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# The Influence of Edge Fresh Water on the Giant Zelten Oil Filed, Central Sirt Basin, Libya

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**ABSTRACT**

The Zelten oil field in the Sirt Basin, central Libya, primarily consists of Upper Landenian age fossiliferous limestone, introduced by Barr and Weegar in 1972. It occasionally contains anhydrite dolomite and shale. It's bounded by the Khalifa or Gir Formation below and the thinner Harash Formation above. Zelten Formation's depositional cycle is similar to Harash Formation but relatively thinner in thickness.

The Zelten oil field, part of the Zelten platform, is a giant field in Concession 6, about 180 km south of the Mediterranean coast. It comprises three main oil pools, discovered in 1959 by Esso oil company. The north pool's discovery well, C1-6, reached peak production of 1/2 Million BOPD. Cumulative production by June 1997 includes 2.254 BBls oil, 2.945 BBls water, and 1.497 TCF of gas, with a recovery rate of 47.1% of the original oil in-place.

Zelten Formation's porosity is influenced by sea level fluctuations and carbonate build-up facies, reaching 40% around the crest area of the three structures. Hydrocarbons are sourced from Cretaceous shales in the Hagfa Troughs. The Zelten Formation reservoir age is Paleocene limestone, with average net reservoir thickness of 325ft, 22% porosity, and permeability up to 1500 md.

Reservoir pressure remained stable at around 2,250 psi for over 60 years, thanks to the bottom-edge fresh water from the Domran Formation, faulted down adjacent to the Zelten Formation reservoir, providing a strong edge water drive. This drive maintains pressure and can be used for enhanced oil recovery. Over 13 wells in the Zelten field, including horizontal wells, have contributed to hydrocarbon production.

**Keywords:** Influence, Edge. Fresh Water, Zelten Oil Filed, Central Sirt Basin, Libya

## 1. Introduction

The Pre-Jurassic structure in the Sirt Basin is unclear, but it is inferred from the distribution of Late Paleozoic to early Mesozoic sediments in the basin on another hand, The Late Mesozoic tectonic evolution of the Sirt Basin can be described as two distinct phases of rifting, separated by a period of tectonic quiescence, erosion, and deposition of non-marine sediments.

The first rift occurred during the Late Jurassic and was associated with hotspot activity. It was limited to the eastern segment of the Sirte Basin and resulted in the Anti-Sirtica fault trend system and half-graben structures. This rift controlled the deposition of the Lower sand and varicolored shale unit of the Nubian cycle.

The second rifting phase occurred near the end of the Lower Cretaceous and affected the entire basin. It led to the formation of alternating horst and graben structures controlled by the Sirtica fault trend system and resulted in the deposition of the Upper Nubian sandstone unit. [1]

Recent biostratigraphy work identified three different Nubian deposits in the Sirt Basin, including reworked young Paleozoic sediments. The Pre-rift Nubian cycle is of Permo-Triassic age, while the Eo-rift Nubian cycle consists of sediments from the Jurassic and Lower Cretaceous periods.

The first cycle was identified in wells on the Amal platform and in the Maragh trough area in the northeastern part of the basin. The Jurassic Nubian cycle is found only in the western and southeastern segments of the basin, while the Lower Cretaceous Nubian cycle is expected to be present in the major troughs of the central segment. Some wells drilled in the Sirt Basin have also encountered erosional remnant sediments from the Silurian to Devonian age. [2]

Different hypotheses have been proposed regarding the geology of the Sirte Basin. One suggests that the basin arched at the end of the Paleozoic era and later collapsed into horsts and grabens during the Early Upper Cretaceous. However, another hypothesis proposes that the entire basin formed in a single tectonic event, but this is not supported by the chrono-stratigraphic data. A hotspot model suggests a hypothetical hotspot during the early Cretaceous, causing westward drift of the North Africa region and subsequent northward drift of the entire African continent, connecting the Haggar massive with the Sirte Basin region. [2]

The Zelten oil field, discovered in the late 1950s, is located in the central part of the Sirte sedimentary Basin. Fig.1.

The exploration activity started in Sirte basin of the Mesozoic age during the late fifties as one of the major five sedimentary basins of Libya Fig.1. Since that time geological knowledge about the history of the basin has increased enormously. Sirte basin covers an area of approximately 400,000 Km square Fig.1. Generally, the tectonic features of the basin are aligned NW-SE into the offshore areas.

