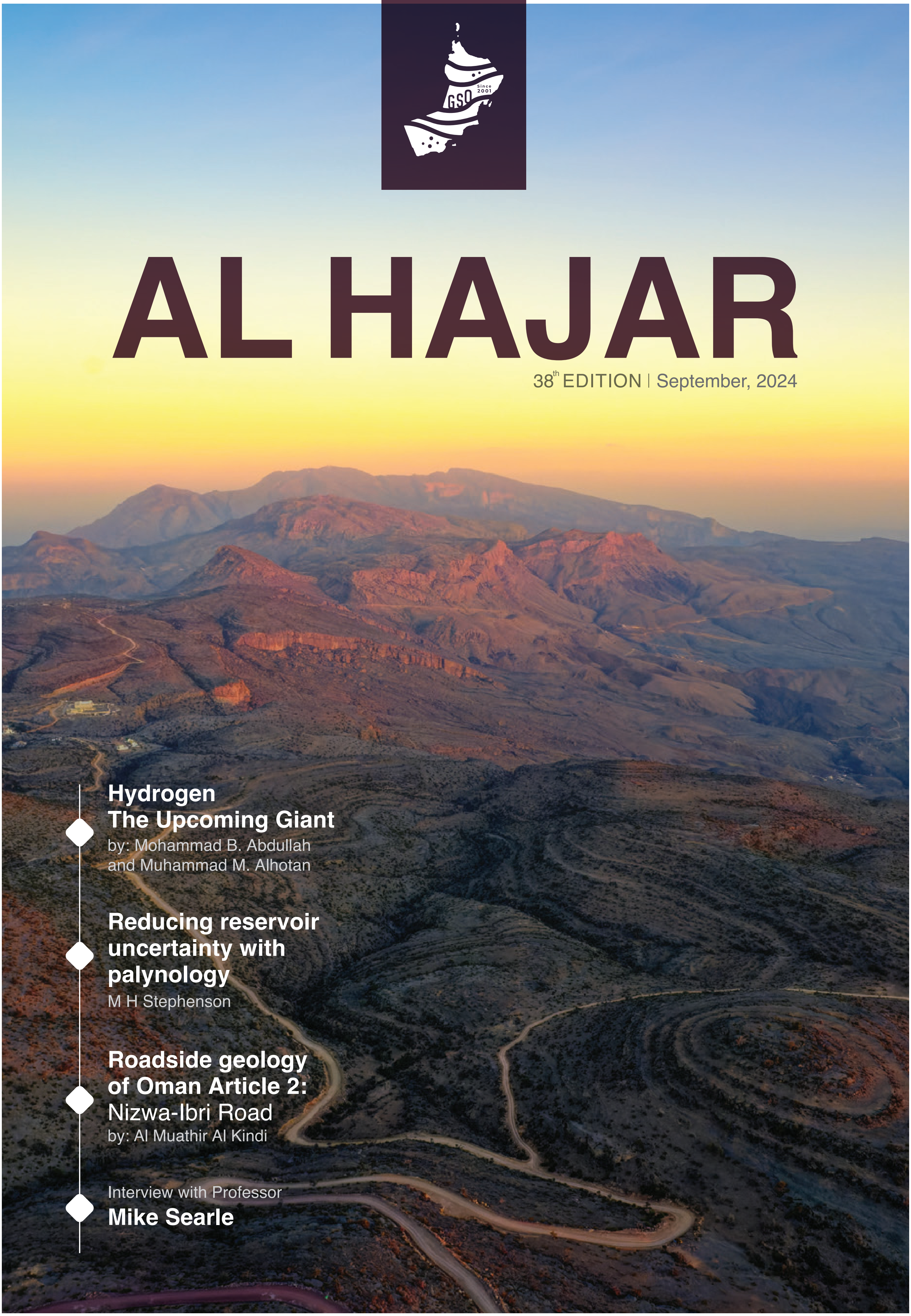

AL HAJAR

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Contents:

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The Geological Society of Oman (GSO) was established in April 2001 as a vocational non-profit organization which aims to advance the geological sciences in Oman, the development of its members and to promote Oman's unique geological heritage.

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Welcome, Geoscience Enthusiasts!

We are delighted to present you with the newest edition of AL Hajar magazine. As always, it is our sincere privilege to share the wonders the geological landscape and the advancements being made in the ever-evolving field of geoscience. In this edition, our feature article, Hydrogen: The Upcoming Giant, explores the potential of hydrogen in a sustainable energy economy and the role that GCC countries will play in the future. We also take a closer look at the geology of Oman's Nizwa-Ibri road in our "Roadside Geology" section. In addition, we delve into the world of palynology and how it can help reduce reservoir uncertainty. And don't miss our exclusive interview with Professor Mike Searle, where he shares his insights on the future of geology. We hope you enjoy reading this issue as much as we enjoyed putting it together! We trust you will find the content both intellectually stimulating and personally enriching. As ever, the Geological Society of Oman remains dedicated to fostering a deeper appreciation for geology and propelling the field of geoscience forward.

Warm regards,

Laila AL Zeidi
GSO Content Editor

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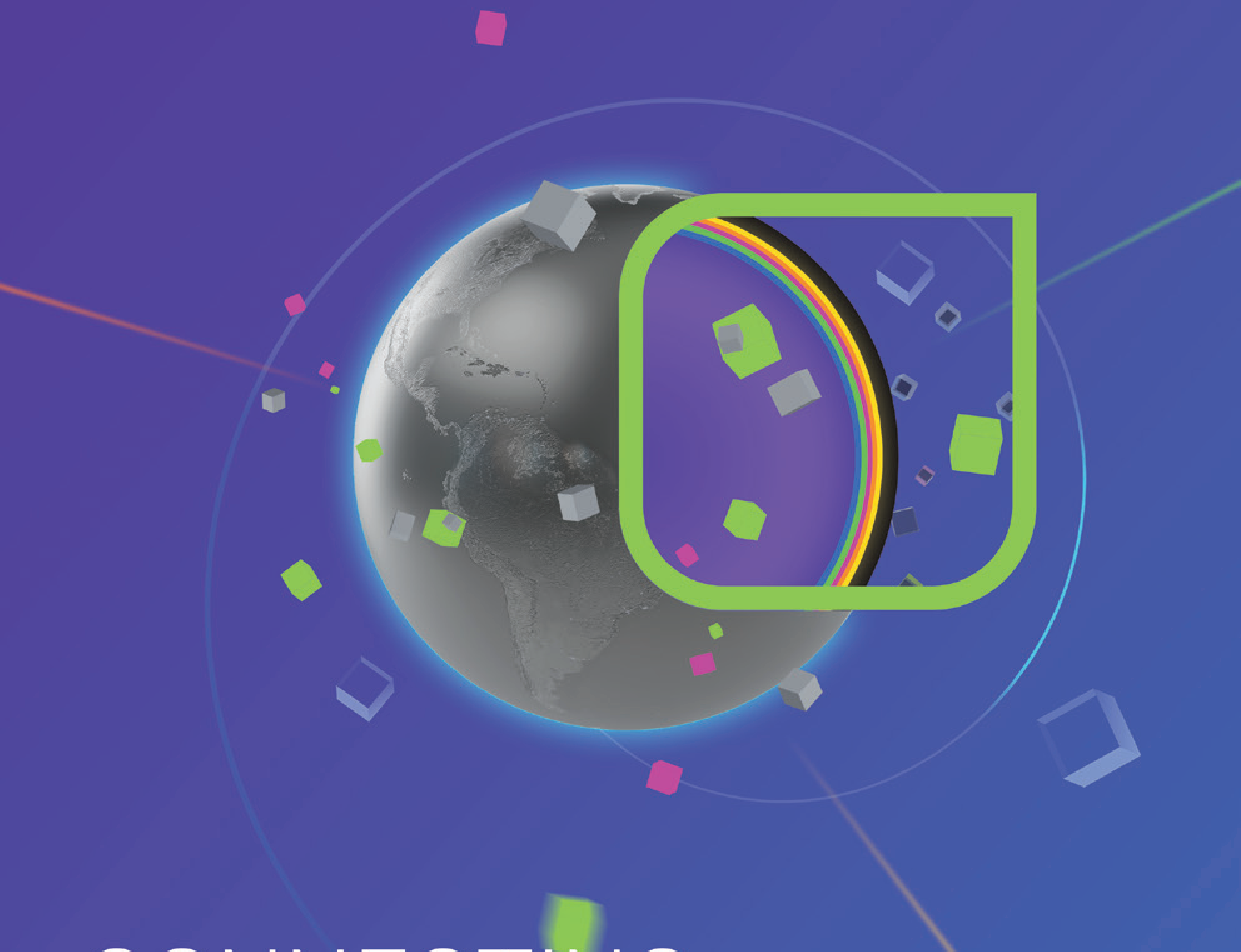

Hydrogen
The Upcoming Giant

By: Mohammad B. Abdullah[1,2], Muhammad M. Alhotan[1,3]

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Recent interest in hydrogen

As nations commit to reducing their carbon emissions, the interest in low-carbon emission energy has gained significant momentum in the past few years. Hydrogen has become an attractive option that many countries are interested to add to their energy mix as hydrogen combustion produces only water vapor and it has a high energy content by weight, being three times that of natural gas (Heinemann et al. 2018). Hydrogen is not an energy source but rather an energy carrier. Its potential lies in the fact that it can be used to store large amounts of energy for later use while having low carbon emissions. This potential is especially attractive when paired with renewable energy, as hydrogen gas can be produced from surplus solar or wind and then stored or transported for later use when and where needed. Historically, hydrogen has important uses in industry, space exploration, and as a transportation fuel. The global demand for pure hydrogen was nearly 90 million tons (Mt) in 2020, with a 22% increase compared to 2019 and a 50% increase since 2000 (IEA 2019, 2021b). According to the International Energy Agency (2021a, 2021b), demand for hydrogen is anticipated to grow to 212 Mt by 2030 and 450 Mt by 2050, with 20 countries developing strategies for hydrogen utilization. Figure 1 illustrates a simplified diagram of the hydrogen value chain.

