



33RD EDITION

ALHAJAR

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Speech**

**Oil Seepage Near the
Coast Behind Nafun
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**Ancient Copper Mining
Shafts and Refineries at Wadi Susah
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ABOUT GSO



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

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Dear readers,

It gives me great pleasure to welcome you again to a new issue of Al Hajar Magazine. It is from this platform that the Geological Society of Oman strives to consistently provide you with a variety of valuable geological information, news and stories. As a new committee that just complete our first year of service, we have worked hard to continue in this distinguished intellectual tradition. It has not been easy due to the challenges and complications caused by the Covid-19 crisis, but now that restrictions are lifting, we look forward to providing an even higher level of services to our membership and to accomplishing and achieving more in the year to come.

We are grateful to the authors who have contributed to this issue. Alan Heward presents an interesting story of the history and facts concerning what could be an active petroleum system near Nafun Island in Duqm – are there really oil seepages in that area? Al-muathir Al Kindi gives an account of a recent visit to Wadi Susah, near the states of Nizwa and Bahla, where he observed ample evidence of ancient copper mining and refining activity in that area. And we also thank Professor Abdullah Al-Amri, from the Saudi Society of Geosciences, for his contribution of an article on the Seismicity of the Arabian Peninsula, which gives an excellent summary of the historical and geological context for seismic events occurring around the Arabian Plate.

We wish you an exciting and enjoyable read of this issue. Please feel free to provide feedback and ideas for future articles and papers. We welcome your participation and communication as we are all part of GSO.

Thank you!

My Regards,
Yousuf Al Darai
Al Hajar Magazine Editor

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THE GSO PRESIDENT'S SPEECH

On completion of our first year
as the new committee of the
Geological Society of Oman



Distinguished Members of the Omani Geological Society

Assalamu Alaikum,

After Greetings,

Despite the challenges and difficulties faced by the Geological Society of Oman due to the Covid-19 pandemic and the consequent changes and precautionary measures to limit the virus spread, the Geological Society of Oman was able to conduct many successful events and activities that were managed by the administration and its affiliate members in a dedicated and innovative manner. These events and activities were scientifically diverse in their geological content to suit and target a wide range of scientific segments of the affiliate members and those interested in earth sciences. The topics were related to the oil and gas and mining sectors, as well as sustainability, geo-tourism and exploration.

In addition, the Geological Society of Oman launched a new logo as part of its celebration of the 20th anniversary of its establishment. This proud celebration marks the continuous efforts that GSO has invested in educating Omani society about their geological heritage, developing GSO members, conducting research and publishing various geological reports.

The commemoration also included the inauguration of the society's updated vision and a presentation of the strategy that aligns our vision with Oman's 2040 vision and also with the United Nations sustainable development plan for 2030.

The members of the Geological Society of Oman have organized many administrative workshops to search for best practices to ensure the continuity and sustainability of the Geological Society. The discussions in these workshops focused on how to keep and revitalize the affiliated members of the Society in the coming years and encourage new members to join. It also discussed how to diversify the society's sources of income for financial sustainability, develop a geological database, and draw clear mechanisms that will help motivate members to submit scientific publications and encourage them to contribute to the society's various programs. In addition, the Geological Society of Oman has created several opportunities for job-seekers and students to participate in its various forums, such as creating the geological content for awareness exhibitions and organizing the activities of the society. Students and job-seekers also are provided with training opportunities, by experienced GSO members, to help refine their talents and leadership and research skills that will help guide them in finding future careers.

This annual report includes more information about the events and activities organized by the Geological Society of Oman during the past year, along with the financial budget and the statistics of its members. All of these achievements would not have been possible without the efforts of the members of the Board of Directors, members of the Executive Committee, the active members, and the assistance provided by the various parties and the supporting bodies, for whom we extend our appreciation and sincere gratitude.

In conclusion dear members, we extend our invitation for you to renew your annual membership and to also encourage your earth science acquaintances to join the Geological Society of Oman. We also welcome opinions and suggestions that contribute to the society and that help us achieve our vision, which is to be the premier platform for the advancement of earth sciences in the Sultanate of Oman.

*With my regards and respect,
Husam bin Salem bin Hammoud Al-Rawahi
President of Geological Society of Omani*



WAS THERE, IS THERE, An Oil Seepage Near the Coast Behind Nafun Island?

Alan Heward
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Malvern, U.K.

Nafun may conjure up all sorts of ideas in one's mind; the name of a distinctive coastal feature (Figure 1), a small fishing village, busier since the transformation of Duqm, a geological subdivision of the Huqf Supergroup, one end of the Nafun-Haushi-Maradi Fault Zone, but probably not the location of an oil seep. Oil seepages in Oman are relatively rare for several reasons, one being that the water table onshore is often below ground level and so seepages, if they are present, are not obvious (Figure 2). This article brings together several strands of evidence which suggest there may have been, or may be, an oil seepage near Nafun.

There were repeated communications in the 1920s between officials in the Gulf and the Anglo-Persian Oil Company in London about the prospects for oil in Oman and evidence for this from oil seepages.

October 1922- *'I have now learnt privately from the Political Resident whom I visited ... that black crude oil is reported to be oozing from the ground in the neighbourhood of Masirah Bay in the Sultan's territory, close to the coast. The report was confirmed by a man specially sent by the Sultan, who added that the people of the neighbourhood wished to keep it a secret as they did not wish to be interfered with.'*²

March 1924- *'It would be of interest to us to receive samples of the oil obtained from the Maseira seepages, but this may be difficult to arrange.'*



Figure 1. Hamar an Nafur (Nafun Island) a prominent sea stack of Oligo-Miocene marine limestones, Al Wusta.

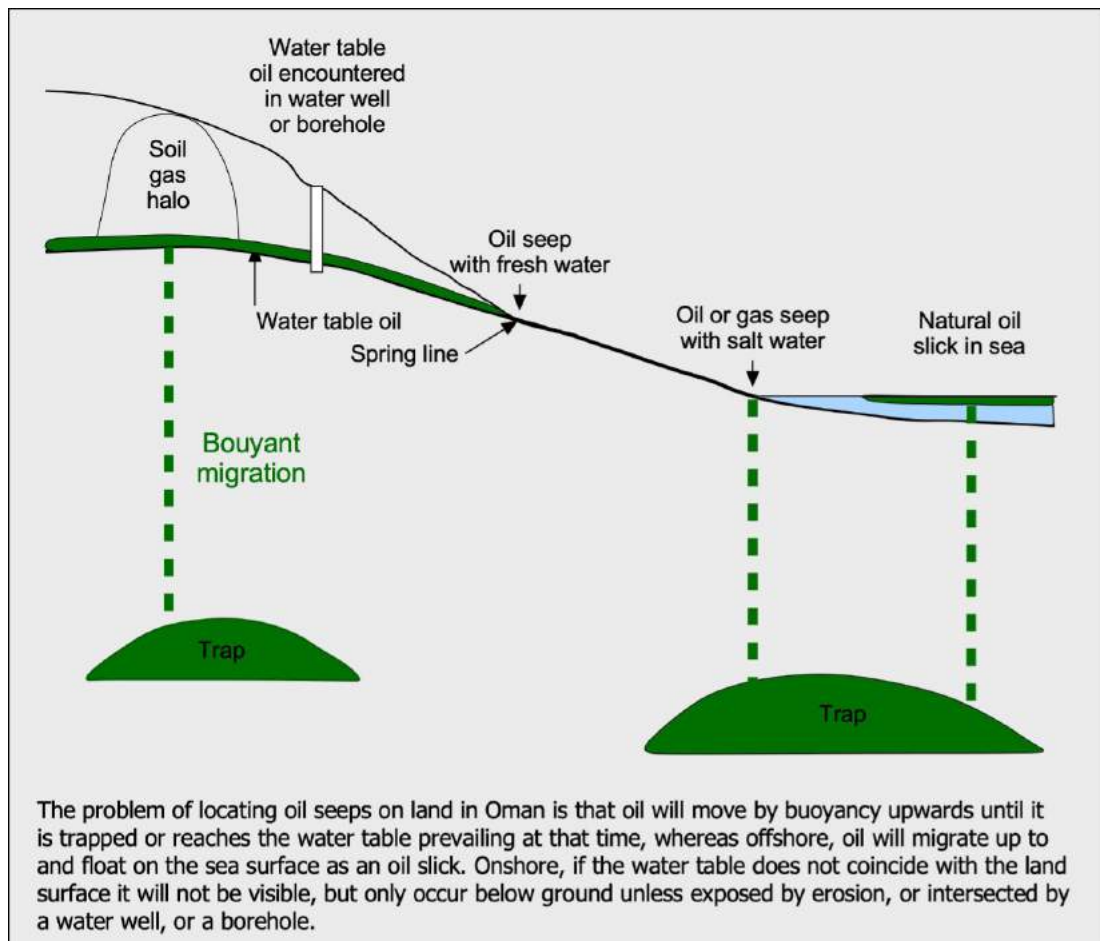


Figure 2. Oil seepages, adapted from Clarke and Cleverly (1991, GSL SP59, 265-71). For examples of Oman's seepages see Al Kindi et al. (2022).¹ Migration need not necessarily be vertical but along permeable carrier beds.

October 1924- *'The oil seepages have been reported at various times as being near the coast behind Ras Markaz and inland from the coast opposite the island of Hamar al Nafar, but in the last talk I had on the subject with His Highness [Sultan Taimur bin Feisal], he said he believed the main show to be south west of Wadi Khalbuh, which runs from near Nizwah ... to Mahot on the Gulf of Masireh. Questioned as to how far inland this show was, he became vague ... but he did not think it was very far from the sea.'*³

June 1925- *'There are only three places in which there is any mention of the existence of oil. One is in Masirah Bay behind the island of Hamar an Nafur. I have not been able to discover anyone who has actually seen the so-called seepages but many people are very definite that it is oil which comes out there and are prepared to say what it is like and where it is. On the other hand the Senior Naval Officer (SNO) Persian Gulf landed near there a short time ago and says that as far as he could make out from the people there it sounded as though it was only a sulphur spring. This may however be only an artifice to keep outsiders away ... The place pointed out to the SNO as the place where the seepage is located is in a low hill about 5 miles inland.'*²

Based on these reports and Anglo-Persian wanting a first look at the prospects of Oman before any competitor did, the Company agreed an Exploration Concession with Sultan Taimur bin Feisel in May 1925. G.M. Lees and K. Washington Gray undertook a 5-month geological field survey in the winter of that year. Lees duly visited Nafun on 27th January 1926, when travelling by ship (HMS Triad) back up the coast from Dhofar to the Muscat area.

Lees and Washington Gray 1926- *'When the location was visited the natives proved sullenly hostile ... No information could be extracted from them, not even the names of topographic features. They professed complete ignorance of any oil seepage or bitumen deposit... It is possible there may be a seepage – perhaps some thick bitumen oozing out – perhaps usually obscured by blown sand.'*⁴

Lees 1928- *'Owing to lack of time and the unfriendly attitude of the local tribesmen, I was not able to penetrate further westwards...'*

Bertram Thomas 1929- *'Here lay the plain opposite the island of Hamar Nafur, where oil seepages had once been reported, and where I recalled that two years before a geological party had landed and was greeted by a hail of stones.'*

This reception, by 150 Jenebi tribesmen, was almost certainly 'staged' by Sheikh Mansur in the hope of obtaining a further payment for access further inland and his own oil concession.

