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Investigating Cap Rock Efficiency of Laffan Shale Formation in Sirri Oil Fields, Offshore Iran

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Abstract: This study investigates the sealing efficiency of the Laffan Shale Formation as the caprock of the Sirri oil fields. Available information sources from Laffan Formation include drillhole core samples, daily drilling and geology reports and petrophysical logs of drilled wells. Type and quantity of minerals are determined by direct and indirect methods. In the next step in order to study the distribution of minerals and fabric of the shale samples SEM photomicrographs are taken. Petrophysical characterization by mercury porosimetry and laboratory experiments to measure total organic carbon and cation exchange capacity of samples are the next steps. Pore pressure of Laffan Formation is determined by using data obtained from both acoustic and resistivity logs. Laffan Formation in Sirri oil fields is a shale formation comprising kaolinte clay mineral and calcite and quartz cement. It has a very low permeability. Laffan is a relatively thin and brittle formation but the presence of organic-rich layers and being buried at deeper depth has improved the chance of its lateral continuity and can be classified as a good seal. This study shows that similar results are obtained from direct and indirect methods in determining type of and mineralogy and also indicates that good correlations is achieved when taking into account of permeability and total organic carbon. The next purpose of this paper is to provide a research process that can be applied in similar geological settings.

Key words: Caprock-sealing efficiency; Shale formation; Clay mineral; X-ray diffraction; Scanning electron microscopy; Ductility; Total organic content

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1. INTRODUCTION

In a hydrocarbon reservoir, caprock is an impermeable formation laying over the main reservoir rock that prevents the migration of valuable fluids to surface[1]. Lithology, thickness, ductility and fracture density are the main influencing factors on the sealing efficiency of a caprock[6]. Any lithology can be a seal for a hydrocarbon accumulation. The only requirement is that minimum displacement pressure of the sealing formation be greater than the buoyancy pressure of the hydrocarbon column in the accumulation[10]**.** Fine pore sizes, very high specific surface area of minerals, strong physic-chemical interaction between water molecules and the mineral surfaces and very low permeability provides good sealing characteristics for shale formations[6]. Laboratory studies are useful to assess fundamental sealing properties of a shale formation but they cannot be extrapolated to the reservoir[17]. These studies include determining the type of clay minerals, fabric of the shale rock, pore fluid properties, activity of the formation, permeability, brittleness and total organic content of samples[1&6&13]. After gathering and interpretation of all results the seal efficiency of the formation can be estimated. To achieve accurate results in experiments shale samples should be in their original conditions.

2. FIELD PROFILE

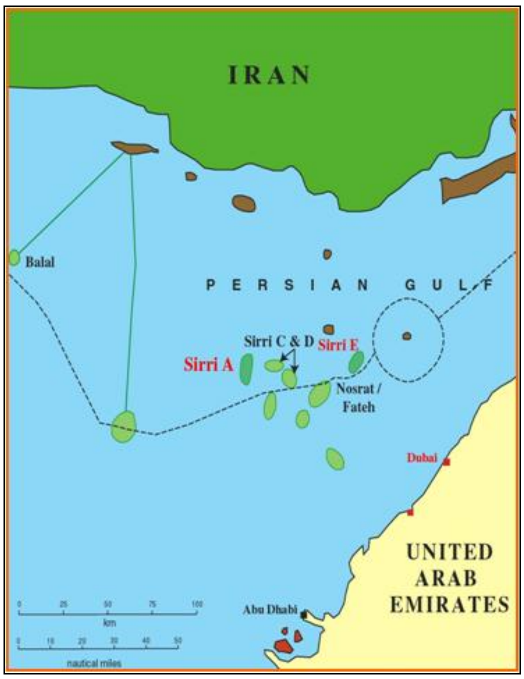


Fig. 1: Location Map of the Sirri Oil Fields in the Persian Gulf

Tab. 1: Lithology Sequence in Well F1 in Sirri-C Field

Formation	Depth (m)	Lithology
Aghajari & Mishan	83-380	lumachellic limestone- clay interbedded with layers of gypsum and anhydrite
Guri	380-495	limestone, dolomitic at the top-some calcareous shale layers
Lower Fars	495-1082	Interbedded of Anhydrite and Marl-Shale with some anhydrite beds-shaly limestone-Interbeded of Anhydrite and Marl- sandstone thin beds
Asmari	1082-1287	dolomite-limestone-pyretic limestone-some chalky soft bioclastic
Jahrum & Pabdeh	1287-2100	limestone-shaly limestone (gray, soft)
Gurpi	2100-2272	argillaceous limestone and marl (gray, soft) -shale (gray to dark, gray and blackish, indurated splintary, glauconitic)
Ilam	2272-2371.5	limestone, chalky (white soft) and limestone locally piritic
Laffan	2371.5-2390.5	shale (brown, gray, soft to medium hard splintery, locally calcareous, piritic, micro conglomeratic)
Sarvak	2390.5-2439	limestone

