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Deep Gas Potential of Onshore Bahrain Field

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Abstract

Bahrain Island is surface expression of a large anticline at depth - the Awali Field. It is one of the oldest producing fields, since 1932, in Middle East. Known producing reservoirs are in Cretaceous and Jurassic. In 1980s, E & P companies in Middle East started looking further below known reservoirs and there was regional success in Paleozoic Unayzah and Khuff Formations, which opened up new exploration frontiers in deeper gas. By late 1980s recognition of Paleozoic petroleum system started in Middle East. Discoveries made in Devonian reservoirs in Bahrain, Saudi Arabia & Turkey; Ordovician reservoirs in Jordan, Carboniferous reservoirs in Syria, and Silurian & Ordovician reservoirs in Iraq.

Authors attempted examining and assessing 325 Sq Km of 3D seismic and 400 line km of 2D seismic data, with six deep wells. Considerable Paleozoic section is deposited at Awali field and the anticlinal structure continues well into it, thus forming a basis for exploring an entrapment potential as deep gas play. Horizons interpreted below, producing Khuff and Unayzah, have numerous potential structures and their associated reservoirs in Jubah, Jauf, Tawil, Ra'an, Hanadir and Saq formations. The potential source rocks, such as Qusaiba Shales, also lie within Paleozoic section. Jauf reservoir of Devonian age is found to be gas bearing, and it needs appraisal and development. Fault Trap play anticipated for Jauf and below reservoirs. Its analogue has proven successful on the flanks of Ghawar structure in Saudi Arabia. Seismic data interpretation suggests some stratigraphic truncations, in lower parts of Paleozoic section and on the flanks of its structure, which in turn create a stratigraphic play. Considering high potential of hydrocarbon accumulation in Paleozoic, further exploration efforts are needed and authors initially propose new seismic acquisition campaign specially designed for imaging deeper plays in Awali.

Introduction

The Middle East holds estimated proven reserves of about 745 billion bbl of crude oil and 2540 Tscf of natural gas, approximately 56% and 41% of the world reserves, respectively. This fact led Murris (1980) to describe the area as the world's richest hydrocarbon habitat. These reserves are found mainly in Mesozoic and Tertiary reservoirs in a northwest-trending zone from Oman to Turkey. Crude and condensate production from these reserves were reported (in 2005) to be approximately 3.25 billion bbl/year (EWG report- 2007). Bahrain's Awali onshore field lies in the heart of this highly rich petroliferous basin **(Figure 1)**.

In addition to Tertiary and Mesozoic reservoirs, the Paleozoic section has been known to host significant reserves. This fact substantiated by oil discoveries in Oman and by the delineation of the giant Permian Khuff gas fields in the central Gulf is and the Zagros fold belt during the early1970s. Activities, especially since the late 1980s, have established the economic attractiveness of the Paleozoic petroleum systems throughout the Middle East. In particular, the highly successful campaign in Saudi Arabia and Bahrain for the Unayzah play establishes the presence of a hitherto unknown hydrocarbon province (**Figure 1**). Discoveries in Ordovician reservoirs in Jordan, Carboniferous reservoirs in Syria, Silurian and Ordovician reservoirs in Iraq, and Devonian reservoirs in Bahrain, Saudi Arabia, and Turkey are all charged essentially by Silurian source rocks, establishing productive Paleozoic petroleum system.