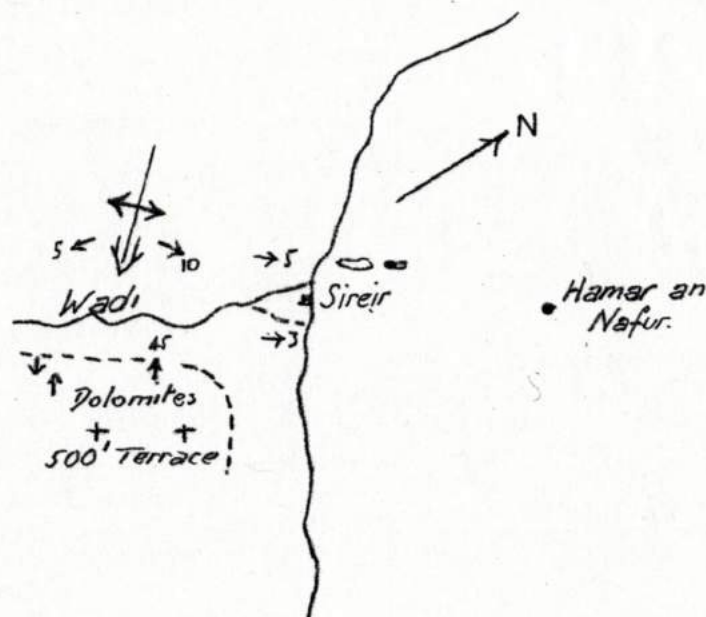
The Iraq Petroleum Company established a camp and logistical base at Duqm in February 1954, with the Sultan's Muscat and Oman Field Force camped at Nafun, near the brackish water well. IPC geologists progressively explored and mapped the Huqf, discovering the Haushi oil seepage in January 1956, and reporting a 'possible' bitumen impregnation near Akaba Woolley in November 1958 that was never confirmed.⁵ No mention was even made of an oil seepage near Nafun, or in the shallow waters of Masirah Bay where some staff enjoyed fishing in their leisure time.⁶

The Huqf was part of PDO's concession until 1969, whereas offshore Masirah Bay was one of the first two offshore oil licenses, awarded by Sultan Said bin Taimur to Wendell Phillips in 1965 (Al Hajar 32nd issue December 2021). That concession was explored by Sun Oil in the 1970s and Amoco in the 1980s. Shows of oil were encountered in Nafun dolomites, Abu Mahara clastics and in the Shuaiba carbonates in the three wells drilled. ⁷ Amoco also sponsored extensive fieldwork in the Huqf, the Oman Mountains, and the Batain in the 1980s. ⁸

One of the researchers who carried out work on the Huqf was Paul Wright, an eminent carbonate sedimentologist. In 2010, I exchanged emails with Paul over a photomicrograph of an ooidal Huqf dolomite which he had included in a textbook and that showed a pore fill of dead oil.

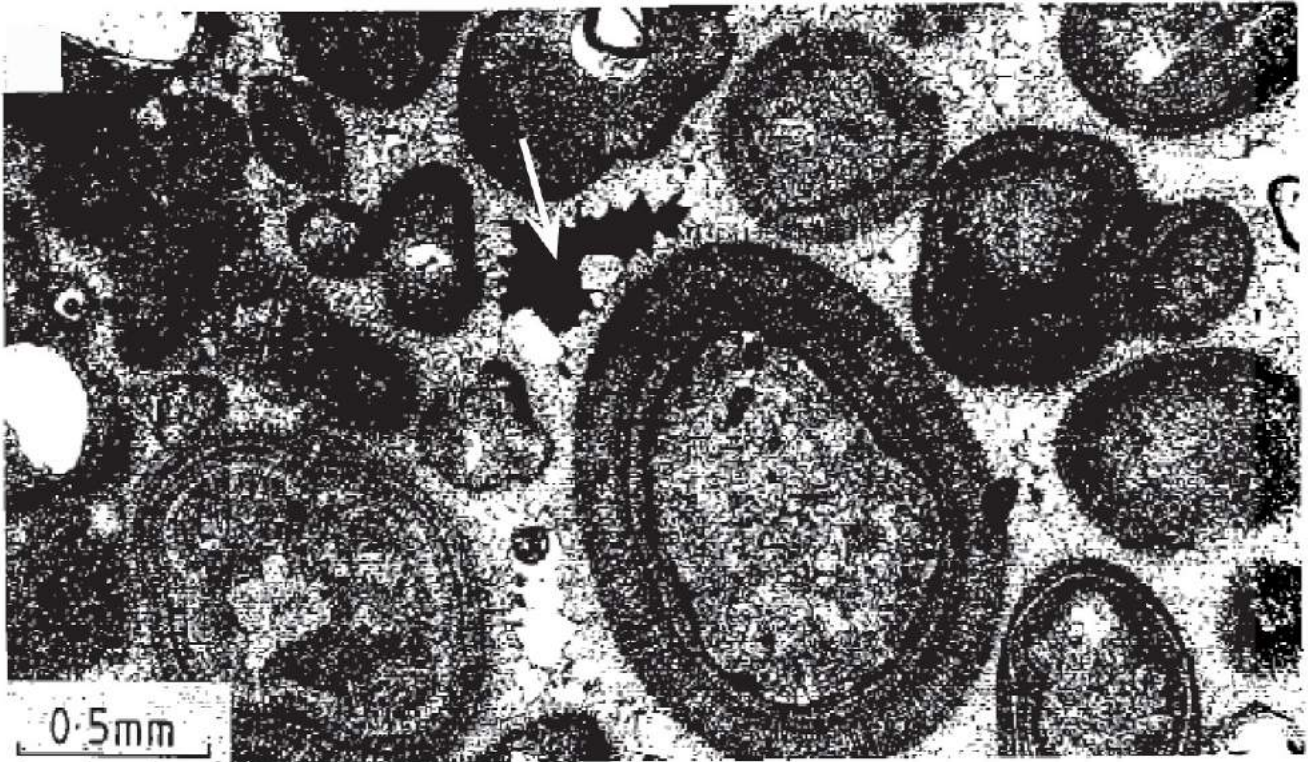
27th January 1926. HAMAR an NAFUR

We landed at a small cove at Sireir. There is an Arab village here but no houses. The people seem to live under trees. There is a well in the shingle bed of a wadi about a mile from the coast but the water is rather gypseous.



Eocene rocks outcrop on the shore at Sireir, dipping gently N.E. There is a well-defined wadi with a broad shingle bed running S.W. from here. This wadi is flanked on the right bank by cliffs formed by a steep flexure in dolomitic lsts. The dips are from 30 to 50 and the strike N.N.E. - S.S.W. Further up the wadi there is a steep syncline. This flexure is very local and only involves about 300 ft. of beds. The dolomites flatten out to horizontal immediately and form a well-marked 500-ft. terrace

Figure 3. Extract from G.M. Lees' typed-up field notes (Lees and Washington Gray, 1926). Sireir = Surayr on recent maps.



Types of ooid. (B) Radial concentric ooids with finely preserved radial calcite microfabric. Note dead oil-filled pore (dark). Late Precambrian Huqf Group, central Oman.

Figure 4. Ooidal dolomite from the Khufai Formation, Oman, with pore fill of dead oil (arrowed) from Tucker and Wright (1990) Carbonate Sedimentology, Blackwell, Oxford, 482p.

Paul Wright, June 2010- *That photo is a problem as I think it was from a roadside sample north of Nafun. I kept it because it showed good oolitic radial texture whereas the majority of Khufai ooids were replaced aragonite. On our 6 weeks of mapping in the Huqf in 1983 we were only lost twice – well not lost but not sure where we were – and that was one of those occasions ... somewhere north of Nafun ... so that sample was one I remember well.*

It may be that this observation of dead oil is irrelevant and one might dismiss it as such, if it did not relate to the same geographic area. There has been an oil charge through this area at some period in the past 600 Ma!

Triton Energy briefly explored Masirah Bay in the late 1990s and Hunt Oil in the 2000s (Figure 5).

Both operators acquired new geophysical surveys and reprocessed existing data, and Triton acquired satellite images for the identification of marine oil slicks, an exploration technique in-vogue at the time. Neither company drilled new wells.

Following Hunt Oil's relinquishment in 2007, a prospect map was included in the Ministry's next licensing-round in January 2009 showing the location of the oil slicks identified by Triton. Most were detected in the north of the bay, over a possible fault transfer zone, but it is easy to dismiss them as perhaps drifted there, from ships discharging their tank-washings as they plied the route along the east coast of Oman. None of them are shown near Nafun.

Circle Oil, who explored the offshore Sawqirah Bay concession to the south, also claimed, in a farm-out brochure, 'Evidence of a working petroleum system by offshore seeps.'

The Masirah Bay concession was subsequently awarded to Rex Oil and Gas and Petroci Holding in 2011, and an operating subsidiary Masirah Oil was established.

The first offshore oil discovery in Oman was made by their GA South-1 well in 2014, subsequently developed as the Yumna field in 2020 (Figure 6). Masirah Oil's Exploration Manager, Lars Hüberr, recently made a very interesting presentation at a conference on Hydrocarbon Seals. ⁹ His talk was about a thin, tight, Arada limestone

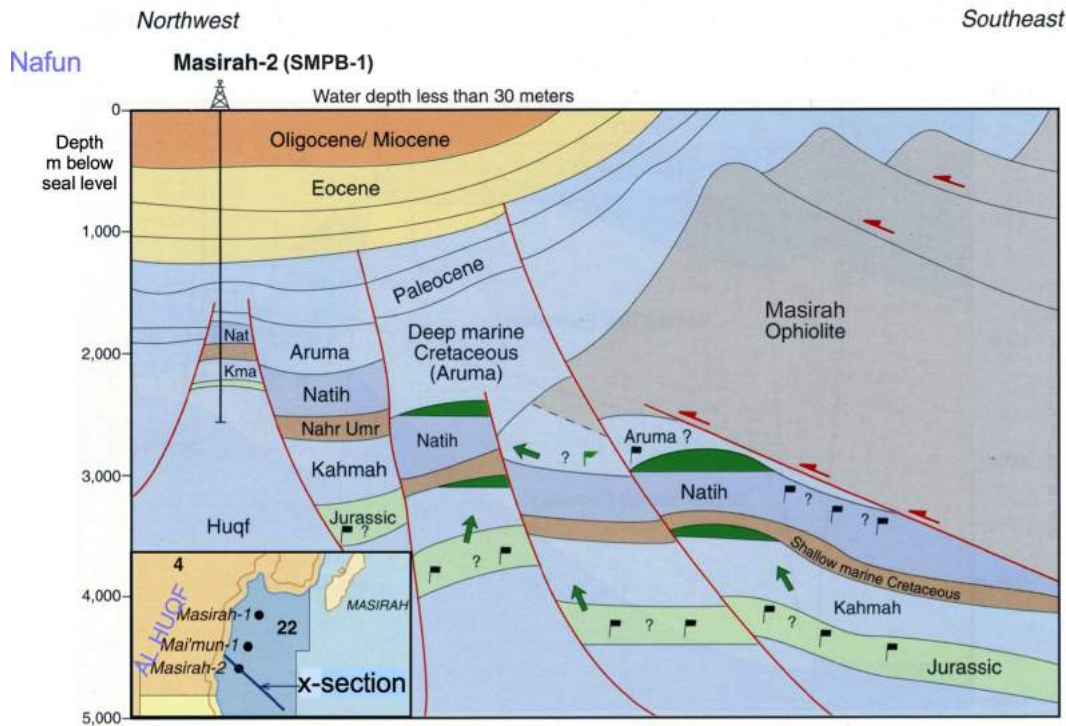


Figure 5. Play concepts for Masirah Bay for The Ministry of Oil and Gas' licensing-round in 2000. Jaman and Al-Hinai (2000). *GeoArabia* 5 (4), p. 592. The Masirah ophiolite was emplaced around 65 Ma.

that has the sealing-capacity to trap a 35-m oil-column in a Lower Aruma sand at Yumna, but not the capacity to retain a potentially larger column in the Manarah-1/Masirah-2 structure. Basin modelling and oil shows at Manarah indicate the structure was charged and Lars' thesis was that the thin seal was breached when the oil reached a critical column height.