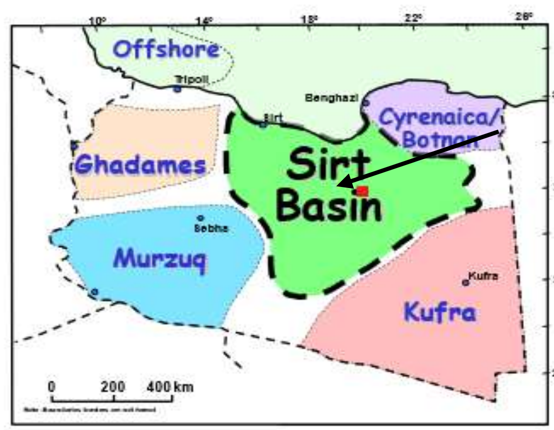


**Fig. 1. Sedimentary Basins of Libya, showing the location of Zelten Oil Field. (NOC bid rounds)**

The basin was floored by a terrain of grabens and horsts since the early Mesozoic filled primarily with clastic sediments partially eroded from the high areas and deposited in the low areas of Sirte Basin. The lows represent the grabens which is filled with tens of kilometers of Mesozoic and Cenozoic sediments of mainly alternating shale and carbonates [2] Fig. 2-3. As a response to the sea level fluctuation in relation to tectonics and climate changes where the thinner sections characterized by many unconformities indicating faults rejuvenations and combined with sea level fluctuations. The eastern area of Sirte basin influenced by the regional tectonic elements were oriented south-west as a result of the Caledonian and Hercynian orogens [3]

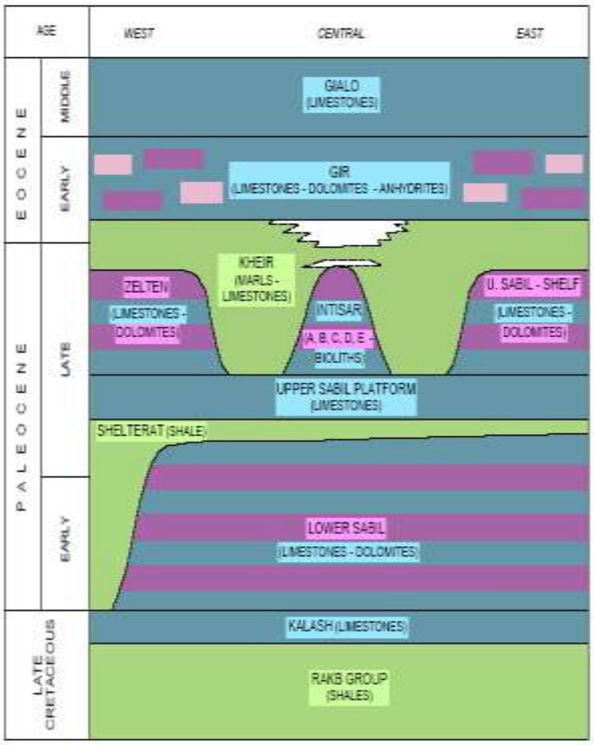


**Fig.2. Sirte Basin main sedimentary sequences of West, Central and East regions [3]**

Reservoirs in the Sirte Basin include sandstone units from the Lower Cretaceous and Triassic periods, such as Nubian, Bahi/Maragh, Waha, and shallow sands. The top sediments consist of Oligocene-age sandstone from the Chadra and Muillah Formations. Carbonate formations like Tagrift, Kalash, Beda, Facha, Gir, Khalifa, Defa, Zelten, Sabil, Rakab, Harash, Gialo, Augila, etc., are deposited on platforms, serving as the main reservoirs for oil and gas fields [4]. They also act as source rocks and seals, extending into the major troughs. Upper Cretaceous shales, lower Cretaceous shales, continental shales of the Nubian, and preserved Paleozoic shales in the deep troughs serve as seals and source rocks. The tectonic setting and periodic fault movements have created various stratigraphic and structural traps throughout the Sirte Basin.