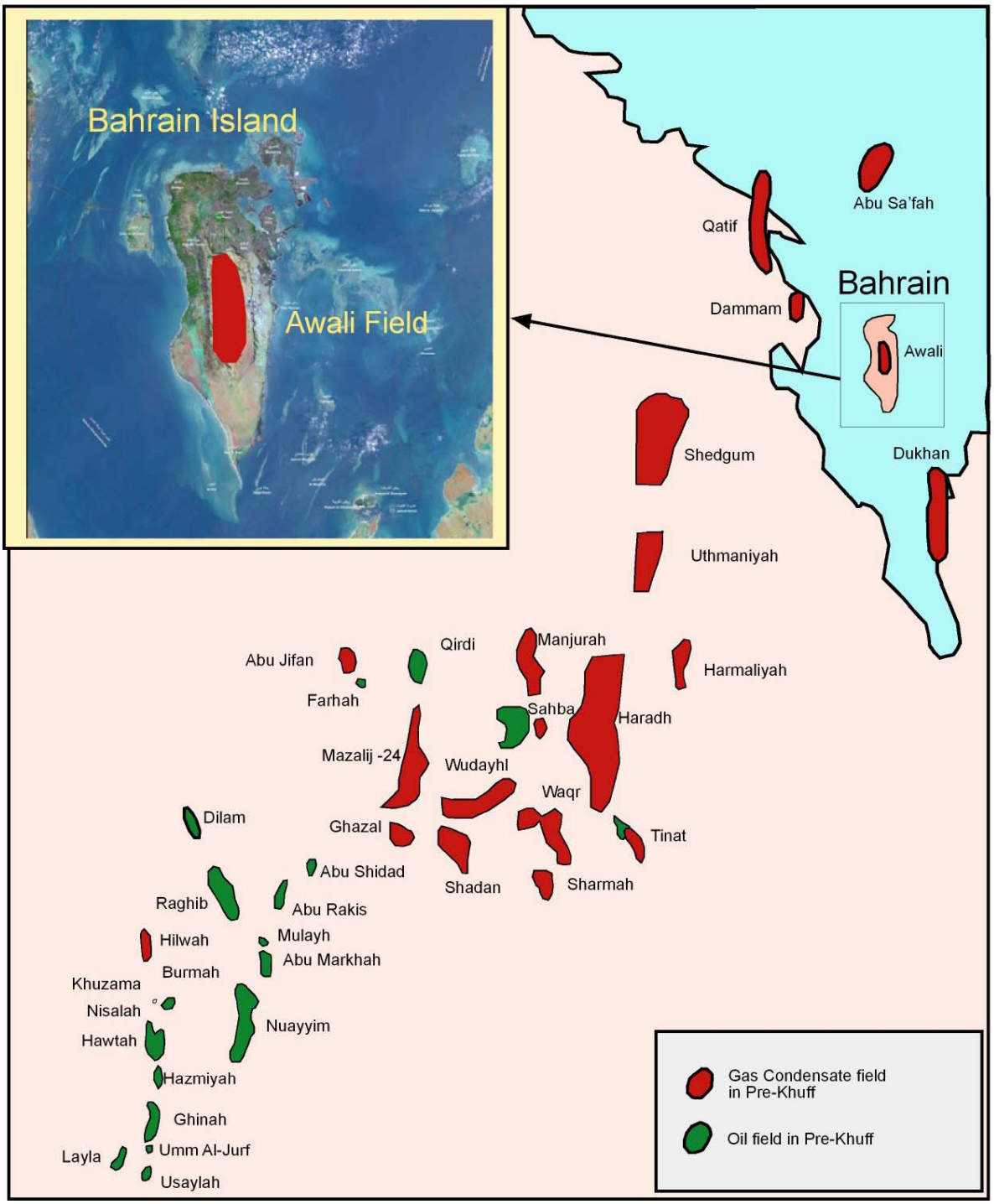

Figure 1. Location map of Awali field and the surrounding Paleozoic pre-Khuff discoveries.

There is a considerable Paleozoic section deposited in the Awali field, and the deepest well has penetrated the Saq sandstone of Cambrian-Ordovician age. Two of the reservoirs in the Paleozoic section are producing gas: the Khuff and Unayzah formations. These reservoirs are the shallowest in the Paleozoic sequences (**Figures 2 and 3**). The sedimentary sequences below Unayzah have numerous porous horizons in the Jubah, Jauf, Tawil, Ra'an, Hanadir, and Saq formations.

Potential for hydrocarbon accumulation exists in the deeper reservoirs (Figure 2), as evidenced by the potential source rocks of Paleozoic that lie within the deeper sections. Initial efforts of exploration for deeper gas determined the Jauf reservoir of Devonian age are gas bearing. The crestal wells that penetrated this reservoir produced gas, but the wells on the flank became water wet. There now exists an opportunity of appraising and developing the Jauf reservoir; new seismic data are needed and a subsequent drilling campaign will be required. An attempt has been made to model probabilistic volumetrics of this reservoir, for which results are encouraging. Another play also exists for Jauf below the fault-trap play. This play has proved successful on the flanks of the Ghawar structure in Saudi Arabia where it is eroded at the crest and present on the flanks. It is juxtaposed

with Qusaiba shales, thus making a fault seal. Such phenomenon may also be present at Awali, but throw of the fault is less and the Jauf reservoir is truncating against itself. Considering the lithology of Jauf formation, sand shale juxtaposition can make the fault a seal. Seismic data suggest some stratigraphic truncations, in lower parts of the Paleozoic and at the flanks of the structure, which in turn create a stratigraphic play.

Six wells have been drilled for exploring the potential of the Paleozoic sequence. Most have targeted the Jauf reservoir; one of them has reached the Saq formation. Apart from a vintage 2D seismic dataset, 3D seismic data was also acquired a decade ago (Figure 3).

The authors estimated the probabilistic volumes of hydrocarbons these plays might contain, which resulted in an encouraging picture.