Nafun Island lies 20 km landward of Manarah and, the coast at Nafun a further 5 km more (Figure 6). If the Manarah trap has failed in the ~60 Ma since it began to be charged,

the oil might have ended up in one of the discontinuous quartz sand bodies that occur in the basal part of the Lower Aruma Samhan Formation (Figure 7), or somewhere else in the overlying Tertiary section, at the water table which prevailed at the time. Perhaps even in Khufai ooidal dolomites 'somewhere north of Nafun.'

Almost 100 years on, the question remains—**was there, is there, an oil seepage near the coast behind Nafun Island?**

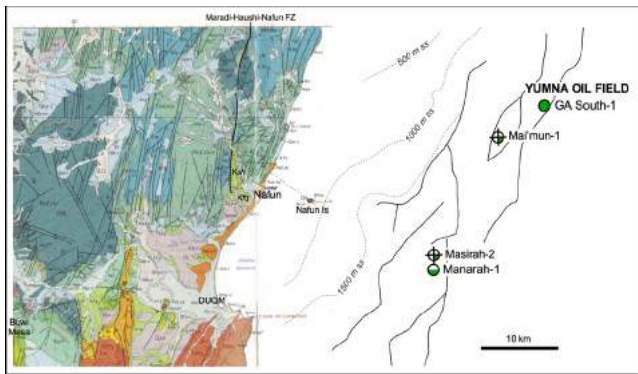


Figure 6. Combination of the onshore Duqm and Madraca geological map (NE40-03/07)¹⁰ and elements of a subsurface map from Hubert (2021). Contours offshore on the Base Tertiary unconformity in metres subsea. The pale green hues onshore represent the Ksh Samhan and Kfq Fiqa Formations. The Arada Member is part of the Fiqa Formation.



Figure 7. Samhan and Fiqa Formations occupying the lower ground and, across the Maradi-Haushi-Nafun Fault zone, the darker grey dolomites of the Buah Formation. Just northwest of Nafun. Inset shows the irregular echinoid *Conulus triadis* Lees 1928 which are common in the Samhan Formation here (coin is 24 mm).

I am grateful to Lars Hübert, Masirah Oil, for permission to use material from his recent AAPG/EAGE presentation and to Mohammed Al Kindi, Jeroen Peters and Todd Woodford for their comments on a draft manuscript.

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Extract from letter from Anglo-Persian, London to A-P, Mohammerah, 24 March 1924.
Extract from Note on Muscat by J.M. Mackie, 2/6/25. All BP70453, BP Archive, Warwick University, U.K.
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- ⁷ W. Beauchamp et al., 1995. Masirah Graben, Oman: A Hidden Cretaceous Rift Basin? *AAPG Bull.* 79 (6), p. 864-79.
SMPA-1=Masirah-1, SMPB-2=Masirah-2 and Mai'mun-1).
- ⁸ Many of the papers in Geol. Soc. London's SP 49 stem from this sponsorship of field geology including: V.P. Wright et al., 1990. Intraplatformal basin-fill deposits from the Infracambrian Huqf Group, east Central Oman. In: A.H.F. Robertson et al. (Eds.), *The Geology and Tectonics of the Oman Region*, GSL, SP49, p. 601-16.
- ⁹ L. Hübert, 2021. Cretaceous and Palaeocene seals and thief sands in the Masirah Graben, Oman. Presentation made during AAPG/EAGE Virtual Conference 'Hydrocarbon Seals of the Middle East,' 12-16 December, 2021.
- ¹⁰ J.P. Platel et al., 1992. Geological Map of Duqm and Madraca. Ministry of Petroleum and Minerals/BRGM. Sheet NE 40-03/07: Scale 1:250,000.
The sandstone at Wadi Buwi Mesa (see Platel et al., 1992, fig. 13) is a well-known example of one of these quartz-rich sand bodies in the Samhan Formation with WNW'ly-orientated cross-bedding, and Sayy is another.

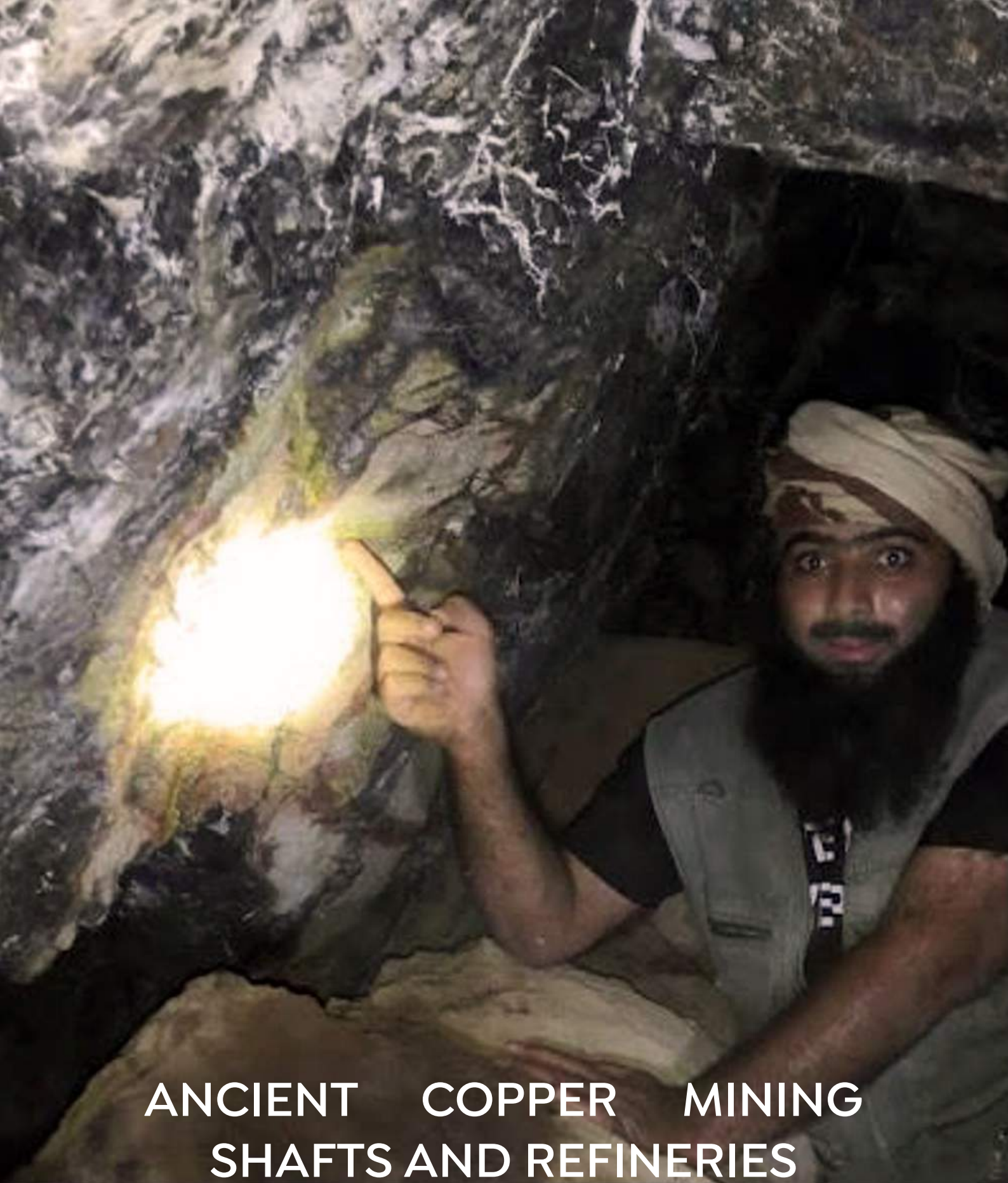


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**ANCIENT COPPER MINING
SHAFTS AND REFINERIES
AT WADI SUSAH IN NIZWA-BAHLA
OPHIOLITE MASSIF**

Almuathir Alkindi

The aim of this article is to document and describe a remarkable site that holds both geological and archaeological significance. This site is an ancient copper-mining area, including shafts and associated refineries, located near Wadi Susah in the ophiolite massif between the towns of Nizwa and Bahla.

GEOLOGICAL CONTEXT

The site is located within the Ophiolite massif that lies to the south of the elevated Jebel Akhdar anticline, commonly known as the Bahla or Bahlah massif, which is one of several ophiolite massifs across the Hajar mountains of Oman (Figure 1). This massif is largely composed of the mantle sequence (Harzburgite and some Dunite Peridotites), and transitions into the crustal sequence towards the southwest (layered Gabbro and Wehrlite (Figure 2).

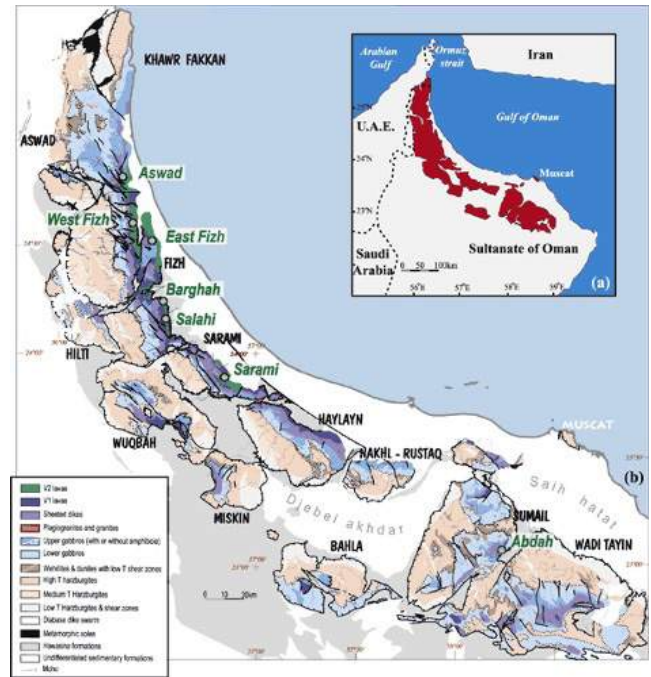


Figure 1. Map showing location of Bahla massif alongside other ophiolite massifs of Hajar mountain range (Godard et al, 2003).

