1001 Million Saharan Nights: The Amazing Geological Story of Southern Libya

PETROLEUM GEOLOGY OF SOUTHERN LIBYA

A film by
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FILM SCRIPT

START FILM 1: **Part 1: INTRODUCTION**	*(Subtitle: „Tripoli, 1981")*
	Tony, you know I always liked your work. You are one of our best explorers. - But this here, is simply over the top. A waste of time. You are hunting a phantom, a complete illusion. If we were a company producing, let's say sand – great. There is plenty of it down there. But as you may remember – we are looking for oil. So better forget about the south of Libya. The Ghadames Basin hasn't worked too well. So why should Murzuq work – the two basins are very similar as you know. And even if you were to find something: Are you going to pay for the 800 kilometres of pipeline yourself? And Kufra!? You are kidding me? You may find more oil on the moon than in Kufra! Everybody knows that there is no source rock in Kufra! No, no my friend. We will keep staying in the Sirte Basin! A great place!. Dozens of big oil fields, close to the coast, plenty of infrastructure, a superb Campanian source rock. Therefore as of today I have transferred you to the Sirte group. And please. Do me a favour: Forget about the south of Libya!
	Text screens: *"In the mid 1980s Rompetrol discovered a total of six oil fields in the Murzuq Basin.* *The largest of these fields has more than one billion barrels of oil in place"* *"In 1997 Lasmo discovered the giant Elephant oil field in Murzuq"* *"In 2000 the hot shale source rock was found in the Kufra Basin"*
	It's quiet in the Sahara. Frighteningly quiet. When the wind rests, you start loosing your senses. You can see the desert, yes, touch it. ---- But you cannot hear it. Just you, sand, the barren rock. --- And nothing else. No sound. And whole decades without rain. There are few places on earth that are more arid than the Sahara. And it's hot. ----- Up to of 50° centigrade in the shade - if you find shade. And it's large. ----- The world's largest hot desert: 9 million square kilometres. About as large as the United States.
INTERVIEW Jonathan Craig	*Probably the biggest challenge for exploration today in the southern Libyan basins is that it is still an extremely remote area. It's a long way from facilities. It requires time and effort to get into the field in order to be able to acquire data, to understand the geology. So simply from a logistics point of view it remains a significant challenge.*
	Somewhere out here, hidden beneath rock and sand are oilfields.
	There are various techniques for finding oil. Some more, some less successful. *(throwing darts on a Libya map, rolling dice, fortune teller)*

	This film concentrates on the most successful of all techniques: Understanding the geology behind the oil.
Part 2: GEOLOGICAL FRAMEWORK SOUTHERN LIBYAN BASINS	
	Southern Libya is dominated by two sedimentary basins, the Murzuq Basin and the Kufra Basin. Each of these basins is as large as Germany - or California. Parts of the basins also extend into northern Niger, Chad and Sudan. The two basins are separated from one another by the Tibesti Mountains. Other basin boundaries are formed by the Djado Plateau, the Hoggar, Gargaf Arch, Jebel Dalma, Jebel Aweinat and the Ennedi Mountains.
	Like many other Saharan basins, the Murzuq and Kufra are Palaeozoic sag basins. The first sediments were deposited here already during the late Cambrian, in some areas even as early as the late Neoproterozoic, the so-called Infracambrian. Since then, several kilometres of Phanerozoic strata have accumulated in the Murzuq and Kufra basins, of which up to 4 km are preserved today. Sandstone and shale, shale and sandstone. Hardly any carbonates.
	Geologists working in southern Libya must consider themselves fortunate because every single stratigraphic rock unit comes to surface somewhere where it can be studied in detail. The strata form concentric rings around the basins, monotonous belts, some 100s of kilometres long. In places the rocks are eroded away but then they are re-appearing not far away in another belt. The oldest strata lie at the basin edge, younging progressively towards the basin centre. As in every syncline. Jurassic to Cretaceous continental sandstones cover the large central parts of the Murzuq and Kufra basins. The structural tilt towards the basin interior created the typical Saharan cuesta morphology at the basin margins: Ridges made of Palaeozoic sandstone and valleys underlain by soft shales. Once you are familiar with the characteristics of the various geological units, you will hardly need a geological map again: Just follow the outcrop belts and you will find your way around. Mapping the geology of southern Libya for the first time in the 1920s must have been a real pleasure. And a big adventure, too.
INTERVIEW Klitzsch	*The first phase of exploration in Libya, especially in southern Libya began with the … Italians, in other words during the colonial times. And the pioneer of that time was Desio. Desio divided the Mesozoic from the Palaeozoics and the basement, Precambrian. And within the Palaeozoic, Desio did some subdivision. But this of course was very preliminary. …*
	Professor Ardito Desio was clearly in love with the Sahara. Between 1927 and 1975 he managed to publish 120 papers on the geology of Libya. Many of the formations he defined at the time are still being used today. Among these the prominent Tanezzuft and Akakus formations of the Silurian.

