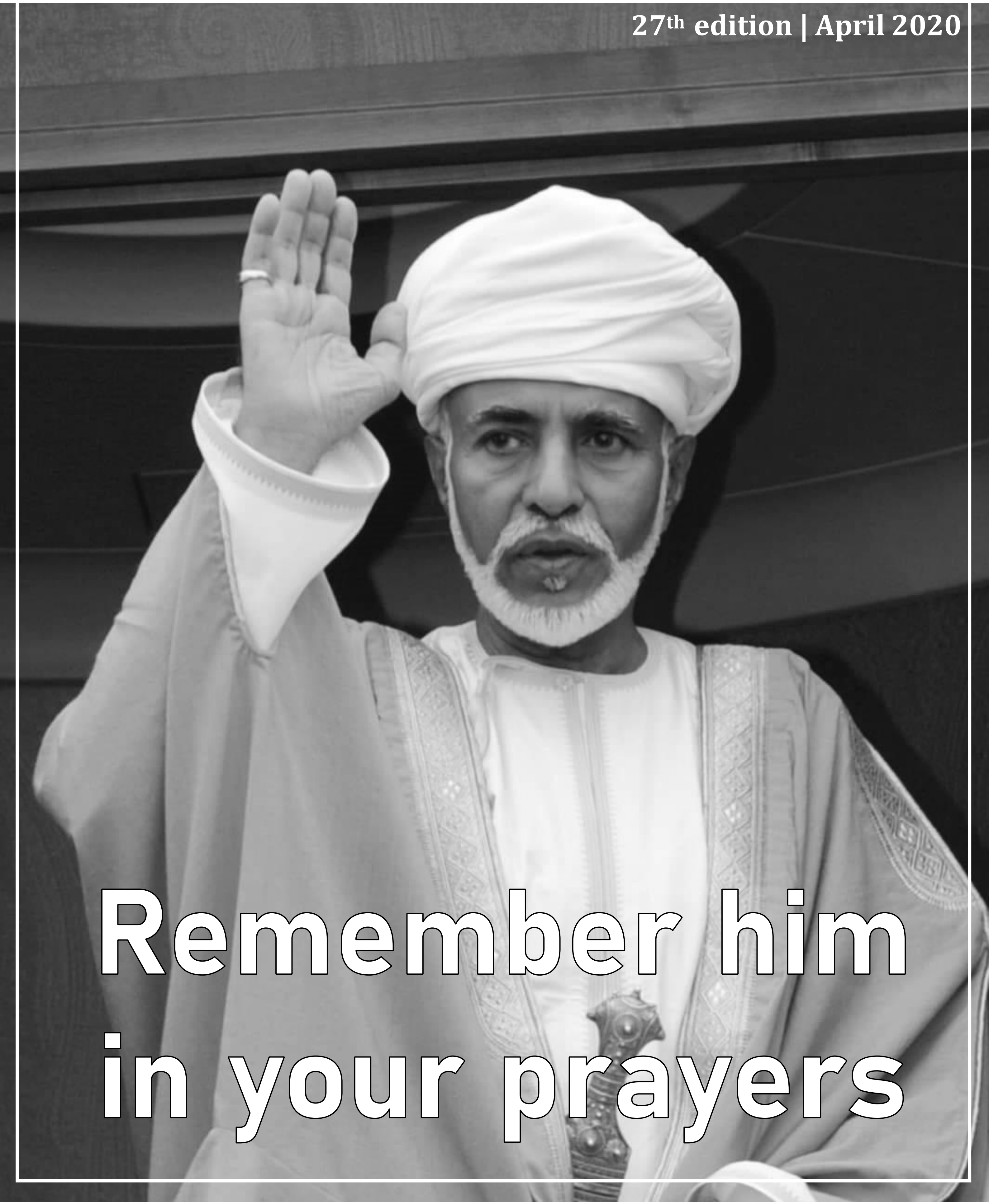
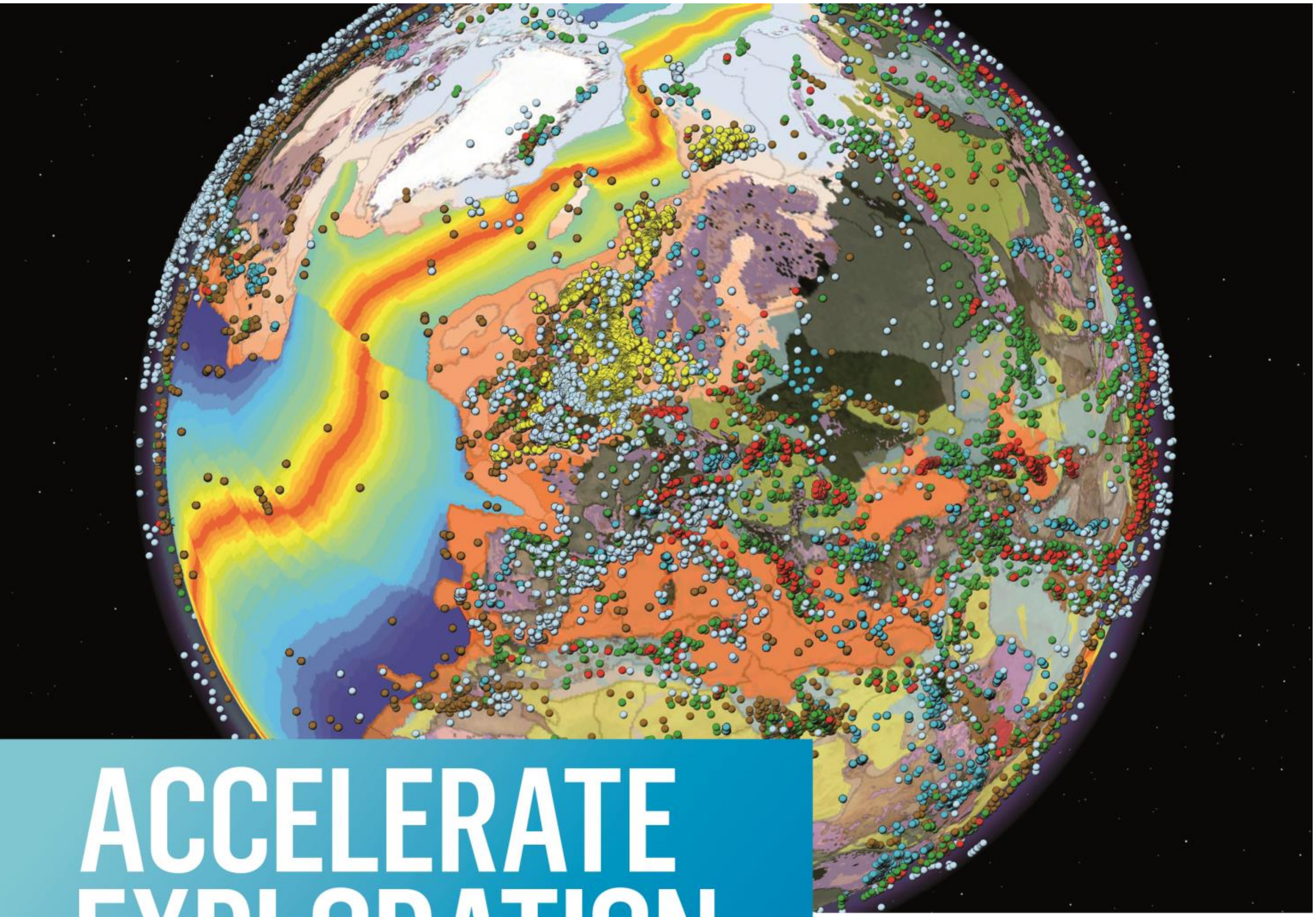
Al HAJAR

27th edition | April 2020





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ON THE COVER

Photo of His Majesty Sultan Qaboos bin Said, the Sultan of Oman from 1970 to 2020. He is the fifteenth-generation descendant of the founder of the House of Al Said

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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BY THE EDITOR

Dear GSO member,

We started this year with a very sad news of the demise of His Majesty Sultan Qaboos bin Said who was a visionary leader who built Oman to a better place. May his soul rest in peace and may God have mercy upon him. In his last year, a Royal decrees was issued stating that the responsibility of protecting the geoheritage was given to Ministry of Heritage and Culture. This decree shows us that our visionary leader knew the importance of the geological wonders of Oman and considered them as a heritage for Oman. It is up to us -the geoscientists- to preserve this heritage and this can be done only by educating, teaching and learning about it. Hope you will enjoy the articles chosen for this issue and I hope it would inspire you to share your geoscientific findings with us. Stay healthy, stay safe and stay at home.

Husam Al Rawahi
GSO Editor
Petroleum Development of Oman

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Naima Al Habsi
Daleel Petroleum LLC

Dr Aisha Al Hajri
Petroleum Development of Oman

Dr Talal Al Aulaqi

President Address

Dear colleagues,

We introduce the 1st edition of the al Hajar magazine for this year one of main publications of the geological society of Oman. We all share our thoughts and deep sorrow for the loss of the great pillar of Oman Sultan Qaboos bin Said. A great beloved leader recognized worldwide who built Oman for the past 50 years and now we are blessed by Sultan Haitham bin Tariq who will drive the country to a bright prosperous future.

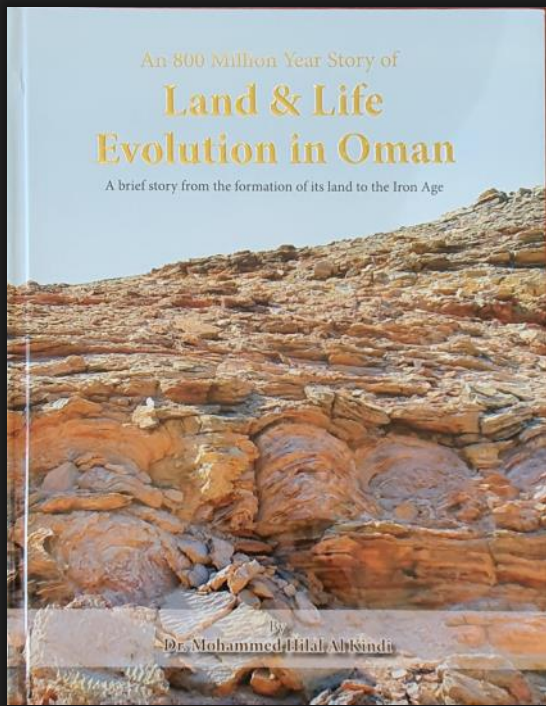
Since the Corona pandemic hit the world and all sectors have been affected and shut down due to quarantine and restricted travelling. This of course affected our activities and also postponed the AGM for 2019. We will try and setup other means of communications to deliver our programs using online platforms and we will continue supporting the publication of new books to reach our tempting readers.

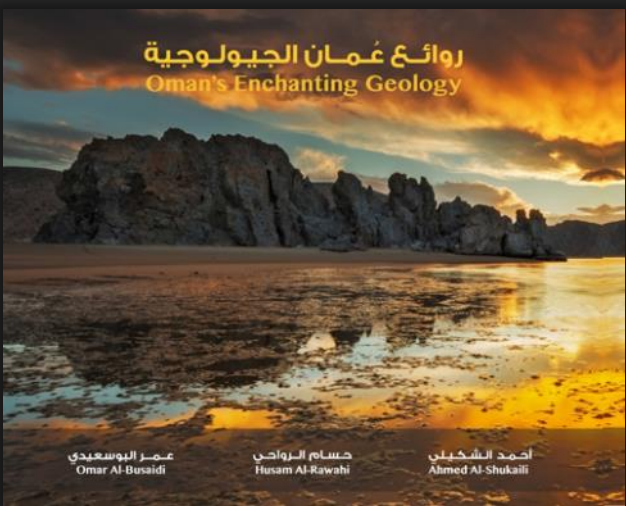
At the end, I hope the oil and gas operators and service companies will continue supporting and sponsoring our programs for the year 2020.