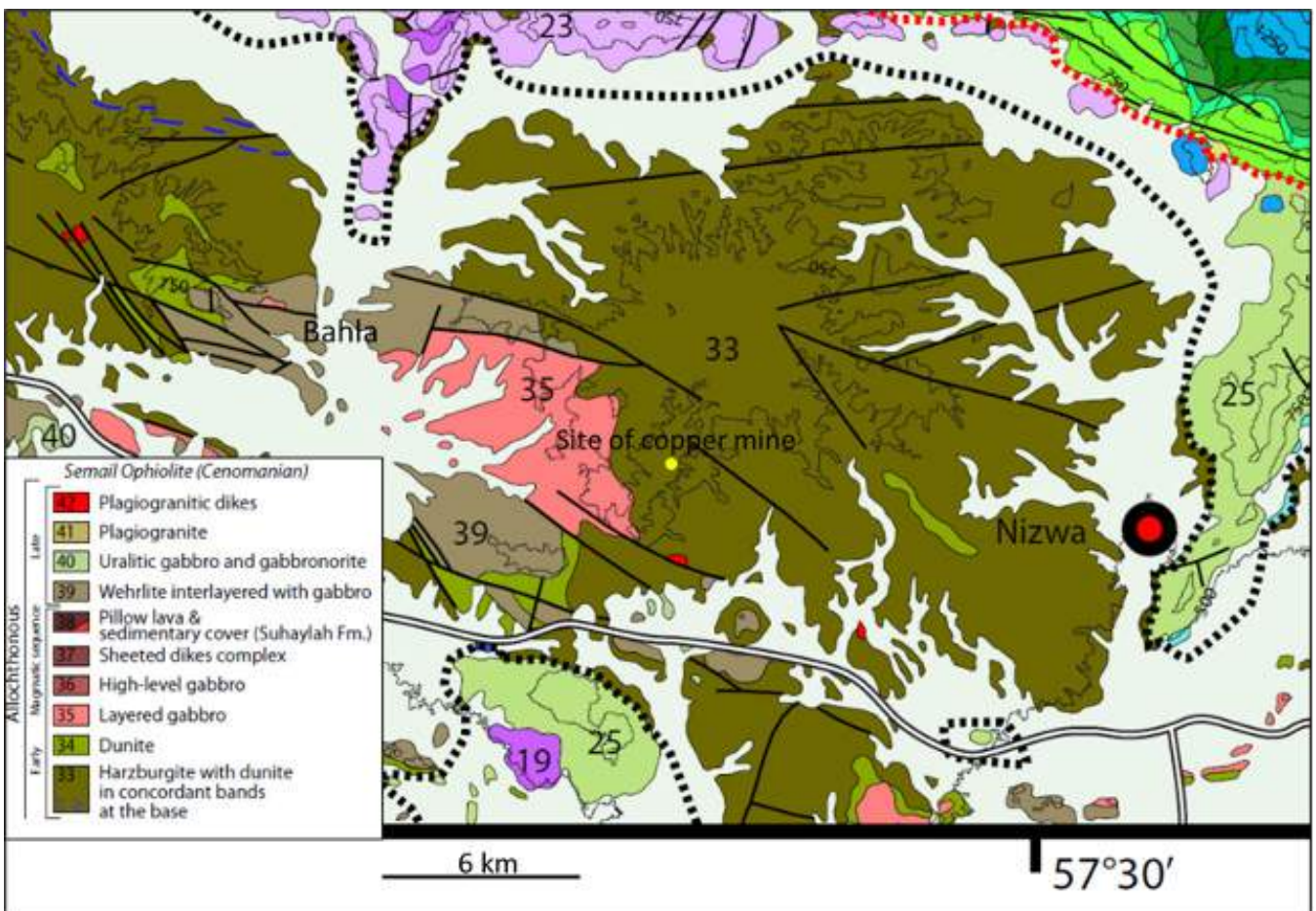


Figure 2. Map showing location of Bahla massif alongside other ophiolite massifs of Hajar mountain range (Godard et al, 2003).

OPHIOLITE AND COPPER

Figure 3 summarizes hydrothermal processes across a typical cross section of oceanic crust, showing the relative abundance of copper (Cu) more likely to be present near the magmatic volatile-enriched zones between the gabbros and the overlying sheeted dyke complex.

Since the location of interest is within the upper part of the mantle sequence, close to the Moho boundary that separates mantle from crustal sequences, it would be expected to contain copper in the form of secondary precipitation in veins within the peridotite shear zone rather than primary gossans.

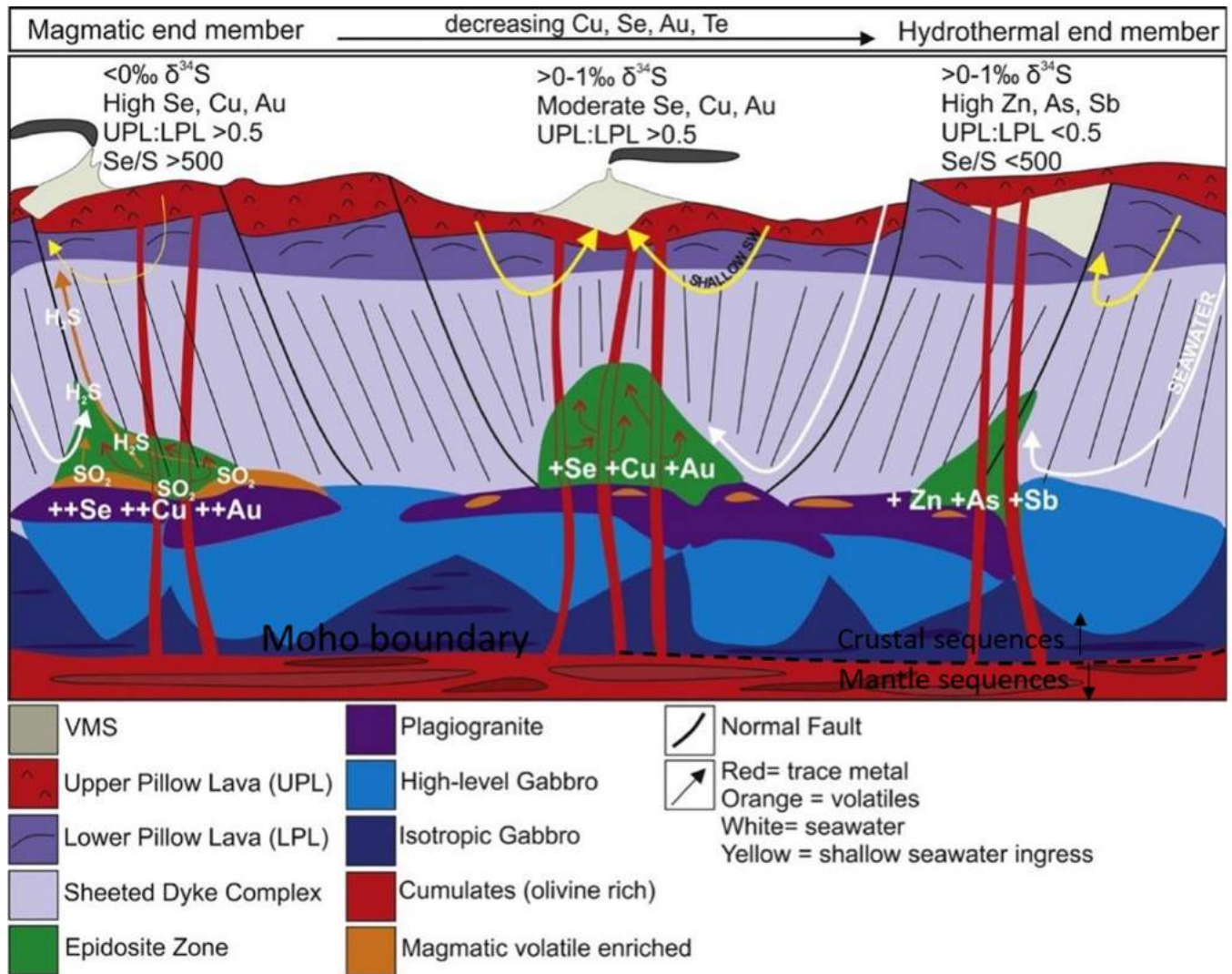


Figure 3. Cross section showing Summary of VMS (volcanogenic massive sulfide) formation in oceanic crust (Martin et al, 2020).

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OVERVIEW OF THE SITE

The Major sites that have been documented in this field visit are:

- Copper mines, in the form of a set of hand-dug shafts and tunnels that penetrate into the ophiolite ridges, (Figure 4).

- Copper refinery: artefacts of a copper refinery in a flat alluvial terrace on the side of the wadi, (Figure 4).

There are also ruins of some abandoned settlements on the sides of the wadi, likely to have been active during mining.

Historically, the onset of the metallurgical processes has likely been in the Bronze age, as commonly found in various similar sites across Oman. Around the site and adjacent ruins, the availability of graves oriented in the direction that indicates Islamic age would indicate that the mining site had activity up to medieval times, and has largely been abandoned and scarcely populated since the decline of those activities.



Figure 4. Satellite view of the region, courtesy of Google Earth TM.

COPPER REFINERY

The refinery and mineralogic artefacts are situated at a flat alluvial terrace at the base of the ophiolite hills that host the mines, and are on the low-relief route following the course of the wadi to the major nearby towns. The floor of the terrace, with several meters square area and partly incised by the wadi erosion, has abundant pieces of copper slag remaining from the copper extraction and refinery processes,

characterized as pieces containing significant iron content and bubble pores from melting process, and coated by blue copper oxide that stained those pieces through time (Image 1).

There is also a mound of pink to bright reddish chert pebbles, that were likely imported from relatively distant locations such as the Hawasina nappes to the south, and were beneficial in the metallurgic processes, as iron ore and chert were typically used

for dressing and fluxing processes that sort out the valuable minerals prior to smelting (Hauptmann & Weisgerber, 1981). The typical hardness and sharpness of chert have also been characteristics of advantage as cutting utilities. (Image 3).

In the same ground, there are ruins of some rooms (about 2x2 m²) built of peridotite and gabbro cobbles (Image 4). There is also a man-made rectangular chamber carved into the base of a peridotite hill, which was likely the location of a furnace used to melt and refine the copper (Image 2).



Image 1. Pieces of copper slag, indicating metallurgical refinery processes.



Image 2. Chamber carved into base of peridotite hill.

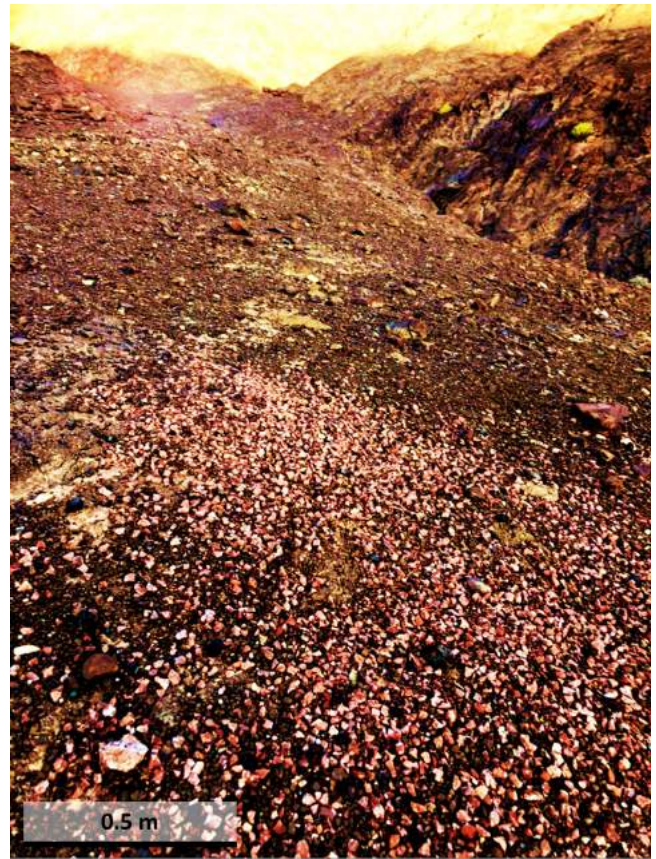


Image 3. Pieces of reddish and pink chert, imported from distant locations (likely from Hawasina nappes 20 km southwards).