	After a hiatus associated with the Second World War and Libya's Independence, systematic fieldwork in southern Libya resumed in the late 1950s. International oil companies had picked up blocks in the Murzuq Basin. Management sent out some brave, young, men to go out to the desert and study the rocks. One of these second-generation pioneers was Eberhard Klitzsch, working for Dea at the time.
INTERVIEW Klitzsch	*I began to work in Libya in early 1959. …This was an extreme challenge for me because except for some fieldtrips I never was out of Germany before. And found myself … in southern Libya, in Dor El Gusa. It was extremely interesting within the first weeks to see practically any stratigraphic unit from late Precambrian up to Tertiary. Including practically every formation which you can imagine. Because I had some idea about palaeontology and I had my index fossils of North America with me I was able to divide all the strata from… Ordovician and Silurian strata … up to the Tertiary, to the Paleocene and Eocene. And this was within a few square miles. Northern Dor El Gusa and surrounding. So this experience to find out that even as a young geologist in an area which is not really explored to do geology from scratch from the base and also find out that the structural developments had changed during the history or during the time between the Cambrian and Tertiary several times … …*
	Klitzsch published his results about Dor El Gusa in the early 1960s, around the same time as the French geologist Jacqué who in parallel had also studied the eastern Murzuq margin for the Compagnie Française des Pétroles. Even today, these two publications remain the only comprehensive geological descriptions from this area. In the following 4 decades the eastern Murzuq margin was essentially forgotten. Only a handful of geologists have visited this remote area afterwards. Today, air-conditioned 4-wheel drive vehicles and satellite navigation have lowered the logistical hurdle for fieldwork in the Sahara. It is nearly unthinkable for modern geologists how to navigate in the desert without GPS. Today we plot our GPS trackpoints in real-time on high resolution satellite images or geo-referenced geological maps. Satellite phones transmit your location to any place in the world within seconds. But how was it in the early days of southern Libyan exploration?
INTERVIEW Klitzsch	*The only map we had was the aeronautical chart. And of course Desio's geological maps. And the guidelines on his geological maps were not bad. I mean he subdivided what he called the Nubian, or the younger continental strata, from the Carboniferous and the Carboniferous from older Palaeozoic strata. This was more or less his subdivision. And within these borders he was more or less correct.*
INTERVIEW Klitzsch	*The aeronautical chart was no help. The position of the oasis was correct and some of the tracks were correct. But others were not shown or there were tracks which were not on the map.*
INTERVIEW Klitzsch	*Except for the aeronautical chart our base were at least after a while … oblique photographs which were useful because at least you could identify where you were. But you could not identify those coordinates because it was within 10 or 15 km of what you thought you were. …But it was relatively easy, at least in the eastern Murzuq Basin to follow the geology, I mean to go down on the Visean shale was a very clear topographic help if you want so. … this was more or less our network. Some geology, some old tracks, there was the track to Kufra from Sebha via Waw El Kebir and Wau Anamus to Kufra.* *And there was at least in northern Libya - not so much in southern Libya- plenty of seismic lines, lines of gravity parties and what not. So one of my jobs was several times to bring people back who got lost, following the wrong tracks. It was always people from our seismic crew. And normally it was experienced people which got lost because they were careless. They went without water, sometimes without spare parts, without spare tyre and sometimes even without jacket or so. One we had to look for 4 days. And*

