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On Permanent Geologic Repository for Spent Nuclear Fuel: What can UAE Geology Offer?

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Abstract.
A variety of geologic media and concepts for the disposal of Spent Nuclear Fuel have been investigated worldwide.
Two sources of uncertainty envelop geologic disposal: Financial and Technical (Aleatory (Stochastic) and Epistemic (lack of data)).
Two geologic repository options considered in the world are: mined disposal and deep borehole disposal (DBD) in basement rock.
UAE's geology is preponderantly Carbonates. However, metamorphic rocks formed during ophiolite formation and obduction also exist; called Semail ophiolite.
The Semail Ophiolite Complex includes layered gabbro and harzburgite/peridotite that could be candidates for a mined repository. This rock type is similar to the Swedish repository; expected to be suitable for mined repository based on the KBS-3 method.
Like all Arabian Gulf states, UAE's geology is preponderantly Carbonates.
Quantitative characterization of carbonates is a challenge: Advanced techniques, like model-based interpretation methodology and artificial neural networks for rock type analyses, are now used to evaluate carbonates.
Three carbonate formations in the UAE might fulfil the requirements of Spent Nuclear Fuel deep geologic repository: The Rus Formation, Nahr Umr and Hith.
Rus Formation is a cap rock of the aquifer below. Hence the low permeability of its interbedded anhydrites deposits. Rus needs detailed characterization to be considered as a potential repository.
Two principal cap rocks sealing the oil/gas reservoirs in UAE: Nahr Umr shale (sealing the Thamama Group), and Hith Anhydrite (sealing the underlying Arab Formation)
Secondary seals and barriers also exist in the stratigraphic sequence in the UAE.
Cap rocks Nahr Umr and Hith are impermeable rocks, commonly shale or anhydrite, forming a barrier or seal above and around the reservoirs underneath so that fluids cannot migrate beyond the reservoir.
Permeability of these cap rocks is ~ 10^{-6} to 10^{-8} Darcy (μm²).
Nahr Umr and Hith need in-depth characterization to ascertain their sealing capability.

KEYWORDS: Spent Nuclear Fuel, Disposal, Geologic Repository, UAE, Carbonates, Ophiolite

1 INTRODUCTION

Management of Spent Nuclear Fuel has seen several challenges internationally. The technical challenges faced internationally over the past five decades have impeded efforts at permanent disposal of Spent Nuclear Fuel from nuclear power reactors.
A number of approaches to spent fuel management have been and will be adopted around the world due to differences in the adopted technologies and organizational arrangements which, in turn, arise from a range of technical and societal factors.
There is a clear consensus that spent fuel management must encompass all activities from discharge from the reactor core to emplacement of fuel and/or waste in a disposal facility.
A number of national strategies prefer to make available sufficient spent fuel storage capacity to bridge the gap between the generation of spent fuel and the foreseen commissioning and operation of deep geological disposal facilities.
Three sources of uncertainty need to be considered in very long-term projections of the performance of geologic disposal systems of Spent Nuclear Fuel: *Financial*, *Aleatory* and *Epistemic* **[1].**
There is a need to quantify the levels of uncertainty, and understand how that uncertainty propagates through the analyses supporting the safety case for a permanent geologic disposal system. The information that would be collected through research and development provides a basis to communicate the safety case for a generic repository or geologic disposal system in a specific medium.Financial cost and a lack of sustainable funding is a concern for many countries stocking Spent Nuclear Fuel and high-

level waste.The importance of the integration of the various stakeholders involved in the implementation of the spent fuel management programs from the beginning and maintaining this network while implementing activities is essential. Public understanding is paramount and key as a first driver and second step must be politics as decision makers.