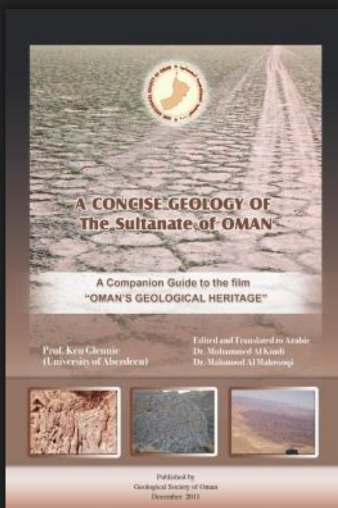
Elias Al Kharusi
President of the GSO

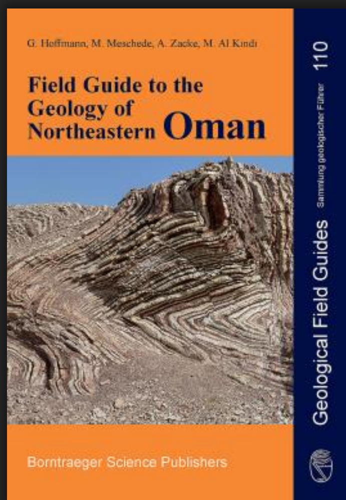
“WE WANT YOU TO TELL ABOUT GEOLOGY OF OMAN”

THESE PUBLICATIONS WILL HELP YOU AT YOUR MISSION









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إنا لله وإنا إليه راجعون

WE BELONG TO ALLAH AND TO HIM WE SHALL RETURN

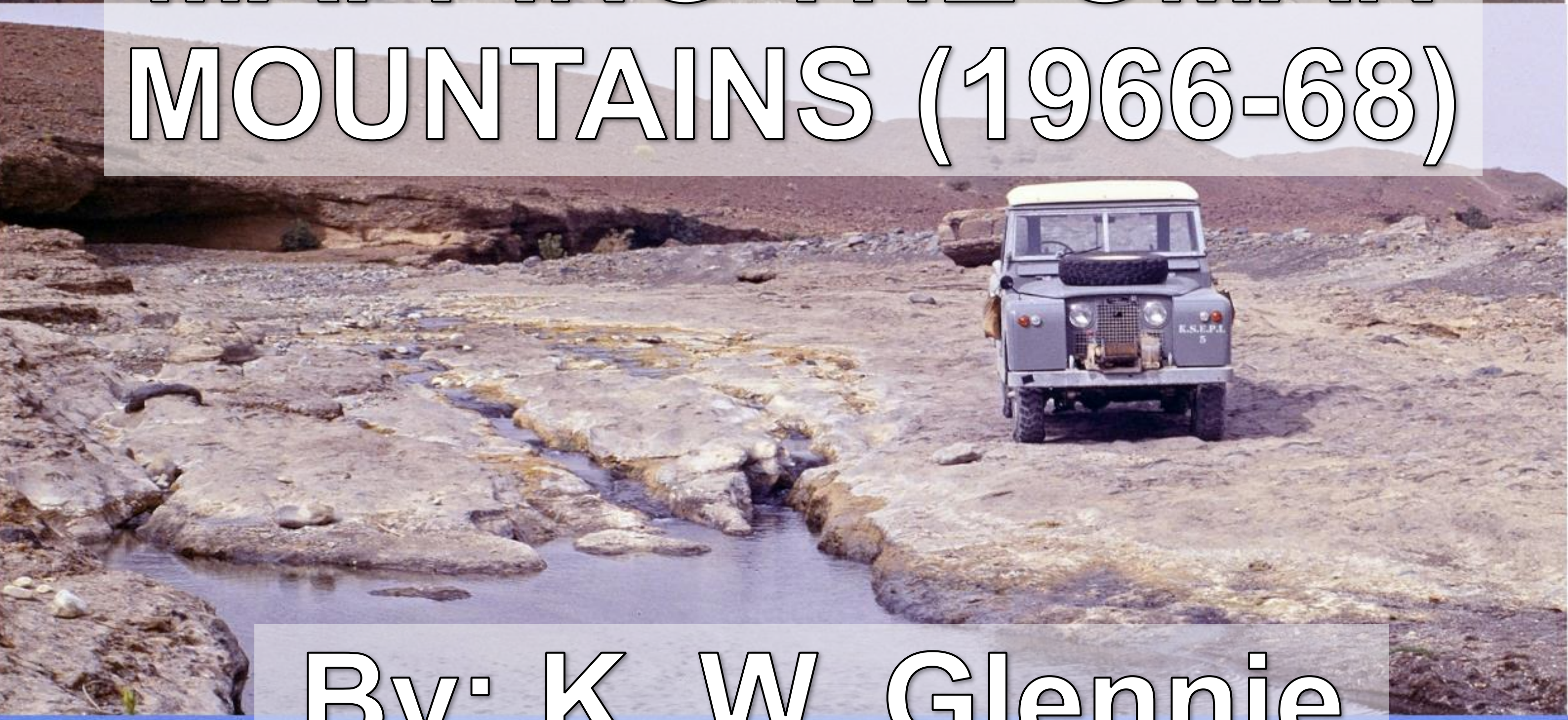
For our beloved leader and father

His Majesty Sultan Qaboos bin Said

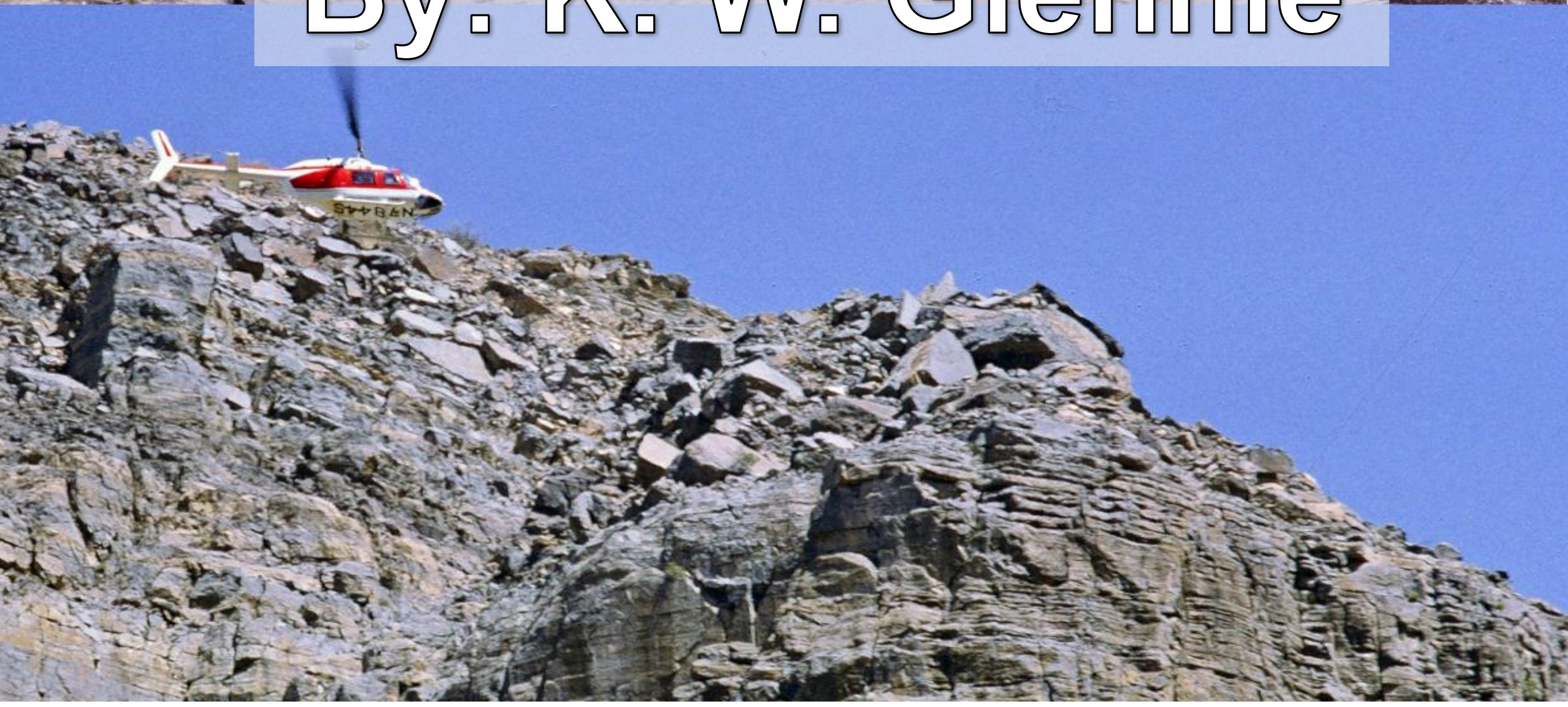
May God have Mercy upon him

Remember him in your prayers

MAPPING THE OMAN MOUNTAINS (1966-68)



By: K. W. Glennie



This text below was written by Ken Glennie - deceased November 2019 - in 2003 when a multi-author book on Oman's oil fields was being considered. With Ken's passing, though parts of it have been published before, it was thought worthy of a wider appreciation. The text referred to photographs in his collection of colour slides which he presented to GSO in 2005 and a selection are included here, as are a few figures from Glennie et al. (1973, 1974) and Glennie (2005). Fundamental geological research was always close to Ken's heart: trying to understand and explain because there is so much we still don't know.

What began as an Exploration 'hunch' to be investigated, became a 'landmark' geological study and, incidentally, allowed much of the mountains, the Batain and Masirah to be relinquished from PDO's oil concession in December 1969.

Alan P. Heward

Abstract

A major effort to map the Oman Mountains began in 1966 following a field trip through the mountains by Shell's Head of Exploration. The task of mapping the mountains was given to me in Shell Research because of my previous work on desert sediments in Oman and the UAE. Following the construction of a photogeological map, a small team of geologists calibrated the map stratigraphically and tectonically over the next two winter field seasons 1966-7 and 1967-8. Progress was enhanced in the second season by the use of a helicopter. The Oman Mountains consist of a lower autochthonous sequence deposited in mainly shallow waters on the Arabian Plate, and two overlying, tectonically-emplaced, allochthonous units, the Hawasina and the Semail, deposited and formed in deeper waters of the Hawasina ocean (Neo-Tethys 1).

What began as an Exploration 'hunch' to be investigated, became a 'landmark' geological study

Article's title page photos:

PDO's Azaiba (batchelor) camp in the mid 1960s. It later become a J&P contractor camp and more recently an MBPS yard. Middle: Landrover 'KSEPL 5' in Wadi Jizzi. Base: Bell helicopter in Wadi Sham, Musandam.

Early Exploration

The earliest geological investigations of Oman were by members of the Indian Geological Survey and by individuals on journeys or landing from ships. Of greater significance was the expedition by G.M. Lees of D'Arcy Exploration, now BP, in the mid 1920s. Lees recognised that nappe tectonics had played an important role in building the mountains, an interpretation that was rejected by later geologists (e.g. H.H.Wilson, 1969). The opinion of Wilson and his IPC/PDO predecessors was that the Hawasina were in-situ, deposited in a deep basin, flanked by extrusions of igneous rocks (the Semail). Their interpretation was in-keeping with 'geosynclinal' theories of the day.

By the time I and my colleagues arrived in Oman in late 1966 to early 1967, parts of the greater Oman Mountains had been mapped by the another generation of PDO geologists (Kapp and Llewellyn (1963-64), Kassler and Haremboure (1964-65), Horstink and Nijhuis (1965-66). Of importance to us was that earlier in 1966 Haremboure and Horstink had developed a new hypothesis in which they believed that the Hawasina had been tectonically emplaced over the autochthonous Wasia Group (echoing the ideas of G.M. Lees). They demonstrated this to Pit Pilaar and I on a field trip through the mountains, including the Hawasina Window in the early autumn of 1966.

Irrespective of the origins of the various geological units of the Oman Mountains, PDO geologists had already recognised a four-fold subdivision of the rock units. In Jebel Akhdar, an unfossiliferous unit (Mistal Formation) was overlain unconformably by shallow-marine limestones ranging in age from Permian (Saiq Fm) to mid Cretaceous (Wasia Fm, which had just been identified as the main reservoir of the Fahud Field). This sequence was flanked by the Hawasina, the greater part of which lay southwest of Jebel Akhdar. The Hawasina was in turn overlain by the basic igneous rocks of the Semail.