Image 4. Ruins of rooms built of local peridotite and gabbro blocks.

MINING SHAFTS

The openings of manually-dug mining shafts, where raw copper ore was initially mined, are located towards the tops of the peridotite ridges that overlook the wadi. Reaching them requires a climb of about 100-m elevation gain from the metallurgic refinery site at the base.

One of the largely intact shafts has a narrow entrance opening (about 70 cm wide – Image 5), oriented parallel to the vein and fracture surfaces, which widens to a chamber (Image 8) that leads to a multi-floor system of tunnels and shafts. The general mine layout consists of tunnels with a length of a few meters, cutting perpendicular to the vein strike directions, which are connected by vertical shafts (1-2 m) that follow the vein dip orientation and are used for ascent and descent to the interconnected tunnels (Image 9).



Image 5. Mining shaft entrance at the surface.

The mineral veins largely consist of copper sulfides or chalcopyrite (Images 6 and 7), and are analogous to copper veins found in the Tabakhat mine (about 7 km east) and in other copper mine sites throughout Oman (Bailey & Coleman, 1981). At this site, the veins have steep and semi-vertical dip angles, and follow northwest to southeast strike orientations that are consistent with the general mapped fault strike orientations (Figure 2), indicating that the mineral veins are filling some of the fault planes and slickensides.



Image 6. Chalcopyrite veins filling branched fracture (hand for scale).



Image 7. Remaining copper oxide at surface of mined-out fracture plane.

The initial chamber (Image 8) is topped by a ceiling with an opening that leads to an upper-floor tunnel on the side. The same chamber also contains two descending holes a few meters apart that lead to the same lower-ground tunnel, which terminates at another shaft. This shaft descends to a narrower tunnel that cuts through lower extensions of the mineral vein, and leads to some shorter branching tunnels and cavities that take advantage of vein branches.



Image 8. Manually excavated 2x2m mining chamber.



Image 9. Vertical shaft of about 5 m height, connecting multiple tunnel levels.

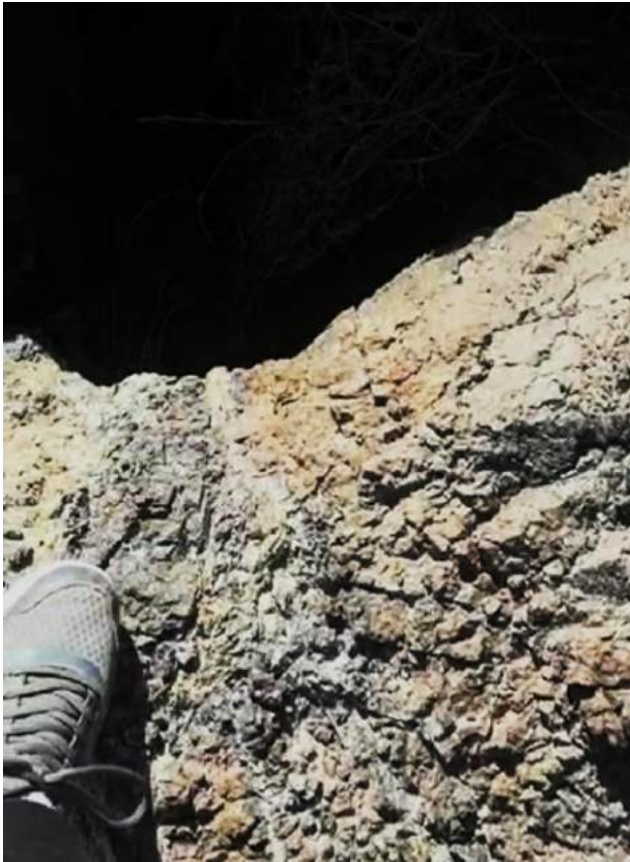


Image 10. Surface exposure of a mineral vein that has been followed downward by shaft excavation.

CONCLUSION

The primitive ore exploration processes likely started at the surface (Image 10), where there are found exposed extrusions of mineral precipitate veins that host copper ore. This was followed by the processes of manually digging shafts that followed the steeply oriented extensions of those mineral veins. The raw copper sulfides would then be taken to the refinery at the base of the ridge, where copper, extracted by metallurgical processes, would eventually be hauled to the historical towns of Nizwa, Bahla and others.

Overall, the site at Wadi Susah shows good models of metallurgy from mining to refinery stages, with impressive exploration strategies with regards to the remoteness of the location from civil centers and the limitedness of techniques and conditions of their time of operation, with extracted metallurgic quantities that were feasible at their time, but in the current time would serve in geo-archaeological and tourist value rather than economic metal quantities.

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Lat: 19.650816°

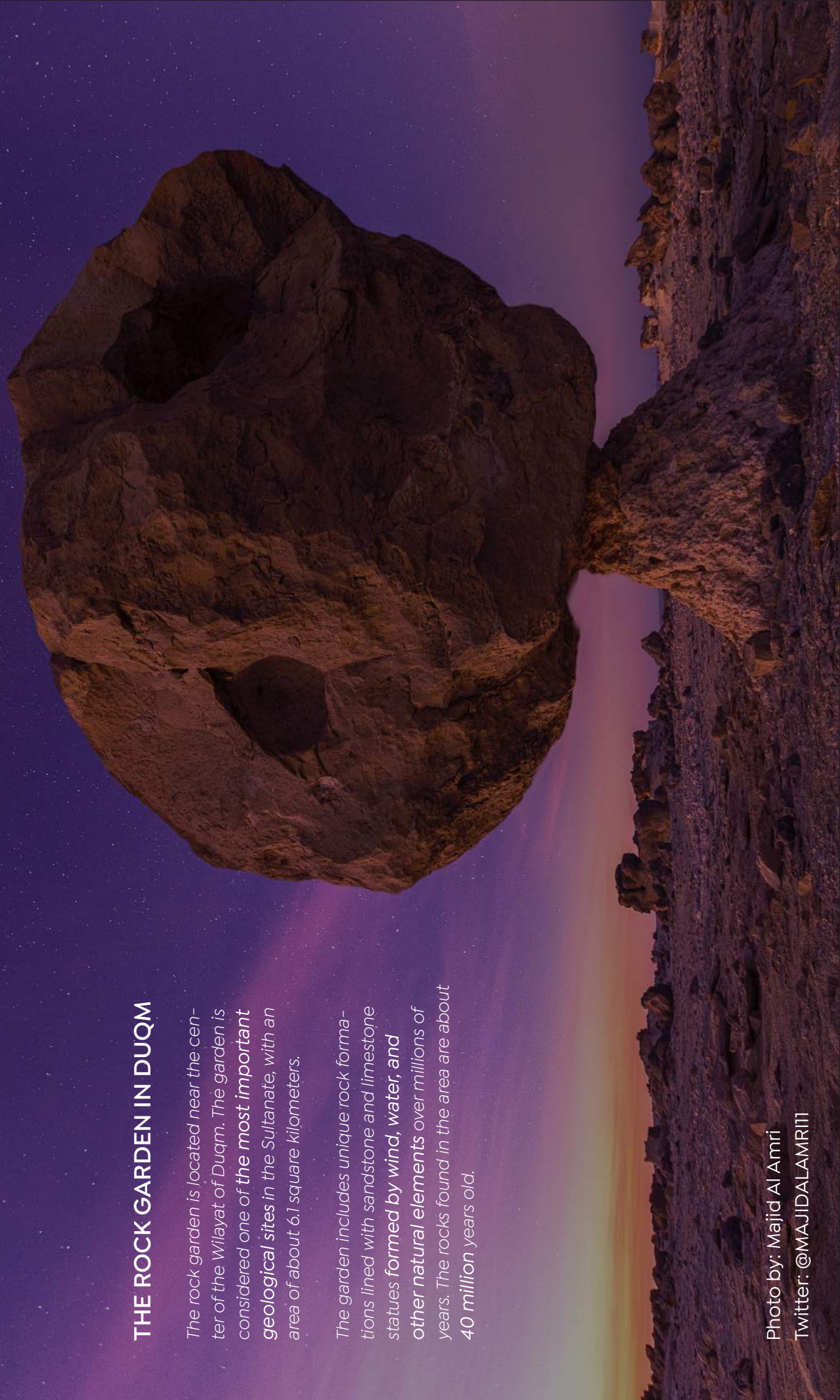
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THE ROCK GARDEN IN DUQM

The rock garden is located near the center of the Wilayat of Duqm. The garden is considered one of the most important geological sites in the Sultanate, with an area of about 6.7 square kilometers.

The garden includes unique rock formations lined with sandstone and limestone statues formed by wind, water, and other natural elements over millions of years. The rocks found in the area are about 40 million years old.

Photo by: Majid Al Amri
Twitter: @MAJIDALAMRIII



SEISMICITY OF THE ARABIAN PENINSULA

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Saudi Society of Geosciences, President
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INTRODUCTION

The Arabian Peninsula is an area which is characterized very poorly seismically and for which little existing data is available. While for the most part aseismic, the area is ringed with regional seismic sources in the tectonically active areas of Iran and Turkey to the northeast, the Red Sea Rift bordering the Shield to the southwest, and the Dead Sea Transform fault zone to the north. Throughout recorded history, many damaging earthquakes have occurred along the Arabian Plate boundaries. These events have damaged buildings, and resulted in injuries and fatalities, and there is obviously potential for damaging earthquakes in the future. As the population increases and new areas are developed, the seismic risk to human life and to infrastructure increases.

While Saudi Arabia is relatively aseismic, it is affected by large devastating earthquakes that have occurred nearby. Large earthquakes in the Zagros Mountains can cause shaking in buildings along the Gulf coast. On June 2, 1993, an earthquake of magnitude 4.7 occurred in Kuwait near the Minagish oil field. In spite of its modest magnitude, the earthquake was widely felt and caused panic in the city of Kuwait. More recent events in the Minagish area include a magnitude 3.9 earthquake on September 18, 1997 and a magnitude 4.2 event on December 30, 1997. On January 2002 a moderately large earthquake shook the Musadam Peninsula on the border region of Oman and the United Arab Emirates. Another major source is the Makran subduction zone, located at the southern end of the plate boundary, where the Arabian plate around the Gulf of Oman subducts underneath the Eurasian plate.

Such subduction zones can create very large earthquakes. The great Makran earthquake of November 1945 had a magnitude of 8.1. While seismologists rely on average attenuation relationships for different regions, these often fail to predict actual shaking behavior. Attenuation relationships typically apply to high-frequency shaking, above 1 Hz. Shaking at lower-frequencies is more complex because three-dimensional elastic structure can cause dispersion, focusing and amplification in a deterministic fashion.

The Arabian Gulf is adjacent to one of the most seismically active fold-and-thrust belts on Earth, the Zagros Mountains. Broad-band seismic records of earthquakes in the Zagros Mountains recorded on the Arabian side of the Gulf display long duration surface waves. While shorter periods (< 1 s) are attenuated from crossing the deep sediments (> 10 km) of the Gulf basin, the long period energy is relatively unaffected. Consequently, large earthquakes in the Zagros could result in possibly damaging ground motions at long-periods (1-10 s). Such ground motions are of concern for large engineered structures, such as tall buildings and long bridges with resonant periods in the same frequency band (period of 1-10 s).