2 CURRENT STATE-OF-THE-ART IN SNF GEOLOGIC REPOSITORY

Slow progress in the deployment of geological disposal facilities and reduced use of reprocessing has led to an increase in the inventory and duration of spent fuel storage in the world. A range of approaches to the management of spent nuclear fuel have been considered in different countries.
National strategies for spent fuel storage and disposal have been developed in four countries that have committed programs (Finland, Sweden, USA and France).
In their development of a national policy for Spent Nuclear Fuel and radioactive waste management, these countries started by establishing a legal framework that:

- Provides a consistent system involving clear allocations of responsibilities, licensing, prohibitions, institutional control, regulatory inspections, documentation and reporting.
- The framework also enables the enforcement of applicable regulations and terms of the licences,
- The regulatory body has qualified staff and financial resources necessary for its activities,
- The legislation clearly stipulates that the State has the ultimate responsibility for safety aspects of Spent Nuclear Fuel and radioactive waste,
- The Operator has the primary responsibility within the State for the safety of Spent Nuclear Fuel and radioactive waste management,
- The legal framework corresponds very well to the objectives of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management:
    - Spent Nuclear Fuel management should be aligned to the national policy for final dispositioning of the fuel,
    - Given the long timeframes associated with geological disposal facility site selection and the management life-cycle associated with nuclear fuel, selection of national spent fuel storage arrangements should reflect the need for efficiency of delivery of the whole Spent Nuclear Fuel management strategy. The strategy should ensure that unduly increased costs due to an expedient short term focus are avoided,
    - Commercial and financial arrangements should ensure that spent fuel management decisions do not unnecessarily preclude future management options. This will minimize the constraints placed on future fuel handling, packaging and disposal activities,
    - Having the capability to allow for extended storage of Spent Nuclear Fuel, either at reactor sites or at a centralized facility, potentially over periods of several decades, may give increased flexibility in the design of future packaging or disposal concepts,
    - Storage of spent fuel over 100 years or more using existing technologies, or foreseeable evolutions of them, is technically feasible and operationally credible,
    - The use of multiple approaches to fuel storage, and continued evolution of the design of storage facilities, indicate that there is no single best storage technology and that local factors such as existing infrastructure, approach to fuel cycle management, existing experience and capability and short-term cash flow considerations all influence technology selection,
    - Both wet and dry storage systems continue to receive regulatory approval and are generally considered to be acceptable.

Societal Acceptability: There seems to be a growing public and government awareness in the world that the implementation of radio-active waste management programs has to be viewed in a wider societal context and focus on social acceptance and public confidence. All the countries producing Spent Nuclear Fuel waste have experienced local resistance to transportation of nuclear waste or to the siting of facilities, and there seems to be a general opinion that there is a need for increased public confidence in the radioactive waste management system selected, as well as in the ambitions and efforts of the institutions responsible.
Uncertainties: Three sources of uncertainty need to be considered in very long-term projections of the performance of geologic disposal systems of Spent Nuclear Fuel: Financial, Aleatory and Epistemic.

There is a need to quantify the levels of uncertainty, and understand how that uncertainty propagates through the analyses supporting the safety case for a permanent geologic disposal system. The information that would be collected through research and development provides a basis to communicate the safety case for a generic repository or geologic disposal system in a specific medium.

The Safety Case: The ***safety case*** for geologic disposal include a ***safety strategy*** that has three components: a ***management strategy***, a ***siting and design strategy***, and an ***assessment strategy*** **[2].**

The safety strategy is the high-level approach adopted for achieving safe disposal. The safety strategy encompasses the requirements of the project.

A ***management strategy*** incorporates good management and engineering principles and practice, including maintaining sufficient flexibility within a step-wise planning and implementation process, to address unexpected site features, technical difficulties, or uncertainties that may be encountered. This includes the strategies for the overall management of the various activities required for repository planning and implementation, for siting and design, and for performing safety assessments. It also should seek to be aware of and take advantage of advances in scientific knowledge and engineering techniques. This management function keeps work focused on project goals, allocates resources to particular activities, and ensures that these activities are correctly carried out and coordinated.

The ***siting and design strategy*** is generally based on principles that favor robustness in natural and engineered components that could be important to waste isolation, and limit uncertainty, by using of a multiple-barrier concept. The siting and design strategy seek to select a site that meets regulatory requirements, and develop practicable engineering solutions, consistent with the characteristics of the selected site and the waste forms to be disposed.

The ***assessment strategy*** must ensure that safety assessments capture, describe and analyze uncertainties that are relevant to safety, and investigate their effects. The assessment strategy should endeavor to define the approach to evaluate evidence, perform safety assessments, and analyze the evolution of the system. This information can be used to develop or update the safety case. These components are closely connected in that a sound management strategy and a well-sited and designed repository system will facilitate the development of a competent and convincing safety case. All are required, however, and shortcomings in any one cannot be overcome by excellence in the others.