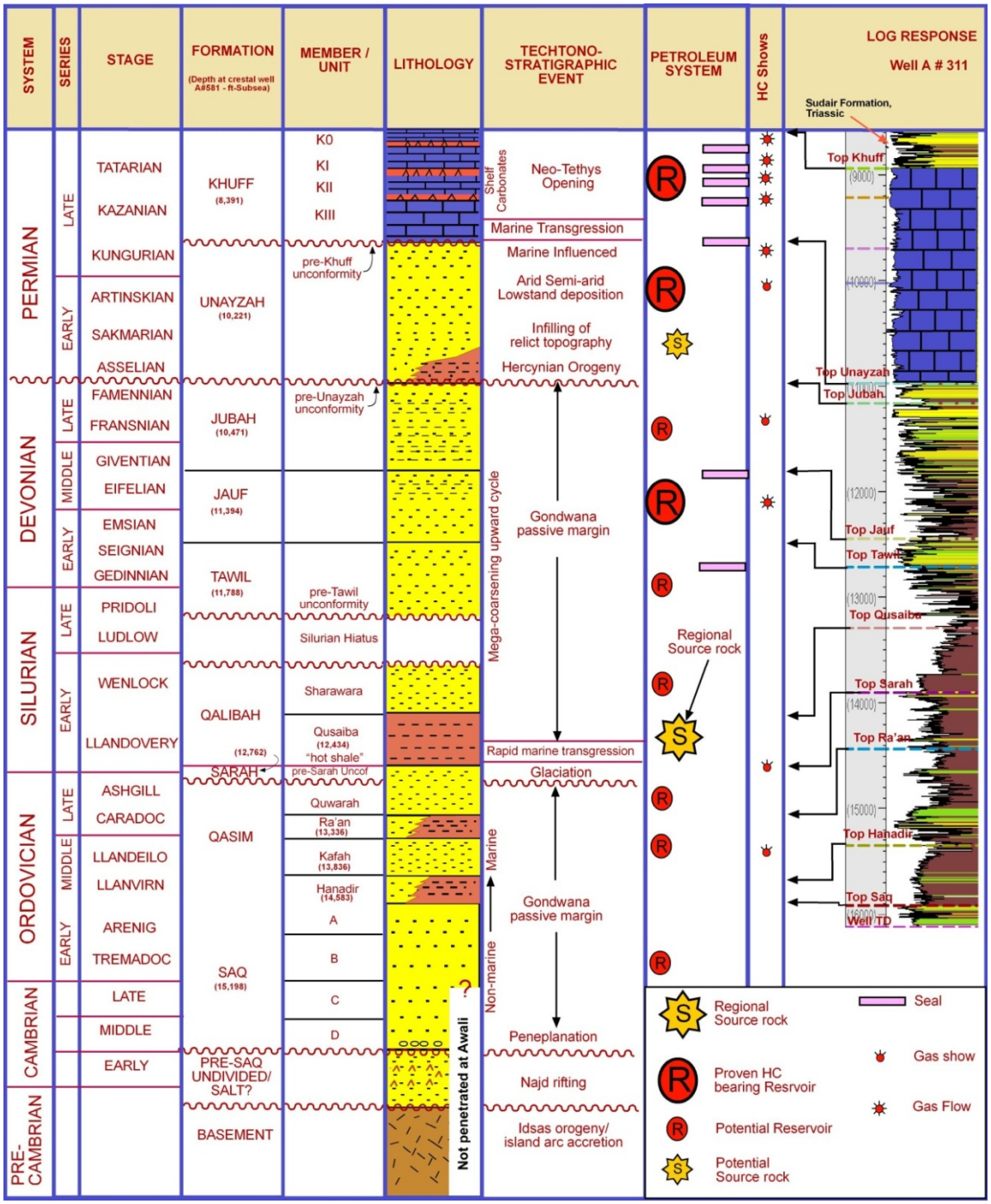

Figure 2. Paleozoic stratigraphy of Awali field.