	when we fund him he was almost dead. It was in winter. It was minus 5-6 degrees. And he had no jacket, nothing to drink, nothing to eat. It was tough. *But we brought him back. That was an engineer from Bavaria. But he was not the only one. And several got lost and never came back. Not in our teams but there is several people got lost. One truck got lost west of Jebel Harudj. He went south instead of north. He had plenty of water but not enough fuel or Diesel to return to the main road after he found out that he was wrong. He was found fifty years later. Dead. Ja er war verhungert. And several people lost their head by leaving a helicopter in a sand area and the helicopter turned to one side and this was the end of the heads…. So it was – I will not call it dangerous because these were rare cases, there were plenty of geologists on their way. But it was adventurous – in a way, yeah.*
	Comparing the southern Libyan basins to other regions of the world, the story initially may appear very simple: Sometime around the dawn of the Palaeozoic, two bowl shaped basins begin to form. They keep deepening until they reached their maximum depth today. The newly created accommodation space gets continuously infilled by sediment dumped into the basin. Rock layer after rock layer is formed, until the basin is eventually full. A simple and easy- to-understand basin history model. But unfortunately completely wrong. You may find more oil using the darts technique than employing this “continuous sag basin model”.
	So: How did the basins really evolve? When and where were the hydrocarbons generated – and for how long were the source kitchens active? What were the key migration routes? Which rocks offered the hydrocarbons a new home? And most importantly: Are the hydrocarbons still there?
Part 3: FORMATION OF GONDWANA: THE PAN-AFRICAN OROGEN	
	Continents have been drifting over the surface of our planet for most of the past four and a half billion years. Lonely pieces of land surrounded by crashing waves on all sides. During rare occasions in earth history, however, these cratonic blocks were called to come together. As if a giant magnet was suddenly switched on, the landmasses’ paths suddenly converged. It is during such a continental reunion where our geological story of southern Libya begins.
	Subtitle: *600 Million years before present. The Neoproterozoic*
	Numerous continents, cratonic fragments and island arcs were on the move. Eventually they collided during the so-called Pan African Orogeny to give birth to the legendary southern megacontinent of - *Gondwana*. Gondwana was the united South America, Africa, India, Australia and Antarctica. Two large cratonic blocks dominated the area at the time that today is North Africa: The West African Craton and the East Saharan Craton.