3 UAE GEOLOGY; A FORESIGHT TO SITE-SELECTION OF SPENT NUCLEAR FUEL REPOSITORY

This section presents “Generic Criteria” of the UAE geology. The aim is to lay down an initial foundation for site-suitability criteria pertinent to UAE’s geologic formations and their physical characteristics vis-à-vis permanent geological disposal of Spent Nuclear Fuel and high-level nuclear waste.

Like all the Arabian Gulf states, UAE’s geology is preponderantly Carbonates. During the Late Paleozoic (Upper Permian) to the Cenozoic (Tertiary) eras the vast Arabian platform lay along the southern margin of the Tethys Ocean. During this period epeiric shelf carbonates associated with only minor clastics and evaporites were deposited. Sedimentation patterns were controlled by many factors such as epeirogenic vertical movements due to basement tectonism, halokinesis, climatic variations, and, most importantly, sea-level variations. The Late Paleozoic to Cenozoic stratigraphic sequence shows lateral variations in formation thicknesses as well as in the distribution and continuity of lithofacies characteristics.

Although UAE’s geology is preponderantly Carbonates, UAE however, also has metamorphic rocks formed during ophiolite formation and obduction. Obduction is a geologic process in which the edge of a tectonic plate consisting of oceanic crust is thrusted over the edge of an adjacent plate consisting of continental crust. For example, UAE is interpreted as a metamorphic sole to the Semail *ophiolite*.

3.1 Semail Ophiolite

When tectonic plates made of dense oceanic crust material meet plates of more buoyant continental crust material, the oceanic plate moves beneath the continental plate and sinks into the earth’s mantle in a process known as *subduction*. Occasionally, however, an opposite process, called *obduction*, thrusts sheets of oceanic crust and upper mantle rocks over the top of less dense continental material **[3, 4, 5, 6, 7, 8]**.

Although *obduction* is regarded as a geodynamic anomaly **[9],** it is not a rare event. The evidence of such a violent geodynamic process is found in O*phiolites*, which are sequences of oceanic crust and upper mantle rocks found near the surfaces of continents. By far, the largest, best exposed, and most studied ophiolite complex is the *Semail ophiolite* in the eastern corner of the Arabian Peninsula, spanning Oman and the United Arab Emirates (UAE) **[3, 4, 5]**.

The Semail ophiolite, Fig. 1 and 2, is also known as the Oman-United Arab Emirates (UAE) ophiolite complex. The Semail ophiolite is 150 kilometers wide and stretches for 700 kilometers, and it exposes the Semail ophiolite thrust sheet, which is roughly 15–20 kilometers thick. Beneath the exceptionally well preserved Semail ophiolite, a series of thrust sheets of oceanic sedimentary and basaltic rocks, emplaced from northeast to southwest, separates the overlying ophiolite from the Arabian continental rocks beneath **[4]**.

The Semail ophiolite is the largest and best preserved sliver of oceanic crust exposed on Earth's continental crust. It comprises a complete section from upper mantle harzburgite rocks, through to the uppermost pillow basalts. The middle to lower crustal structure of the UAE-Oman mountains remains an enigma **[5]**. Although scientists have mapped and studied the surface geology of this region in detail, the middle to lower crustal structure of the UAE-Oman mountains remains an enigma. After more than 40 years of detailed geological studies, there is still a lack of high-resolution geophysical imaging beneath the UAE-Oman mountains.

In an attempt to understand the structure beneath both the Semail ophiolite and the underlying crust of the UAE-Oman mountain range, researchers from the Petroleum Institute, Abu Dhabi (UAE), have teamed up with geologists and geophysicists from the University of Oxford. Their detailed geophysical and geological observations represent significant progress toward solving the ongoing debates about the ophiolite emplacement processes **[4]**.

One unique thrust slice, the Bani Hamid thrust sheet in the northern Oman-UAE mountains, shows a 1-kilometer-thick sequence of extremely high grade marbles and quartzites (granulite facies). This sequence was formed during the latter part of the obduction process, when these buoyant rocks were jammed in the subduction zone and then thrust into the middle of the ophiolite [**213]**. The thickness of the ophiolite thrust sheet and the structures in the underlying deeper part of the mountain belt, however, remain poorly known.