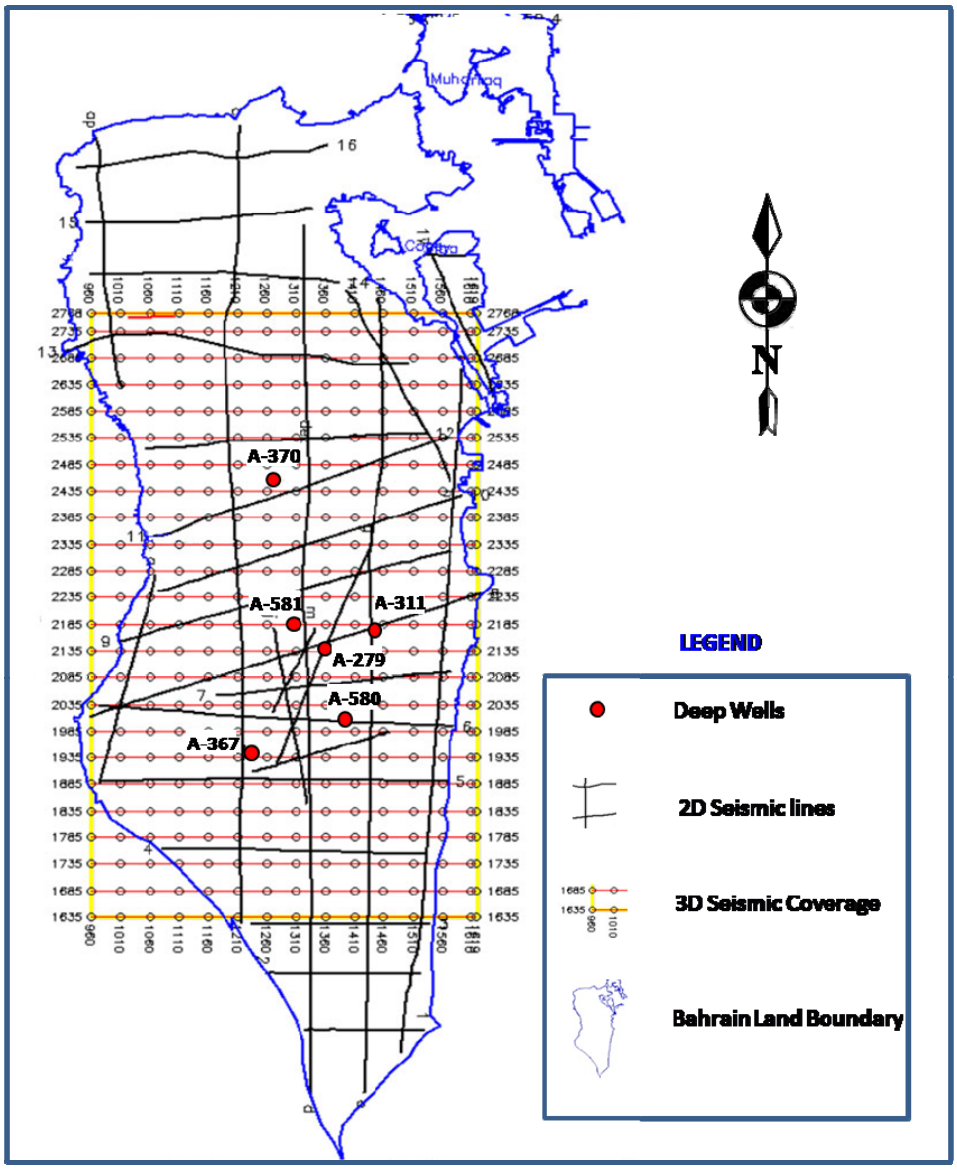

Figure 3. Location map of seismic surveys and deep wells in the study area.

Hydrocarbon Plays

There are three conceptual plays: deep gas play, fault-trap play, and stratigraphic play (**Figures 4**). The deep gas play is a structural play concept and all the elements of the petroleum system are favorable in Awali. The main risk lies in the reservoir distribution and quality, and with current data quality its difficult to resolve. The answer lies in new seismic, specifically designed for imaging deep reservoirs.

The fault-trap play concept has been successful along the flanks of the Ghawar structure in Saudi Arabia because the Jauf reservoir is eroded at the crest and again appears on the flanks. It is juxtaposed with Qusaiba shales, thus allowing for fault seals. Such phenomenon may also exist in the Awali as Seismic data suggest the Jauf reservoir is truncating against itself on the flanks of the structure.

In the stratigraphic play, seismic data suggest some stratigraphic truncations in the lower parts of the Paleozoic and at the flanks of the structure, which in turn create a stratigraphic play. Further exploration efforts are needed to consolidate this play concept.

Deep Gas Play

There is a considerable Paleozoic section deposited in Awali, and the deepest well has penetrated the Saq sandstone of Cambrian-Ordovician age. Two of the shallowest reservoirs in the Paleozoic are already producing gas (Khuff and Unayzah formations), and gas has also been discovered in the Jauf sandstone of Devonian age (**Figures 2 and 4**). The sedimentary sequences from the Unayzah to Saq formation have numerous porous horizons in the Jubah, Jauf, Tawil, Ra'an, Hanadir, and Saq formations. The Silurian Qusaiba formation is considered the source rock for the Khuff, Unayzah, and Jauf at the Awali structure; it is considered a regional source for the Paleozoic petroleum system. Regionally, the crystalline basement is

overlain by the Saq formation. Therefore, the Paleozoic strata below the Unayzah have the potential of being hydrocarbon-bearing zones.

Paleozoic strata have a significant potential for commercial accumulation of hydrocarbons in the Awali structure, based on the surrounding discoveries in the region (Figure 1). The structure is already producing hydrocarbons from the Permian Khuff and Unayzah formations. The Khuff formation's four sand horizons K0, KI, KII, and KIII of the Unayzah formation are producing gas. The deeper Jauf formation below the Unayzah has produced gas from A-279 and A-581 wells at 2 MMsf/d and 14 MMscf/d, respectively.

Based on results from the deepest well, A-311, hydrocarbon shows have been observed throughout the well to total depth. It is interesting to note that the well has penetrated the Saq formation of Cambrian-Ordovician age. Saq is a sandstone reservoir.