If mapping by PDO geologists was proceeding effectively and eventually seeming to arrive at the nappe-emplacement hypotheses (although this was not known in The Hague at that time), why was I asked to lead a new team to map the geology of the mountains?

Commercial oil had been discovered in northern Oman a few years earlier and by the time KSEPL arrived on the scene, a pipeline from Fahud and Natih to Saih al Maleh (later Mina al Fahal, on the Sultan's orders) was being constructed through the Semail Gap.

KSEPL (Shell Research) Involvement

My first involvement with SE Arabia was in the Spring of 1965 when, in pursuit of an interpretation of the possible desert origins of the Permian Rotliegend of NW Europe, I continued my studies of modern desert sediments in the UAE and interior Oman. To that end, Brian Evamy and I travelled overland from Sharjah to Oman via Buraimi. PDO hired an empty commercial aircraft (on its way back from Azaiba to Doha for another load of fresh food) to take us on a day-long aerial reconnaissance with cameras clicking away as fast as we could go. We joined the plane at the Suneinah-1 well, flying over the Umm as Samim, the Al Liwa oasis, the west side of the Oman mountains and Musandam.

Early in 1966, Shell's Head of Exploration, Rudi Beck, paid a visit to Oman to see the oil discoveries for himself. Following a guided tour through the mountains, he realised that oil (Fahud and Natih) had been discovered in close proximity to the *Steinmann Trinity* (serpentinite, pillow lavas and radiolarian chert). If this proximity was meaningful in Oman, could it be used to find oil elsewhere in the world? Beck did not want a busy exploration company to be saddled with such theorising. Instead, he decided that it was a problem for Shell Research (KSEPL) to resolve, and I happened to be the person to whom he turned.

My reaction was that to get a proper feeling for the problem, extensive mapping of the Oman Mountains was required. Beck agreed and, in order to prevent the PDO Exploration Manager from diverting me to cope with his exploration problems, I was asked to set up an entirely independent research team with its own budget, transport and accommodation (with, I must add, considerable on-the-spot-help from PDO's management). To this end we had our own portacabin in PDO's Azaiba camp, where we could leave our European clothes and get a bed during occasional trips to the coast. At first Beck offered the assistance of one newly joined Swiss geologist (Ben Reinhardt) who had experience of mapping ophiolites in the Swiss Alps. When I pointed out that the Oman Mountains were some 700 km long and up to 140 km wide (the Swiss Alps are only half that length – and how many decades did it take many more geologists to map them?), I was offered two more field geologists, Pit Pilaar (Dutch) and Michel Boeuf (French), plus a biostratigrapher, Mike Hughes Clarke (British) who already had some experience of Middle East stratigraphy through working with the Consortium in Iran. PDO insisted that an arabist also joined the team for liaising with the local tribesmen (John D'Olier-Lees, who joined us at the beginning of 1967).

To guide us in the field, in September 1966, Reinhardt and Boeuf were given the task of preparing a photogeological map from aerial photos that had been shot in 1957 at the time of the rebellion in Jebel Al Akdhar. This they finished in draft form, at different scales, by the end of the year. In the meantime, Pilaar and I began our studies, with a guided tour from PDO's camp at Azaiba, led by Haremboure and Horstink, and later on our own, based for some weeks with PDO's liaison officer in Ibri.

Vehicles were imported from Europe for our needs, two 3-ton, two-wheel drive Bedford trucks, three Landrover pickups and one Landrover stationwagon, all standard equipment with PDO at that time.

Beck realized that oil was found close to Steinmann Trinity. If this proximity was meaningful in Oman, could it be used to find oil elsewhere in the world? it was a problem for Shell Research (KSEPL) to resolve, and I happened to be the person to whom he turned.

Field Work January – May 1967

Field-work began in earnest in January 1967. We originally planned to work as two 2-man field parties operating from separate tented camps. This proved to be impracticable as we had to give the Sultan, in Salalah, four weeks notice of every camp move (via PDO's General Manager, Francis Hughes, in Muscat). We turned this limitation to our advantage by discussing our major findings over dinner each evening. By this means, we gained an overall knowledge of the mountains and could better appreciate the importance of new evidence, which was emphasised by seeing key outcrops of other team members.

We set up the first of our camps in the Hamrat Duru Range. From there we had reasonable access to the main units: the Semail Nappe, a variety of sections through the Hawasina, and the Maastrichtian to Early Tertiary limestones that overlay parts of the Semail and Hawasina. We began to recognise different sequences within the Hawasina that would form the basis for classification into different formations. Occasionally corrections had to be made to the stratigraphy or tectonic relationships that had been established by PDO geologists, the most important of which was to place the Muti Formation at the top of the Autochthon ('in place') rather than at the base of the Allochthon (i.e. the Hawasina). Other rock units, including the Permian and younger autochthonous sequences of Jebel Akhdar, were studied, especially along the famous section in Wadi Mi'aidin. That first spring, field work was concentrated in and around the central Oman Mountains, from the Semail Gap northwest as far as Wadi Jizzi (Fig. 1). Indeed, our traverse of Wadi Jizzi took about one full day because the track had to be built up in several places to enable the 2-wheel drive Bedford trucks to progress.

For safety in the field, we worked as far as possible with sub-teams of two geologists, each with its own Landrover pick-up, and an Omani helper. The vehicles did not have individual radios but, using a chinagraph pencil, each team plotted its intended route daily on a plastic overlay to an aerial-photo, and contact was maintained with PDO every evening using our base radio. PDO had a duplicate set of photos in case an aerial search ever became necessary- fortunately it was not.

The stratigraphic ages of the rocks collected on field traverses were determined by Mike Hughes Clarke, mostly from microfossils contained in samples we sent him. Mike was based in Doha, Qatar, where PDO's Exploration Department was located until about 1969. Mike found that samples could be sent to him in Doha by empty aircraft returning after a fresh-food supply run to Azaiba. Mike trained an assistant (Rashid) to make thin sections, from which fossil determinations, and thus ages, could be deduced. He would then send back, almost by 'return post', the results of priority samples. These results were not only the age range but, also the likely depositional environment (shallow, open or restricted marine, pelagic or benthic, deep marine, at or below the CCD). Critically, Mike was able to confirm the tectonic repetition of the Hawasina units across the Hamrat Duru Range. Samples were sent to Azaiba on every truck that went there for supplies. Mike eventually studied more than 11,000 thin sections prepared by Rashid and in excess of 2000 more from PDO's files.

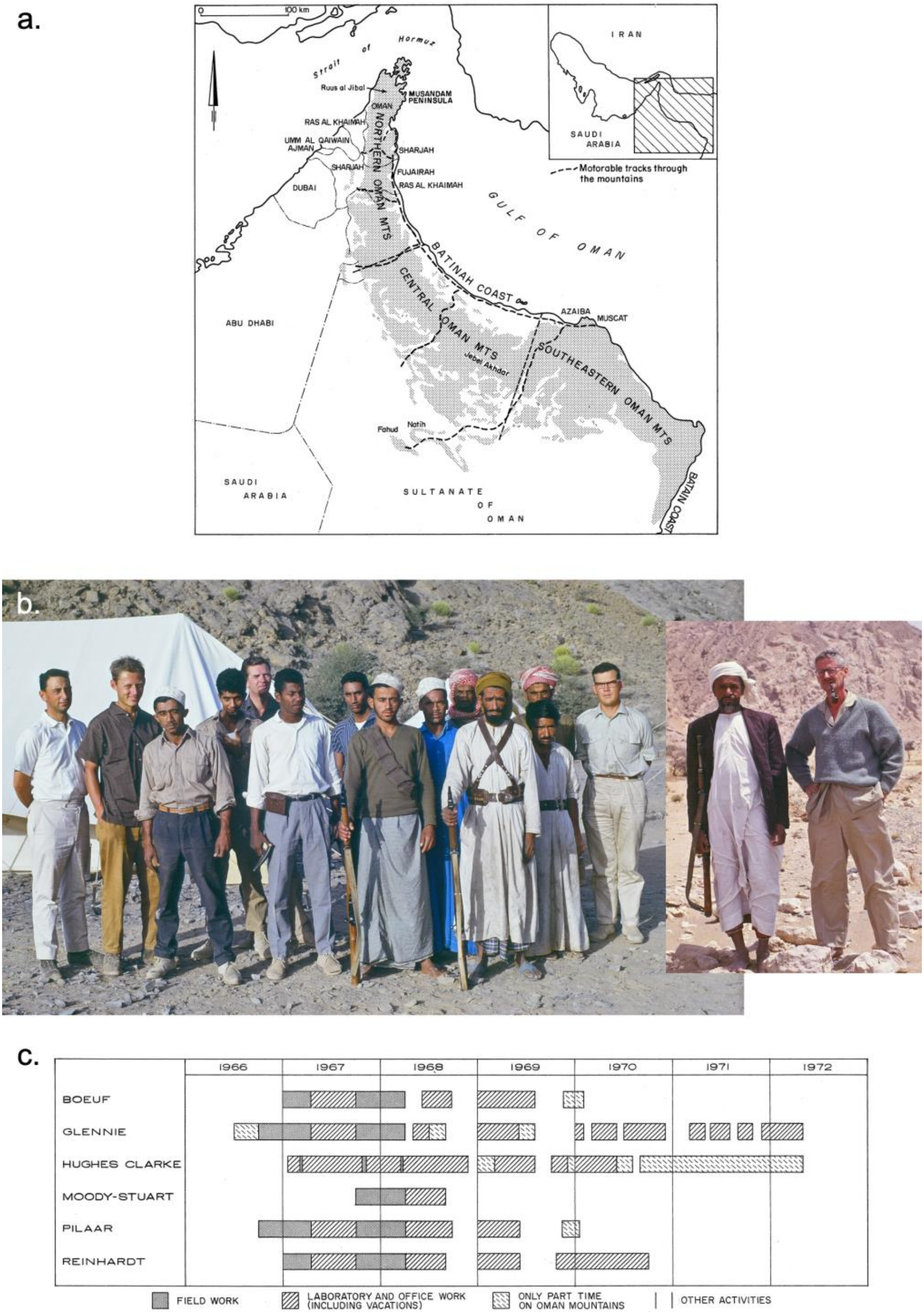
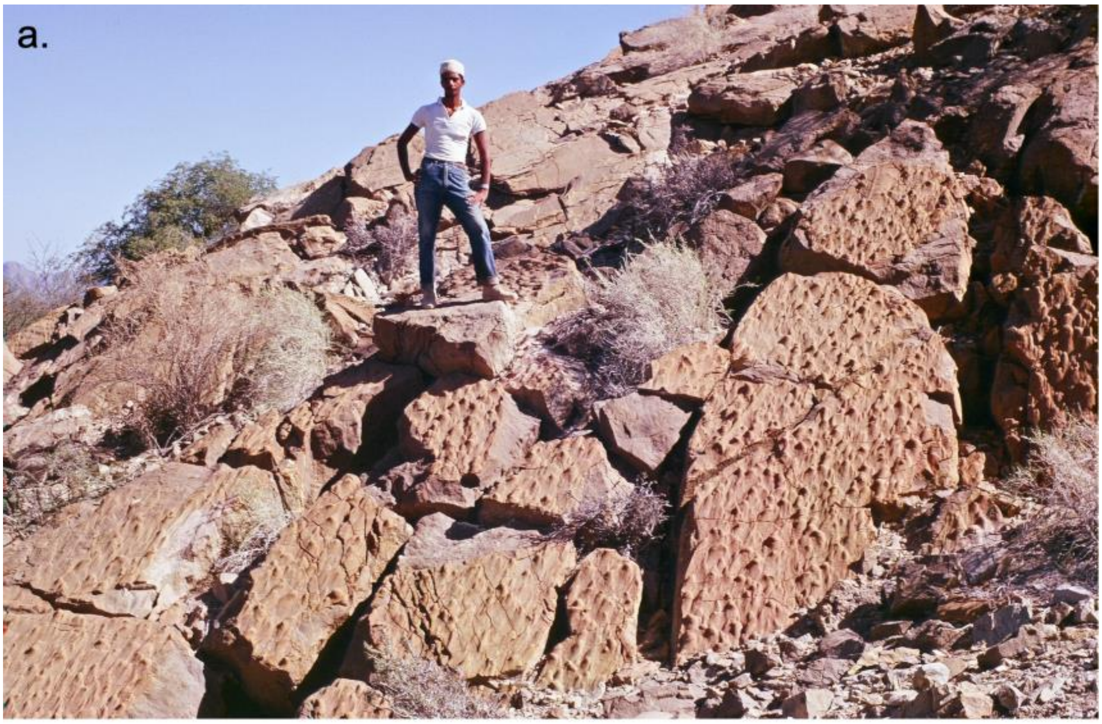


Fig. 1: a) Subdivision of the Oman Mountains (Glennie et al., 1974); b) Oman Mountains mapping team in February 1967. Michel Boeuf at left, Ben Reinhardt second from left, John D'Olier-Lees fifth from left, Pit Pilaar third from right and Ken at right smoking a pipe; c) Employment schedule of Oman Mountains team (Glennie et al., 1974).