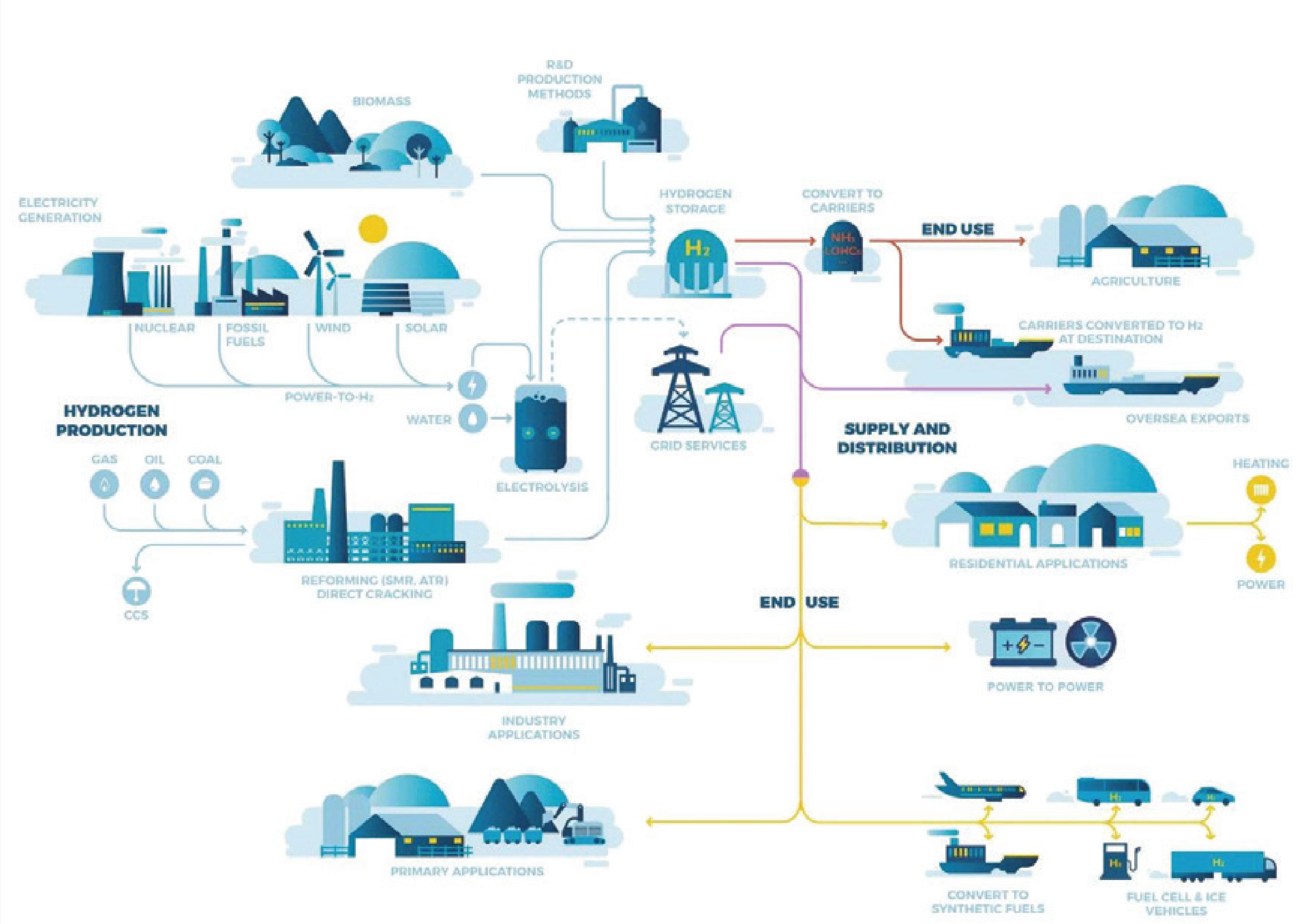

Figure 1: Hydrogen Value Chain (Hydrogen TCP, 2023)

Why select hydrogen compared to other gases?

Hydrogen distinguishes itself not only through clean combustion products but also through its exceptional properties as a gas. It has the highest energy density per mass among gases and the lowest density per volume. For example, 1 kg of hydrogen delivers three times the energy of 1 kg of gasoline. However, a liter of hydrogen contains 3,000 times less energy than a liter of gasoline (Durbin and Malardier-Jugroot 2013). These properties make hydrogen especially advantageous for certain uses and problematic for others. Its high energy density, for instance, makes it an ideal fuel for lightweight jets and aerospace applications. Nonetheless, hydrogen's low density of 0.089 kg/m3—8,000 times less than that of gasoline under standard conditions—requires it to be stored at high pressure or in large volumes, typically in the form of subsurface storage, to manage surplus seasonal energy (Muhammed et al. 2022).

How is hydrogen generated?

Although hydrogen is the most abundant element at the Earth’s surface, its high reactivity prevents it from existing freely in its elemental form. Producing hydrogen is energy-intensive, involving either reforming or non-reforming hydrogen production methods. Reforming methods, which account for over 90% of global hydrogen production, involve converting materials containing hydrogen (e.g., natural gas) into pure hydrogen. Reforming is commonly done through steam methane reforming (SMR). SMR is highly energy-efficient, with efficiencies ranging from 65-85% (Holladay et al. 2009, Amid et al. 2016, Shadidi et al. 2021). The process includes a reaction of methane with steam in the presence of a catalyst, under pressure and heat, producing hydrogen and carbon monoxide. The latter reacts further with steam to generate additional hydrogen and carbon dioxide. On the other hand, electrolysis, a common non-reforming method, produces hydrogen by splitting water into hydrogen and oxygen via electrochemical cells with energy efficiencies between 55-90% (Holladay et al. 2009, Amid et al. 2016, Nasser et al, 2022).

The industry categorizes hydrogen production processes by different colors, depending on the energy source used and the management of the by-product CO_2 , as illustrated in **Figure 2**. However, the color classification system is not universally applied and can lead to confusion due to the various technologies involved **(Figure 3)**. Consequently, the Green Hydrogen Organization recently introduced a simpler categorization based on carbon emissions, defining hydrogen as either "low carbon" or "high carbon".

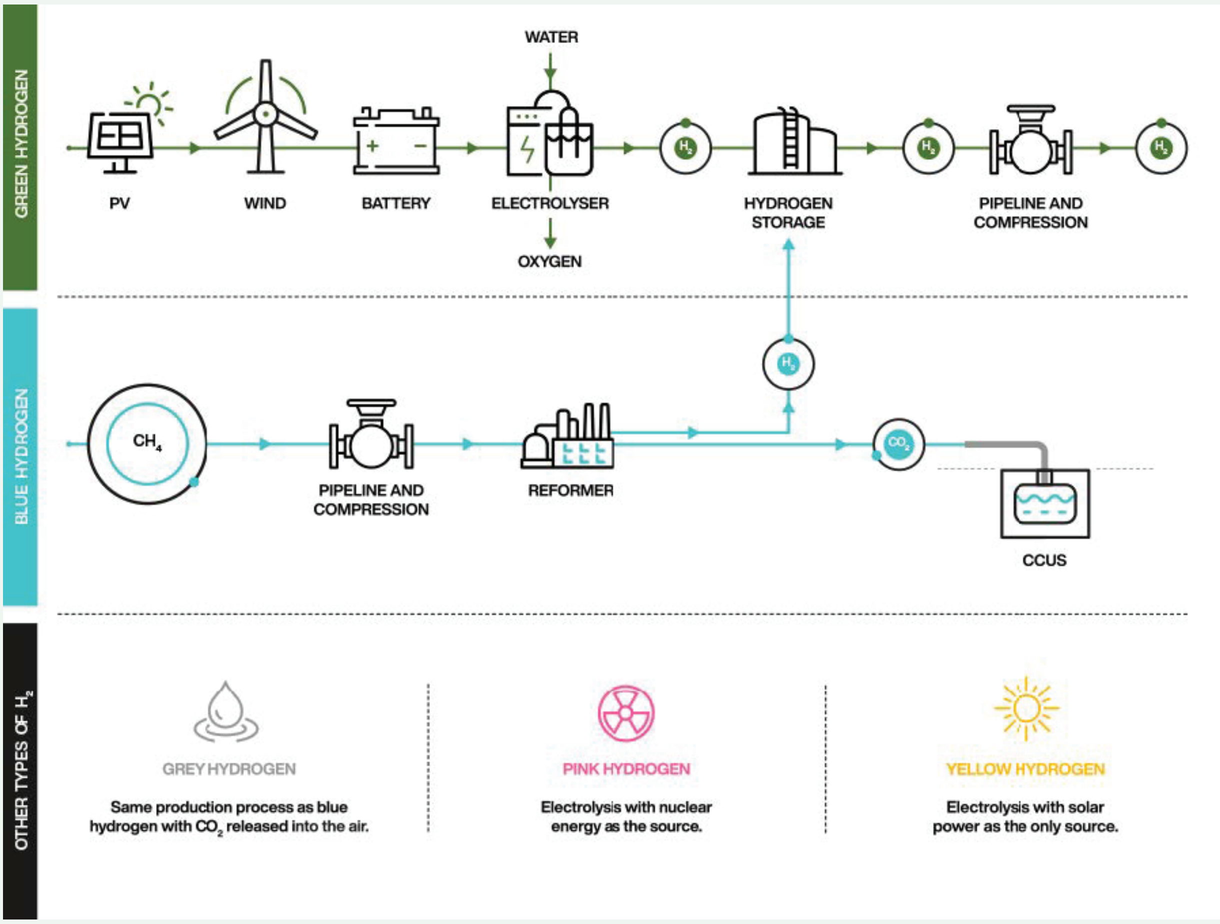

Figure 2: Different colors of hydrogen (Haynes 2022)

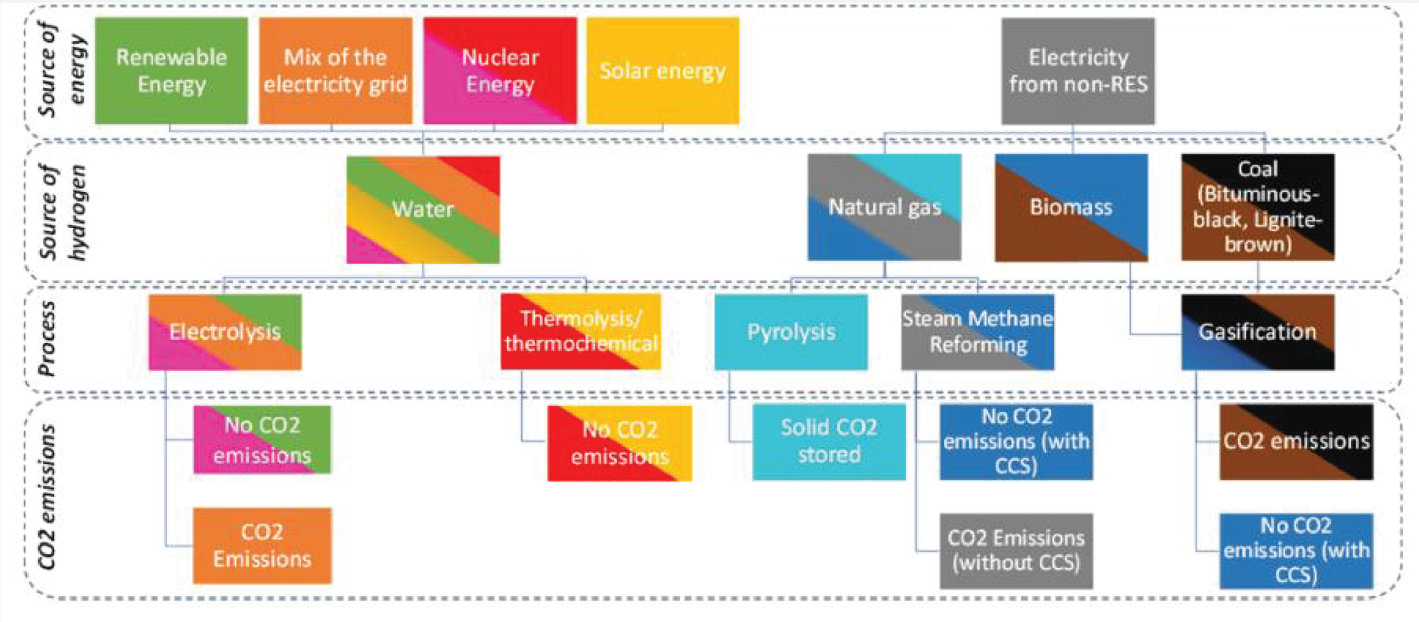

Figure 3: Schematic summarizing the colors of hydrogen in literature based on its source and emission (Incer-Valverde et al. 2023)

How is the energy extracted back from hydrogen?