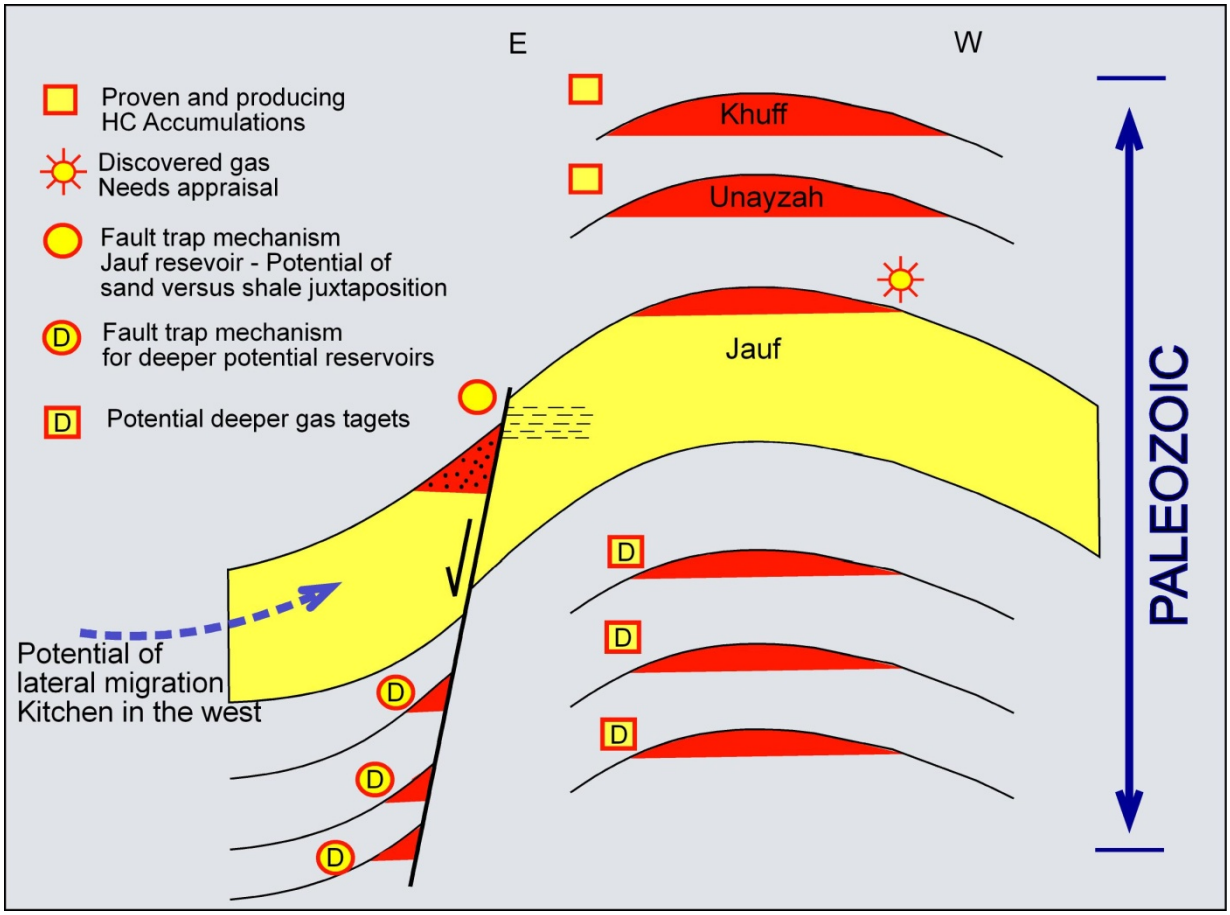

Figure 4. Envisaged structural plays in the Awali structure.

There are numerous porous horizons in the Jubah-Saq sandstone sequence (Figure 2). All these horizons, including Tawil, Ra'an, and upper parts of Hanadir and Saq, have potential reservoirs. The trap for deep gas play is one of the most promising petroleum system elements, with a very high chance for existence, as the Awali structure is preserved up to the Lower Paleozoic. The source rock charging the Paleozoic is most probably the Qusaiba shale of Silurian age. It is believed that this same rock has charged the Khuff, Unayzah, and Jauf formations. All the potential reservoir rocks may have been sealed by their intraformational shales, as indicated by the log data of A #311 and A #581 (Figure 2).

In addition to the information just presented, the seismic data indicate some features related to hydrocarbons (**Figure 5**), such as shadow zones. Shadow zones occur as the result of variations in velocity caused by the presence of hydrocarbons.