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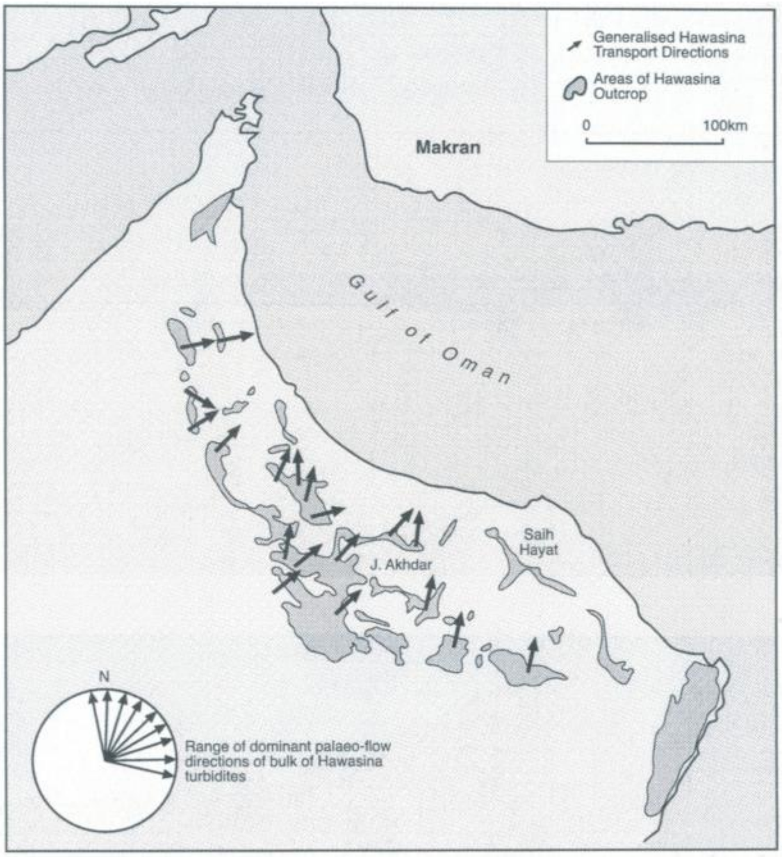

Fig. 2: a) Flute casts on the base of (overturned) grainstone turbidites of the Hawasina Wahra Fm, near Hayyal, December 1966; b) The relatively consistent (offshore) palaeocurrents and deep water interpretation of these deposits were key evidence towards the allochthonous origin of the Hawasina units (Glennie, 2005).

Much of the Hawasina was confirmed as comprising turbidites and, despite their tectonic complexity, the logging of flute-casts and other palaeocurrent indicators pointed to sediment transport to the NE (Fig. 2). With careful logging of the formational units above and below tectonic contacts, it eventually became clear that there was a remarkably consistent order of superposition within the Hawasina and, with one exception, the thickest and coarsest-grained sequences occurred at the base of the tectonic pile and the thinnest and most shaly (or most cherty) at the top. The exception was the shallow-marine Oman Exotics, which overlay the Hamrat Duru Group and which were themselves overlain by the Semail. The Semail Nappe had its own vertical sequence, ranging from peridotites (commonly sheared at the base), through gabbros and diabase dykes to extrusive pillow lavas at the top. This appeared to match what was being described as 'oceanic crust' in the Atlantic and Pacific oceans.

The first field season ended late in April 1967 when the bare rocks of the mountains became too hot to touch by mid-day, making climbing a dangerous occupation. With no suitable summer accommodation available in Oman, the field geologists returned to KSEPL in The Netherlands to study their findings and to prepare an interim report.

After that first field season it became clear that our future studies would concentrate on the comparative development of:

1) The Permian to Cretaceous autochthonous rocks of the mountains,

2) The tectonically complex, but age-equivalent, turbiditic rocks of the Hawasina, which were deposited to the NE, and

3) The Semail Nappe which was somewhat of an enigma. That summer in the Hague, Reinhardt, reading Vine and Mathews' ground-breaking work on mid-ocean ridges, realised that the Semail Ophiolite was probably the product of sea-floor spreading.

Because of the rough terrain, and especially the difficulty of driving through boulder-strewn wadis, it meant that on some days only about four hours of field work could be achieved out of a fourteen-hour day. Thus, in the early summer of 1967, I reported to Beck that, at the present rate of progress, it could take us another 4 to 5 years to complete the mapping. If, however, I had the use of a helicopter we could finish the mapping next field season. Beck was concerned at the possibility of geologists being tied up for years of mapping. Furthermore, PDO had a real interest in our work as they had a major relinquishment to make in two years of about one third of their concession. Could the mountains form a large part of the area to be relinquished? We got our helicopter for the next field season.

Field Work November 1967 – April 1968

In order to keep the helicopter fully utilised, one more geologist (Mark Moody-Stuart) was assigned to the team; and an Arabic-speaking ex-army officer (Mike Brentford) was recruited as camp manager to enable me to undertake more fieldwork. The addition of a helicopter to the field party meant that we had to accommodate and feed a pilot and an engineer, and obtain helicopter fuel from Doha. As a team, we worked seven days a week. Because the helicopter had a radio, we had better communication with the geologists on the ground. Even so, from a safety point of view, no change in plan was permitted unless the helicopter engineer had logged it on the plastic overlay to the appropriate aerial photo and acknowledged the change.

During this second field season, the areas of geological responsibility were divided as follows: Autochthonous rocks of the Oman Mountains – Pilaar, The Hawasina – Boeuf and Moody-Stuart, Metamorphic Rocks and the Semail ophiolites – Reinhardt. I joined all the teams, but gave the greatest support to Pilaar.

Our first camp of that second season was established NE of Ibri (Fig. 3). To enhance each person's appreciation of the overall geology into which their work fitted, apart from daily discussions in camp, each member spent some time in the field seeing the rocks that were the responsibility of others.

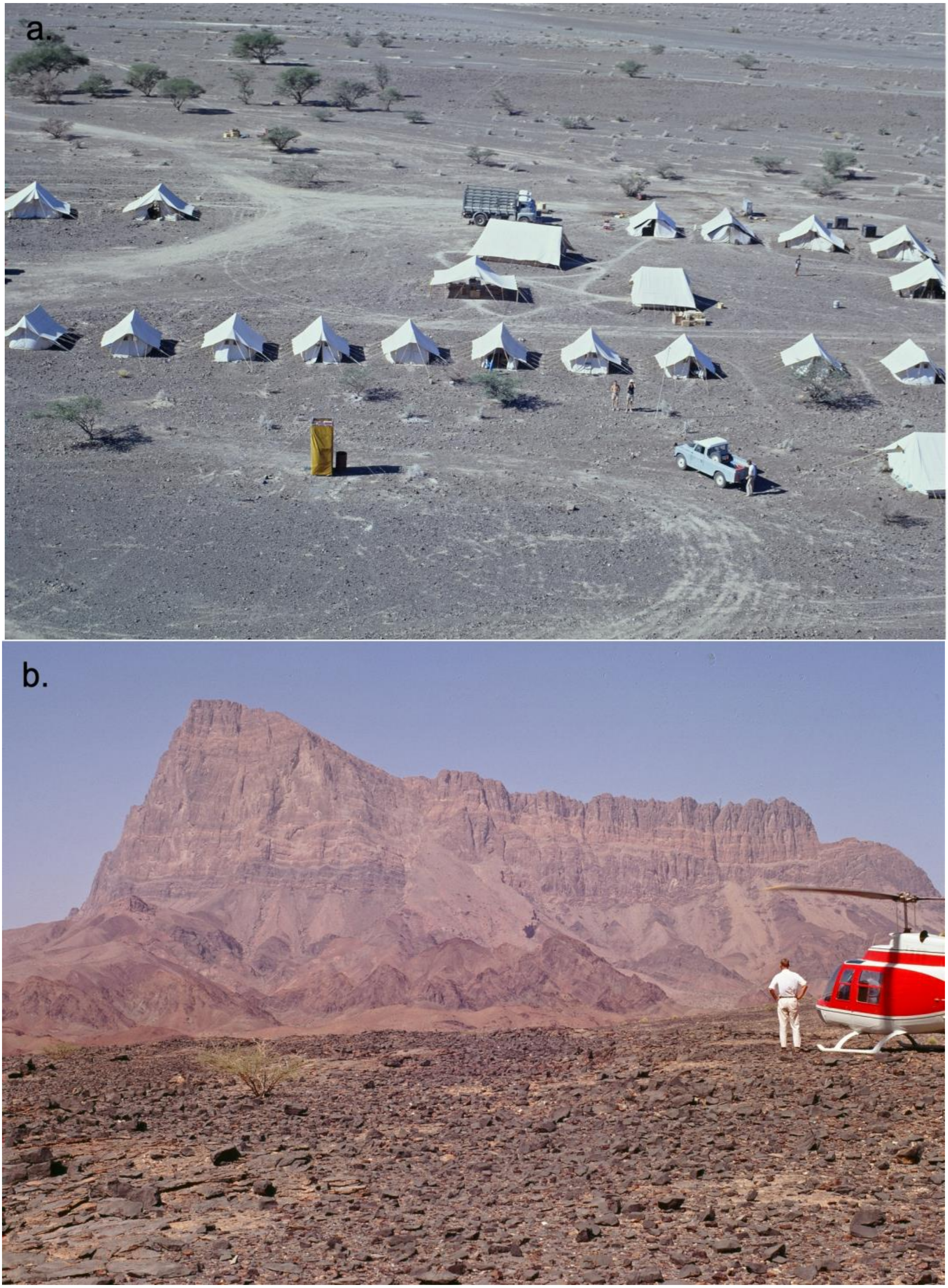

Fig. 3: **a)** Hayyal field camp, NE of Ibri, November 1967; b) The Bell Jet Ranger helicopter dwarfed by Jebel Misht.

With a 5-seater helicopter, in addition to carrying the pilot and a representative of the Sultan (a sheikh who liaised with the local population every time we landed) there were still three more passenger seats available for such 'mixed' parties. And to keep Mike Hughes Clarke in the picture, he paid several visits to the field from Doha.

Later, our operations were extended northward into the UAE, where we set up camp in the Emirate of Sharjah. There, we informed the air force of our daily flight plans as we did not wish to meet a jet flying low through one of the narrow mountain gorges. The Sultan prohibited us from undertaking field work in Musandam because of safety concerns. Pit Pilaar and I did, however, manage a reconnaissance trip to the northern end of the peninsula (beyond rifle range!) to check the photogeological map.