Energy can be extracted from hydrogen either through combustion or via fuel cells. In hydrogen combustion, power is generated by burning hydrogen, which involves mixing hydrogen with air and igniting it in a combustion engine. In contrast, fuel cells operate in a manner opposite to water electrolysis; they convert hydrogen into electricity through a chemical process (Ali and Salman 2006). Comparing the energy efficiency of these two methods is similar to comparing a traditional gasoline combustion engine to a battery-powered electric motor. Fuel cells generally offer greater energy efficiency than hydrogen combustion engines.

Challenges (storage, transportation, generation):

Hydrogen has the lightest weight in the periodic table with one of the smallest molecule sizes, which entails high gas penetrability within the carrier medium and higher pressure required for storage (Gregoryanz et al. 2020). Thus, hydrogen production, transportation, and storage are challenging technically and economically when considering hydrogen as a low-carbon energy source. Production of hydrogen is mainly done by electrolysis or steam methane reforming. The process is expensive for electrolysis in its current form since it has not yet been developed for an economical scale. However, substantial investment plans exist to develop this technology at a scale that achieves economic viability. According to Custom Market Insights (CMI), the water electrolysis market size was estimated at USD 11.5 Billion in 2022 and is projected to more than double in size by 2032. With such investment and expansion, the cost of producing low-carbon hydrogen via electrolysis is expected to become more economically viable.

Hydrogen's economic merit, as with many other forms of energy, can be sensitive to the available transportation infrastructure. Hydrogen transportation via pipeline may cause serious degradation in steel alloy pipes (known as hydrogen blistering) when transported at high pressure and concentrations. Its small molecule size results in high diffusivity that induces serious leakage problems through pipe walls - up to five times the amount of methane gas leakage when transported in a natural gas system polymer pipe (Tarkowski 2019, Zivar et al. 2021). Wide-scale growth of hydrogen demand will require research and development solutions for expansion of supply chains to areas of new deployment.

One option for hydrogen's supply chain challenge is to convert it to ammonia. A recent study by Fluor (2023), commissioned by the Port of Rotterdam and 18 other industry giants, found it is technically and economically feasible to safely convert ammonia into around 1 million tonnes of hydrogen annually at the port using a large-scale cracker. Additional research is underway to evaluate and develop methods to utilize existing natural gas pipelines and infostructure to transport gaseous hydrogen, which can drastically reduce its end cost to the consumer.

As for storage, current storage options include surface tanks and subsurface geological ones. Each option has merit, and the most effective option varies depending on the application. For example, surface tanks are more practical for industrial applications. However, for large-scale hydrogen energy consumption, the volumes needed are so high that underground storage options such as salt caverns, depleted oil/gas reservoirs, and aquifers, become appealing.

Potential subsurface storage reservoirs or caverns:

The requirements of suitable subsurface geological storage sites for hydrogen are sufficient storage capacity, containment with minimal losses, cost-effectiveness, and a delivery rate that reliably meets power demand. Potential storage options include depleted hydrocarbon reservoirs, aquifers, and salt caverns. The capacity of the storage medium is particularly vital. Salt caverns have a relatively small capacity compared to underground porous media, ranging from 30 to 274 GWh (Langmi et al., 2022; Sambo et al., 2022). Depleted hydrocarbon reservoirs and aquifers have a much higher capacity (Zivar et al. 2021). Aquifers and hydrocarbon reservoirs are also estimated to be more cost-effective in the long term and more abundant worldwide (Kobos et al. 2011; Lord et al. 2014). Another critical factor to consider is the hydrogen lost during storage. Several published investigations indicate that depleted hydrocarbon reservoirs and aquifers have significant losses relative to salt caverns (Amid et al. 2016; Muhammed et al. 2022). These factors suggest that while salt caverns are advantageous for small capacity purposes, depleted hydrocarbon reservoirs and aquifers are more suited for economic scale energy requirements.

Aquifers have an abundant storage capacity, require more straightforward modeling and fluid characterization, and can maintain hydrogen purity when produced back. However, aquifers have some drawbacks such as the lack of a proven trapping structures, the risk of leakage with new wells, and the added cost of fully characterizing the formation and building infrastructures such as pipelines and production facilities. On the other hand, depleted hydrocarbon reservoirs have a proven record of adequately trapping oil and gas, and would require less capital investment given the existing reservoir characterization and infrastructure. Their drawbacks manifest in the complexity of three-phase (oil, water, and gas phases) flow, which requires extensive fluid characterization and complex numerical modeling. Also, storing hydrogen in these reservoirs will cause a mixing of hydrogen and the in-situ hydrocarbons, decreasing the purity of the hydrogen that is stored.

What would it take to make hydrogen economically feasible?

The economic feasibility of hydrogen, mainly green hydrogen, hinges on several critical factors, including technological advancements, market demand, policy, support of governments, and infrastructural developments. The current technology for producing green hydrogen is electrolysis, which is energy-intensive and expensive. Advances in electrolysis and other production methods, such as photobiological processes and thermochemical water splitting, are essential to reduce costs and improve efficiency. Enhanced carbon capture and storage (CCUS) technologies also play a pivotal role, especially for blue hydrogen production. The International Energy Agency (IEA) suggests that hydrogen could account for almost one-fifth of total energy consumption by 2050. Key markets include Asia, Europe, and North America, where hydrogen could replace conventional fuels and support the transition to cleaner energy systems. Robust policy frameworks that promote clean energy, carbon pricing, and emissions reductions are vital to encourage investments in hydrogen technology and infrastructure. International agreements, such as the Paris Agreement, also influence national policies by setting broad emissions reduction targets. Establishing hydrogen production, storage, and transportation infrastructure is crucial for its economic feasibility. This includes pipelines for hydrogen distribution, refueling stations for hydrogen fuel cell vehicles, and facilities for exporting hydrogen or hydrogen-derived fuels like ammonia.

Historical background and ongoing projects:

Hydrogen generation through water electrolysis has been known since the 1800s. In the early 1900s, hydrogen was utilized in airships. A notable hydrogen incident was the Hindenburg airship fire in the US in 1937. This accident initially led to widespread beliefs that hydrogen was a hazardous gas, until investigations revealed that the use of flammable paint on the airship was the actual cause of the disaster. In the late 1950s, NASA employed hydrogen for spacecraft activities, and subsequently, various countries used liquid hydrogen fuel in their spacecraft. Since the early 1900s, the demand for hydrogen has increased, particularly for plant fertilization (Okano 2016).

Steam reforming of hydrocarbons began in the 1930s and has been the most economical method for hydrogen production since the 1960s. Currently, over 90% of the world's hydrogen is produced through steam methane reforming (Holladay et al. 2009, Okano 2016).

Energy extraction from hydrogen gained momentum during the oil crisis of 1973. In 1986, Germany promoted the use of green hydrogen through various international projects. From 1986 to 1995, a joint German-Saudi Arabian project called "Hysolar" was developed. This project utilized a 350 kW solar power system installed in the Saudi Arabian desert to produce hydrogen through electrolysis. Recently, various projects have been announced to align with the global zero-emission climate policy by utilizing hydrogen as a clean energy source (Okano 2016, Zivar et al. 2021). Some notable projects around the world include Canada's Spirit of Scotia and Fleur-de-lys hubs, each expected to produce up to 43 million tonnes of hydrogen annually using offshore wind energy. In Mauritania, the Nouakchott project aims for 8 million tonnes, leveraging a 10 GW electrolyzer. Australia's Western Green Energy Hub and Hydrogen City in Texas, USA, are set to produce 3.5 and 3 million tonnes, respectively, driven by significant wind and solar investments. Europe's contributions include the NortH2 and AquaVentus projects in the Netherlands and Germany, each planning to deliver about 1 million tonnes of hydrogen per year from renewable sources.

Recent interest in GCC:

Within the GCC, Saudi Arabia, Oman, and the United Arab Emirates (UAE) are prominently positioning themselves as future hydrogen hubs. Saudi Arabia is investing in large-scale green-hydrogen projects, such as the planned production facility in Neom, which is designed to be powered entirely by renewable energy sources. Oman is developing a comprehensive national hydrogen strategy, which includes creating a supportive regulatory framework and advancing large-scale projects, particularly in Duqm. This project, spearheaded by India's ACME Group in collaboration with OQ and international partners, aims to utilize Oman's solar and wind resources to produce green ammonia from hydrogen. The UAE is also advancing its hydrogen ambitions, which are highlighted by projects like the green hydrogen initiative at the Mohammed bin Rashid Al Maktoum Solar Park in Dubai. Recently, Kuwait announced a 5 billion USD project for grey, green, and blue hydrogen production. The project is part of Shagaya Renewable Energy Park, which aims to deliver 4 gigawatts of green electricity after commencement in 2030 (Shehabi and Dally 2021).

In summary, transitioning to an economically viable hydrogen economy hinges on technological breakthroughs, establishing strong policy frameworks, robust market demand, and significant investments in infrastructure. As nations increasingly prioritize decarbonization, hydrogen presents a pivotal opportunity to redefine global energy dynamics. The GCC countries, with their strategic initiatives and investments, are uniquely positioned to become central players in the hydrogen sector. Leveraging their substantial renewable resources and existing energy infrastructure, they are poised to meet their own sustainable energy needs and become leading exporters of clean hydrogen to the world. By capitalizing on these strategic advantages, the GCC can significantly influence and accelerate the global shift towards cleaner energy systems, complementing the ongoing use of fossil fuels with a sustainable and scalable alternative that aligns with global climate goals.

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- **Real-Time Position Determination:** Provides continuous monitoring with limited data transfer and storage capabilities, enhancing receiver position accuracy through averaging multiple RTK coordinates over time.

Impact on Geomonitoring in Oman

Happy Monitoring is set to revolutionize geomonitoring in Oman by providing a simplified, precise, and efficient solution. Its advanced RTK-GNSS technology and innovative algorithms ensure reliable monitoring across vast and challenging terrains, as well as critical building projects. This breakthrough will play a crucial role in maintaining the safety and stability of Oman's geological structures, offering an accessible and user-friendly way to monitor landscapes such as the Hajar Mountains and ensuring the integrity of both natural and artificial structures.

René Schnider, Founder of Happy Monitoring, emphasizes, "Happy Monitoring is designed to be user-friendly, eliminating the need for specialized knowledge and significantly reducing operational costs. Our aim is to provide real-time, reliable data to enhance efficiency and minimize human error."

Reducing reservoir uncertainty with palynology

M H Stephenson

Palynology is the study of fossil spores and pollen that are commonly found in sedimentary rocks and particularly in argillaceous rocks. Such studies may promote better understanding of the uncertainty caused by geological heterogeneity, specifically the size and arrangement of mudstone baffles which impede fluid flow in geological reservoirs, be they oil and gas, carbon dioxide or geothermal. This article describes how recent fieldwork in 2022 and 2023 on Jordanian Permian fluvial clastic sedimentary sequences has shown how different types of mudstone baffle, for example crevasse splays, channel fills or oxbow fills, can be identified by their palynological assemblages. This kind of analysis can help define the heterogeneity and natural fluid flow pathways in fluvial clastic sedimentary sequences elsewhere in the Middle East, for example the Unayzah Group in Saudi Arabia, and the Gharif Formation in Oman.

Heterogeneity in reservoirs

Geological reservoirs in clastic sedimentary rocks of fluvial or marine origin naturally contain heterogeneities which can impact the ability of those reservoirs to hold or transmit fluids, such as oil gas, carbon dioxide (in carbon capture and storage), and hot or warm water in geothermal. These heterogeneities can result from primary sedimentological and paleoenvironmental factors, from diagenesis, and from tectonic and structural change. Biostratigraphy and palynology that is traditionally done in the oil and gas industry all over the Middle East can help to identify and correlate suitable reservoirs, but recent research shows that palynology coupled with sedimentological analogue outcrop study can also offer insights and predictive tools to understand heterogeneity.