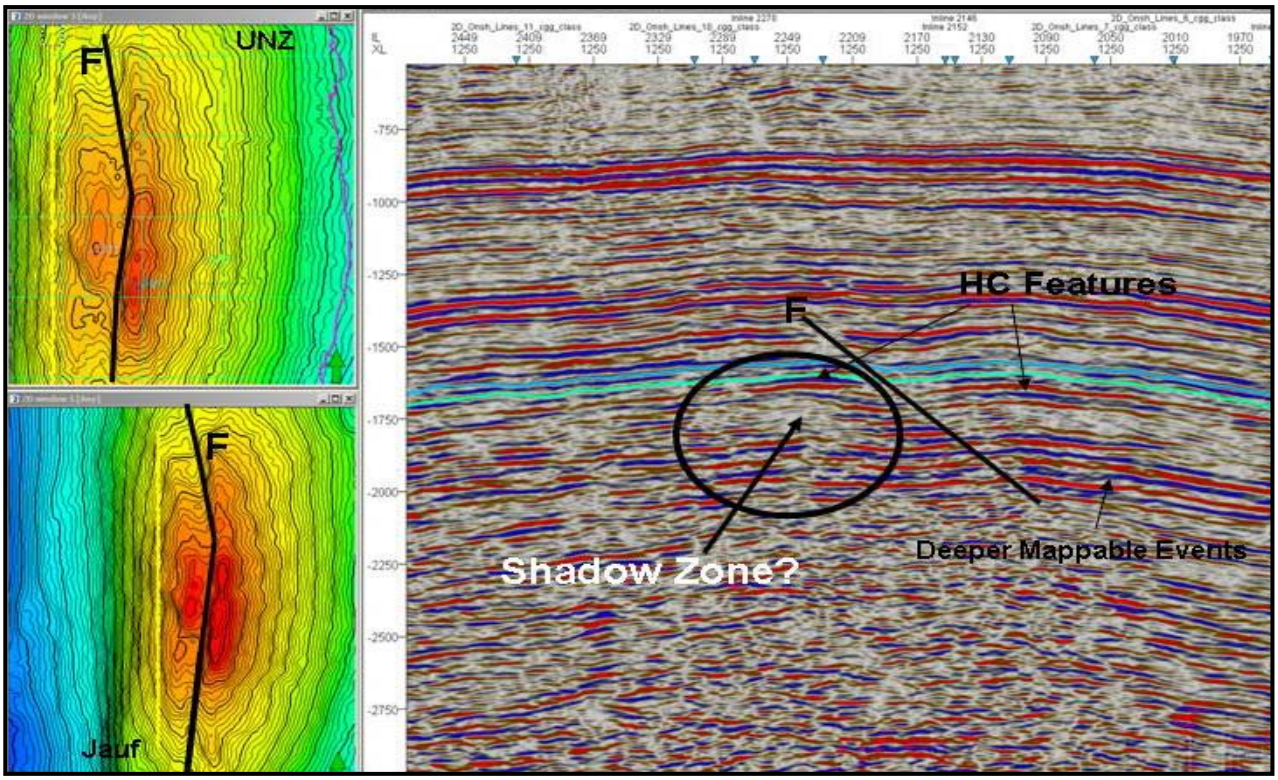

Figure 5: A seismic cross line (from the existing 3D volume), showing interesting anomalous features deeper, below the Unayzah.

Jauf Appraisal and Field Development

The Jauf reservoir is regionally a good reservoir. It bears hydrocarbons in the flanks of the Ghawar anticline, where it truncates against faults (Figure 5). The Jauf sandstone is also a highly prospective exploration target in the Awali field, since it has proved to be gas bearing in the crestal part of the structure through Well A#279. A second well, A #581, also located at the crestal part of the structure, was tested with an interval of 33ft in Jauf formation. It produced gas at 14 MMscf/d. To avoid sanding problems the well was not fully opened to flow.

In addition to A #279 and A#581 wells, there are four others that have penetrated the Jauf formation. Out of these six wells, three gave clear gas shows:A #311,A #370, and A #580. Testing could be done only on A#580 and A#367, which flowed water. Wells #580 and #367 are located at the flank of the structure.

Stratigraphic Truncation Play

The Awali structure has good 3D and 2D seismic coverage, extending almost over the entire structure. Based on seismic data evidence we observe some stratigraphic anomalies within the Paleozoic sequence (**Figures 6 and 7**).

The deepest mapped seismic horizon in the Paleozoic section is the Jubah; these possible truncations lie much below. We tried initially to examine the idea by flattening the Unayzah and Jubah (Figures 6 and 7). These truncations and onlap features can be seen on the flanks of the structure, which give rise to a stratigraphic play model.

The 3D seismic data acquired in 1998 was not designed to image the Paleozoic. Therefore, quality of data at the truncations level is not as good as desired. The authors had difficulty in resolving these apparent truncations, which sometimes appear as imaging artifacts. Data quality hits hard at this play concept, and it is difficult to proceed with further examination unless data of improved quality is made available.

Further investigation is needed to consolidate the play concept, yet it adds substantially to the prospectivity of the Paleozoic sequence.

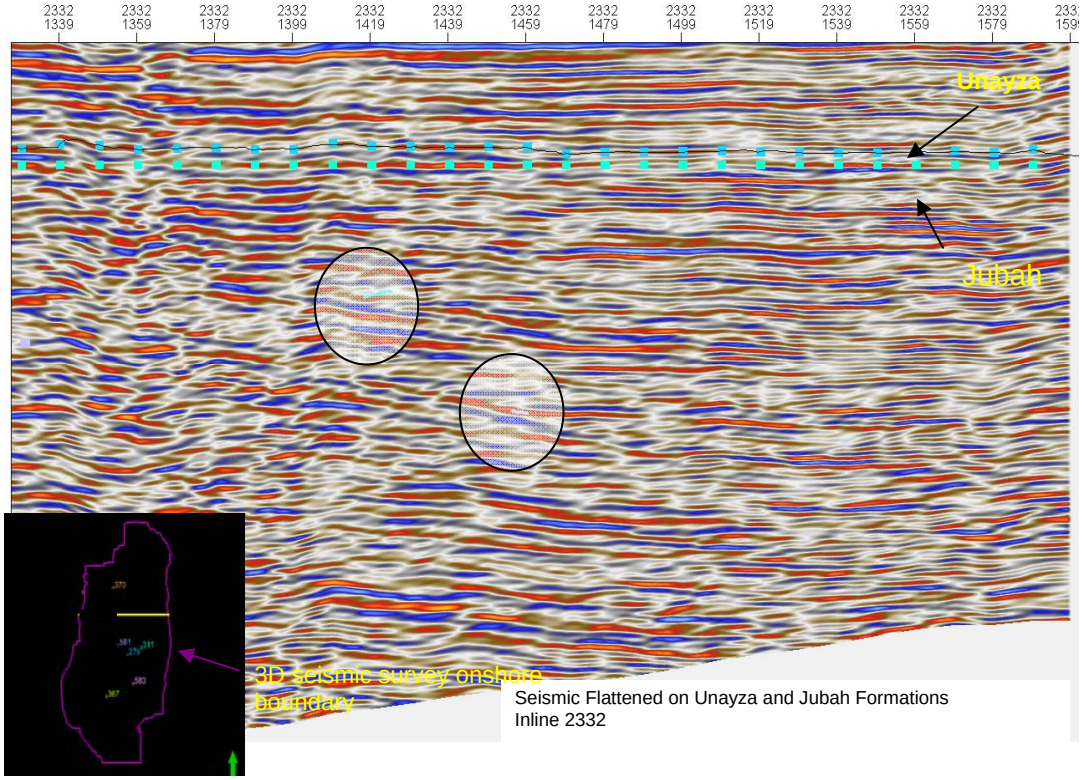

Figure 6. Possible stratigraphic truncations observed below the Jubah horizon in the seismic data.