Sirri oil fields in the eastern part of the Persian Gulf like other neighboring hydrocarbon fields developed largely as flexures over salt diapirs (Figure1). In these fields upper part of the limestone Sarvak Formation provides suitable reservoir characteristics. Late Cretaceous brackish to fresh water Laffan shale is a prodeltaic sedimentary rock laying over the eroded surface of the Turonian carbonates. The Laffan Shale Formation forms the cap rock of the Sarvak reservoir[5]. Laffan has the thickness of 20 to 30 meters in this area. The reservoir temperature changes from 220 to 225 ℉ and the static pressure gradient is 0.342 PSI/ft. Water depth in the area is around 86 meters. Sequence of formations in this field is determined by examining various sources including well graphic logs (Table1).

3. X-RAY DIFFRACTION STUDIES

Lithology is a very important factor affecting the sealing efficiency of a formation[11]. Permeability and ductility of a rock is controlled by lithology. At the first step, the mineralogical composition of the formation samples is studied. Minerals type and quantity is determined by direct and indirect methods. XRD analysis of core samples is done. XRD is a common technique to characterize the mineralogy of rocks and determine the types of clay minerals. A major advantage of this technique is that it can be used for both qualitative identification and quantitative estimation of phases[4]. Samples used in the experiments came from three different drilled wells: SIC-F1, SIC-F2 and SID-A1. (Table2).

Tab. 2: Core Samples Information

Field	Well	Core No.	Laffan formation base (m)	Coring interval in Laffan (m)	Core Recovery	Company	Date
Sirri-C	SIC-F1	1	2391	2390 to 2391	100%	Sufiran	Oct/1976
Sirri-C	SIC-F2	1	2855	2848 to 2855	100%	Sufiran	Dec/1976
Sirri-D	SID-A1	1	2772	2770 to 2772	100%	Sufiran	June/1976

A brief macroscopic visual characterization of core samples is in Table3.

Tab. 3: Macroscopic Visual Characterization of Formation Samples

Sample	Lithology	Colour
SIC-F1	shale with organic compounds	Grey
SIC-F2	Silty Shale with fossils	Dark grey to green gray
SID-A1	Fissile Shale	Dark grey to black

At first step XRD analysis of the bulk rock is done. Figures 2 to 4 show the XRD patterns of the samples.