SEISMOTECTONIC SETTING

The Arabian platform consists of the Paleozoic and Mesozoic sedimentary rocks that unconformably overlays the shield and dip very gently and uniformly to the E-NE towards the Arabian Gulf (Powers et al., 1966). The accumulated sediments in the Arabian platform represent the southeastern part of the vast Middle east basin that extend eastward into Iran, westward into the eastern Mediterranean and northward into Jordan, Iraq and Syria.

The Arabian shield isolated the Arabian platform from the north African Tethys and played an active paleogeographic role through gentle subsidence of its northern and eastern sectors during the Phanerozoic, allowing almost 5000 m of continental and marine sediments to be deposited over the platform. This accumulation of sediments represents several cycles from the Cambrian onward, and now forms a homocline dipping very gently away from the Arabian shield.

Figure 1 shows a map of the Arabian Peninsula along with major tectonic features and earthquake locations. Active tectonics of the region is dominated by the collision of the Arabian Plate with the Eurasian Plate along the Zagros and Bitlis Thrust systems, rifting and seafloor spreading in the Red Sea and Gulf of Aden. Strike-slip faulting occurs along the Gulf of Aqabah and Dead Sea Transform fault systems.

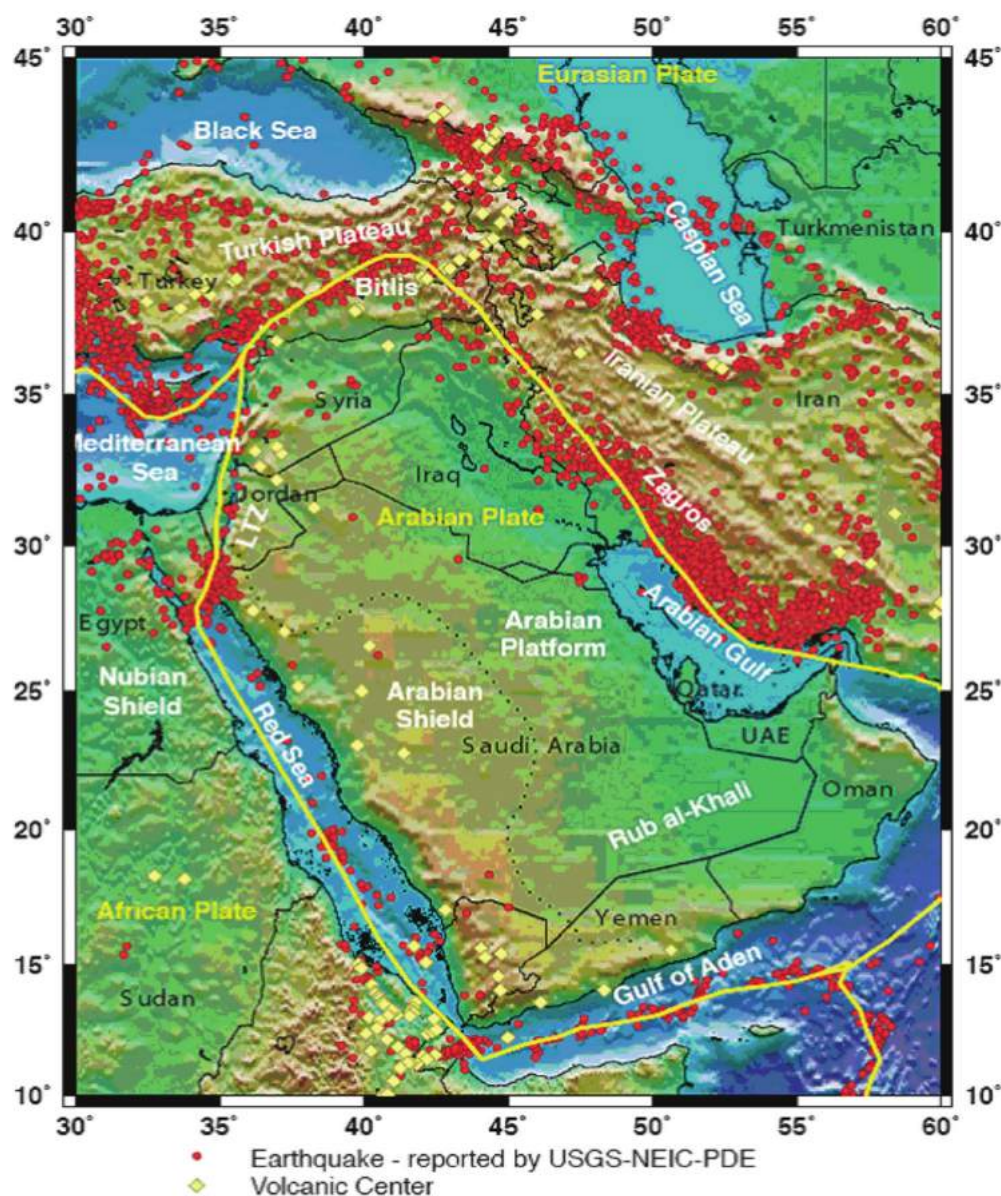


Figure 1. Map of the Arabian Peninsula and surrounding region. Major geographic and tectonic features are indicated. Plate boundaries are indicated by yellow lines. Earthquakes and volcanic centers shown as red circles and yellow diamond, respectively.

The great number of earthquakes in the Gulf of Aqabah pose a significant seismic hazard to Saudi Arabia. Large earthquakes in the Zagros Mountains of southern Iran may lead to long-period ground motion in eastern Saudi Arabia. The two large regions associated with the presence or absence of sedimentary cover define the large-scale geologic structure of the Arabian Peninsula. The Arabian Platform (eastern Arabia) is covered by sediments that thicken toward the Arabian Gulf. The Arabian Shield has no appreciable sedimentary cover with many outcrops. Figure 2 shows the sediment thickness, estimated from compiled drill hole, gravity and seismic reflection data.

Several structural provinces can be identified within the Arabian platform: 1) An interior homocline in the form of a belt, about 400 km wide, in which the sedimentary rocks dip very gently away from the shield outcrops. 2) An interior platform, up to 400 km wide, within which the sedimentary rocks continue to dip regionally away from the shield at low angles. 3) Intra-shelf depressions, found mainly around the interior homocline and interior platform. Also, the crust of the Platform appears to be 3-5 km thicker than in the Shield. The Moho Discontinuity beneath the western Arabian Platform occurs at a depth of 40-45 km, and the velocity of the upper mantle is about 8.2 km/sec (Al-Amri 1998; 1999; Rodgers et al., 1999; Tkalcic et al., 2006).

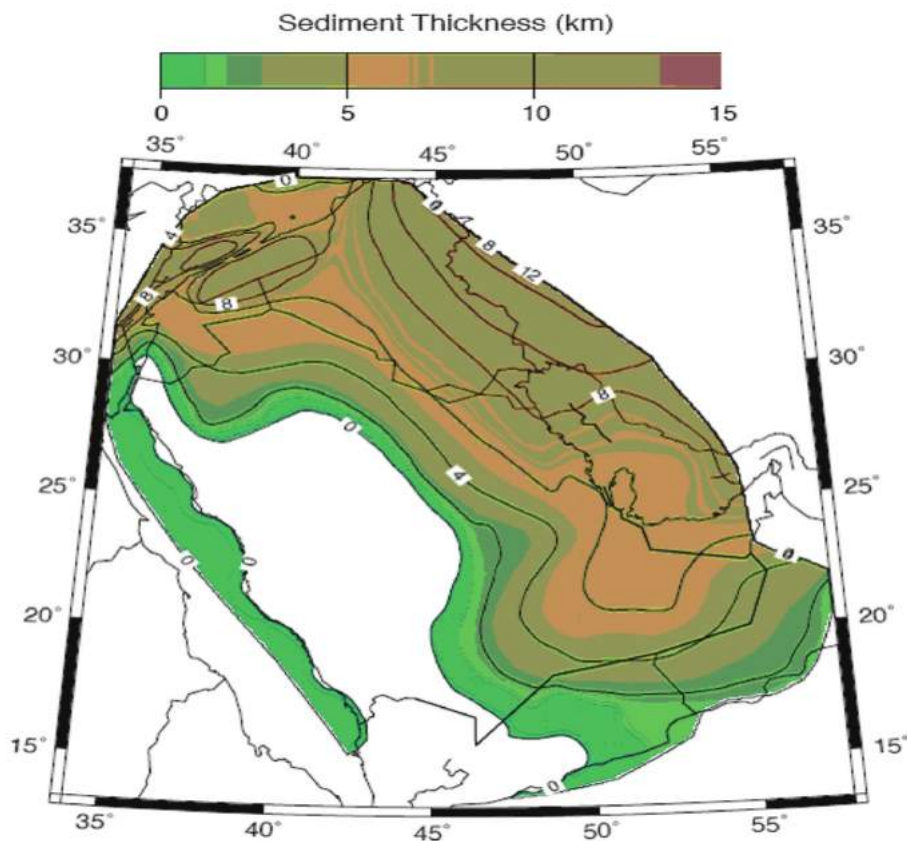


Figure 2. Map of sediment thickness of the Arabian Plate.

High-frequency regional S-wave phases are quite different for paths sampling the Arabian Shield than those sampling the Arabian Platform (Mellors et al., 1999; Al-Damegh et al., 2004). In particular the mantle Sn phase is nearly absent for paths crossing parts of the Arabian Shield, while the crustal Lg phase has abnormally large amplitude. This may result from an elastic propagation effect or extremely high mantle attenuation and low crustal attenuation occurring simultaneously, or a combination of both. High-frequency Lg does not propagate as efficiently across the Arabian Platform compared to the Shield but Sn does propagate efficiently. This suggests that crustal attenuation is low in the higher velocity crust of the Arabian Shield, or the sedimentary structure in the Arabian Platform attenuates and disrupts the crustal waveguide for Lg. These observations imply that high-frequency ground motions will propagate with lower attenuation in the Arabian Shield compared to the Arabian Platform.

It is known that high-frequency regional phase behavior in the Arabian Plate is quite variable as demonstrated by Al-Damegh et al. (2004). They investigated the attenuation of Pn phase (QPn) for 1–2 Hz along the Red Sea, in the Dead Sea fault system, within the Arabian Shield and in the Arabian Platform. Consistent with the Sn attenuation, they observed low QPn values of 22 and 15 along the western coast of the Arabian Plate and along the Dead Sea fault system, respectively, for a frequency of 1.5 Hz. Higher QPn values of the order of 400 were observed within the Arabian Shield and Platform for the same frequency.

Their results based on Sn and Pn observations along the western and northern portions of the Arabian Plate imply the presence of a major anomalously hot and thinned lithosphere in these regions that may be caused by the extensive upper mantle anomaly that appears to span most of East Africa and western Arabia.

The seismicity map of the Arabian Platform for the period from 1980 to 2020 for magnitude 3 and above is shown in Figure 3 which indicates a sparse distribution of seismic events in the Arabian Platform and western portion of the Arabian Craton. At the central portion of the Arabian shelf, three earthquake events are shown to be positioned among the great anticlines (Summan platform, Khurais–Burgan and Ghawar–En Nala anticlines, Qatar arch) that are bounded by the Wadi Batin and Abu Jifan faults. In the Arabian gulf from the Hormuz salt basin up to the Mesopotamian foredeep of southern Iraq is seen a sparse distribution of epicenters. Southeastward of the Arabian shield and south of the central part of the Arabian shelf, three seismic events have epicenters in the Rub Al-Khali basin and two more in the Hadramaut arches in eastern Yemen.