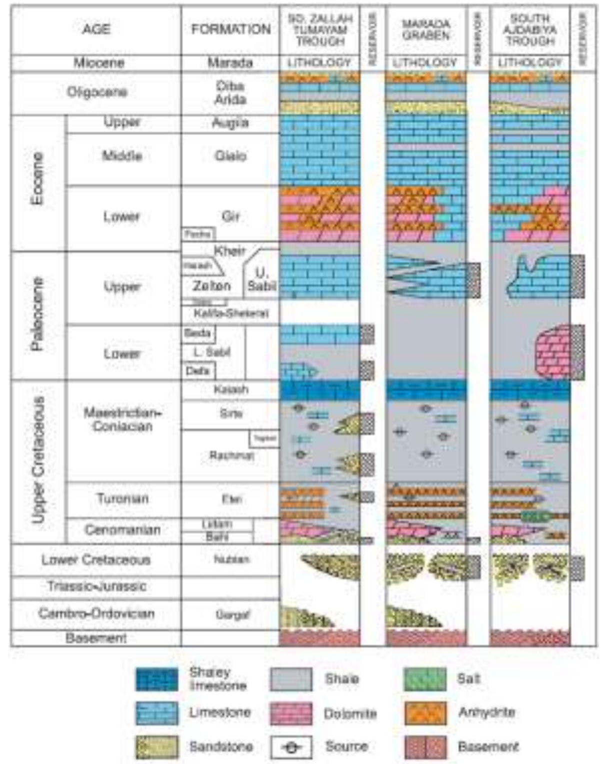


**Fig.3. Schematic E-W stratigraphic section showing Formations distribution and the lithology of main reservoirs, seals and source rocks [3]**

Zelten oil Field a part of south central Sirt Basin of Concession 6 operated by Esso oil company discovered the field in 1959 as part of Zelten platform, about 180 Kms south of the Mediterranean coast. The first exploratory well C1-6 drilled in the north pool as the major discovery in Libya which drew the attention of other large oil companies to the area of Sirte Basin (Ilhamali, 2019). The discovery well, C1-6 was spudded on 1/03/1959 and flowed at a rate of 17,500 BOPD of 37degree API gravity from a depth of 5,665ft. KB in Oct. 1961.

The field is comprised of three pools (north, south, and southeast) and separated by two undefined saddles with a total area of approximately 340sq. km. Fig.4. Within two years and a half after the discovery, the first oil shipped was from Brega port in central coast of Libya and started production in 1961with a peak of 1/2 Million BOPD with OOIP estimated at 5.3 BBls. [5]

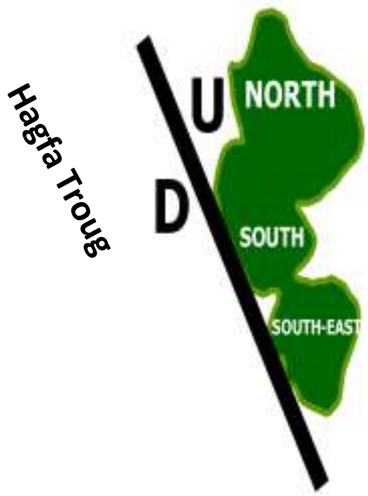


**Fig.4. Zelten oil Field comprised of three oil pools adjacent to Hagfa trough located in central Sirte Basin Libya**

Detailed geological studies have been conducted on Zelten oil field to understand the reservoir models and separate different carbonate lithological layers. The most comprehensive data was published by Bebout and Pendexter in 1968, provides valuable information. Recent studies focus on increasing oil production through infill wells (vertical and horizontal) using the latest 3D seismic surveys.

Zelten formation is a widely distributed fossiliferous limestone in the Sirt Basin. It is equivalent to the Upper Sabil Member in other areas of the basin. This formation is serving as the main reservoir and consists of shelf carbonate with variable facies containing abundant Bryozoan, Corals, Corallina, and Echinoids fragments. The facies range from deep to moderately deep marine along the Hagfa trough and Western shelf of the Sirt Basin [6]. The Zelten Formation exhibits mostly open-to-shallow marine facies, with restricted water circulation observed on the Al-Jahamah Platform. The porosity of the Zelten Formation is highly influenced by secondary porosity, reaching up to 40%. The reservoir is composed of Paleocene limestone with an average net reservoir thickness of 325ft. Average porosity is 22%, and permeability ranges from 1500 md to 8 Darcy in crest areas, possibly influenced by minor faults and fractures associated with major Strike Slip faults. [2] Fig.5.

