trap possibilities also exist, such as the pinch out of the Burgan sands, which are still in their infancy.

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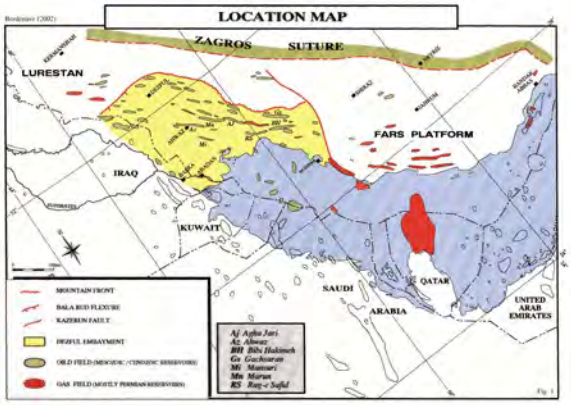

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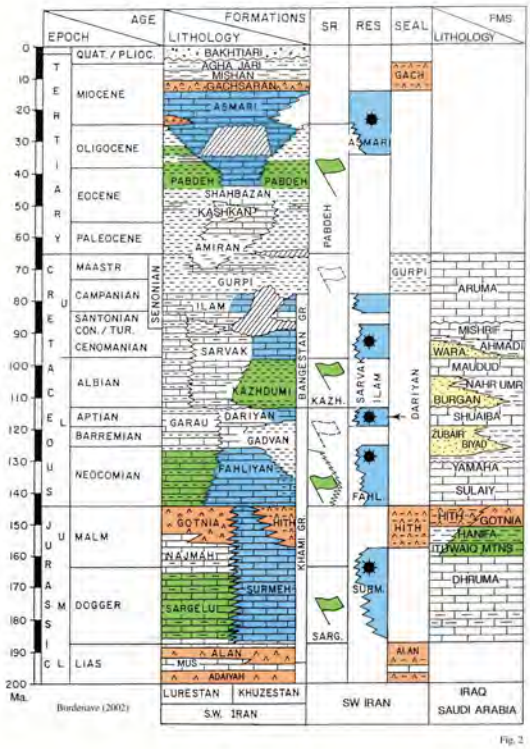
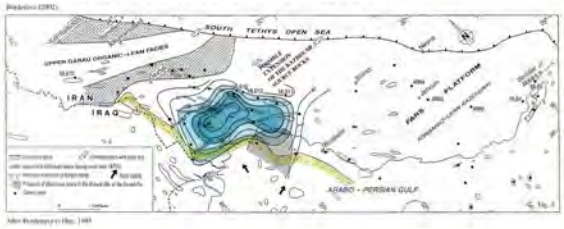


ISOPACH MAP OF THE KAZHDUMI BITUMINOUS FACIES (TOC>1%)



ISOPACHS OF THE ORGANIC-RICH LAYERS OF THE PABDEH FORMATION