The Semail ophiolite complex extends over 700 km from the NE coast of Oman, to Dibba in the UAE. The Semail ophiolite is a thick allochthonous sequence of peridotite, gabbro, diabase, pillow lava and pelagic Cretaceous sedimentary rocks, Fig. 1 and 2 **[5, 10].**

3.2 Carbonates

Like all the Arabian Gulf states, UAE's geology is preponderantly Carbonates. Carbonate rocks are one of the most important and abundant constituents of materials on the earth surface. This is because Carbonate rocks not only possess natural resources, such as valuable minerals and including fossil fuels, but also contain history of the earth surface environments in the past. Thus, identification and quantification of the abundances and proportions of carbonate minerals in the rock is essential for site selection and understanding the "generic criteria" of carbonate geology characterization **[12, 13]**.

The rocks constitute a mosaic of minerals and naturally complex geologic mixtures, such as intimate mixtures, grain size variations, weathered constituents, and alteration products. Those mixtures can create a major obstacle to mineralogic identification, particularly determining the proportions of mineral mixtures. Conventional methods to identify carbonate minerals in rock samples include X-ray diffraction (XRD), scanning electron microscopy (SEM), different thermal analysis (DTA), thin section analysis, staining method **[14, 15, 16]**.

Advanced techniques, like model-based interpretation methodology, advanced laboratory-based imaging hyperspectral sensors, such as SisuCHEMA, and artificial neural networks for rock type analyses are now used to evaluate carbonate rocks **[12]**.

Carbonates have complex pore-size distributions, leading to wide permeability variations for the same total porosity, making it difficult to predict their fluid flow parameters, or sealing, characteristics **[20]**.

The main (peak) tectonic event that shaped most of the carbonate structures occurred at the end of the Middle Cretaceous, and was related to the obduction of the Oman Ophiolite and the formation of the Oman Mountains.

Quantitative characterization of carbonates is a difficult challenge. Carbonates are **[17]**:

- Highly Heterogeneous (many litho-facies; hydraulically connected through capillary pressure: same Pressure but different Saturation at the boundary,
- Highly Anisotropic,
- Tensorial stress/strain fields,
- Highly faulted (seismic & sub-seismic) & fractured (all sub-seismic),
- Low compressibility (Cv),
- High variation in density,
- High variation in thermal conductivity (Kth) (due to variation in mineralogy),
- High variation in sound wave propagation velocity (tensorial) & travel time (Vp, Vs, Rho),
- Karstic formation,
- Vuggy (generating super permeability).

Advanced techniques, such as model-based interpretation methodology and artificial neural networks for rock type analyses, are now used to evaluate carbonates.

3.2.1 Cap Rock Sealing Formations as Potential Candidates for UAE Repository

Rus Formation

There are potentially three carbonate formations in the UAE that might fulfill the requirements of SNF/HLW geologic repository: The ***Rus*** Formation, ***Nahr Umr*** and ***Hith***.

In the Lower Eocene a wide evaporitic platform exists over most of the Abu Dhabi region giving rise to the evaporitic /carbonate sequence of the **Rus Formation,** above the Umm Er Radhuma (Paleocene), and below the Dammam (Middle Eocene). Umm Er Radhuma and the Dammam are huge aquifers. However, Rus is too tight to be an aquifer; porosity is virtually nil.

The Rus formation consists of massive anhydrites representing subaerial supratidal conditions. The Rus formation is composed of dolomites and limestone with crystalline anhydrite and some shale. The argillaceous limestone at the base of Rus represents lagoonal conditions. Porosity is virtually nil in these rocks except for infrequent unfilled fractures, vugs and oomolds, due primarily to cementation and chertification. Rus thickness is about 67 meters in the north and more than 280 meters in the south. It consists dominantly of massive anhydrite representing sub-aerial supratidal conditions. Minor argillaceous limestones at the base represent lagoonal conditions. Rus is not considered as a good aquifer, but as a cap rock due to the interbedded anhydrites deposits. Because of its shallow depth, Rus has not been of interest to the oil and gas industry. Hence, lack of detailed characterization of Rus calls for in-depth characterization of Rus to ascertain its sealing capability before it can be considered as a potential repository for Spent Nuclear Fuel and High-Level Nuclear Waste for UAE.