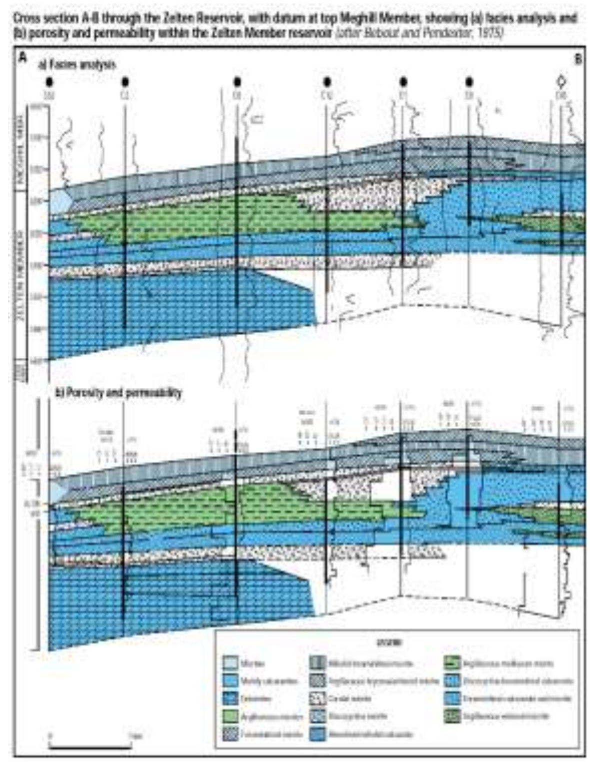


**Fig. 5. After Bebout and Pendexter 1975. Showing facies analyses in relation to Porosity distribution across the Zelten Oil Field**

The original reservoir pressure was reported to be 2,435 psi and the reservoir pressure in 1997 was reported to be 2,250 psi. This shows that the Pressure of the Zelten oil Field maintained providing strong bottom and edge fresh water drive mechanism. Of the wells that have been drilled in the area of Zelten field, more than 13 of which are horizontal wells. The production currently has declined.

The early logging data using old logging technology and some are not complete over the important part of the reservoir in some wells were not logged, in addition to the facies variation, resulted in difficulty of correlating permeable, and tight layers of the upper 100 feet of Zelten main pay.

Horizontal drilling into the upper units of Zelten carbonate started in 1994 to increase production. It was not easy to find a suitable location because of the advanced depletion, strong water drive, the rising of oil water contact, and high vertical porosity/permeability in parts of the field. More than 13 horizontal wells (1997) have been drilled with initial production reaching as high as 1,700 BOPD Fig.6.

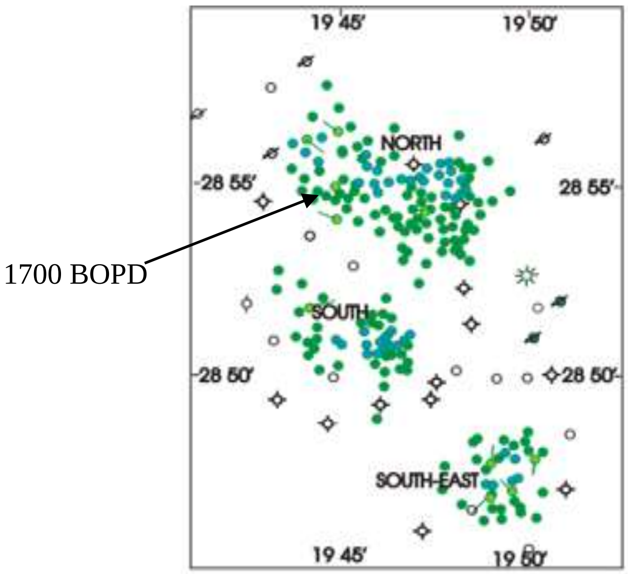


**Fig.6. Wells drilled in Zelten oil Field to date, more than 13 of which are horizontal wells**

## 2. Stratigraphy

The Gargaf and Bahi Formations are economically significant pre-Upper Cretaceous rocks. Gargaf is well-cemented, fossiliferous, silica-clastic strata, while Bahi is noncalcareous sandstone largely derived from eroded Gargaf. These units are unconformably overlain by Upper Cretaceous sediments of the Kalash and Waha Formations, which in turn unconformably overlie the Bahi/Gargaf sequence. The lithology of the Waha Formation varies from calcareous sandstone to skeletal limestone, and its distribution is irregular, influenced by underlying paleo topography. The Waha Formation is a major reservoir in the south and southeast pool of the Zelten oil field. The Kalash Formation, a chalky, micritic limestone, is widespread in the Sirte Basin.

In the Paleocene sequence, from bottom to top, are the Hagfa shale, Khalifa limestone, Zelten Formation, and Harash Formation. The Zelten Formation is widespread and serves as a primary Paleocene reservoir in the Zelten Field area. It represents a shelf carbonate with variable facies, being part of the lower sequence of the Jabal Zelten Group and present throughout the entire Zelten Field area.