One of the important discoveries of this 2nd season was datable micro-fauna within the inter-pillow spaces at the top of the Semail. This caused a quandary at the time, as Late Cretaceous (both Cenomanian and Coniacian) ages were indicated, which did not fit a presumed pre-Hawasina (Permian) age for ophiolite generation by sea-floor spreading. Our worries were resolved years later by the Open University team, who confirmed a Cenomanian age from further studies of the inter-pillow faunas and by radiometric means.*

A senior Omani was recruited to run the field camp. At each new camp site, John D'Olier-Lees and I liaised with the local sheikh for fresh water, camp guards (the sheikh's honour was at stake if anything went missing) and kitchen helpers. The Omani assistants had their own sleeping and mess tents. Our cook catered for everyone and was supplied by Spinney's, who were PDO's caterers at the Azaiba camp. Initially, this turned out to be a disaster; our first cook was an excellent chapatti maker but has been known to start cooking 'minute steaks' a 3 pm for a 6 or 7 pm dinner – we could almost sole our boots with the results. It was to be another year before we had a good cook. For the start of the 1967-68 field season, the chapatti maker was replaced by an ex-P & O shipping-line pastry cook. He made delicious puddings but could not cook meat. Much to my surprise, my team persuaded him to make a birthday cake for me on the theme of "Desert Sedimentary Environments", a book which was then under review. He became homicidal when suffering from a bout of malaria and had to be sent back to the coast, to be replaced by his brother, an all-round cook who was excellent in every respect – from then on, the last six weeks or so in the field, we fed well.

Our first cook was an excellent chapatti maker but has been known to start cooking 'minute steaks' a 3 pm for a 6 or 7 pm dinner – we could almost sole our boots with the results

* Our attempt at dating the Semail radiometrically via Shell Oil in the USA failed because of insufficient potassium in the sample to obtain an age. [correction- The Cenomanian-Turonian radiolaria in cherts in the ophiolite was first determined by the USGS group (led by Bob Coleman and Cliff Hopson), not the OU group].

Food, fuel (in 44-gallon drums) and any incoming mail were transported from the coast in one or other of our two 3-ton Bedford trucks. The vehicles were maintained by our excellent vehicle mechanic Omar, a Beluch, who I am certain could completely dismantle a Landrover and reassemble it without a misplaced nut, bolt or washer.

Main Geological Results

By the end of the second field season we had reached a fairly firm interpretation on the origin of the main constituent sequences. They comprised one autochthonous sequence (the 'in-place' Hajar Super-Group, and two overlying tectonically-emplaced allochthonous units, the Hawasina and the Semail (Fig. 4).

The autochthonous rocks of the Hajar Super-Group were deposited in relatively shallow water during the Mid Permian to Cenomanian. During the same time interval, the bulk of the of the Hawasina was deposited as turbidites, transported offshore to the NE. The associated sediments of the Sumeini Group were interpreted as having been deposited on a submarine slope that lay between the shallow -marine conditions of the Hajar Super-Group and the deeper marine ones of the Hawasina. The sediments of the higher Hawasina nappes were deposited in both shallow water (Oman Exotics) and deep -water environments over areas which, from the

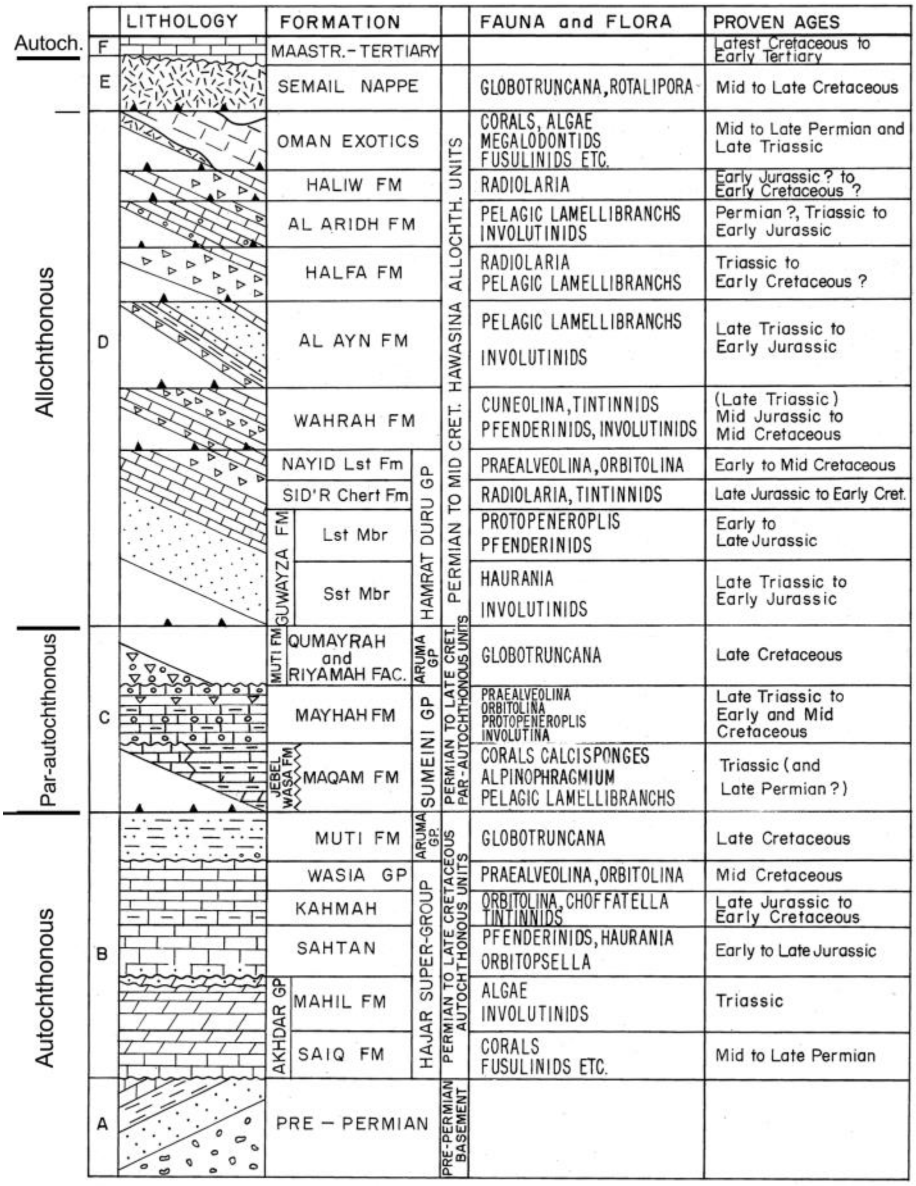

Fig. 4: Stratigraphic and tectonic relationships of the main rock units of the Oman Mountains (and the fossil fauna and flora from which the ages were determined; Glennie et al., 1974).

associated basic igneous activity, could be interpreted as oceanic crust. The overlying ophiolites of the Semail Nappe represented a fragment of former oceanic crust.

The tectonic sequence (stacking order) of the Hawasina formations is systematic. Each formation occupies the same relative position with respect to other formations. If some Hawasina formations are missing because of non-emplacement or tectonic removal, then a formation of higher tectonic position might lie directly on one that occupies a lower position or even directly on the autochthonous rocks of the Muti formation or the Hajar Super-Group.

Because of this systematic order, a reasonable palinspastic reconstruction of the Hawasina nappes can be made by assuming that the higher tectonic units originated farther away from the Arabian continental margin than the lower ones. Since most of the planes of imbrication dip to the northeast, the unfolding of each higher nappe takes place in the same direction. From this simplified reconstruction we deduced that the Hawasina depositional basin must have lain northeast of the Arabian continent during the same time span as the Hajar Super-Group was laid down. The Sumeini Group was deposited closest to the Arabian continental margin, followed to its northeast by the Hamrat Duru Group, and the Oman Exotics were deposited farthest away. It is a corollary of this

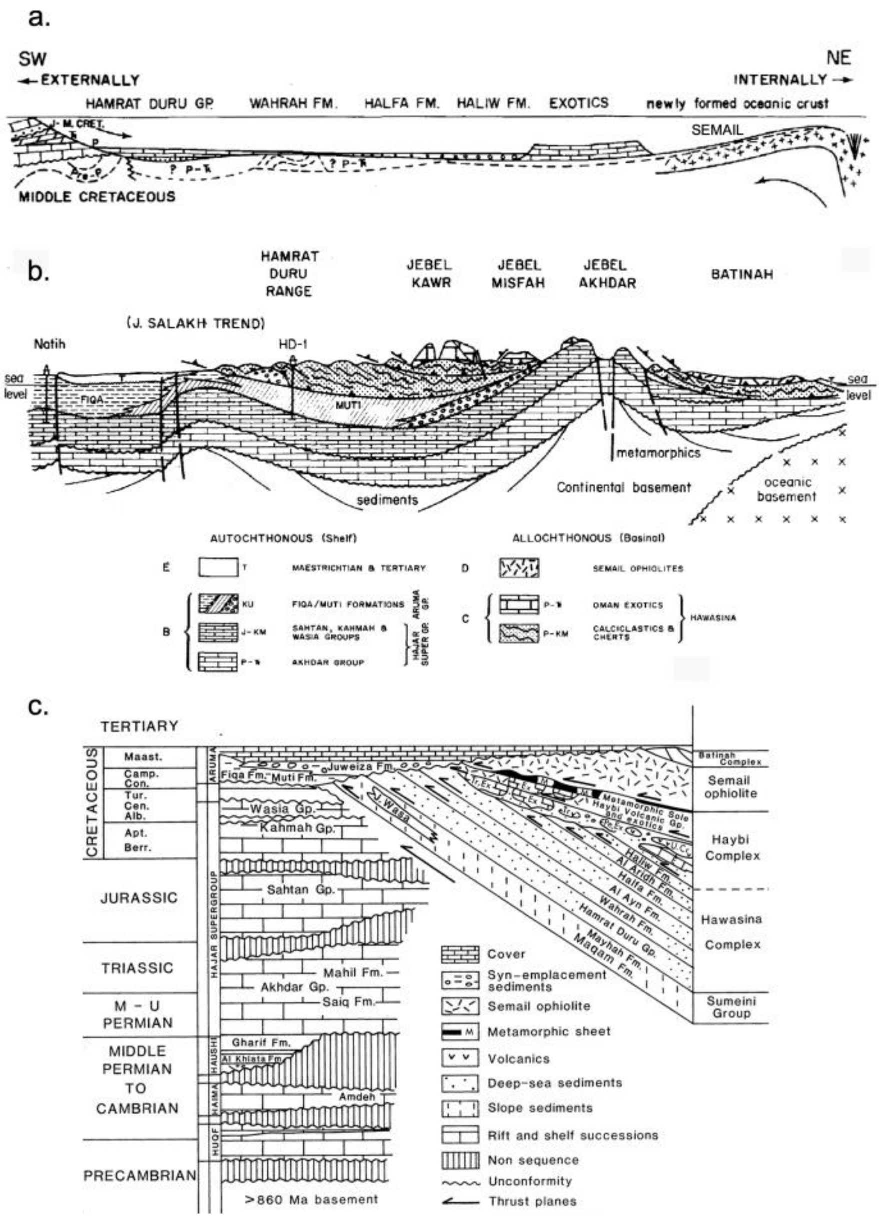

Fig. 5: a) Palinspastic reconstruction of the Hawasina ocean (Neo-Tethys 1) in the Middle Cretaceous (Glennie et al., 1973); b) Schematic cross-section of the plate margin after the obduction of the Hawasina and Semail in the Late Cretaceous. and the uplift of the Oman mountains. HD-1 = Hamrat Duru-1 (Glennie et al.,1973); c) An updated and diagramatic summary of the Oman Mountains 'stratigraphy' from Robertson and Searle (1990; Geol. Soc. Spec. Pub. 49, 3-25).

reasoning to infer that the site of the next higher nappe, the Semail ophiolites, lay beyond the Oman Exotics (Fig. 5a). The Hamrat Duru Group comprises a fairly thick sequence of turbidites that was deposited relatively close to the basin edge. The thinner sequence of the Wahrah Formation was deposited even farther from the basin edge and, apparently, in water not far from the carbonate compensation depth (CCD) of some 4 or 5 km, where it merged with the cherts of the Halfa and Haliw formations.