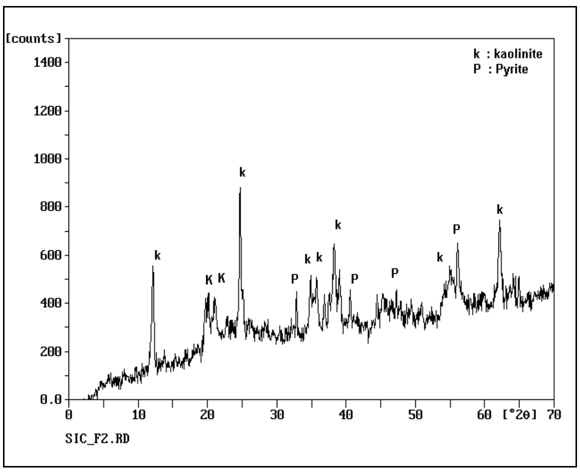


Fig. 2: XRD Pattern of the Sample SIC-F1

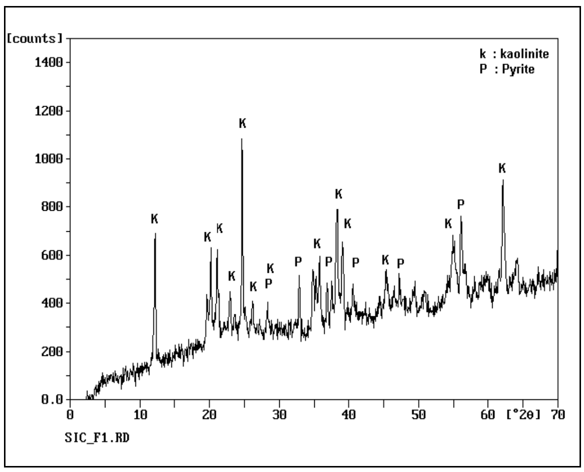
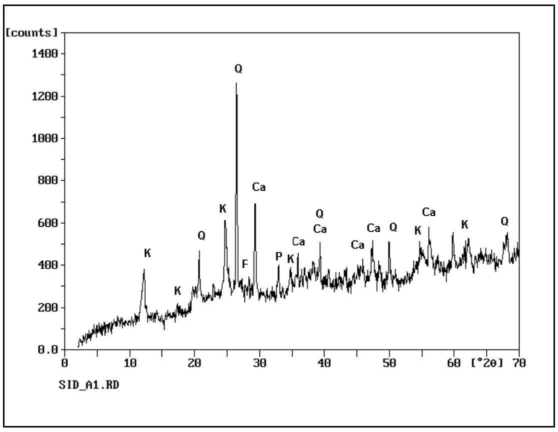


Fig. 3: XRD Pattern of the Sample SIC-F2



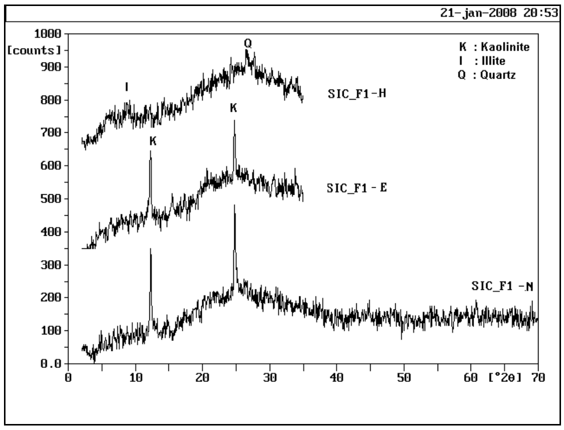
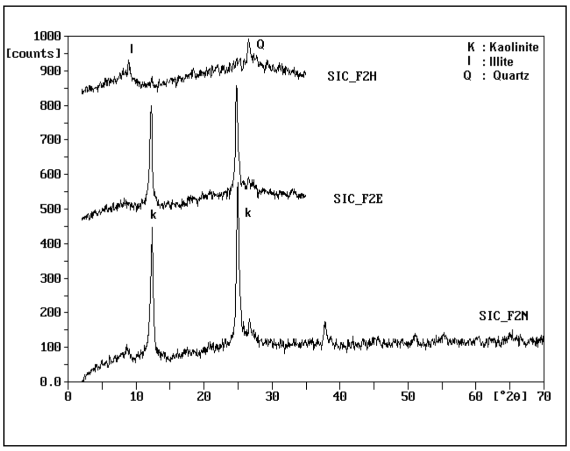


Fig. 4: XRD pattern of the sample SID-A1

Fig. 5: XRD Pattern after Heat Treatment and Ethylene Glycol Treatment of Sample SIC-F1

Minerals identified in the studied samples include kaolinite, ilite, quartz and pirite. The whole clay mineral content of samples is between 30 to 70%. Difficulty is encountered in identification of kaolinite in the presence of other clay minerals by XRD because of overlaying picks. In such a case additional techniques such as glycolation and heating are used[4]. In this study the <2 micron clay fraction phases of samples are extracted. The clay samples in three separate conditions normal state, after ethylene glycol treatment and after heating to 550 °C for 30 minutes are prepared. XRD patterns of treated clay fraction of shale samples are shown in figures 5 to 7.