Most of the world's giant fields (like in the Arabian Gulf region) produce hydrocarbons from carbonate reservoirs. Correspondingly, there are two principal (cap rock) sealing formations in the UAE **[10, 11, 18, 19, 20, 21],** Fig. 3:

- **Nahr Umr** shale (sealing the Thamama Group), and
- **Hith** Anhydrite (sealing the underlying Arab Formation)

The Tithonian Hith Anhydrite and the Albian Nahr Umr Shale are in the Jurassic and Cretaceous reservoirs. However, secondary seals and barriers also exist throughout the stratigraphic sequence. In the UAE, these are the main cap rock seals for the oil and gas accumulations in the underlying Arab Formation and Thamama Group, respectively **[18, 19]**. The cap rocks are relatively impermeable rocks, commonly shale, anhydrite or salt, that form a barrier or seal above and around the reservoirs underneath so that fluids cannot migrate beyond the reservoir. It is often found atop a salt dome. The permeability of a cap rock capable of retaining fluids through geologic time is ~ 10^{-6} to 10^{-8} Darcies (μm²).

Nahr Umr: is a shale formation throughout the southern part of the Arabian Gulf and forms the cap rock to many major reservoirs in the region. In the UAE, Nahr Umr Formation is a series of shales, siltstones and mudstones, with increasing carbonate content toward the north of UAE. It thickens gradually from about 70m in the north to a maximum of 180m in the south and southwest and thins to approximately 90m in the extreme east of the offshore area towards the Northern Emirates. Nahr Umr consists of a sequence of variegated shales with some rare sand lenses, glauconitic silts and occasional beds of limestone—mostly packstones and wackestone. Nahr Umr comprises of dark brown-black silty andmicaceous shales with small phosphates. Macro and microfossils are very rare and a clear bed of black-green clay full of glauconite and small black is seen [**13, 21]**.

Recent literature reports major wellbore instability problems in the UAE when drilling through Nahr Umr Shale Formation. Well-bore instability was noticed in new wells and in re-entry wells, especially with the rise of water-based muds and stricter environmental control, making wellbore stability in this shale an extremely challenging operation for drilling/mud engineers. Hence, Nahr Umr suitability as a host rock of a deep borehole repository of Spent Nuclear Fuel must be meticulously ascertained. Further investigation of Nahr Umr should include coring with non-intrusive (neutral) drilling muds to acquire scientific and technical knowledge (Rock Typing, Porosity, Permeability, Capillarity, Faults (sealed, open), Fractures (sealed, open), Stylolites, Karstic conduits, tensorial Stress and Strain Fields, Density, Compressibility (horizontal vs vertical vs multidimensional), Thermal conductivity,…..).

Hith Formation: Has a thickness range of 60-100 meters and consists principally of anhydrite with subordinate dolomite in the western part of the area, while to the east the anhydrite content of the formation decreases gradually.

The Hith formation is mainly composed of anhydrate. Such materials are nonporous and less heterogeneous, which is consistent with the small scattering attenuation in this formation. There is only little published description of the Hith Formation beyond a cursory description of the nodular and wire-mesh character of the anhydrite and its thickness. It is believed that the depositional settings of the Hith Formation in the subsurface match those of the present-day supratidal evaporite depositional setting along the Arabian Gulf coastal area. However, in contrast, the Hith represents a mega-environment covering a much greater geographical area and produced a much thicker sequence of sediments dominated by evaporites, with much less carbonate than in the Holocene sabkha sediments of Abu Dhabi. The ultimate top seal for this Holocene sabkha sequence in western Abu Dhabi was previously thought to be the Hith Anhydrite. However, more recent literature suggests that it might rather be the tight limestones of the basal Cretaceous Habshan Formation. One evidence for this is that sour gas of similar composition to that in the Arab-ABC has been found in the Manifa Formation that overlies the Hith Anhydrite in the same area. Oil and gas with high H2S content has also been found in Habshan. This suggests that sour gas has migrated into even higher overlying reservoirs, possibly along fault planes. The lack of data on Hith calls for in-depth characterization of Hith to ascertain its sealing capability before it can be considered as a potential Spent Nuclear Fuel repository.

4 CONCLUSION

Management of SNF/HLW has seen several challenges internationally. The process started several decades ago, however until now, only four countries are committed (Finland, Sweden, USA and France). Even in the committed countries, the challenges have so far prevented the licensing of a geologic SNF repository, because siting a permanent geologic repository for SNF turned out to be a hard societal, financial and technical challenge. As a result, most countries envision the SNF disposal repository developed in a series of steps.