The Oman Exotics formed isolated carbonate platforms on a volcanically active volcanic substrate close to sea level. At the time we believed that they were deposited either close to a very shallow crest of a spreading oceanic ridge or on volcanic piles associated with a leaky transform fault. The conglomerates of the Al Aridh Formation represent detritus eroded from the Oman Exotics and deposited on their flanks in deeper water, as seen especially on Jebel Kawr. Deposition of the Exotics ceased when the rate of upward reefal growth was unable to compete with the rate of Late Triassic subsidence, and then became current-swept non-volcanic guyots .

The Hawasina sequences are cut locally by basic igneous dykes, and also have some beds of basaltic pillow lavas. These igneous rocks occur within sedimentary sequences dated faunally as old as Mid- to Late Permian but also occur within Cretaceous strata. This is taken as evidence that the Hawasina was deposited within a basin that was floored by oceanic crust. The palinspastic unfolding of the nappes indicates that the area of Hawasina deposition measured some 600 km parallel to the continental edge and at least 400 km at right angles to it (the Red Sea is about twice the length but only half the width).

More Recent Interpretations

In the autumn of 1968, the KSEPL team undertook two months field work in the Makran of Iran to study, what we thought was, the other side of our Hawasina ocean. What we found was that not only was the geology much more complicated than in Oman, but there seemed to have been two oceans separated by a long microcontinent (the Sanandaj-Sirjan Range). The northern extension of the Hawasina ocean, was eventually christened Neo-Tethys 1 and the other ocean which opened later, Neo-Tethys 2. The southern extension of Neo-Tethys 2 may to be represented in Oman by the Umar Group and the Sanandaj-Sirjan possibly by the Ordovician Rann Quartzites of the Dibba fault zone and the Oman Exotics of the Kawr Group.

As already mentioned, another major advance in interpretation was the recognition by Open University geologists that the Semail ophiolites were generated during the Cenomanian by back-arc spreading– this explained the Cretaceous age of our interpillow faunas.*

* The OU group were the first to suggest the ophiolite formed above a subduction zone dipping NE (there is no real 'arc' per se). This came about because of the geochemistry indicated a boninite or arc-tholeiite origin of the lavas (Julian Pearce and co), and the metamorphic sole amphibolites were formed from subduction of older basalts (Haybi complex) to depths of >40km at the same time as the ophiolite crust was forming (Searle, 2019, Geology of the Oman Mountains, Eastern Arabia. Springer, 478p.].

Other important interpretations leading to our present understanding of the origins of the mountains include:

- ◊ The recognition that *subduction* was an important process at converging plate boundaries and that the hanging wall of subduction trenches could be *obducted* onto continental margins.
- ◊ The uplift of the Oman Mountains (with its constituent obducted sequences and underlying autochthon) has occurred in the past few million years due to the opening of the Red Sea and the ensuing continent-ocean collision (Fig. 5b).
- ◊ What still has to be determined is the influence Neo-Tethys 1 and ensuing obduction had on the depositional and erosional history of interior Oman (e.g. possible creation of source and reservoir rocks) and of its hydrocarbon resources.

Acknowledgement

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A Honorary GSO member and a geologist who is considered by many as the father of Geology of Oman.

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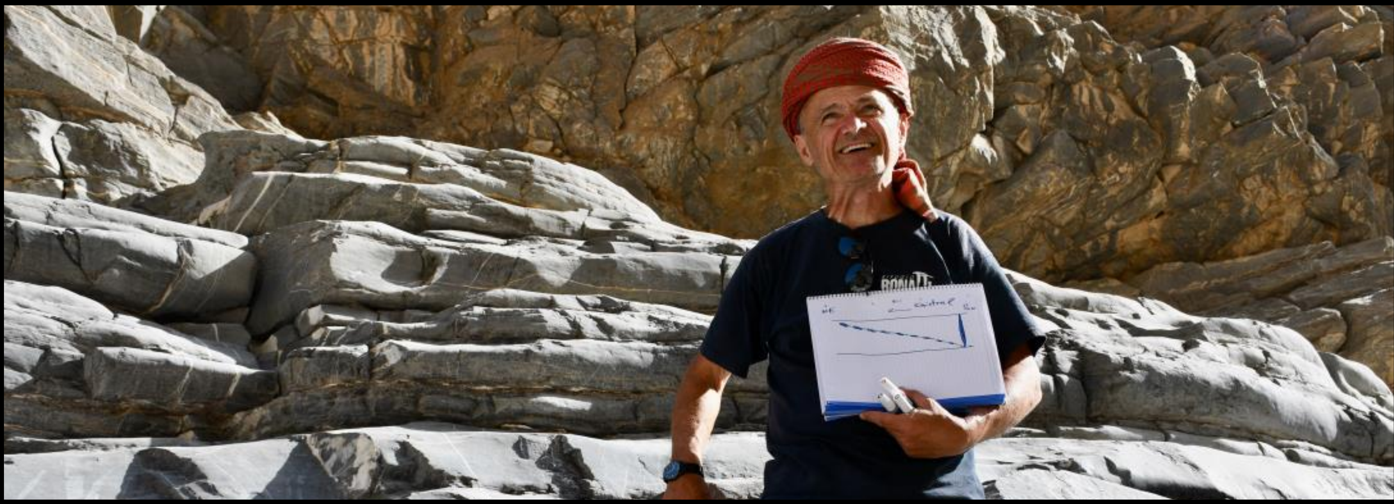
A Honorary GSO member and a geologist. Alan is one of the very active members of the GSO.



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LOW-POROSITY LAYERS ENCLOSING THE LOWER CRETACEOUS LIMESTONE RESERVOIRS OF ARABIA

By : Stephen N. Ehrenberg

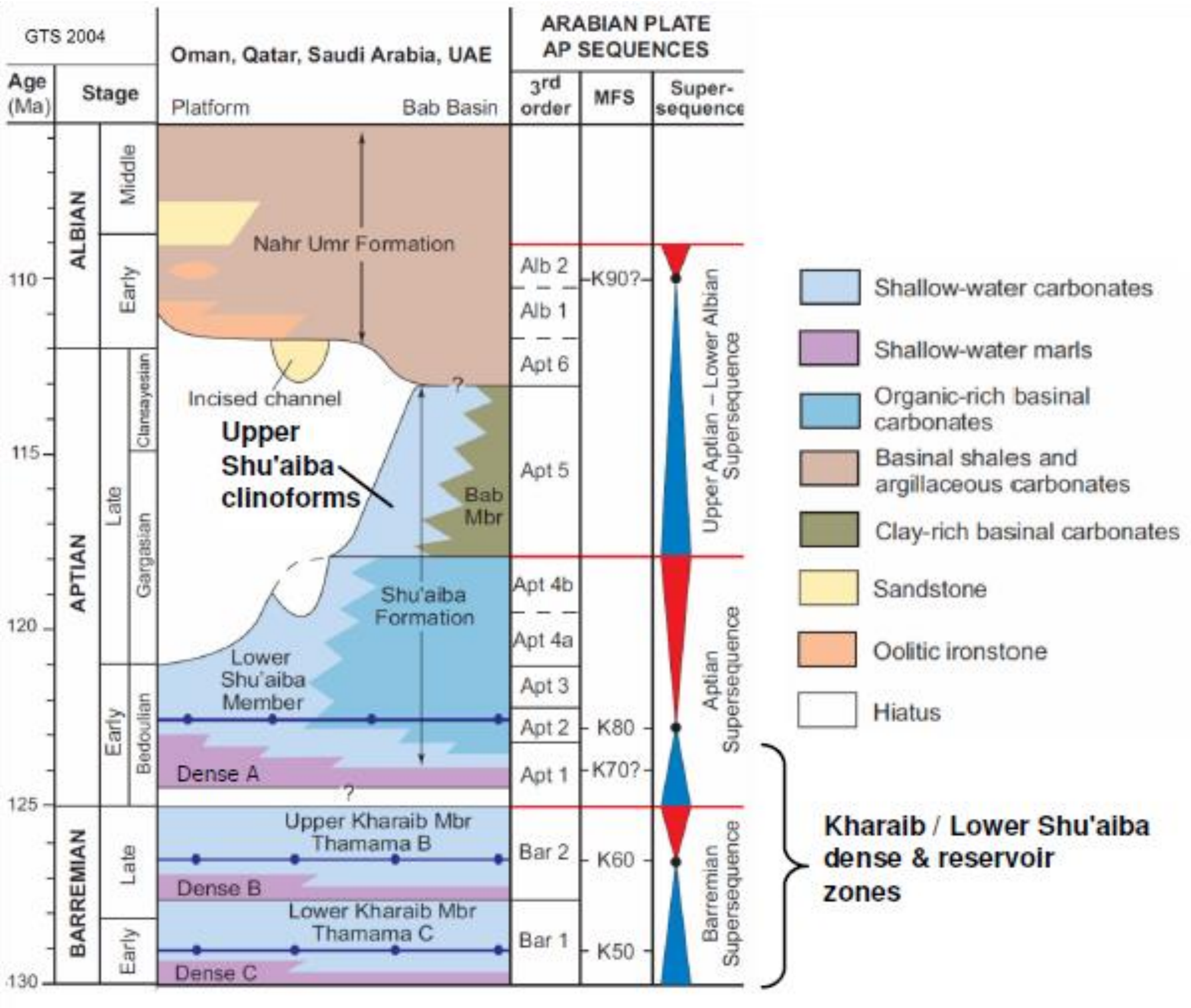

Fig 1. Chronostartigraphy of the studied intervals. Modified from van Buchem et al. (2010).

Lower Cretaceous limestone reservoirs are important oil produces in the countries of the Arabian Gulf. Study of the factors defining the limits of these high-porosity intervals is of both economic and scientific interest. Recent research projects focused on the Upper Shu'aiba Member (late Aptian age) in Oman (Al Habsi et al., 2014; Al-Tooqi et al., 2014) and the Kharaib Formation (Barremian to early Aptian age) in Abu Dhabi (Ehrenberg and Wu, 2019) have provided new knowledge of the depositional and diagenetic processes common to the low-porosity layers that enclose the producing zones (Fig. 1). In both studies, thin sections and bulk-chemical analyses were acquired from the same locations in well cores that were used for conventional core analysis of porosity and permeability. Although holding no oil reserves, the low-porosity zones are important elements of reservoir architecture and essential components of any sequence stratigraphic interpretation.

Upper Shu'aiba Argillaceous Zones. Several small oilfields in northern Oman produce from Upper Shu'aiba limestones that were deposited as the Bab intrashelf basin was infilled by a series of around 20 low-angle clinoforms. Each clinoform onlaps and terminates against the previous clinoform and thins towards the basin center. Each clinoform comprises a transgressive basal "argillaceous zone" of low-porosity limestone and an overlying highstand "reservoir zone" of clean, porous limestone (Fig. 2).

The lower porosity of the argillaceous zones is believed to be caused by their higher content of detrital clay, as evidenced by the overall inverse correlation of porosity with bulk-rock alumina in the samples analyzed (Fig. 3A). X-ray diffraction analyses show that each 1% bulk alumina content corresponds with approximately 4% total clay content in these strata. Figure 3A does not show a linear relationship, but the range, maximum, and average porosity values decrease as alumina increases.

Kharaib Formation Dense Zones. So-called "dense zones" (intervals of very low porosity) separating thicker, high-porosity reservoir intervals in Lower Cretaceous limestone strata in the Abu Dhabi subsurface were studied in cores from a giant onshore oilfield. The two dense zones enclosing the upper, ca. 50-m-thick Thamama-B reservoir zone of the Kharaib Formation have similar ranges of bulk chemical composition, with higher aluminum, iron, potassium, thorium, and uranium than the intervening reservoir zone, but are very different from one another in depositional texture. The upper "dense-A" zone (Hawar Member) consists mainly of peloid–orbitolinid packstone deposited in current-agitated, shallow water, whereas the next-lower "dense-B" zone consists mainly of mudstone deposited below wavebase, possibly at depths of several tens of meters, although comparison with the range of water depths represented by the reservoir zones is problematic because of the higher turbidity and nutrient levels inferred for the dense zones. Organic matter is generally low (average 0.2–0.3 wt. % total organic carbon), consistent with intense bioturbation throughout both dense zones. Unlike the reservoir limestones, both dense zones contain abundant pyritized ("blackened") grains, indicating widespread local reducing conditions, possibly within burrows, with subsequent mixing with more abundant non-pyritized grains in the oxygenated conditions of the overall depositional setting.