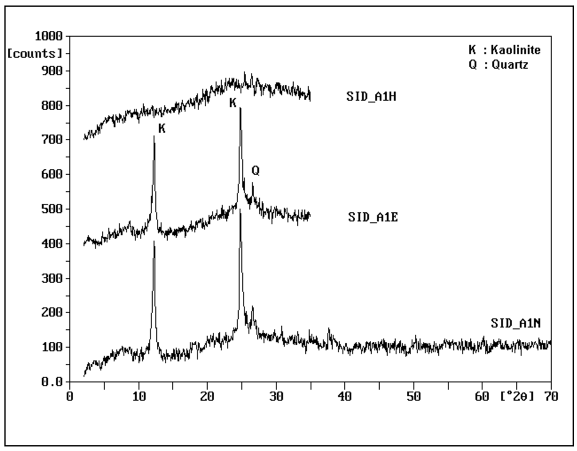


Fig. 6: XRD Pattern after Heat Treatment and Ethylene Glycol Treatment of Sample SIC-F2

Fig. 7: XRD Pattern after Heat Treatment and Ethylene Glycol Treatment of Sample SID-A1

Since kaolinte has not an expanding lattice and interlayer cations to solvate it does not react with ethylene glycol treatment[4]. By heating kaolinite mineral to 550 °C it completely dehydroxylates and its structure is destroyed and the peaks will disappear[4]. The results show that the peaks have entirely disappeared after the heat treatment and have been unchanged after ethylene glycol treatment which confirms the kaolinite type of mineral. A semi quantitative XRD analysis was done and the percentages of kaolinite out of clay minerals were calculated by calculating the percentage of diffraction peak heights and are given in Table 4.

Tab. 4: Mineral Composition

Sample	Mineral composition By XRD
SIC-F1	Kaolinite 73%-Ilite-Quartz-Pirite
SIC-F2	Kaolinite 83%-Calcite -Quartz-Pirite
SID-A1	Kaolinite 24%-Ilite-Quartz -Pirite -Calcite

4. SCANNING ELECTRONIC MICROSCOPY STUDIES

SEM micrographs are taken to study the mineral types, direction, form, cementation and pore size and pore shape of the samples. Kaolinite can be as hexagonal plate-like crystals often in stacks[2]. Individual crystals range from 5 to 30 micrometer in diameter[15&16]. The images show the presence of kaolinite clay minerals in a matrix of calcite and quartz and the absence of porosity and permeability (Figures8-13).

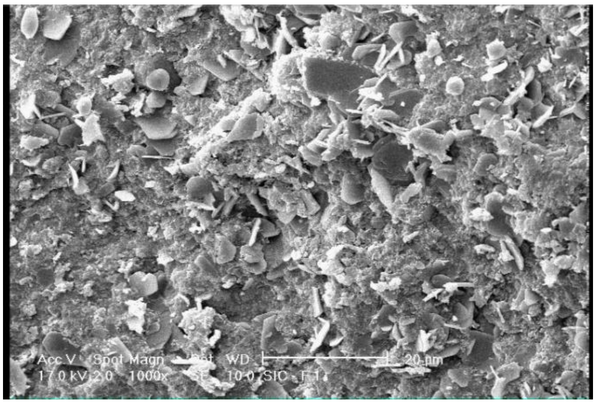


Fig. 8: SEM Image of SIC-F1 Sample, Kaolinite Crystals in a Matrix of Calcite and Quartz

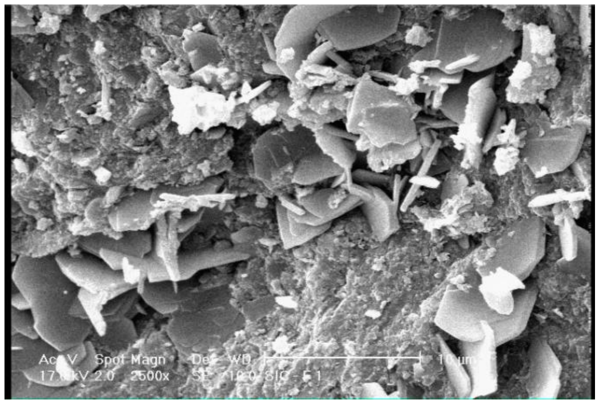


Fig. 9: SEM Image of SIC-F1 Sample, Kaolinite Crystals in a Matrix of Calcite and Quartz