	When these two cratons crashed into each other, a large Pan-African collisional zone developed between them, - the Trans-Saharan Megabelt. Some authors say the western *Murzuq* got caught up in this collision, whilst the eastern Murzuq laid on the stable East Saharan Craton. And also the present-day Kufra Basin was rather safely positioned on this block. East of Kufra, however, another war zone erupted. Series of island arcs were thrown against the East Saharan Craton and were accreted. The resulting East African Orogen is more than 2.000 kilometres wide and extends over Egypt and the Arabian Peninsula. Never again since these times have continents collided so close to southern Libya.
	The rocks preserved from this phase come from the deep. Formed several kilometres beneath the earth surface they speak of high temperatures and enormous pressures. Banded and strongly recrystallized metamorphic rocks, plutonic granites. -- The crystalline basement of southern Libya. A basement which is of Neoproterozoic age in the Pan-African mobile belts, but which can be much older on the cratons. The Precambrian basement comes to surface in several places around the Murzuq and Kufra basins. A good area to study the Pan-African action of the region is the Hoggar Massif in neighbouring Algeria which is part of the Pan-African Transsaharan Megabelt. Here, the structural fabric of the central North African basement is revealed. A fabric that also extends into the subsurface of southern Libya and forms the basis for much of the later structuration. The Hoggar's Precambrian basement is disrupted by deep-reaching vertical shear zones that generally trend in north-south directions. These shear zones often represent the former terrane boundaries of the small continental fragments involved in the Pan-African collision. Wounds in the Saharan body which never healed again, until today.
INTERVIEW Hammuda	*Prior to the Cambrian, in the Precambrian, the structural lineations were mostly broad and N-S…. So at that time most of the sedimentary basins … were not created.*
	Ever since, every little pushing and tilting has caused southern Libya and Algeria pain along these reactivated, old zones of weakness. Depending on stress directions, the land was pushed up or down – intraplate transpression and transtension.
INTERVIEW Belhadj	*… So many tectonics have been involved within the basin itself. Their structures have been rejuvenated from time to time, up and down. There are faults that have disappeared even though they have been there. They went up and they went down, so seismically you cannot see that.*
	To reach this remote part of the Sahara at all, the stress propagates over thousands of kilometres from the Phanerozoic collisional zones far across the stable Saharan Platform. As in every modern mountain belt, there were also *sediments* deposited during the Pan African Orogeny. But none of them survived. They were either cooked and squeezed or simply stripped off again. The Precambrian crystalline basement forms the substrate of southern Libya. Now the stage is set --- for 540 Million years of Saharan geology. Let the sedimentary action begin.
Part 4: INFRACAMBRIAN EXTENSION AND	

SEDIMENTATION	
	Sediments need space to be deposited. And towards the end of the Pan-African orogeny right into the early Cambrian, northern Gondwana created some space. Gondwana and the Pannotia megacontinent came under tensional and strike-slip stress. Laurentia, Baltica and Siberia separated from Gondwana. The Iapetus, the proto-Atlantic opened up. East Gondwana pushed heavily into the East African –Antarctic Orogen and triggered off escape tectonic movements on the Arabian Peninsula and in Egypt. And to make things worse, the newly formed Pan African orogens gradually began to collapse. Destructive times all across Gondwana. Half-grabens and pull-apart basins opened up locally and were infilled with sands and muds. Away from the siliciclastically contaminated zones, vast stromatolite colonies developed. In oxygen-deprived deeper parts of the shelf, organic-matter was deposited and preserved. These Infracambrian organic-rich shales and carbonates have sourced large oil fields in the Omani salt basins. And also to the west of Libya, the Infracambrian is a working play. Gas shows in the Mauritanian Taoudenni Basin speak a clear language. In Libya, the Infracambrian play and its potential is still extremely poorly understood.
INTERVIEW Jonathan Craig	*Specifically for the Infracambrian in southern Libya we rely at this point in time very largely on the very sparse seismic datasets that we have. But it is very clear that under the Kufra Basin for example there is a remnant halfgraben, in fact several remnant halfrabens which almost certainly contain Infracambrian sediments. And we are able to make correlations on the seismic data between the sequences we see in the Kufra Basin and for example the sequences we see in Oman where there is a very prolific Infracambrian, Neoproterozoic petroleum system. So there may well be a direct analogue between those two.*
	Nobody knows what sort of sediments are hiding in these Kufra halfgrabens. There are no wells. Is it just boring sand? Or is there any chance for more interesting stuff, for example an Oman-type organic-rich carbonate facies? We simply don’t know at the moment. Although there is something at the eastern Kufra margin that fuels our hopes.
INTERVIEW Abdallah Khoja	*As far as we have seen in the field there are some marbles, Infracambrian, metamorphosed carbonates.*
	Marbles. Sitting directly on basement. Maybe of Infracambrian age, but just maybe. There are structures in these marbles that look not too different from stromatolitic bedding. Or is it all just metamorphic foliation?
	And also at the eastern margin of the Murzuq Basin there are strata of Infracambrian age. The Mourizidie Formation. A purely siliciclastic series made of sands, silts and muds. But in an area with potential halfgrabens it is highly unlikely that we deal with layer cake stratigraphy. Strata may suddenly appear – and after a few kilometres abruptly end again. In concession NC101 the A-well found some suspicious Infracambrian deposits: Dark grey to black siltstone. Partly with calcite. Oman surely cannot be too far away.
INTERVIEW Jonathan Craig	*We have not identified at this point in time significant basins underneath the Murzuq basin that are Infracambrian basins, but there is no reason why these shouldn’t exist.*