The type section of Jabal Zelten Group is located in the subsurface of well AA1-59 was first introduced by Barr and Weegar in 1972 [4]. The Group consist of two Formations Harash Formation and Zelten Limestone. The age of Jabal Zelten Group is assigned to upper Paleocene [7]. The Zelten Formation in the type section (AA1-59), is 102m thick, and consists mainly of limestone interbeded with minor Shale. The limestone is creamy to tan and gray, argillaceous to shaly, chalky, fossiliferous calcilutite to calcarenite in places vuggy and glauconitic. The Shales are gray-green, very soft fissile and pyretic. Subordinate amounts of white to brown, hard and dense dolomite occurs at places. The Zelten Formation is conformably overlaying Khalifa Formation or Lower Sabil Carbonates [4], and the upper boundary is conformable with the Harash Formation.

Previous studies indicate the north pool of Zelten Field characterized by an upward expanding “pipe” of carbonate rock developed, surrounded by shales as hypothesis, with no clear evidence supporting this hypothesis. The top seal of the Zelten reservoir is the tight layer of micritic limestone of the upper Zelten Formation and Kheir shales.

The Eocene sequence is represented by Gialo Formation which overlain by the Augila Formation. The Gialo Formation consists of chalky, skeletal nummulitic limestone capped by the Augila shales followed by regressive sequence of Arida sandstone.

Zelten Formation was divided in to porous and non-porous the Layers, of primary and secondary porosity facies based on available log picks and combination of primary and secondary porosity facies studies (F. Belhaj, Unpublished Report).

Dividing the Zelten Formation to porous and tight layers is necessary in order to identify the relationship between production and water coning problems and areas of interest for future infill vertical or horizontal wells, Fig.7.

Zelten Formation can be divided into 5 porous & 5 tight layers. Due to the fact that some logs covering the section of interest in Zelten Formation are not complete or not available which makes the detailed correlation very difficult. Not all wells have porosity logs which is the most important tool used in correlation of the tight and porous layers.

It has been attempted by various workers on the Zelten Field to separate these tight layers from porous layers and to allow mapping of the thickness and the top structure of these porous and tight layers. Only 2 maps are possible to be presented, one porous and one non-porous.

In this paper the Zelten Formation has been divided into porous and tight layers for practical reasons, which helps identify the suitable areas for horizontal and/or vertical wells to be drilled at this stage of late production of the Zelten oil Field.

Zelten Formation in general is a regression sequence. The basal facies are represented by Discocylina-Coralgal micrite. The upper units of the Zelten Formation that represent the maximum regression, have been subjected to subaerial exposure.

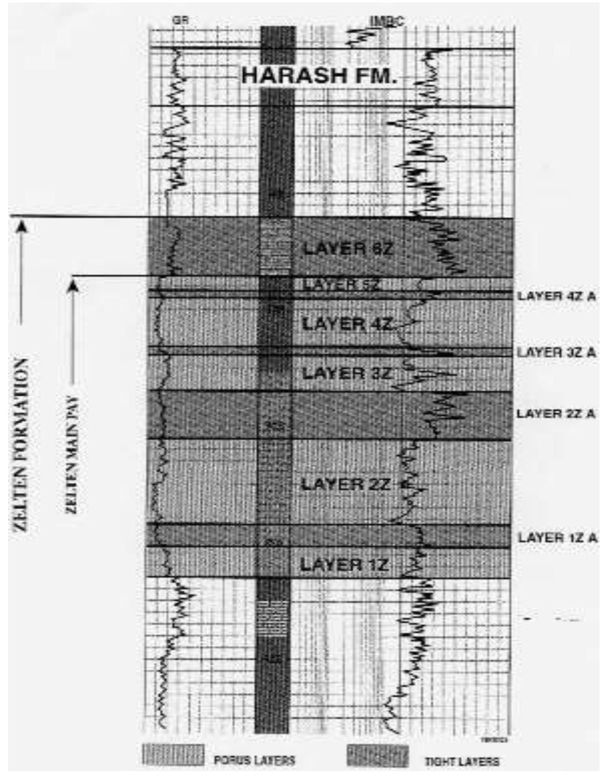


**Fig. 7. Zelten Formation divided into porous and tight layers**

Fig. 7 explains in general the Zelten Formation divisions into porous and tight layers for practical operation purposes to locate newly wells drilled or to be drilled locations. Only the upper 5 layers were discussed in this paper due to the data availability control limitation and the importance of these layers as drilling targets to avoid water coning bottom seal. These layers are divided as follows:

### 2.1 . Layer 4

This layer is a porous unit and considered as the main bay and a target for horizontal drilling, in this late stage of the field production. Layer 4 consists of Coralgal micrite, Argillaceous molluscan micrite, and Discocyclina-foraminiferal calcarenite facies. The thickness of Layer 4 ranges from 16 feet to 56 feet generally in Nasser Field. The maximum thickness lies along the western boundary fault, central south-west Nasser field and the extreme north-eastern area of North Nasser field [8].

### 2.2 . Layer 5

This layer is a porous unit consists mainly of Coralgal micrite and Alveolinid-miliolid calcarenite facies. Layer 5 is present everywhere in Nasser field except the extreme north and north-west area of North Nasser field and along the western edge bounding fault, where layer 4A is absent due to possibly leaching. Layer 5 thickness reaches maximum of about 12 feet in southern area of North Nasser field, central area of South Nasser field, and the central area of South-East Nasser field. Layer 5 is a secondary target for Horizontal drilling when it is thick enough and is used as drilling marker.

### 3. Source rock and oil migration paths

The oil of the reservoir possibly sourced from the Cretaceous shale in the juxtaposed Hagfa Trough. The Zelten Pipe of high vertical porosity provided the conduit or route migration of hydrocarbon from Cretaceous to upward into the Paleocene reservoir Fig.8.

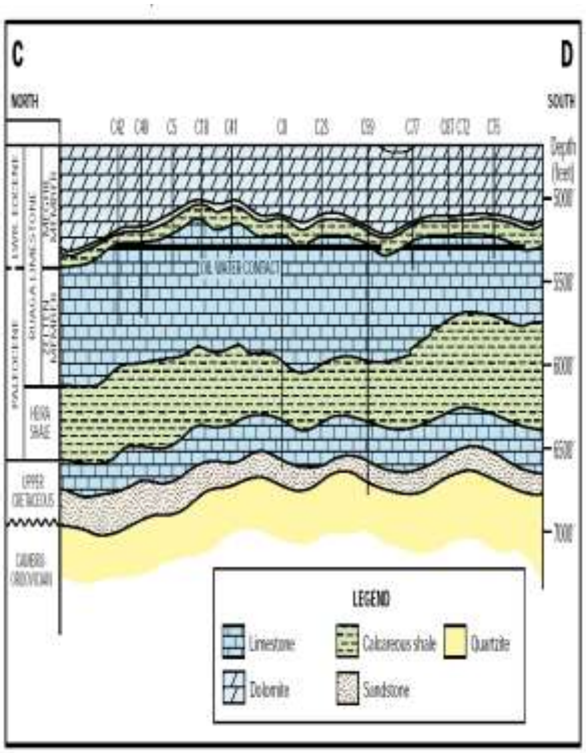


**Fig. 8. The hydrocarbon of the Zelten oil Field reservoir possibly sourced from the Cretaceous shale in the Hagfa Trough adjacent to Zelten oil Field along the western edge of the field**

### 3. Reservoir charactristics

Previous studies indicate a total of 24 facies types that were described in the Zelten oil Field area (North South Pools) utilizing E-logs by previous workers to study the facies of Zelten Carbonate which led to grouping them into eight facies. It has been reported that secondary porosity has reached as high as 40%. Primary and secondary porosity is facies controlled and are best developed in the coralagal micrite when leached Fig.9.