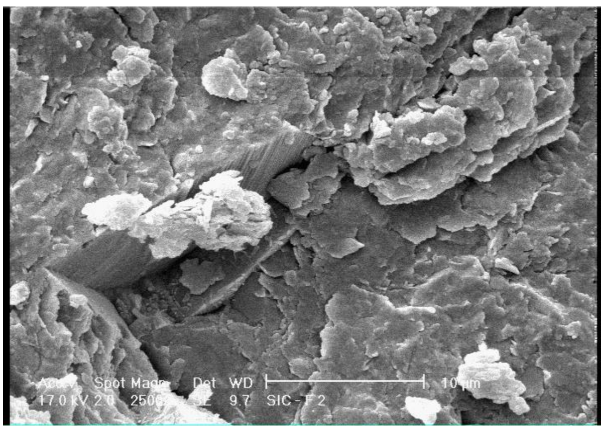


Fig. 10: SEM Image of SIC-F2 Sample

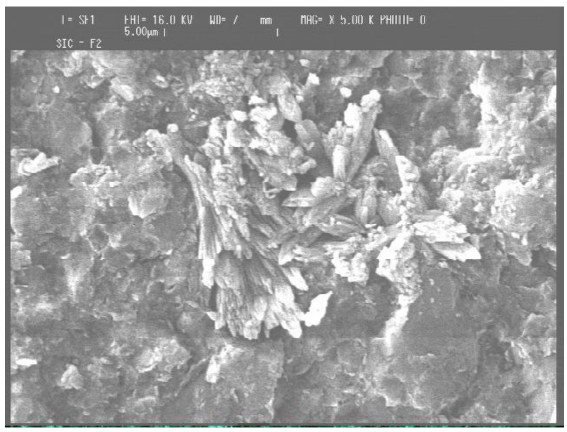


Fig. 11: SEM Image of SIC-F2 Sample

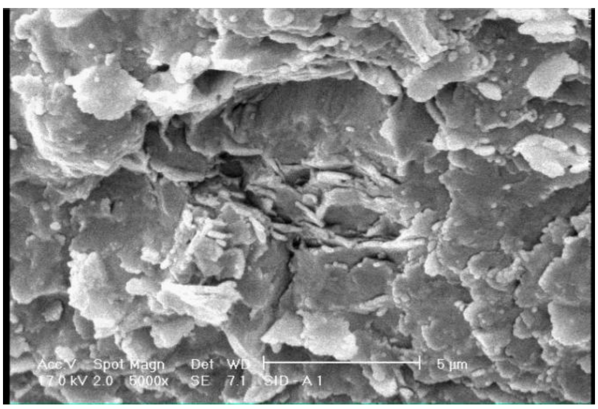


Fig. 12: SEM Image of SID_A1 Sample

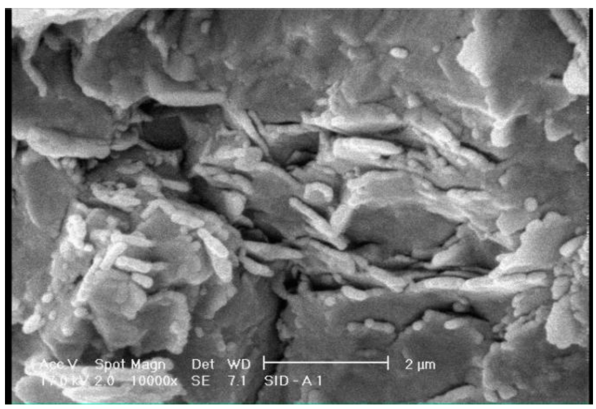


Fig. 13: SEM Image of SID_A1 Sample,

5. PETROPHYSICAL STUDIES

Petrophysical data are interpreted and analyzed by conventional software programe. Type and content of clay minerals and formation pore pressure are determined by these data. Natural gamma log is used to compute the shale volume. Natural gamma spectrometry log is used to determine the type of clay minerals[8]. Pore pressure of Laffan Formation is determined by using data obtained from both acoustic and resistivity logs[3&12]. Results show that Laffan is a shally formation with mainly kaolinite clay mineral and normal pore pressure of 0.34 PSI/f.

6. PERMEABILITY

Leakage of hydrocarbon through a seal occurs when the pressure of the hydrocarbon exceeds the capillary entry pressure of the caprock and fluid flows through the rock or pore pressure exceeds the mechanical strength of the caprock and micro fissures form in the rock and flow occurs through them[6]. Minimum capillary entry pressure of a formation depends on pore-size distribution, interfacial tension between pore fluid and flowing fluid and wettability of pore fluid[1]. Fine grained rocks have very low permeability and high capillary entry pressure. Minimum capillary entry pressure controls the maximum hydrocarbon column height[7]. Permeability of the specimens was investigated by mercury intrusion. Mercury in injected by 1000 PSI pressure to the dry samples and the volume of the injected mercury divided by bulk volume of samples is determined (Table5). The results show that the samples are almost impermeable. In real condition when the samples are saturated by water the permeability will reduce even more.