Analogue outcrop study combined with palynology is not a new thing for understanding reservoirs; oil and gas companies have consistently used outcrop models to better understand their subsurface assets. Perhaps the most interesting aspect for a stratigrapher is the role of the low permeability mudstone layers that can act as baffles to fluid flow.

The importance of palynology in understanding the geometry of mudstones is a newer discovery. Early indications of this usage came about through the study of Permian mixed mudstone/sandstone fluvial successions during three field campaigns in Jordan in 2013 and 2014. At that time, palynology was being done to support the description of some of the world-class fossil plant discoveries in the Upper Permian Umm Irna Formation, a succession similar to parts of the Gharif Formation of Oman, and the Unayzah Group of Saudi Arabia.

Fig. 1 the Upper Permian Umm Irna Formation occupies part of the upper part of the cliff shown (about 500 m high)

The Umm Irna Formation is 70 m thick and outcrops for approximately 40 km north to south along the Jordanian Dead Sea coast (Fig. 1). Detailed field sedimentology allowed the reconstruction of a model which indicated broadly the kinds of palaeoenvironment that might lead to argillaceous sediments being laid down amongst the high permeability channel sandstones that dominate much of the formation. These argillaceous sediments could be laid down as baffles to fluid flow in several different geometries and in lateral and vertical patterns, all of which contribute to permeability heterogeneity in the formation.

During a December 2022 field session, several mudstone units were sampled in great detail to understand not only the general palynological character of different kinds of mudstone baffle, but also how palynology might change within the baffles along their length and through their thickness. The mudstone units sampled fell into three categories:

- Laterally accreting channels with argillaceous point bar deposits
- Large abandoned channel fills
- Small abandoned channels or oxbow fills

These are shown in the context of the palaeoenvironmental model of the Umm Irna Formation postulated by Stephenson and Powell (2013) in Fig. 2.

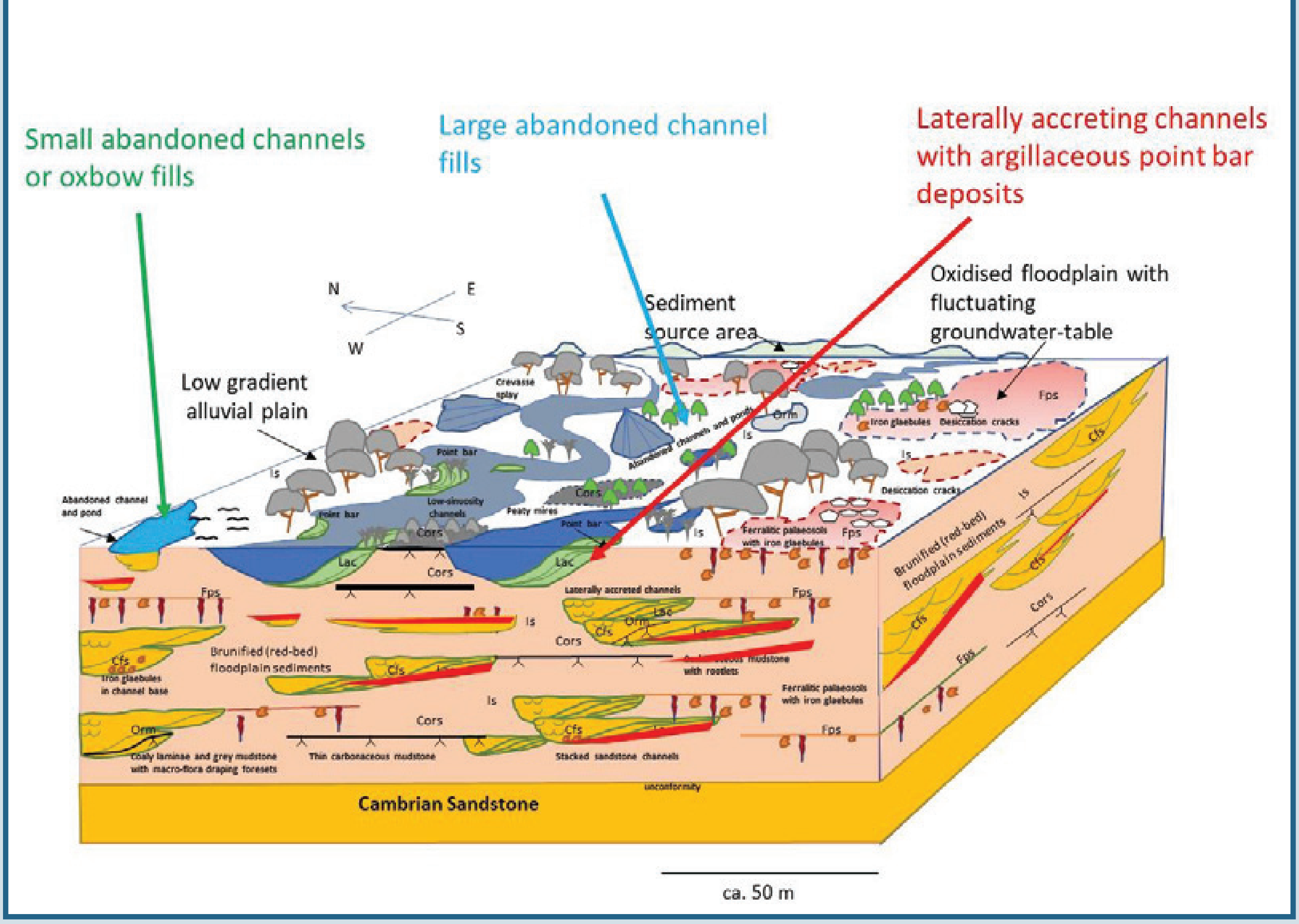

Fig. 2. Mudstone units sampled in this study: (1) Laterally accreting channels with argillaceous point bar deposits, (2) Large abandoned channel fills, and (3) Small abandoned channels or oxbow fills – all in the context of the palaeoenvironmental model of the Umm Irna Formation postulated by Stephenson and Powell (2013)

Preliminary results

The first thing to point out is that these are preliminary results from a small number of relatively well-defined mudstone units; a number of units are yet to be analysed. The units are at approximately the same level stratigraphically, and previous work on the formation (Stephenson and Powell 2013, 2014) suggests that palynological variability within the formation relates mainly to the position on the palaeo-flood plain, rather than evolutionary differences in this relatively short Changhsingian (latest Permian, Stephenson and Powell 2014) time interval.

Laterally accreting channels with argillaceous point bar deposits

A spectacular outcrop at the Dyke Plateau locality (see Stephenson and Powell, 2013; 31° 32' 6" N, 35° 33' 25" E) displays a very large channel (around 50 m wide) and the related point bar sediments (Fig. 3). The palaeocurrents and other characteristics of the channel and point bar are described in detail by Stephenson and Powell (2013). The point bar deposits contain a laterally continuous package of argillaceous sediments of various facies that are well known for plant fossils (e.g. Kerp et al. 2021); but also previous sampling (Stephenson and Powell 2013) indicated that the units yielded palynomorphs. Overall the mudstone package is around 70 cm thick on average, and has a lateral extent along the base of the cliff at Dyke Plateau of around 50 m. Fig. 3 (top) shows a tentative reconstruction of the original extent of the argillaceous point bar deposits, taking into account the geometry and size of the channel. Based on this reconstruction, a rough estimate as to the subsurface area of the unit disregarding modern erosion and exhumation would be at least 2500 m^2. This suggests a large baffle to fluid flow between and within relatively high permeability sediments.

In order to characterise the unit both laterally and vertically, it was sampled extensively in four sections, each section containing around 5-7 samples.

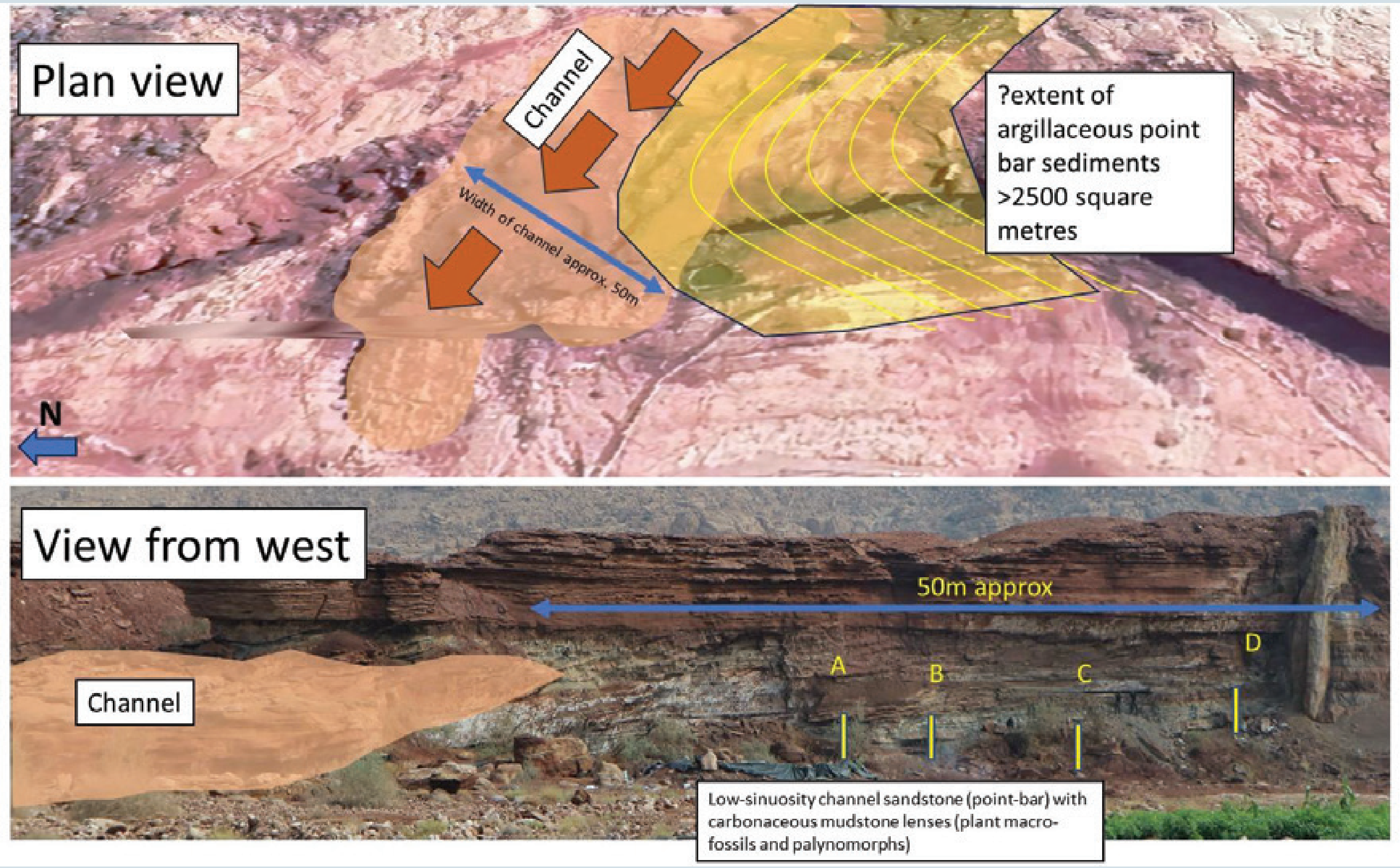

Fig. 3. Laterally accreting channel with argillaceous point bar deposits at Dyke Plateau. Upper diagram shows the plan view with a channel to the north, and a tentative reconstruction of the original extent of argillaceous point bar deposits. Lower diagram shows the view from the west with channel to the left and argillaceous point bar deposits in profile. Sections A to D were sampled for palynology (positions approximate).