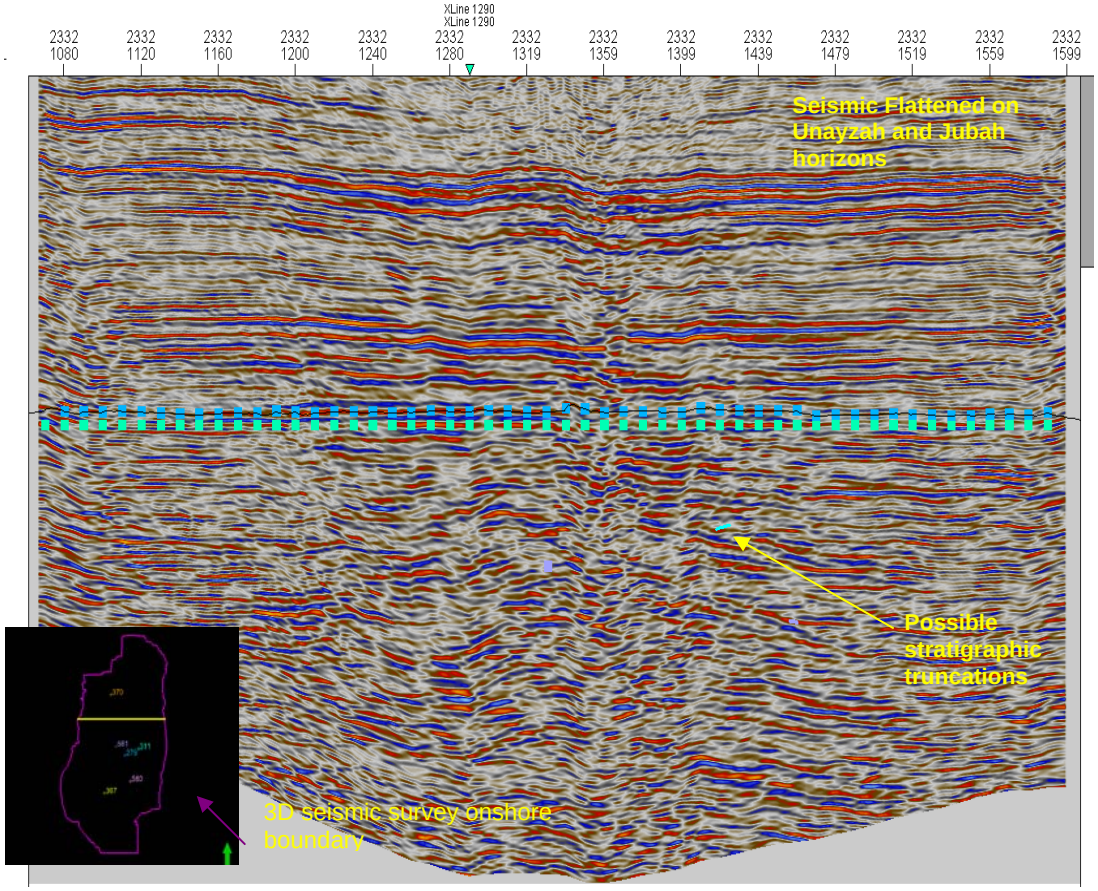

Figure 7. Stratigraphic truncation play deep below the Jubah.

Fault-Trap Play

In the western part of the Awali structure few normal faults are documented; throw of around 50 ms translates to about 80 to 90 ft of throw in depth. The faults apparently cross multiple horizons (from Jubah and Jauf to some deeper horizons such as the Qasim Group). In the north, the well nearest these faults is the A#370. In the south, the nearest drilled well is the A#367 and the closest mapped seismic horizon is the Jauf reservoir. Based on the well data and the seismic structure mapping, some fault trap mechanism can be anticipated. We can have multiple leads (at least two leads near #370 and #367) within the fault-trap play for the Paleozoic section.

Such an analog exists in the Ghawar area where the Jauf reservoir is cut by faulting on the flank of the structure and juxtaposed by shale, making the fault a seal. The Jauf is eroded from the crest; therefore, it is producing hydrocarbons from the fault-trap play in the flanks of the Ghawar area in neighboring Saudi Arabia.

Using only the fault near Well #367, we tried to consolidate our play model (**Figure 8**). The Jauf reservoir is truncated against a fault in the southwest part and then thins at the crest. From current mapping some contours can be seen closing against the fault, thus creating a potential fault-trap mechanism. To initially consolidate the play concept, the GR log of Well #367 has been cut into half and given a 90-ft throw. It gives us a positive indication of sand-shale juxtaposition. The fault can seal where sands juxtapose against shale on the other side, thus providing a trapping mechanism for the Jauf and underlying reservoirs. Good-quality seismic data are needed to further evaluate the play.