Tab. 5: Permeability of Formation Samples

Sample	Weight (gr)	Bulk Volume (cc)	Volume Mercury Injection (cc)	Volume of Mercury injected by 1000 PSI
SIC-F1	7.2177	3.37	0.02	0.6%
SIC-F2	11.1832	4.15	0.02	0.5%
SID-A1	8.9615	3.6	0.01	0.2%

7. THICKNESS

Caprock thickness is important since increases the probability of continuity of the caprock over area of reservoir. Theoretically a few inches of shale formation will provide an adequate seal but a thickness of 50 meters in areas of low tectonic activity is considered good[6]. Laffan formation has an average thickness of 30 meters in this area which is classified in relatively thin caprocks. Laffan can be considered as a deep caprock.

8. DEPTH

Greater burial depths means more effective stresses on the shale formation which results in reduction in porosity and a stronger rock matrix due to stronger interparticle contacts. High pressure and temperature improves the ductility of a formation and reduces the permeability[6]. Average depth of Laffan formation is around 2400 to 2700 meters in this area which is good.

9. TOTAL ORGANIC CONTENT

Total Organic Content (TOC), mineralogical composition, depth and temperature determines the ductility of a formation. Organic-rich shales have a ductile behavior[6]. Ductility indicates the behavior of the seal under deformation. Ductile formations have plastic behavior under shear stresses and remain sealing after tectonic deformation[7]. Organic shales have larger pore throats and more permeability compared to nonorganic shales. TOC data are acquired for samples using standard methods. (Table6) and some organic rich layers are discovered. The results of TOC have good correlation with permeability results[14].

Tab. 6: TOC of Formation Samples

Sample	TOC (%)
SIC-F1	53.63
SIC-F2	37.91
SID-A1	0.25

10. CATION EXCHANGE CAPACITY

Cation Exchange Capacity (CEC) of the samples is determined by methylene blue test and is in range of 3 to 10 milliequivalent per 100 g (Table7). Kaolinite has low cation exchange capacities in the range of 3 to 10 meg/100g[9]. CEC results confirm the low activity of clay minerals and XRD results. Swelling clays content effects on the ductility of the rock[7]. Swelling clays have high CEC values. CEC results confirm the absence of swelling clay minerals in Laffan shale samples.

Tab. 7: CEC of Formation Samples

Sample	CEC (Milliequivalent /100 g)	PH
SIC-F1	1.4	2.17
SIC-F2	5	2.18
SID-A1	6.4	2.2

11. CONTINUITY

When a caprock is influenced by tectonic deformation Lithology, ductility and thickness are critical factors affecting the integrity of the seal. Thick and ductile rocks remain sealing after tectonic deformation[7]. Low thickness and brittle layers in Laffan formation decrease the chance of lateral continuity but Laffan formation comprises of multiple sequences of brittle and organic rich ductile rocks which have provided effective seals against leakage.

12. CONCLUSIONS

Based on the results Laffan Formation in Sirri oil fields is a shale formation with 30 to 70 percent of clay minerals. Main minerals in the samples are kaolinite, quartz, calcite and pirite. In SEM micrographs kaolinite minerals can be realized tightly held in a calcite and quartz cement and limited number of small size pores. Because of the type of clay minerals and cementation Laffan does not show high ductility properties. Because of very fine grains Laffan has a very low permeability and is an excellent capillary seal. TOC of laffan is low but some layers of organic rich shale formations are observed in this study. TOC values have good correlation with permeability. CEC values of core samples confirm the clay mineral types and show good correlation with total organic content. By integration of this information can conclude that Laffan is an impermeable and relatively thin and brittle formation but the presence of interlayer organic rich shale rocks and high depth may be caused the flexibility of caprock during the structural deformations and have improved the chance of lateral continuity of it. Laffan is not an excellent but a good caprock. In this study direct and indirect methods of mineralogy determination have the same results and there is a good correlation between permeability and TOC results. This research process can be applied in similar geological settings.

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