The palynology of the four sections is remarkably consistent. All the assemblages contain the same dominant species, and these and their proportions tend to remain the same both up through the sections and across the sections. Preliminary statistical analysis bears out the internal consistency of the palynological assemblages from these point bar deposits. Fig. 4 illustrates the palynological composition and stratigraphic trends in one of the sections: Dyke Plateau section A.

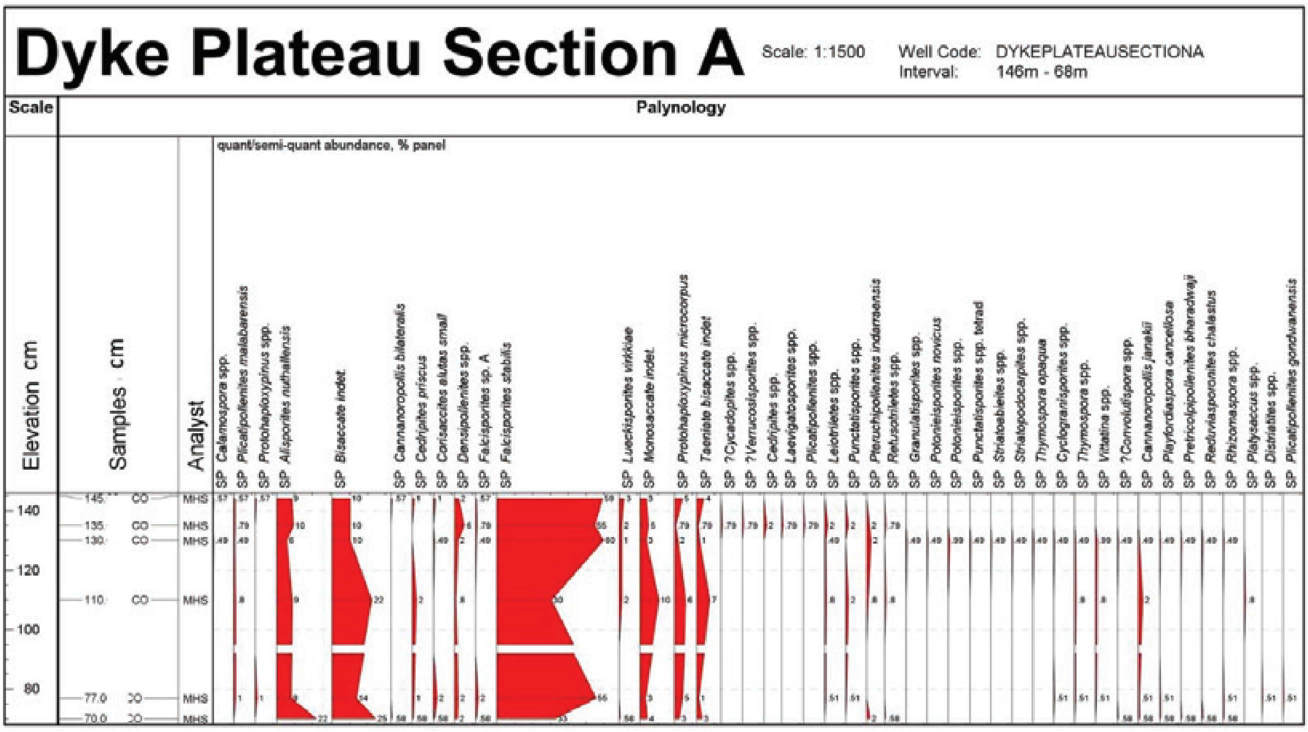

Fig. 4 Composition and stratigraphic trends in Dyke Plateau section A

Large abandoned channel fills

A large abandoned channel fill was sampled in eight sections from a trench related to a new roadcut along the main road from Amman to Aqaba (31° 32' 38" N, 35° 33' 27" E). The trench is shown in Fig. 5. The mudstone unit is around 70 cm thick on average and is exposed on the east and west sides of the trench. It also seems to appear in the main roadcut around 30 m to the west. This would again suggest a baffle of considerable subsurface areal extent, perhaps around 1000 m^2.

Fig. 5. Large abandoned channel fill exposed in a trench related to a new roadcut

The palynological assemblages in the samples are more internally heterogeneous than those of the Dyke Plateau point bar deposits, with more variation between samples and sections laterally and vertically, and more low-yielding or barren samples. Though overall the palynological samples have similar dominant species and similar proportions to the dominant species of those of Dyke Plateau, preliminary statistical analyses indicate that these assemblages overall are significantly different to those of Dyke Plateau.

Fig. 6. Channel fills in outcrops south of Dyke Plateau. Left upper channel fill; right several stacked channels with mudstone fills

Small abandoned channels or oxbow fills

Several small argillaceous units were sampled, including a locality south of Dyke Plateau (31° 31' 57" N, 35° 31' 26" E), consisting of thin and impersistent siltstones within stacked thin sandstone beds, and a locality at Wadi Autun (31° 32' 40.1" N, 35° 33' 31.7" E). Both localities display small argillaceous units that are probably minor channel fills.

Fig. 7. Left: locality south of Dyke Plateau of thin and impersistent siltstones within stacked thin sandstone beds; right Wadi Autun

Fewer samples could be taken from these units because the argillaceous beds were thinner and less laterally persistent suggesting potential subsurface extents of less than 20 m^2, and more likely around 10 m^2, so only minor baffles to fluid flow.

The palynological signatures of these units are very different to those of the large argillaceous units. They contain different dominant species, lower diversity, and considerable variability from one small argillaceous unit to another. For example, the locality south of Dyke Plateau contains common monolete spores and monosaccate pollen. The Wadi Autun locality contains common monolete spores bit also common trisulcate pollen. These spore/pollen groups – particularly monolete spores and trisulcate pollen - are rare in the larger argillaceous units. Statistical tests bear out the high level of difference both between small argillaceous units, and between small argillaceous units and larger units such as major channel fills and point bar deposits.

Preliminary conclusions

This work is in progress but so far it allows a few tentative conclusions.

The first is that larger baffles (2500 m^2 and larger) have diverse palynological assemblages with particular dominant species that tend to be relatively consistent across and through units. The second is that smaller baffles have lower palynological diversity and different dominant species to the larger baffles, but also different dominant species from one baffle to another. The preliminary statistical analysis appears to bear out these differences.

Although this work is incomplete, these early findings suggest that detailed palynological work in core could be used, alongside pressure data and seismic, to contribute to understanding of subsurface reservoir heterogeneity and 'plumbing'. The reasons for palynological variations across the floodplain need to be investigated, but probably represent different abilities of parts of the floodplain to represent the hinterland and local floodplain floral communities.

The use of statistics on the palynological assemblages will allow a more objective, reproducible way of analysing the palynology of mudstone units, rather than relying on purely human observation and interpretation. It may allow, in the long term, libraries of palynological-mudstone unit types defined statistically to be built up, and perhaps extended beyond fluvial to marine successions. Techniques of this kind could be particularly useful in the Permian fluvial successions of the Gharif Formation in Oman and the Unayzah Group in Saudi Arabia, for understanding well established fields where sandstone architecture needs to be understood for well planning, though good core material would be needed and good well coverage. It is likely that the heterogeneity of sandstone reservoirs will be a pertinent subject well into the next few decades with the advent of different uses for sandstone reservoirs including for carbon dioxide storage in carbon capture and storage, for hydrogen storage, and in low temperature geothermal.

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About
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Mike Stephenson is an independent palynologist and stratigrapher specialising in the Palaeozoic of the Middle East.

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Roadside geology of Oman Article 2: Nizwa-Ibri Road

Author: Al Muathir Al Kindi

As a continuation of the roadside geology of Oman theme, this article highlights and documents key geological formations and exposures observed alongside the Nizwa-Al Buraimi road. This strategic route links interior governorates and provinces, and also gives access to several important petroleum fields.

Geographic Background:

The Nizwa-Ibri road spans about 135 km, from Nizwa in Dakhiliya (interior) governorate, past the southwestern piedmonts of Jebel Akhdar and the town of Bahla and towards the town of Ibri at the center of Ad'Dhahirah Governorate (Figure 1 inset). The route follows a roughly arcuate southeast to northwest orientation that is largely parallel to the axis of the western Hajar mountain range. The route largely utilizes the alluvial topographic gaps and plains, resulting in an overall low elevation relief (Figure 2).

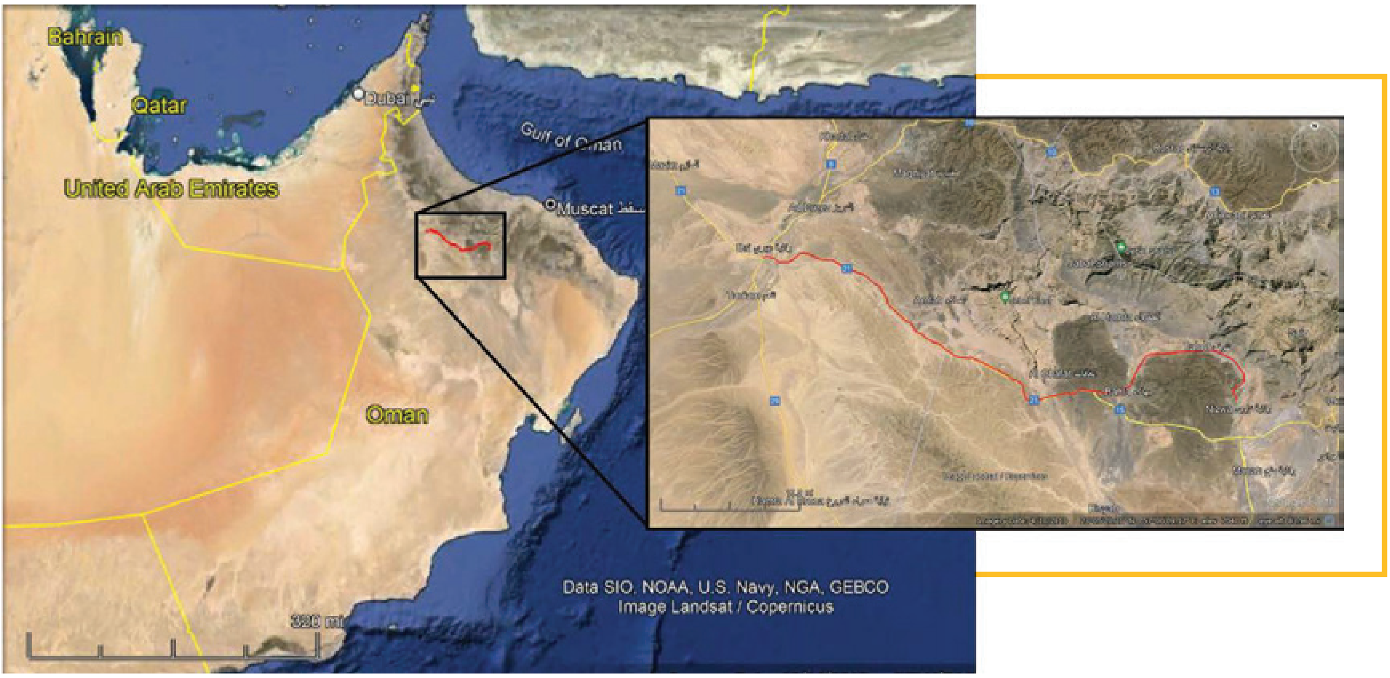

Figure 1: Satellite image showing the extent of the Nizwa-Ibri road (marked in red colour)

Figure 2: Elevation profile of the route (SE left side and NW right side)

Geological Map Overview:

When plotted on geological maps (Figures 3 and 4), the eastern end of the route is shown to start in the alluvial plains that are upon the inferred contact between the Oman ophiolite and the piedmont of Jebel Akhdar dome (autochthonous Hajar supergroup). Heading westward, the route passes by allochthonous units such as the Bahla ophiolite nappe and Hawasina allochthonous sedimentary nappes, and eventually encounters post-obduction Cenozoic carbonates near Ibri.