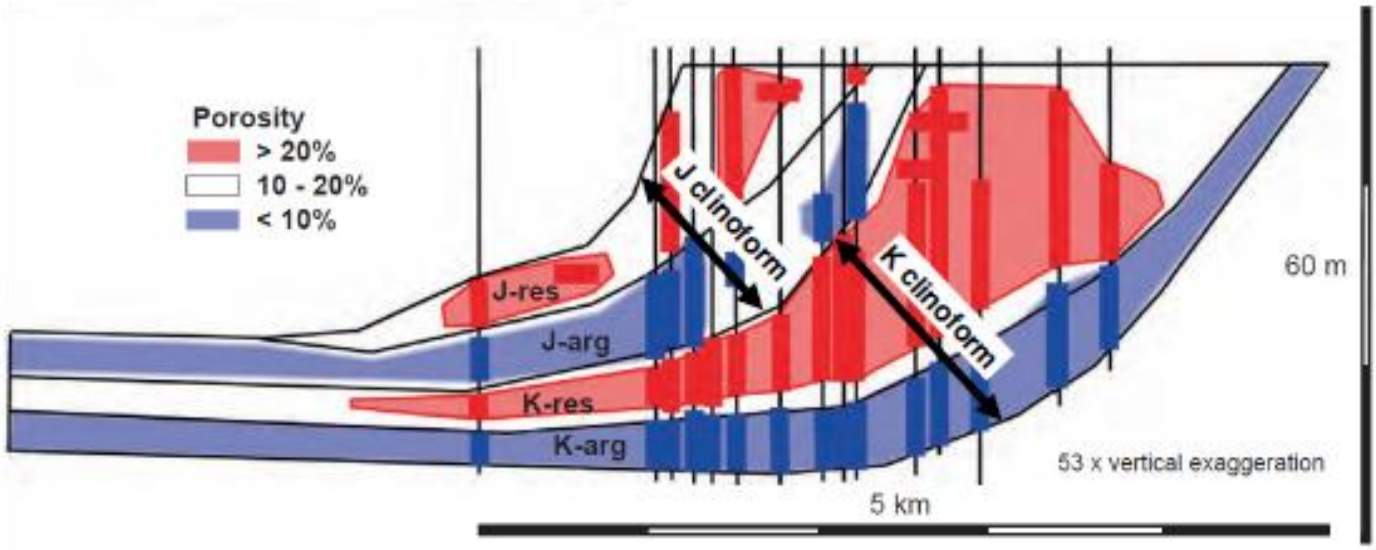

Fig 2. Restored cross section of two Upper Shu'aiba clinoforms from basin margin (right) toward basin center (left), showing positions of wells used for porosity mapping (vertical lines) projected laterally along strike into section. Reservoir zones ("J-res" and "K-res") have higher porosity than the argillaceous zones ("J-arg" andK= K -arg") in each clinoform, From Al Habsi et al. (2014).

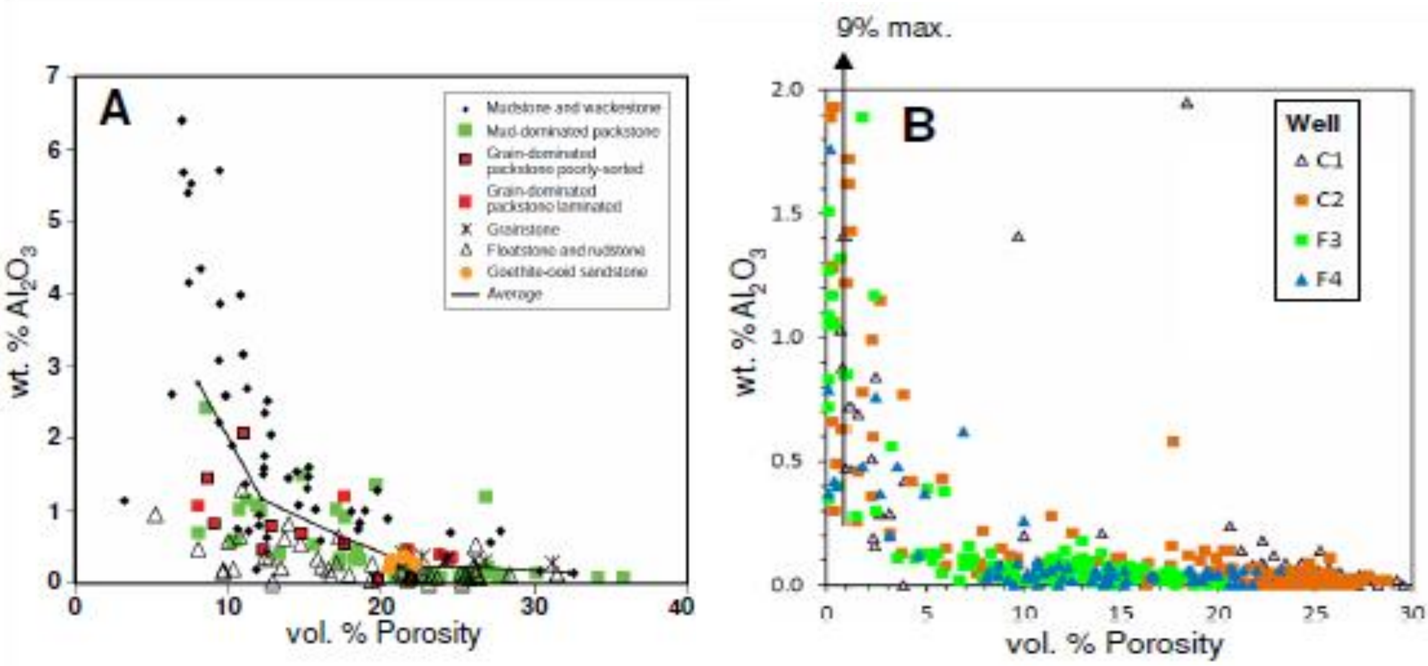

Fig 3. Bulk-checmical analyses of alumina versus porosity measured on one-inch plugs from the same core depths. A) Upper Shu'aiba Member of Oman, with plot symbols indicating lithofacies, From Al Habsi et al. (2014). B) Upper Kharaib Formation of Abu Dhabi, with plot symbols differentiating reservoir-zone samples from four wells in an onshore oilfield. The dense zones above and below the reservoir have average porosity of 0.9% and alumina content ranging from 0.2 to 9 wt.% (black arrow). From Ehrenberg et al. (2018).

The dense zones had high porosity when deposited, but must have lost this during early burial (before oil began filling the structure at around 1 km depth; Oswald et al., 1995) because they have no oil staining on the crest of the field. Also, dense-zone thickness and porosity do not vary between the crest and flanks of the field, whereas the reservoir zone is about 7% thicker and has 36 relative % higher porosity on the crest of the field (Ehrenberg et al., 2016). Porosity and reservoir thickness in this and many other Middle

East oilfields are higher on the crest than on the flanks because of inhibition of chemical compaction and associated calcite cementation by emplacement of oil predating a major portion of porosity loss during burial diagenesis (Litsey et al. 1983; Oswald et al., 1995).

As with the Upper Shu'aiba argillaceous zones, early porosity loss in the dense zones is attributed to their content of detrital clay. Porosity in the reservoir zone shows overall inverse correlation with bulk-rock alumina (Fig. 3B), with the dense zones much more aluminous (average 2.0 and 3.0 wt. % Al_3O_3 in dense-A and dense-B, respectively, compared with only 0.01 % in the reservoir zone). A small amount of clay (corresponding with as little as 0.5 wt. % alumina) appears to have had a much more severe effect on porosity loss in the Thamama-B zone (Fig. 3B) than in the Upper Shu'aiba strata (Fig. 3A). This may be because the studied Thamama-B reservoir is more deeply buried (9000 -9760 ft; Ehrenberg et al., 2016) than the Upper Shu'aiba reservoir (4590-4920 ft; Al Habsi et al., 2014), with correspondingly greater opportunity for clay to have facilitated burial diagenetic porosity loss.

Why Clay Affects Carbonate Porosity. The association between depositional clay and reduced porosity in carbonate strata has been known for a long time (Choquette and James, 1987). Clay tends to promote porosity loss two ways. Firstly, early mechanical compaction may be enhanced by the effect of dispersed clay on reducing the frequency of cemented contacts between carbonate mud particles and between grains. Secondly, illitic clay surfaces may facilitate "pressure dissolution" of adjacent calcite surfaces by locally increasing calcite solubility, resulting in porosity loss by the precipitation of the dissolved calcite in surrounding pore spaces. This effect has been demonstrated experimentally for quartz (Kristiansen et al., 2011), and similar influence can be expected for calcite. Clay-lined stylolites and wispy seams are abundant in both the Upper Shu'aiba limestones and the Kharaib dense zones and are a plausible source for the calcite cement filling former macropores, as well as the calcite microcement that is seen to be abundant in scanning electron micrographs.

Stratigraphic Control of Clay Deposition. The pulses of Upper Shu'aiba clinoform progradation are believed to represent cycles of glacio-eustatic sea-level fluctuation of 400–500 kyr duration, with the argillaceous zones representing the early transgressive part of each cycle. The alternating dense zones and reservoir zones of the Kharaib and lower Shu'aiba formations represent much longer cycles of 2-3 myr (van Buchem et al., 2010). The dense zones are generally regarded as representing the early transgressive systems tract of each third-order sequence, but Ehrenberg and Wu (2019) suggested that the dense-A zone can rather be interpreted as the late highstand systems tract, in other words, immediately preceding rather than following the third-order sequence boundary. In any case, the peak times of clay supply for both Upper Shu'aiba clinoforms and Kharaib sequences are closely associated with falls in sea level.

The higher clay influx at these times may result from both greater exposure of land areas and changes in climate favorable to transport of fine siliciclastics onto the epeiric platform, for example, higher wind velocities or increased seasonal rainfall. Alternation of siliciclastic and carbonate sedimentation linked to sea level fluctuations is in general known as reciprocal sedimentation (Wilson 1967) and has been documented in many settings. Another possible explanation for the higher clay and uranium contents of the argillaceous and dense zones is that these intervals may have had much slower rates of sediment accumulation than the intervening reservoir zones, perhaps due to depressed carbonate production during these times.