If we analyze the prospect risk, the highest risk factor lies with the sealing capacity of the fault, yet sand-shale juxtaposition may hold the key of its sealing capacity.

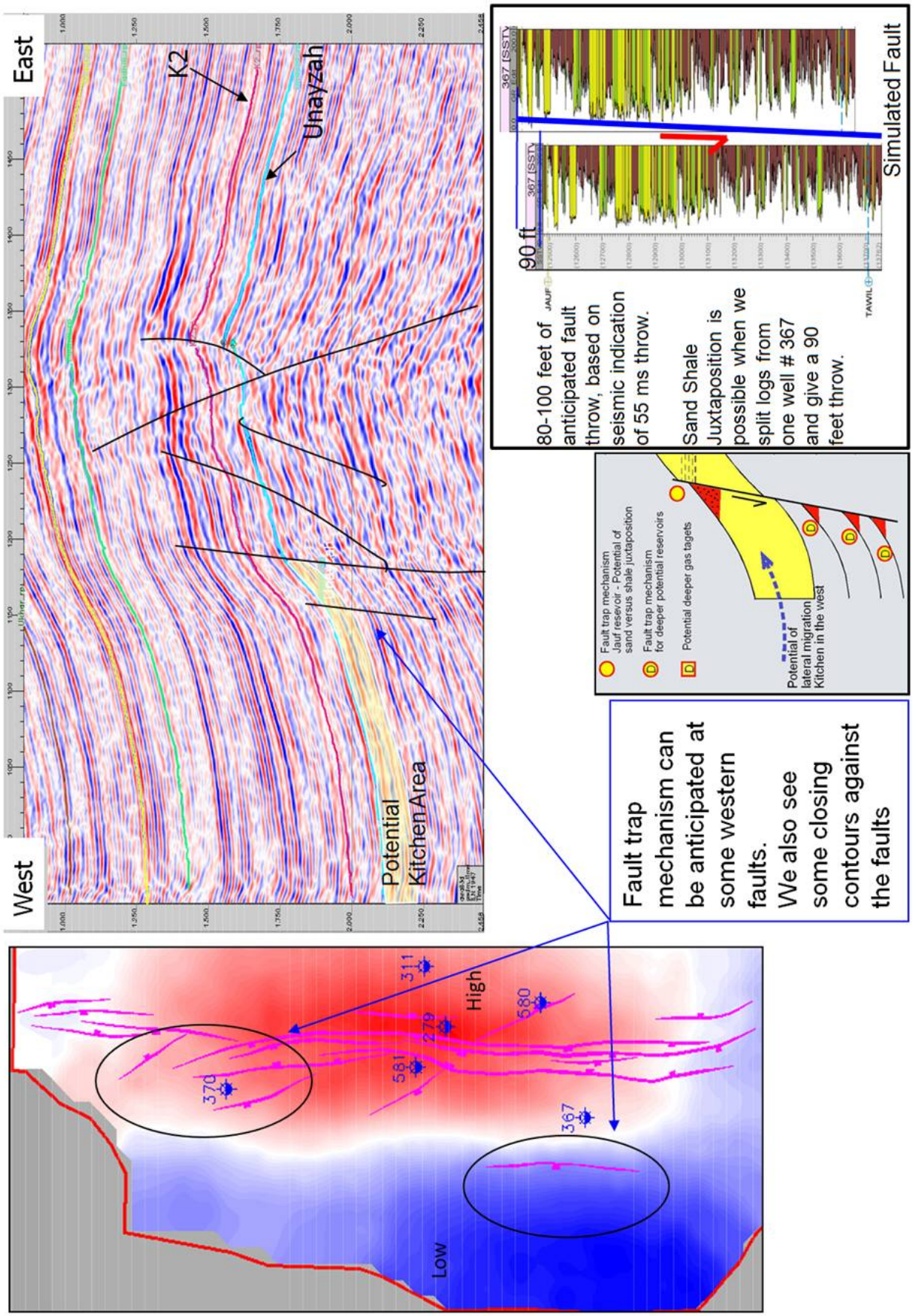

Figure 8. Fault-trap play.

Hydrocarbon Volumes

Hydrocarbon volumes were estimated for each of the play concepts using a probabilistic approach based on Monte Carlo simulation. Probability ranges were calculated on each of the input parameters: reservoir area, net thickness, porosity, initial water saturation, initial gas saturation, reservoir temperature, reservoir pressure, and volumetric gas factor.

The cumulative volumes for all these plays are in the dozens of Tcf of gas, which is highly encouraging from the exploration point of view.

Conclusions

A deep gas accumulation in the Awali structure is highly promising, with gas volumes estimated to be several Tcf. There are numerous petroleum play concepts, such as the deep gas play, the stratigraphic truncation play, and the fault-trap play. The concepts for these plays have working analogs in the neighboring petroleum provinces. The Jauf reservoir has already tested gas in Awali, with gas volumes in ranges of several Tscf. More delineation is needed through new seismic data, proper mapping, and subsequent drilling of a few appraisal and development wells. Thus, a full-field development needs to be initiated.

In short, a new seismic survey especially designed to better image the deeper targets is key to successful Awali exploration.

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