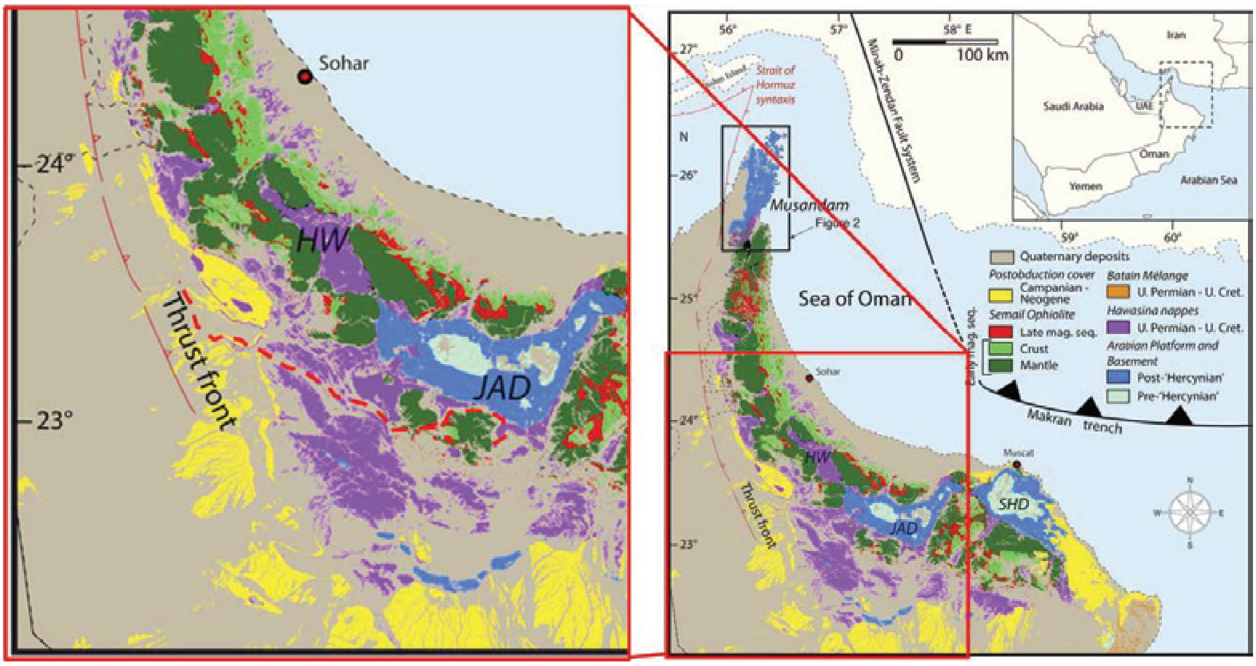

Figure 3 Geological map of Oman showing the route of interest (red dashed line) alongside major components of the Hajar mountains, HW: Hawasina Window, JAD: Jabal Akhdar Dome, SHD: Saih Hatat Dome. Carminati et al. 2020

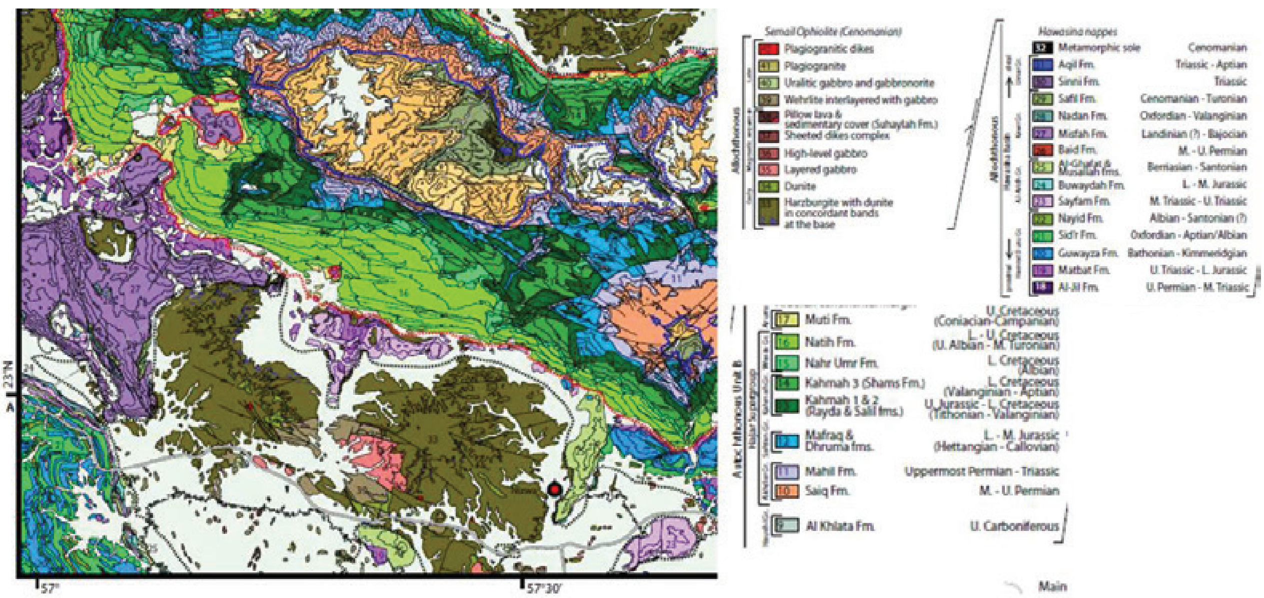

Figure 4: Detailed geological map covering a section of the route across Nizwa and Bahla provinces. (Scharf et al, 2021

Jebel Akhdar Piedmont Alluvial Plains:

Setting off along the route from Nizwa, the northern outskirts of town are located on the fringes of an alluvial plain that extends northwest towards the town of Tanuf, which is well-known for its remarkable geo-heritage sites and also for being adjacent to the mouth of a significant canyon that descends from Jebel Akhdar's peaks high above at an elevation of ~2400 m. The road runs parallel to the orientation of this plain over recent alluvial gravels and follows a gap between the greyish Jebel Akhdar piedmont and adjacent exotic allochthonous carbonate nappes on one side (looking N/NE) and dark brown ophiolite nappes on the other side (looking S/SW).

This section of the route has a similar topographic setting to the Samail gap that was reviewed in a recent previous article on Oman roadside geology. With a roughly perpendicular strike orientation to the Samail gap, this gap to the west of Nizwa similarly runs along an elongated alluvial plain between the inclined piedmonts of Jebel Akhdar dome and the crystalline igneous rocks of the ophiolite nappes that outcrop as relatively less elevated mountains.

The piedmont of Jebel Akhdar has a towering look on this section of the route (Image 1), having a W-NW strike and a S/SE dip. The successive sedimentary cretaceous carbonate layers are clearly visible within the piedmont due to the gorges that erode through it. These layers include the Albian age Natih, Aptian age Shuaiba and older consecutive limestone-dominated formations. They have a topographic signature of resistant cliffs and dipping piedmonts, and include interbeds of shale-dominated formations such as Nahr Umr that are less resistant to erosion and form gentler slopes in between the soaring cliffs. There are also beige-colored allochthonous sedimentary mountains adjacent to the piedmonts and foothills, with the thrust contact between the in-situ platform sedimentary units and exotic sedimentary units visible.

The wadis in this area primarily cascade with high relief southward from the Jebel Akhdar piedmont, while some wadis drain northeast from the ophiolite nappe. A plain is formed where these drainages merge (known locally as Al-Abliya) which contains an aquifer within the alluvial gravel that unconformably overlies ophiolite bedrock and receives an artesian baseflow from the surrounding mountains. This aquifer is a key water supply component of the Nizwa oasis, since it is the source aquifer of the Falaj Daris aqueduct (UNESCO site).

Image 1: Image showing a face of the Jebel Akhdar piedmont near Al-Medaifi, Nizwa. Noting greyish-coloured Jebel Akhdar piedmont and beige-coloured exotic mountains, and alluvial cover in front

Bahla Ophiolite Block

From a roadcut in the ophiolite near Tanuf, the route runs westward through the elongated alluvial plain bounded by ophiolite nappes to the south and exotic mounts to the north. The gravel here has a brownish colour due to the dominance of alluvial input from erosion of the ophiolite blocks. There exists here a drainage divide as evidenced by some distributaries within the alluvial fan that head northeast to conjoin wadis of Tanuf towards Nizwa and into the wadi system that eventually terminates in in the Arabian sea, while other distributaries head westward into Wadi Bahla and eventually reaches the landlocked Sabkha (evaporite lake) of Umm-As-Samim close to Rub' Al Khali desert.

The town of Bahla is remarkable for a magnificent UNESCO world-heritage-site fort that can be seen along the route through the town center (Image 2). The fort was strategically built atop an ophiolite hill in the center of the historical town and overlooks the whole oasis. This agricultural oasis is situated on alluvial muds and clays deposited by wadis that come from as high as the Jebel Shams peak (3009 m) and also from the weathering of the nearby ophiolite to the east and west. Those clays also facilitate the popular pottery industry known in Bahla.

Image 2:Photograph of Bahla fort on top of an ophiolite hill composed of Wehrlite interlayered with gabbro outcropping at the roadside.

Images (3a and 3b), showing hills of peridotite (upper image 3a, north of roadside) and Gabbro (lower image 3b, south of roadside) west of the dual highway intersection to the SW of Bahla.

Beyond the southwestern outskirts of Bahla, the road follows the edge of the western portion of the Bahla ophiolite Nappe. In this area, a section of the road close to the intersection with the dual highway runs through alluvium that has the Moho boundary inferred in the bedrock underneath, as peridotites (mantle rocks) can be seen to the north of the road while gabbros (crustal rocks) are seen on the southern side (Images 3a and 3b).

Jebel Kawr Exotics

There are several exotic mounts seen along the route. Jebel Kawr (Image 4) is considered the most prominent of the allochthonous component of the Oman mountains, with peaks reaching as high as 2730 m above sea level, and its steep piedmonts making the highly elevated portions inaccessible by automobile. The naming of the mountain is derived from its structural appearance, as Kawr is translated to roundness in context of rounded turbans worn by notable characters.

The lithology of Jebel Kawr is mainly composed of a relic of an isolated Late Triassic platform from the Hawasina Ocean, a part of the Neo-Tethys (Bernecker, 2007). Such isolated carbonate platforms were situated in an island arc, which later got emplaced via the collision and obduction processes onto the passive margin of the Arabian continental plate. Relics of that arc are present as a series of exotic paleo-seamount carbonate ridges found in a number of mountains that intermittently appear along a notable section of the Hajar mountains range axis.