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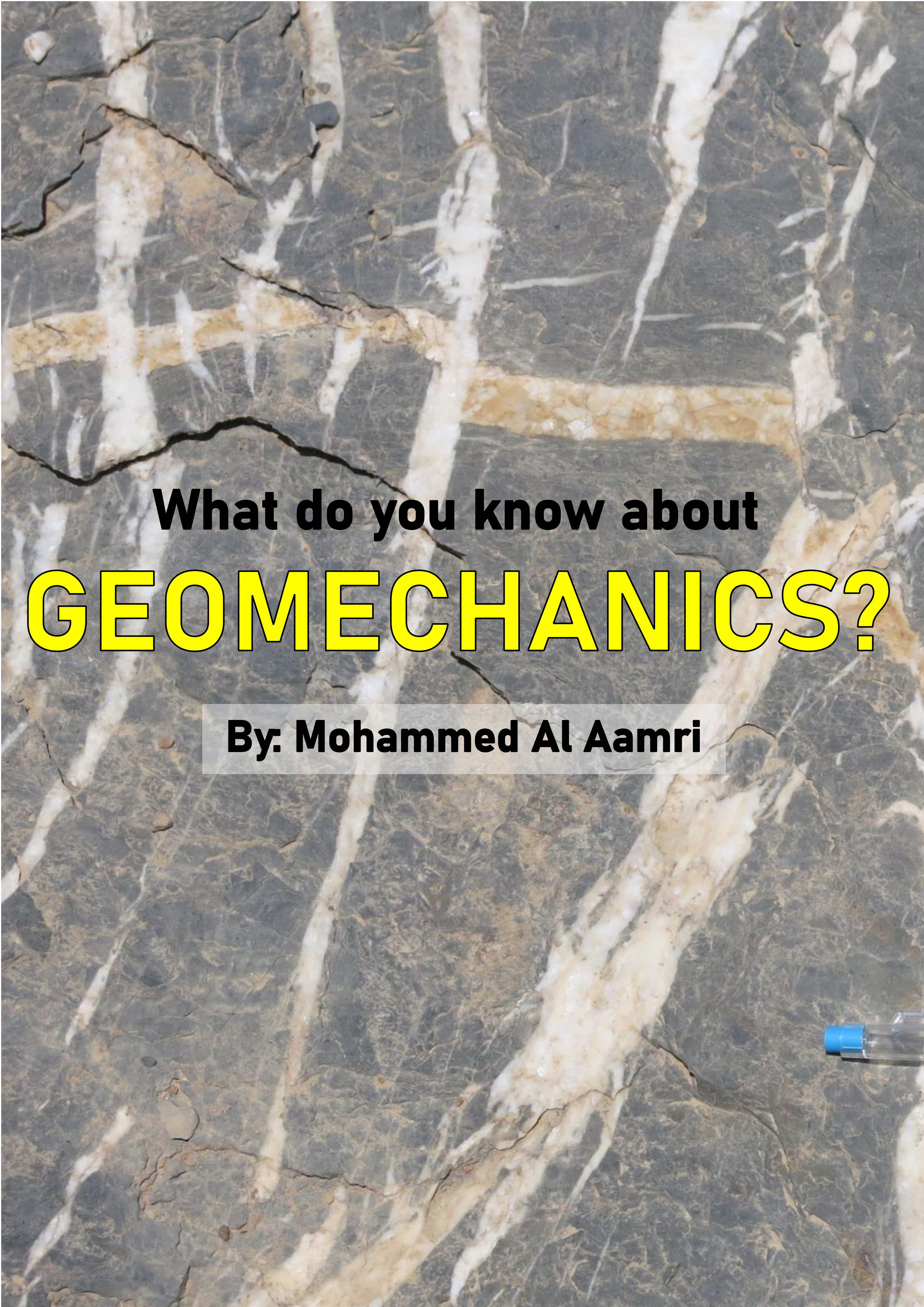

What do you know about

GEOMECHANICS?

By: Mohammed Al Aamri

Geomechanics is a theoretical and applied science that studies the mechanical behavior of rocks, either in reservoir layers or in the surroundings. Geomechanics is applied throughout oil and gas phases, starting from exploration activities to abandonment phase (Fig 1). It is vast in its applications and across all scales, from small scale as well scale (for example: drilling operation) and to as large as field modeling scale (for example: compaction and subsidence). Furthermore, it can be applied in open hole drilling activities and fault and fracture development.

It is a relatively new discipline, but one that is becoming increasingly important, particularly within these days where E&P industry are having more challenges in deep reservoir to understand the rock behaviors.

The main role of Geomechanics is to minimize the risks and/or to maximize benefits resulting from oil and gas exploration and production operations, such as drilling, hydraulic fracturing, etc.

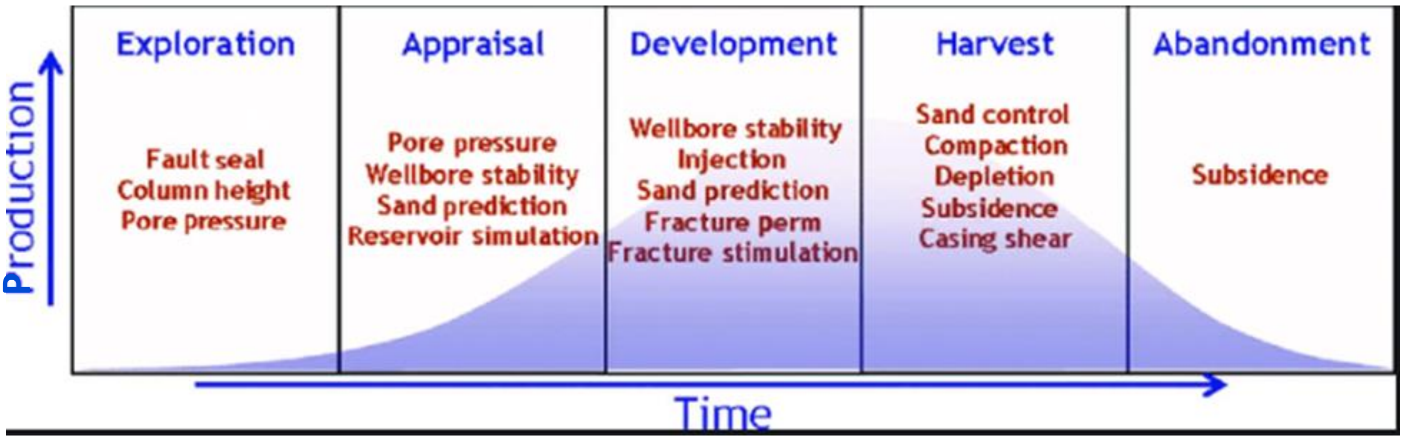

Fig. 1: Geomechanics through the life of a field (courtesy of Barton and Moos, 2008 AQ10)

As we know, the different subsurface layers are subjected to stress resulting from natural activities which are affected since deposition to present day. Each type of rock characterized by its own strength based on several factors. In addition, strength properties are subjected to different changes through the time. Consequently, stress cannot be the same everywhere at one time.

Understanding that the stress and strength of subsurface are in a state of balance. Exploration and development practices such as drilling, fracturing, hot or cold injections may theoretically change this balance. However, if the stress that subjected to material (e.g. rocks) should exceed the material's strength, this may leads to equilibrium or balance changes and failure (deformation) which will results from such changes. The task of Geomechanics is to predict when and how this equilibrium will be changed, or in other words, what the possible risks (e.g. collapsing during the drilling, compaction related depletion. etc) and/or opportunities associated (for example, Hydraulic fracturing) with this alteration.

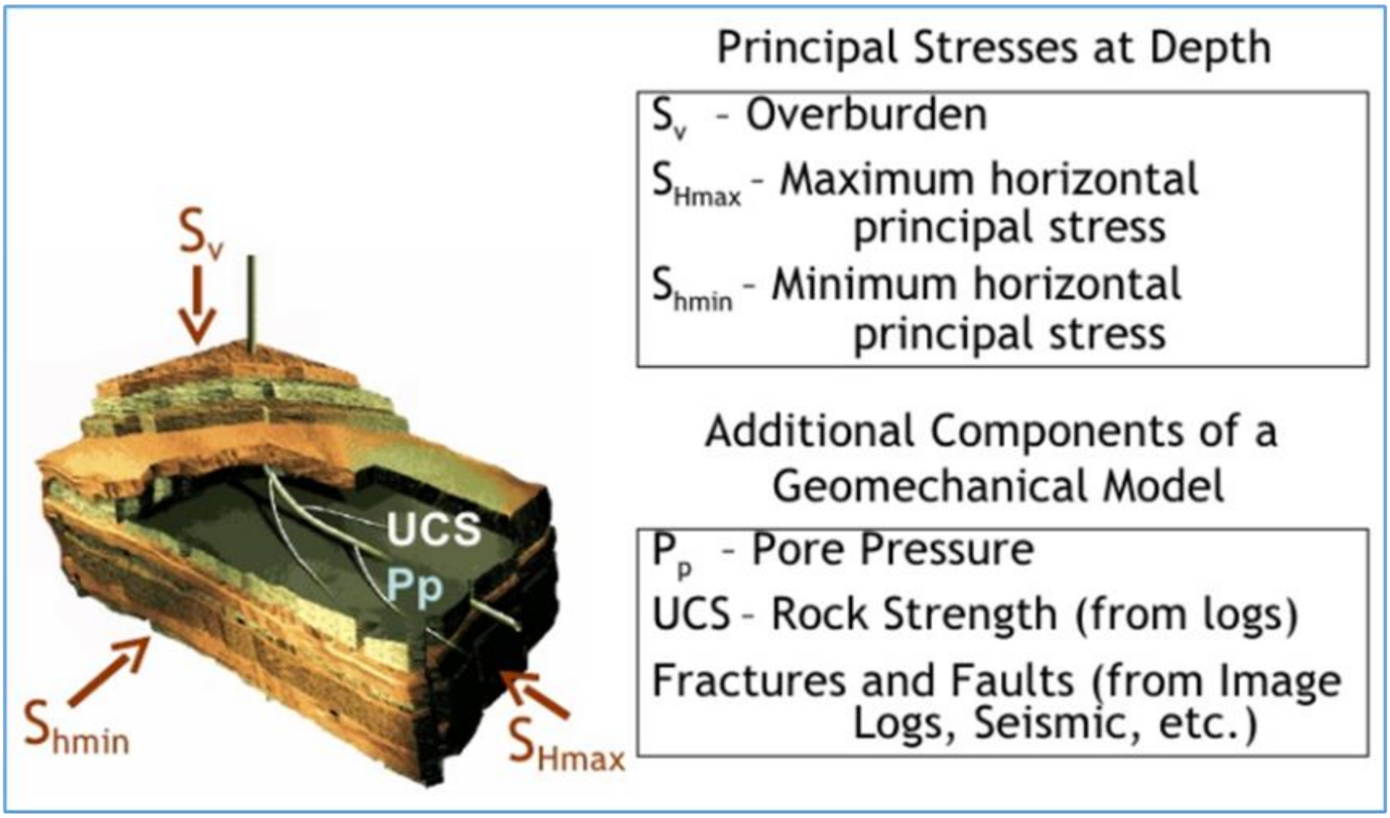

Fig. 2: *Essential aspects for GEOMECHANICS Model (Ref: Baker Hughes (GMI) slides)*

To build any geomechanical model/evaluation, three aspects are crucial to understand (Fig 2). First, determining both the magnitude and direction of applied stresses of the layer are very vital. For sake of simplicity, Overburden stress, two horizontal stress (Min and Max) are the main stresses that are within subsurface. In addition, the geomechanical properties of the rock are important to define the strength of the rock. The last aspect, which require in the geomechanical characterization is the pore pressure profile. How we can define and determine these aspects is out of this article context. For more details, refer to references below.

Applications

Applied Petroleum Geomechanics gives petroleum engineers a much-needed resource to tackle today's advanced oil and gas operations. Here, we list some of Geomechanical applications in oil and gas industry through the field life (See Fig. 1)

1. In situ stress characterization and rock mechanical evaluation
2. Borehole Stability
3. Sand Production Prediction
4. Hydraulic Fracturing (conventional and unconventional)
5. Safe operating pressure and temperature envelopes for primary, secondary or tertiary fields developments to avoid:
   A) Subsidence or surface uplift
   B) Fault reactivation
   C) Tremors (seismicity)
   D) Well integrity issues

Conclusion

Geomechanics has come a long way in recent years, and its implementation has become an essential component of increasing performance, protection and cost reduction. It is gradually incorporated into the workflows of operators and is now an integral part of the process of efficient growth, production and eventually abandonment of reservoirs.

For more information about Geomechanicss, refer to these references below:

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https://www.geoexpro.com/articles/2019/05/an-introduction-to-GEOMECHANICS

Mohammed AL-Aamri

A geologist working as a Geomechanics specialist in the Field Development Centre in Petroleum Development Oman PDO.

PHOTOS FROM GSO MEMBERS

WHO:
Mazin Al Salmani, a geologist from Oman

WHERE:
Qarat Al Kibrit Salt Diapir

WHAT:
An iPhone XS max camera

A spectacular outcrop of Precambrian evaporites salt (lower part) and anhydrite (upper part), in Qarat Al Kibrit. This photo was taken during a field trip organized by GSO to learn more about the prolific Precambrian Ara intra-salt carbonate reservoirs. Qarat Al Kibrit has very important value to understand the subsurface geology and also for understanding the history of the ancient civilization in Oman as they were extracting the salt for the local uses and for exportation.

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