In Oman, two seismic events are located in the Hawasina thrust sheet, while the others are along the Dibba fault and the Makran–Zagros subduction zone. This subduction zone is the only region where an oceanic lithosphere is being subducted, where apparently the oceanic crust in the gulf of Oman is being consumed beneath southern Iran.

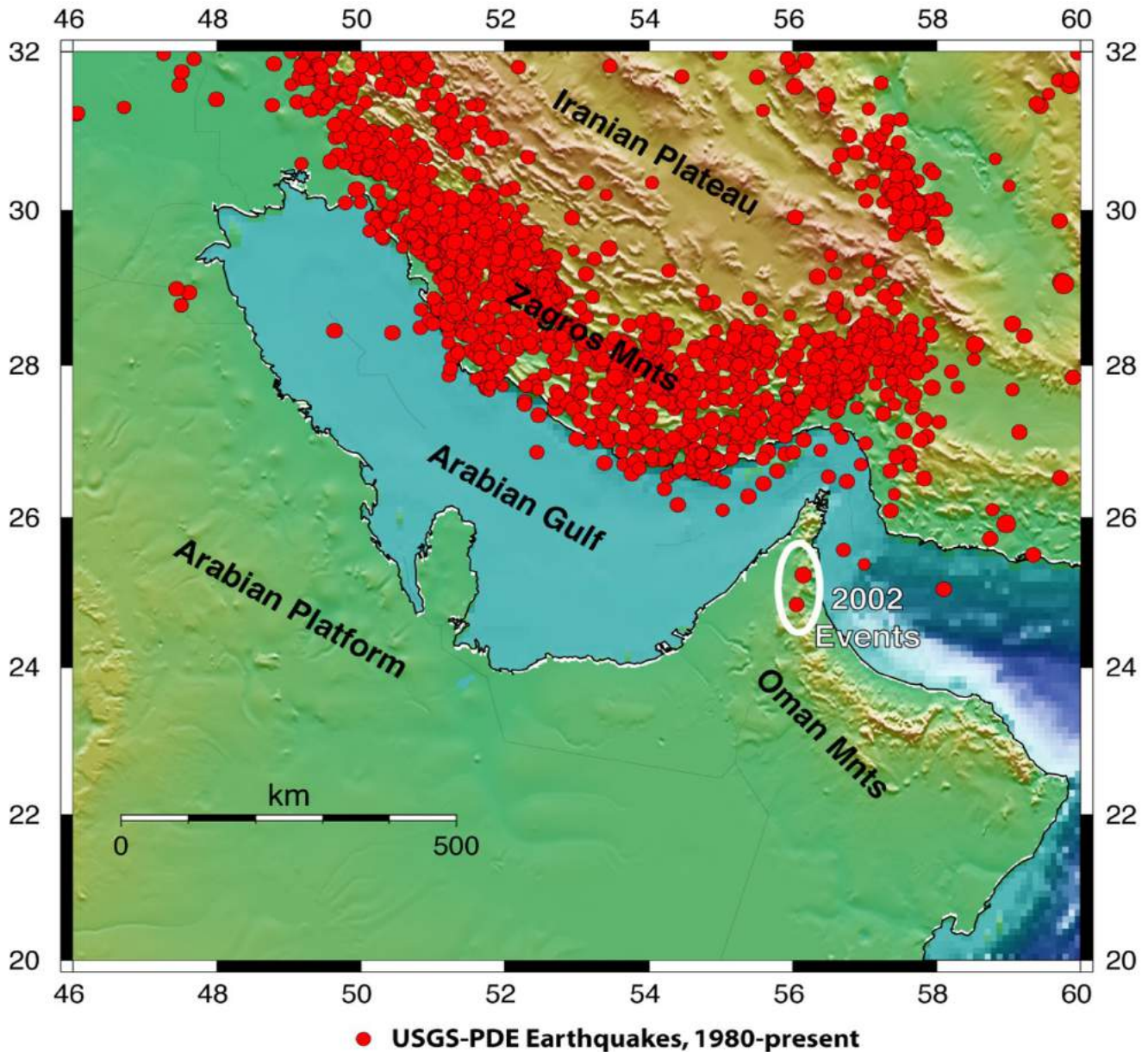


Figure 3. Recent seismicity of the Arabian Platform and adjacent regions.

To the southeast of Oman, along the Masirah trough zone gives one earthquake event. Down south, a spatial concentration of seismic events can be seen. This distribution is in the East Sheba ridge which is between the Alulak-Fartak trench in eastern Yemen to the west and the Owen fracture zone to the east. The ridge is also between the Socotra island in the south and the Masirah trough in the north. The ridge is part of a line of epicenters that connects the gulf of Aden to the west and the Carlsberge ridge to the south.

However, there is an increasing concentration of earthquake epicenters going toward the northeast directions of the Arabian platform and the zone of convergence below the southwestern direction of Lut block in Iran and parallel to the Oman line. One of the concentrated spatial distribution of seismic events is shown to occur in the Zagros Mountains folded belt that extends for a distance of about 1500 km in a northwest-southeast direction and is about 250 km in width. The earthquakes in the Zagros folded belt mostly originate within a 200 km wide zone that runs parallel to the fold belt.

The majority of earthquakes occur in the crustal part of the Arabian plate that is subducted along the folded belt. Magnitude 5 earthquakes are frequent and magnitude 6 may occur sometimes yearly. This tendency of increasing seismicity thins out in the Main Zagros Thrust (MZT) and the Sanandaj-Sirjan ranges in Iran. The nature of deformation across this zone is complex, involving both thrust and strike-slip as indicated by earthquake focal mechanisms (Telebian and Jackson, 2004).

To the west of the Musandam Peninsula, Arabia is under thrusting the southern Eurasian margin along the Zagros Thrust. To the east of the Musandam Peninsula, convergence is much slower given the seismicity along the Makran coast. Strike-slip motion probably occurs along reactivated thrust planes associated with obduction of the Semail Ophiolite (Oman Mountains). The Makran subduction is the region where the Gulf of Oman continues to subduct under the southern region of the Eurasian plate. It differs from other subducting segments of the Arabian Plate in that it is an oceanic crust rather than continental crust that is being subducted beneath Eurasian Plate. This oceanic crust extends eastward to Owen Fracture Zone (OFZ) along the Indian Plate boundary.

A moderate (M~5) earthquake struck the town of Masafi in the northeastern UAE on March 11, 2002 (Figure 3). The event was large enough to be detected and located by global networks at teleseismic distances. The region is generally believed to be aseismic, however no regional seismic network exists in the UAE to determine earthquake occurrence.

Generally speaking, twelve seismogenic source zones were delineated and identified

based on seismological and geological parameters with the higher priority given to the spatial distribution of epicenters. These source zones are composed of systems of faults whose boundaries do not traverse generally other tectonic units. Some of the seismogenic source zones are relatively large due to scarcity of earthquakes in the Arabian Platform (Alamri, 2013).

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INTERNATIONAL

EXPLORATION NEWS

The commentary below covers the key relatively recent exploration highlights, for the respective countries.

MIDDLE EAST

IRAQ

Several companies are focused on development and appraisal drilling across the Kurdistan Region and South Iraq. Highlights from the Kurdistan Region include Genel Energy's appraisal drilling at the Sarta field in the Kurdistan Region; the appraisal drilling programme is to appraise the Jurassic reservoirs in the field including back-to-back wells. OP Hawler Kurdistan Ltd, a subsidiary of Forza Petroleum Ltd (formerly Oryx Petroleum Ltd), will complete the Ain Al Safra 2 appraisal well during 2022, targeting the Triassic reservoir. The well was temporarily suspended in August 2014 due to security developments in the region. HKN Energy has also been active, starting a 3D seismic campaign in the Sarsang Block, Kurdistan region – to find new drilling locations in the block.

TURKEY

At the end of Q1 2022, 19 exploration license applications remained under consideration for approval by the government, covering five basins. During Q1 2022, 10 new licenses were awarded across the Türkiye Petrolleri A.O. (TPAO) and Arar Petrol ve Gaz Arama Uretim Pazarlama A.S. TPAO has been active in the deepwater area of the Black Sea; drilling wells at two new prospects.

Both wells are around 50 km southwest of the Tuna 1 discovery (Sakarya gas field). This is a focus area for TPAO, alongside drilling, the company has drawn up plans to carry out seismic acquisition around the Sakarya Gas Field in neighboring blocks in the western part of the Black Sea, which is likely to start during 2022.

SAUDIA ARABIA & QATAR

Saudia Arabian Oil Co (Saudia Aramco) has committed to the lease of 20 offshore and 50 onshore rigs for 10-years beginning from 2022, from two contractors. In addition, the company has guaranteed the purchase of 50 new onshore rigs from its domestic joint venture company. The precise scope and nature of drilling operations planned are not known. Presumably, it will involve a mix of exploration and development activity as plans to produce at max capacity of crude oil markets and the potential transition of some country's from Russia oil supply, in light of the current situation in Ukraine. In February 2022, the Minister of Energy His Royal Highness Prince Abdulaziz bin Salman bin Abdulaziz confirmed that Saudi Aramco had made at least five new conventional and unconventional hydrocarbon discoveries across four key areas within the kingdom during 2021. The discoveries were announced in the Central Region to the south of Ghawar, within the Empty Quarter, the Northern Border Region, and the Eastern Province.

Qatar is still focused on Liquefied natural gas (LNG) expansion projects, secondary or tertiary oil recovery an imperative and International Oil Company (IOC) negotiations for participation in North Field East and North Field South LNG expansion projects are edging closer to resolution. Whilst negotiating new LNG concessions, Qatar is returning existing 25-year agreements to state ownership.

UAE

Activity in UAE has been focused on the appraisal of existing recent discoveries by IOCs. Oxy is understood to have had some early success within its onshore Block 3 concession, which was awarded in February 2019 following the closure of the Abu Dhabi Licensing Block Bid 2018. Eni and ADNOC announced the Offshore Block 2 gas discovery (XF-002) - which is positive news, the resumption of its exploration campaign in Oman's offshore Block 52 (Juzor Al Hallaniyyat) is highly anticipated. ADNOC Drilling Company PJSC (ADNOC Drilling) is expanding its land, marine and island-based rig fleet to accommodate a forthcoming surge in conventional and unconventional drilling activity. Following a successful IPO on the Abu Dhabi Securities Exchange (ADX) in 2021, it is embracing an integrated drilling service (IDS) model of operating and seeking to expand operations within the region

SYRIA

SPC is continuing its gas development and appraisal campaign in the Palmyra Fold Belt and announced a new gas discovery at the Zamlat Al Mahr 1 well in early 2022; a second well is due to spud shortly.

OMAN

In Oman, all eyes are on the 2021 licensing round, launched by The Ministry of Energy and Minerals (MEM). The round closed on 31 March 2022.