Image 4: Southern tip of Jebel Kawr, observed from highway near Muaylif, Bahla

Hamrat Duru Exotics

After the Nizwa-Ibri route crosses the braided stream of Wadi Al-A'la, which drains the eastern portion of Jebel Kawr and heads southward to converge with Wadi Bahla, the route crosses the inferred thrust fault between the exotic sedimentary groups; Kawr group and Hamrat Duru group (Images 5 and 6).

In an orientation largely parallel to the thrust front orientation, the route follows an elongated wadi stream path between the sedimentary units that are repetitive in a NE-SW cross-section view due to thrust emplacement and overriding. This section represents the northeastern fringes of the type-locality of the Hamrat Duru nappe, which is a significant component of the Hawasina deep-marine allochthonous nappes, and extends as a zone of rolling hills over 2000 km^2 to the edges of the desert plains.

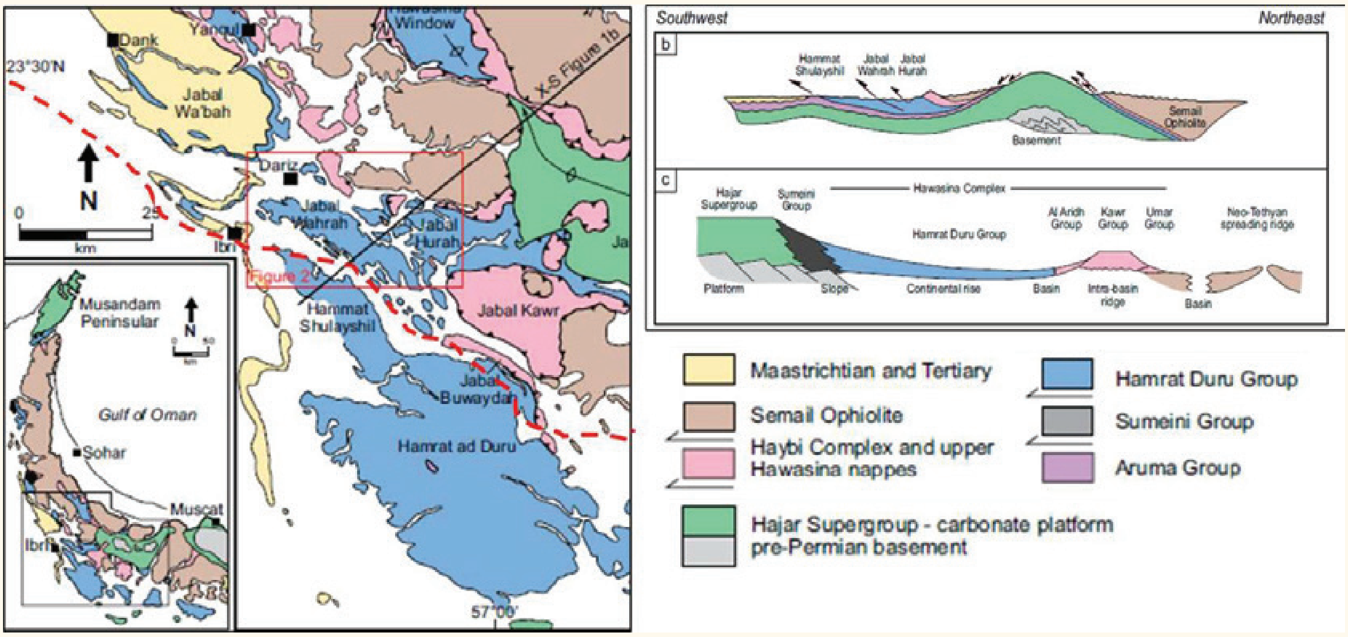

Figure 5: Geological map focused on the Hawasina complex, Bahla-Ibri section of route (cooper, 2011)

Image 5: outcrop near Najd Al-Musalla, Bahla, showing exposure of the Hamrat Duru Group (Nayid/Sidr/Guwayza formations), with structural deformation due to the thrust

Image 6: Outcrop immediately westward of the outcrop in image 5, showing inclined strata from Hamrat Duru group (Nayid/Sidr/Guwayza formations) dipping northward (relative to the thrust sheet termination).

Beyond this topographic corridor between the Hamrat Duru group hills, the route follows a thin alluvial plain overlooked by an allochthonous carbonate ridge known as Jebel Al-Haddah (translated to sharp mountain), an elongated ridge with sharp tips (Images 7 and 8), lithologically belonging to Al-Aridh group (a component of Hawasina complex)

Image 7: Panoramic view of the eastern Jebel Haddah ridge near Al Buwaydah, Ibri, and the alluvial plain upon an inferred thrust contact with the Hamrat Duru-group hills in the background.

Image 8: A view of the western end of the Jebel Haddah ridge near Al Buwaydah, Ibri behind rolling hills of the Hamrat Duru group. Jebel Kawr's western piedmont appears distantly on the left side of the image.

As the route passes by the village of Kubarah and proceeds to the northwest, it passes in between two nappes of the Hamrat Duru Hawasina thrust sheets represented by Jebel Wahrah to the northwest and Jebel Hammat Shilayshil towards the southwest (Images 9 and 10). The road runs parallel to the course of Wadi Al-Ain, one of the major wadis descending into the town of Ibri.

Image 9: Outcrop near Kubarah, Ibri. Inclined strata with thin bedding and lithological variation indicated by color contrasts.

Image 10 Panoramic view of Jebel Wahrah rolling hills near Luqaya', Ibri. showing strata belt repetitions due to thrust contacts of the Hamrat Duru group formations

Ibri Carbonates:

As the route approaches the outskirts of Ibri from the southeast, one of the well-known natural landmarks indicating arrival to the town is the Sulayf dune (Image 11). This is an aeolian sand dune settled on the side of a carbonate mountain that bounds the Ibri oasis on the east. The dune sand is likely derived from alluvial deposits coming from wadis eastward and erosion of relatively unconsolidated Hawasina exposures.

Image 11: Sand dune of Sulaif, Ibri, leaning upon a carbonate cliff (left side).

Finally, the route crosses the Eocene carbonate ridge that outcrops just prior to entering Ibri. The town of Ibri is the municipal seat for Al-Dhahira governorate and Wilayat Ibri. The vast geological variation surrounding Ibri and the town's strategic location at an important crossroads make it an area that would be worth elaboration in upcoming Oman roadside geology articles.

Overall, remarkable geologic exposures are seen all along the Nizwa-Ibri road. Geology students and enthusiasts alike will appreciate traveling this route parallel to the southwestern fringe of the Hajar mountains range axis while experiencing views of the Hajar supergroup, obducted ophiolites and associated extensive allochthonous sedimentary units, before terminating at the post-obduction Eocene carbonates near Ibri.

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SQU team wins the first place in IBA2024

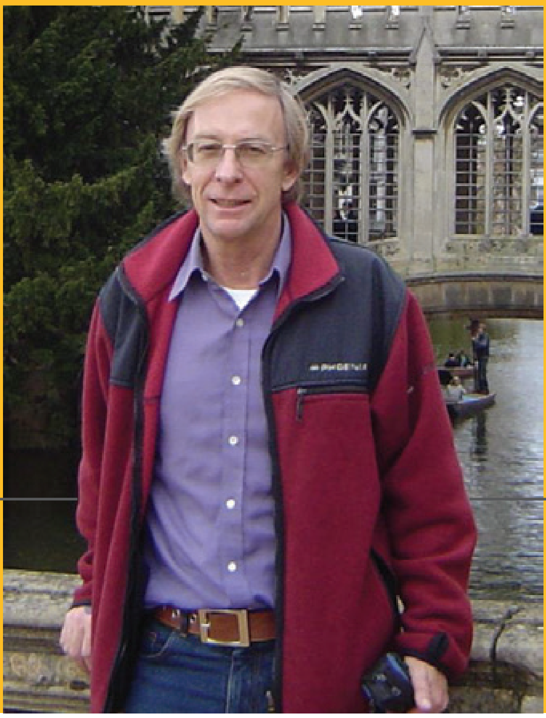
A team of five students from Sultan Qaboos University Earth Sciences Department has secured the first places in the Imperial Barrel Award (IBA) competition of the American Association of Petroleum Geologists (AAPG). The IBA is a competition where students work on real geophysical data (seismic, wells, etc.) and geological data (tectonic, stratigraphy, geochemistry, etc.) to explore for opportunities and potential accumulations of hydrocarbons. They use latest software programs and technologies adopted in oil industry. The students every year work on new field from different world basins. The wining team over the Middle East region will represent the region in the final world competition and compete against top world universities in the field of Geoscience. At the Middle East level, universities participated from Oman (SQU and GUTech), Kingdom of Saudi Arabia (King Abdullah University, King Abdul Aziz University), and from Irak (Tikrit University). The SQU team comprises students Hiba Al-Saqry, Juawiria Al Abri, Maather Al-Owaisi, Abdullah Al-Mayahi and Salim Al-Rawas. The team was mentored and supervised by Dr. Mohammed Farfour, Associate Professor of Geophysics from the department of Earth Sciences.

The team worked on a data from a field from the Gulf of Mexico. The area and the data were full of geophysical, geological and technical challenges. The students overcome all the challenges and found 10s of potential zones that can be considered for drilling by oil and gas companies.

Interview with Professor

Mike Searle

— a Geoscientist Pioneer —



- *Please tell us about yourself*

My father worked for PDO from 1968-1979 so I first went to Oman as a schoolboy. My mother worked in the Mission Hospital in Muttrah with Don and Elouise Bosch. I went out on school holidays and loved the country. I did my PhD at the Open University in the UK working on the Oman ophiolite metamorphic sole (1977-1980). I then carried out field mapping consulting work for Amoco in the UAE and Musandam (1981-1986). From 1990 onwards I worked in Oman every winter as a post-doctoral fellow from 1981-2006 and then as a Lecturer at Oxford University), often with PhD students, then a Full Professor from 2008 until I retired in 2022. . We worked mainly in the Saih Hatat area (As Sifah, Wadi Mayh, Wadi Aday, etc). For the last three years, I have been working with Bruce Levell and Henk Droste (both ex-PDO) on the Jebel Akhdar - Jebel Nakhl area. I proposed 50 GeoPark sites and 3 World Heritage sites (for UNESCO) including (1) the Wadi Jizzi ophiolite, (2) the Jebel Shams - Wadi Nakhr Grand Canyon, and (3) the Musandam peninsula. I wrote a book "Geology of the Oman-UAE Mountains, Eastern Arabia" which was published by Springer. I became Professor of Earth Sciences at Oxford University and retired in 2022.

- How do you believe your work in geology impacts society?