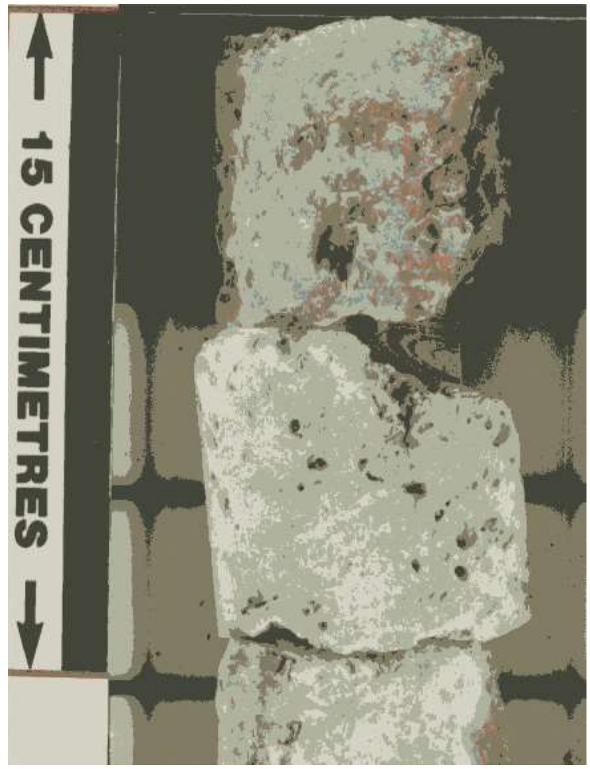


**Fig. 9. The only photo Core available from Zelten Field not referred to any well, example showing leached secondary porosity reaching as much as 40% and permeability is as much as one Darcy**

To the south of the SE Zelten pool, as evidenced by well control of the reservoir quality. To the northeast the Zelten shelf carbonate becomes shalier although the porosity distribution in the Zelten reservoir is generally well defined in the conventional well performance which cannot always be explained using the available parameters. Problems encountered such uncertainty in pinpointing the lost circulation zone which can’t be avoided, either and in some areas of the three different pools.

The zones of high flow potential permitted formation water to move laterally into the well bore above the existing OWC. Therefore, for improving the individual wells behavior of Zelten carbonate reservoir is to divide the Formation into approximately five mappable layers. Only 15 wells selected where total penetration of Zelten Formation was achieved and relatively logged with modern logs made available to this study paper of (1990`s logs). Unfortunately, some of these logs are not reliable because of bad hole conditions due to loss of circulation in the Zelten reservoir or due to the reservoir tightness.

The upper reservoir layer 5 forms a secondary objective within the Zelten reservoir and it is almost a loss circulation free reservoir. The top layer and the bottom are sealed by shale (tight layer). The layer thickness varies from 0 to 25ft. and good target for horizontal drilling locations if it is thick enough. The porous reservoir layer 4 (oil logs transition zone and water-leg) represents the major reservoir in the Nasser field area [8]. The loss of circulation usually occurs within this layer specially in south-east Zelten field. The layer varies in thickness from 20ft. at the highs in the North pool to 42ft. within the South-east pool. Fig.10.

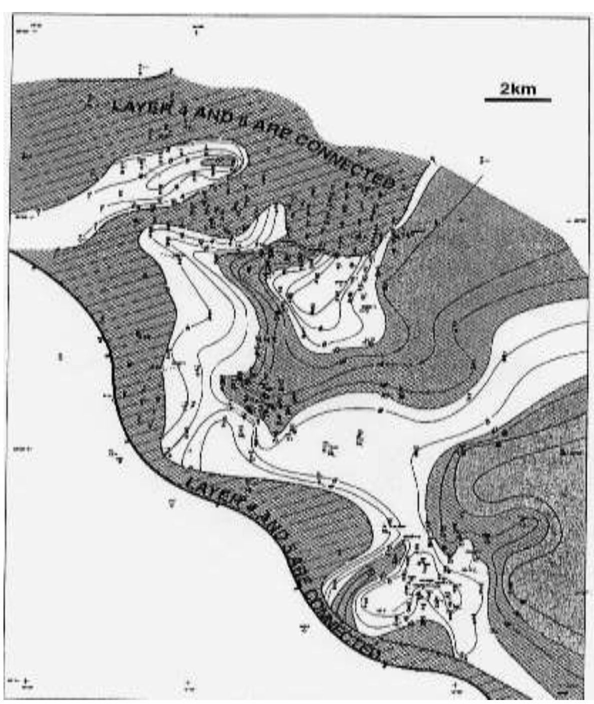


**Fig. 10. Map showing where porous Layer 4 and 5 connected**

## 4. Structure

The Zelten oil field area is located on the Zelten platform west of Hagfa Trough. The platform ramps downwards toward the Wadayat Trough to the east bounded by Hagfa Trough to the west. The major faults are typically trending NW-SE and extended to offshore of Sirte basin towards Tripoli-Sebrath sedimentary Basin.

The three pools of Zelten oil field have three a pronounced distinctive area of closures that partially separated by structural low saddles. The saddles are consisting of dense micritic limestone thick at the expense of the reservoir rocks, matching structural closure on the reservoir of the three pools. Therefore, the trapping mechanism is structural and partially stratigraphic.