A variety of geologic media and concepts for the disposal of SNF/HLW have been investigated worldwide.

Two sources of uncertainty envelop geologic disposal: Financial and Technical (Aleatory (Stochastic) and Epistemic (lack of data)).

Steps of developing SNF geologic repository are: siting, design, construction, operation, and closure.

The safety case for geologic repository includes: safety strategy with three components: management strategy, siting & design strategy, and an assessment strategy.

Two geologic repository options considered in the world are: mined disposal and deep borehole disposal in basement rock.

UAE's geology is preponderantly Carbonates. However, metamorphic rocks formed during ophiolite formation and obduction also exist; called Semail ophiolite.

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characterization to be considered as a potential repository. Two principal cap rocks sealing the oil/gas reservoirs in UAE: Nahr Umr shale (sealing the Thamama Group), and Hith Anhydrite (sealing the underlying Arab Formation). Secondary seals and barriers also exist in UAE's stratigraphic sequence.
Cap rocks Nahr Umr and Hith are impermeable rocks, commonly shale or anhydrite, forming a barrier or seal above and around the reservoirs underneath so that fluids cannot migrate beyond the reservoir. Permeability of these cap rocks is of the order 10^{-6} to 10^{-8} Darcy (μm²).
Again, these cap rocks have not been of interest to the oil/gas industry. Hence, Nahr Umr and Hith need in-depth characterization to ascertain their sealing capability.

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Figure 1: Simplified geological map of the Hajar Mountains in eastern UAE. Inset shows location of the Semail *ophiolite* within the UAE **[8]**

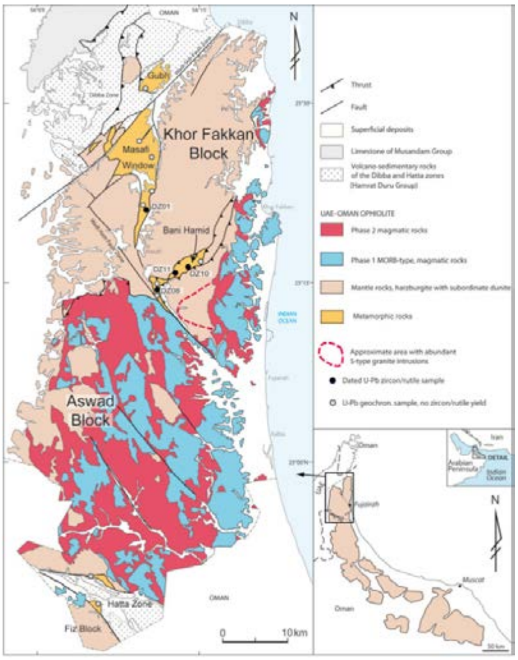

Figure 2: Simplified regional geological map of the United Arab Emirates northern Oman mountains Emirates northern**[13]**

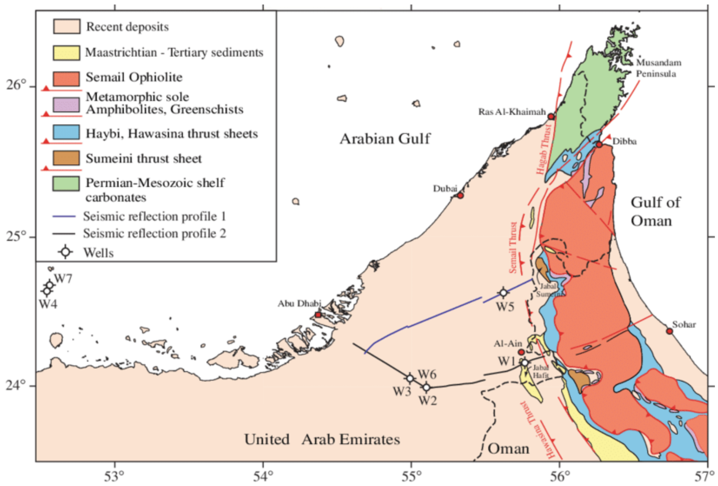

Figure 3: Oil and gas accumulation model for the Upper Jurassic and Lower Cretaceous reservoirs **[14]**