- Block 38 lies in the far southwest of the country on the Oman-Yemen border. The block covers an area of approximately 17,400 sq km and was previously 100% owned and operated by Frontier Resources Oman Ltd. It was relinquished in 2016 after Frontier failed to attract a farm-in partner for the block.
- Block 66 covers an area of approximately 4,900 sq km and was recently relinquished by MOL West Oman B.V. Ltd (MOL). MOL had planned to drill its third exploration well, Men'nah 1, in 2020 however the spud date was indefinitely delayed due to the COVID-2019 outbreak. Two previous exploration wells drilled by MOL in the block had been unsuccessful.
- Block 23 is a newly created block that has been carved out of the southern part of open Block 22; it lies to the east of offshore Block 50 which has Masirah Oil's Yumna field.

EOG Resources Inc is understood to be exiting Oman this year. The company is believed to have made a non-commercial gas discovery in the onshore Block 36 (Fasad) license. A second exploration well was understood to be dry in Block 36; EOG is understood to be planning to relinquish the block later this year as well as leaving Block 49 in which it holds 50% with Tethys Oil AB. Tethys has been granted a 6-month extension for Block 49 exploration phase one until June 2022, the company is in the process of taking 100% ownership of the block.

Continuing with Tethys during Q1 2022, the company has been conducting exploration/appraisal drilling in Block 56 (Mudawrat), the company has a three-well drilling campaign in progress; Al Jumd 2 has completed drilling and Sarha 3 has activity ongoing. Moving offshore, Masirah Oil Ltd plans to re-ignite exploration in Block 50 (Masirah Bay Offshore), a 50 sq km seismic survey and a tentative exploration well are expected this year, confirmed plans are an appraisal well to test the eastern extension of the Yumna field that is producing from three wells.

INDIAN SUB-CONTINENT

PAKISTAN

License round activity and discoveries have been the highlights for Pakistan over Q1 2022. The government launched the Bid Round 2022 in January 2022, offering 14 onshore blocks for bidding – the bids submission deadline has been extended to 18 April 2022. Oil and Gas Development Company Ltd (OGDCL) is relinquishing Bela North and Rakhshan exploration licences. United Energy discovered gas in Mohar 1 exploration well in the Latif block. Drilling activity is still high in the country and OGDCL along with Pakistan Petroleum Ltd continue to actively acquire 2D and 3D seismic across the Indus and Balochistan basins in search of new prospects and appraisal zones.

INDIA

Four license rounds are still active in India during Q1 2022.

- OALP-VII launched on 16 December 2021. OALP-VII offers eight blocks in six sedimentary basins, with the bid submission deadline on 15 February 2022.

- Special CBM Bid Round 2021 launched on 22 September 2021: offers 15 CBM blocks in four basins. Bids submission deadline was extended further to 31 May 2022.

- Third Discovered Small Fields Bid Round (DSF-III) launched: offers 32 contract areas, including 75 discoveries. The bid submission deadline is extended to 31 May 2022.

- ONGC launched a second bidding round of the Marginal Nomination Fields (ONGC MNF Bid Round 2021) under the Production Enhancement Contract (PEC) model; offering 11 onshore contract areas including its 43 small producing fields. The last date of bid submission is extended to 25 April 2022.

Cairn Oil & Gas has continued to lead the way in exploration under the most recent Open Acreage License Round style, it has made another oil discovery, the Durga 1 exploration well within the RJ-ONHP-2017/1 block, in the Barmer Basin. Oil India Ltd has followed suit and begun drilling in the Jaisalmer Basin, spudding one well Soorasar 1 in the RJ-ONHP-2017/9 block. Exploration activity by OIL and Oil and Natural Gas Corporation Ltd is still consistent onshore and offshore in the Cambay, Assam Shelf, Krishna-Godavari and Mumbai Offshore basins.

BANGLADESH

ONGV Videsh Ltd drilled the Kanchan 1 exploration well in SS-04 Block, unfortunately, the company was unsuccessful and did not find hydrocarbons; it was thought the prospect had a possible near 1 Tcf resource potential which would have been significant to Bangladesh domestic gas. The target was an onshore prospect on the southern side of the same large, north-south anticlinal structure drilled by Magnama 1 new-field wildcat (gas discovery in 2007).

Magnama 1 and its appraisal well Magnama 2 were drilled on the northern section; Kanchan 1 will be drilled on the southern section. To improve interest in the offshore area of Bangladesh the government has planned for a large multi-client survey which is to be conducted under a joint-venture between TGS and Schlumberger, acquisition is expected to start later in 2022.

SRI LANKA

Exploration could be on its way to Sri Lanka later this year. Two offshore blocks, M1 and Q1, were preliminarily awarded to a locally-based company Serendive Energy Ltd, in late 2021. The final approval process was underway in early 2022, the company has plans to conduct seismic and drill an exploration well later this year, subject to the official award. The government has plans later this year to re-offer the M2 offshore block that contains the only successful wells, drilled by Cairn India in the early 2010s, two discoveries, Dorado and Baraccuda lies within the block. The government is looking for an international company to come in and develop/appraise further these and commenced domestic gas production for the first time in the country.

SAHARAN AFRICA

EGYPT

The International 2021 Bid Round held last year has seen success in Egypt, the authorities have granted eight blocks. Among the winners are Eni, Energean, INA, ENAP and United Energy. One block was still on offer as part of the 2021 Limited Bid-Round, North King Mariut Offshore in the western part of the Nile Delta Basin, bids were due on 28 February 2022.

LIBYA

Activity has been very low in the country for exploration, only one well was active in January 2022; NOC and IOCs are primarily focused on increasing production but damage to infrastructure and lack of budget will prevent a short-term boost.

TUNISIA

Exploration continues to be relatively even though it is recovering, Government instability reduces the attractiveness of the country with majors leaving. Exploration activity is recovering from 2020 lows. Two exploration wells were active at the end of March 2022. YNG is testing its Araifa-1 well and Eni is nearing TD at the Ambar-1 well.

MOROCCO

Chariot Transitional Energy (Chariot) successfully tested its first appraisal well at the Anchois field in the Lixus Offshore I block. It is likely to further appraisal wells are to be drilled this year; the company has a phase I plan consisting of three to four wells at the field. SDX Energy reignites plans for a second drilling campaign, in the Ksiri – Lalla Mimouna area; drilling had been suspended due to recent restrictions linked to the COVID-19 pandemic on the Moroccan frontier. The drilling operations are now expected to restart in early-Q1 2022. The campaign started late on in 2021 with two wells planned, a development well being the first to be drilled first at Ksiri block, and secondly an appraisal well to be drilled secondly at Lalla Mimouna Sud block, targeting the Tortonian Guebbas Member

NIGER

Operator Savannah Energy Ltd (previously named Savannah Petroleum) is expected to resume drilling exploration wells in 2022, CEO Andrew Knott reported in late 2020.

The British company intends to continue its exploration campaign after the “R3 East Project” goes on production.

SUDAN & SOUTH SUDAN

In South Sudan, a licensing round was launched and then cancelled in the quarter - the Ministry of Petroleum cancelled the South Sudan Licensing Round and has opted for direct negotiations instead from 1 April 2022, despite seven companies showing interest during the bid’s roadshow phase. Petrotec and Zebradata kept the data room open until the end of March 2022. The initial five blocks on offer are unexplored, but available geological data suggest that a fair petroleum system might exist in the Late Cretaceous formations. The blocks are in the southern extension of the Muglad Basin, which currently produces approximately 100,000 bo/d.

With thanks to S&P Global Commodity Insights
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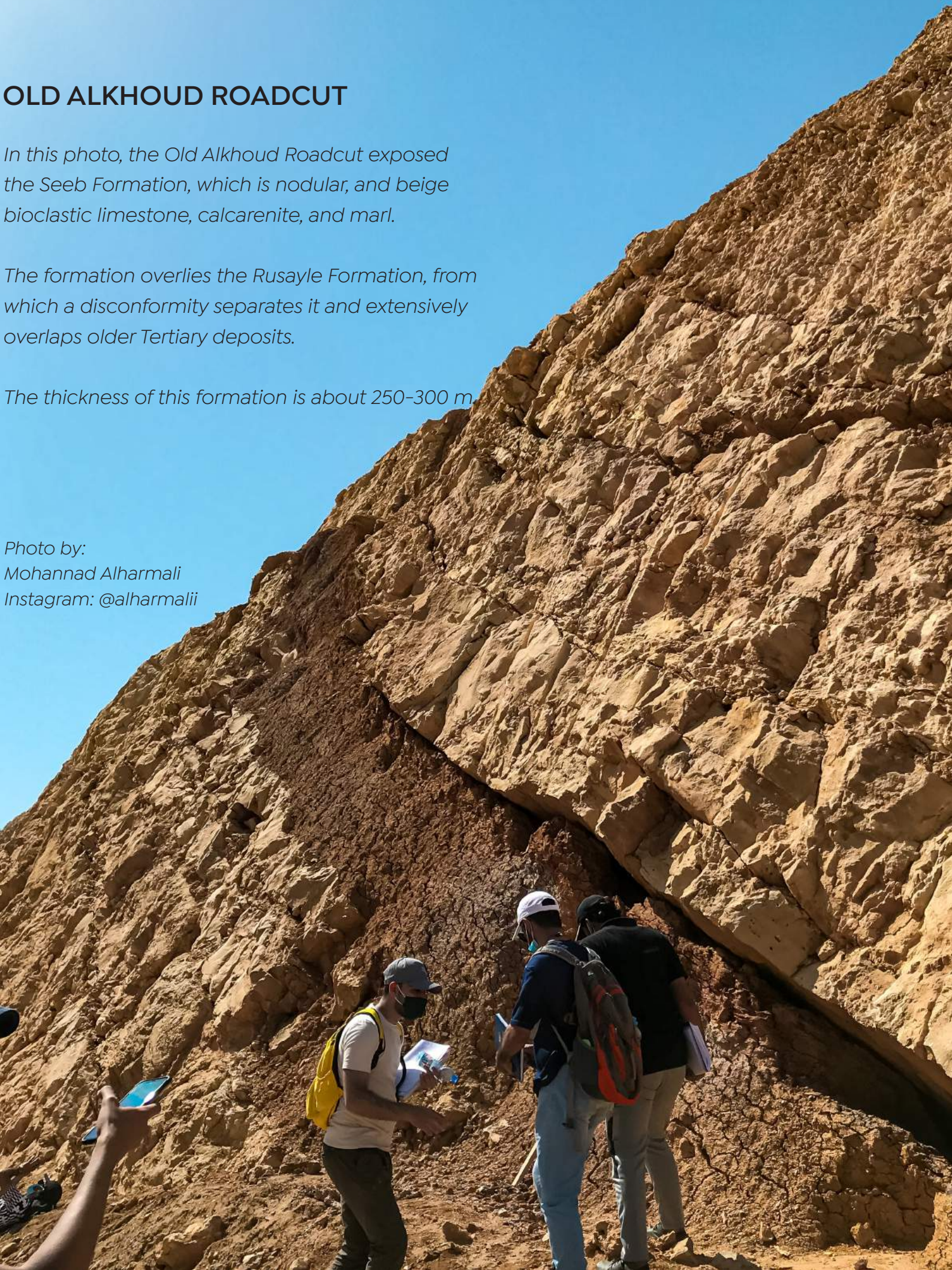
OLD ALKHOUD ROADCUT

In this photo, the Old Alkhoud Roadcut exposed the Seeb Formation, which is nodular, and beige bioclastic limestone, calcarenite, and marl.

The formation overlies the Rusayle Formation, from which a disconformity separates it and extensively overlaps older Tertiary deposits.

The thickness of this formation is about 250–300 m.

Photo by:
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