The three pools are structurally dome/anticlinal features. The crests of these domes are most likely fractured and contain small faults that can't be detected by available geological tools and available seismic. The structure dip probably was higher than today's structure dip due to small vertical movements possibly caused by compaction indicated by the presence of slickensides along the fracture zones observed in the available core of well C70 [9].

The hydrocarbon production and water cut maps show that the crests of these three domes are watered out sooner than the flanks as indicative of the possibility of the presence of fractures and small faults connected vertically with the water zone. Also, the production history of Zelten field shows that the producing wells are located in crests areas produced 50% oil and 50% water approximately to date.

## 5. Oil-freshwater interaction

Horizontal wells drilled in Zelten field in layers 5 and 4 show an indication of intersecting fractures, because these wells show an increase in water cut with time. This case is represented by well 250H which was located near the crest of the North Pool and the oil well watered out sooner than expected.

The water coning in the crests of the Zelten field is still a puzzling question to date, where it has been thought that the presence of high-water cut is due to vertical porosity and permeability only.

The strong water drive is suggested to be supplied by Domran Formation or Gir Formation above Ruaga equivalent to khier, Harash, and Zelten Formations in places also can be equivalent to Mabruk, Khalifa formations underlying the carbonate intervals. The Heira or Hagfa shales overlies upper cretaceous Zmam or Kalash formation. The strong water drive is also influenced the more or less steady pressure during the years of production during the years from 1961 to 1997. Domran Formation was faulted down in the thrown side of the major fault bounding Zelten oil Field area along the western Zelten oil Field area.

The water salinity indicates that the strong water drive is supplied by the less salinity Domran Fm. The salinity in the areas closer to the fault has been reduced dramatically, for example in the South and South-Eastern pools from the original salinity to about 10,000 ppm, where the salinity in the extreme Zelten field away from the fault is about 33,000 ppm, Fig.11.

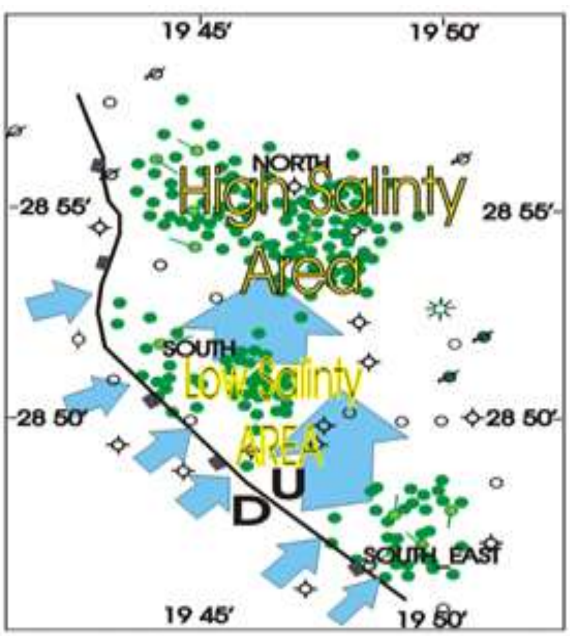


**Fig.11. Sketch Map of Zelten Oil Field showing the influence of fresh water movement into the Zelten oil field reservoir**

## 6. Conclusion

The crests in the three pools in Zelten field are watering out sooner than the flanks.

The relief of the structure was probably much higher than today's structure. The draping of the upper sections over this old structure may indicate that the structure has compacted and affected down by the weight of the above sediments, or the highly leached units within Zelten Fm. with compaction may also produce small vertical faults and fractures which were reported in the core studies.

The watering out crests sooner than the flanks possibly were through the small faults and fractures due to the strong edge water drive effect.

The original oil/water contact probably has moved less than expected.

The seismic reflector of the top Harash is used to map the structure of top Zelten formation which makes it difficult to map the details of small faults and areas of possible extensive fracturing.

Zelten Formation has been attempted to be divided into 10 porous and non-porous layers, only few layers have been possible to map with certainty due to the availability of data.

The extensively leached (producing secondary porosity) areas in the Zelten oil field has been identified and possibly related to the movement of the western edge fault during and after deposition of Zelten Formation.

The flanks and the less leached (low porosity) areas which can be candidates for future drilling.

Wells watered out in the crests of the Zelten oil field can be candidates to be completed in the Harash or even the Galo Formation Reservoirs.

Some of the wells already watered out/or closer to the western bounding fault, can be considered with careful studies to be used as producing water to ease the pressure drive on the Zelten Field.

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