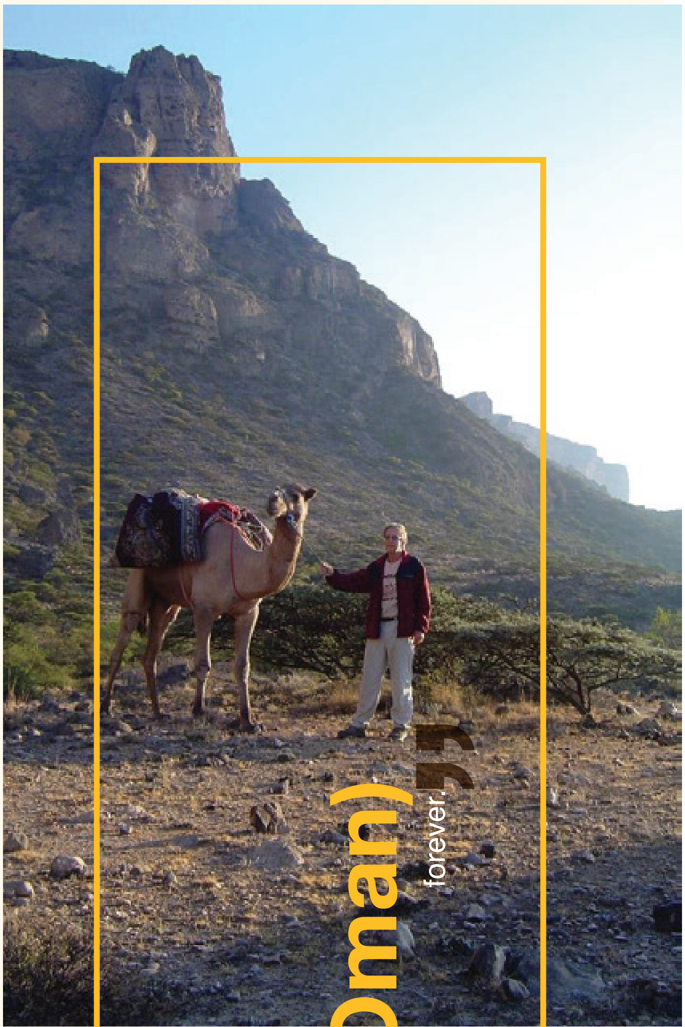
Indirectly, because my main aim is to understand geological processes (how are mountains made, etc) so it is both academic and practical. The most direct impact to society is my efforts trying to preserve our natural heritage (GeoParks in Oman) forever.

- What do you consider the most exciting aspect of geology?

Field mapping and figuring out the large-scale structure of mountain belts like those in Oman, the Himalayas and the Karakoram mountains in Pakistan.

- Concerning your work on the Oman ophiolites, what continued research work do you consider to be important or that you would want to continue?

There is still a lot of academic work still to do on Oman geology, particularly using new techniques of U/Th-Pb geochronology, thermobarometry (pressure-temperature-time modelling). Much of Oman-UAE mountains has been mapped in detailed but the interpretation of geological structures remains controversial. Tectonic models must use data from all branches of the geological science: structural mapping, strain, geophysics (seismic, gravity, magnetics, etc), geochemistry and isotope chemistry, thermobarometry, geochronology, etc.



"the most direct impact to society is my efforts trying to preserve our natural heritage **(GeoParks in Oman)** forever."

- How do you continue to develop your skills and knowledge in geology?

Every time I go into the field, I find something new and exciting. Also learning from others, reading new papers etc.

- If you could go back and give your younger self one piece of advice about a career in geology, what would it be?

I have been extremely lucky in that my branch of the science (field-based structural geology) was well funded when I was a student and Post-doc. I do not regret any decisions I made in my career. It is far more difficult nowadays; university courses in Earth Sciences are very different now from when I was a student, I mean that students now have to have top A-grades in Maths, Physics and Chemistry to get in to Oxford. The course now involves far more computing and is far wider in scope than when I was a student, for example including computer modelling, climate research, oceanographic modelling, etc.

Under The Microscope!

The sample below was taking from strike-slip fault in Barzaman Formation which shows sepiolite under microscope and SEM. The sepiolite has the chemical formula of $Mg_8 (Si_{12} O_{30} (OH)_4 (H_2O)_{3.92}) (H_2O)_{7.72}$ and can be recognized by its fibrous texture and brownish color under the microscope (Fig. 1). In order to precipitate this mineral, a fluid that rich in Mg and Si is needed. Semail Ophiolite is a primary source for these elements. The presence of sepiolite indicates that the fluid form in arid climate and characterized by high PH and salinity

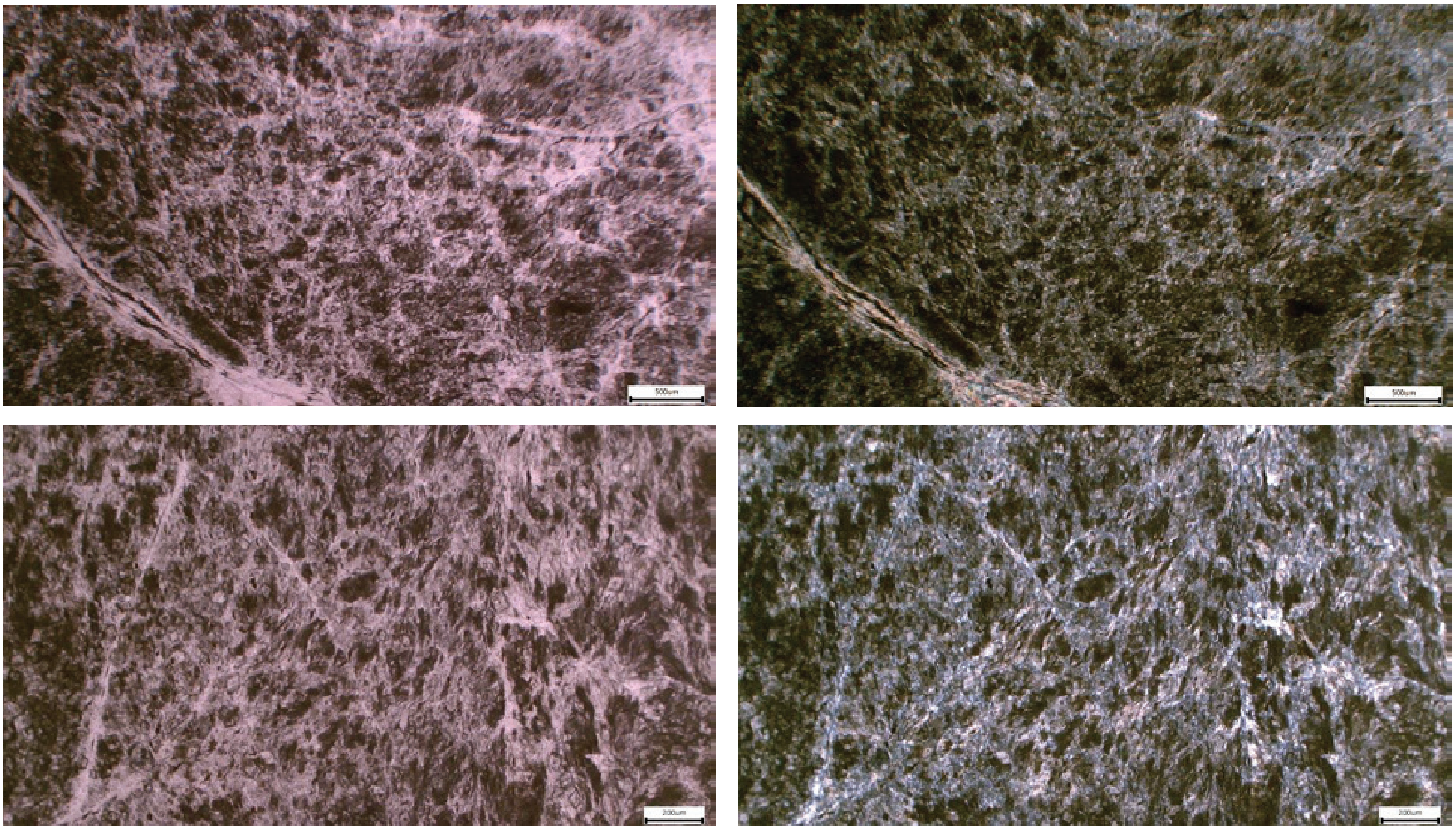


Image 6: Outcrop immediately westward of the outcrop in image 5, showing inclined strata from Hamrat Duru group (Nayid/Sidr/Guwayza formations) dipping northward (relative to the thrust sheet termination).

SEM analysis shows the fibrous nature of sepiolite which has needle -like structure (Fig. 2)

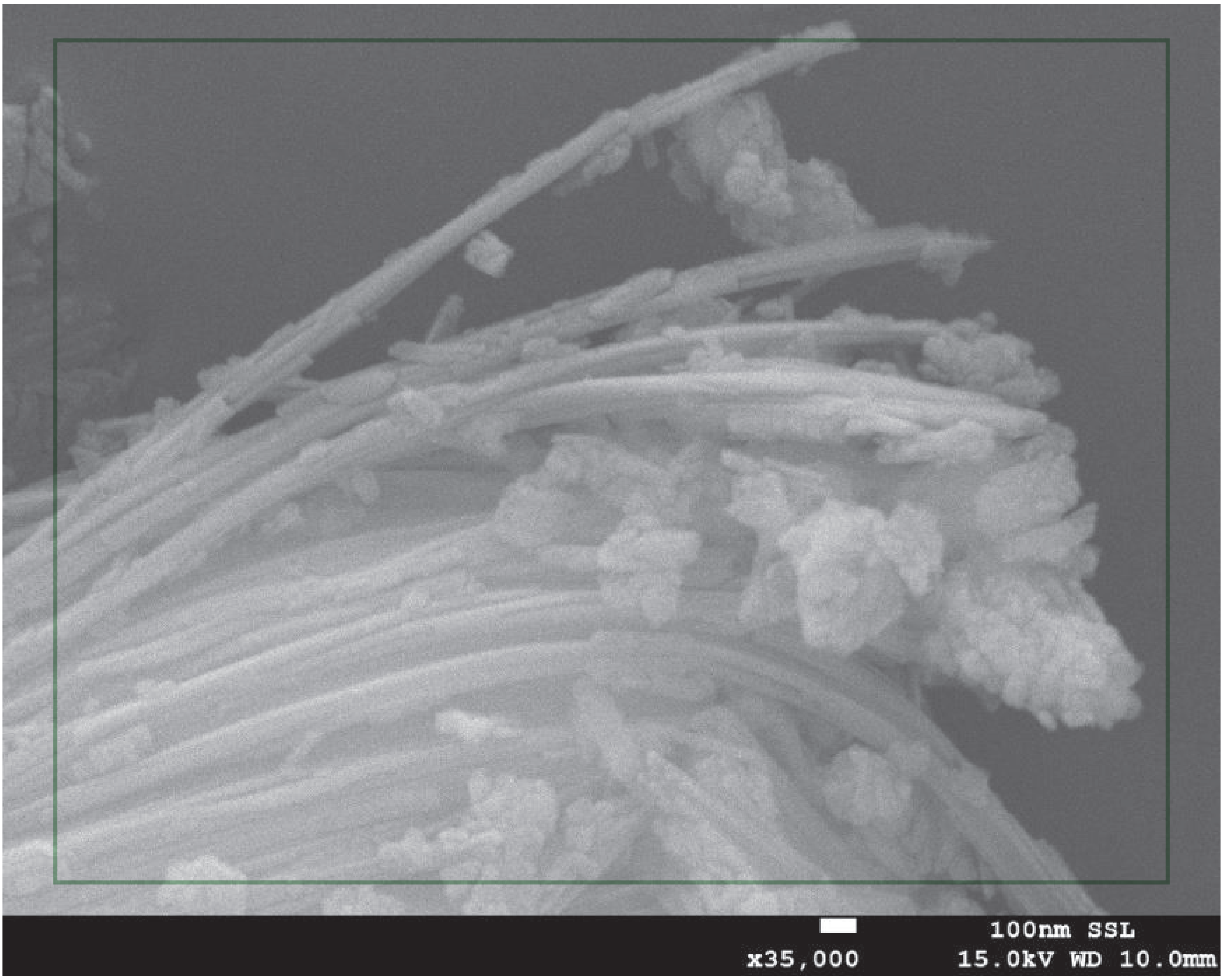


Figure 2. Fibrous texture of sepiolite.

Under The Microscope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