	At the end of their lives, the Infracambrian grabens in Kufra became inverted. This is what the seismic tells us. It is therefore fair to assume that Infracambrian sediments once might have covered larger parts of southern Libya but quickly afterwards were eroded again. The Infracambrian rocks we see today are the erosional relicts of that time.
START FILM 2 **Part 5: UPPER CAMBRIAN TO MIDDLE ORDOVICIAN SANDS**	
	The first strata that formed an areally extensive, continuous sedimentary body over Libya are represented by the Hassauna Formation.
INTERVIEW Fello	*The Hassaouna Formation… is late Cambrian. So the whole section is siliciclastic with shaley stuff. Whole section is intercalation of fluvial to shallow marine area.*
	If you like layer cake stratigraphy – the upper Cambrian is for you. A monotonous pile of sand, pinching- and swelling across the region. In some places the Hassauna is 1 km thick. For example at the eastern Murzuq margin in the Dor El Gusa area and in the northern Kufra in wells A1 and B1-NC43. In other places the Hassauna is more in the range of 100-400 m, such as at the western and northern Murzuq margins.
	Southern Libya at that time lay in high southern latitudes. The climate was moderate because polar ice caps were absent. The onset of Hassauna sand deposition was triggered by a rise in eustatic sea level, creating new accommodation space that could now be infilled.
	The sea had flooded the western Murzuq and eastern Kufra Basin areas. The present-day Tibesti and its flanks, however, stuck out of the sea and formed a large Peninsula.
	Large networks of rivers carried their sediment load into the southern Libyan area. Debris collected and transported over thousands of kilometres from the vast Gondwanan hinterland. Only the toughest minerals survived this arduous journey. What came out of the Hassauna rivers was mostly quartz. Seasoned grains and pebbles, mostly well rounded. More fragile minerals didn't quite make it so far and fell apart already in the early stages of their long journey. It is these Gondwanan quartz grains that are the primary building blocks of the North African Palaeozoic basin fill, not only during Cambrian times but during various episodes during the Phanerozoic. Grains that became trapped in southern Libya on the gradually subsiding shelf.
	Some of the sands already became deposited in the Tibesti fluvial basin, forming monotonous stacks of planar and trough crossbeds. There was no vegetation yet to stabilize river beds. Palaeocurrents flowed generally towards the northwest, a pattern that hardly changed in the following 400 million years.
	Much of the Hassauna sand was eventually dumped into the shelfal sea. A very shallow marine deltaic depositional environment, probably with large tidal areas. The sediments are dominated by planar and trough crossbeds, formed by downstream

	and lateral accretion in channels and bars The sea floor was nicely decorated with wave and current ripples. Channels were cut by fast flowing currents
	For a long time, this is what essentially happened in southern Libya. And it also didn't change very much when the Ordovician finally arrived. The shelfal sea grew a bit - but apart from that, the depositional setup continued to exist. The constant rhythms of nature had a firm grip on southern Libya. Tides came and went. After a day came a night --- and then *another* day: Earth history consists of long periods of boredom and short periods of excitement. ---- But excitement was still many millions of years away at this point in time.
	During the early and mid Ordovician the As Shabiyat and Hawaz formations were deposited. Sandstone-dominated units with a few finer-grained interbeds.
	The most prominent inhabitant of the intertidal to shallow subtidal zones at that time was a worm. In a way it was similar to the modern wadden worm "Arenicola marina" at the North Sea coast. Restlessly Arenicola churns through the top 20 cm of sediment, looking for organic food particles. Every 45 minutes the worm comes to the sediment surface and excretes unwanted sand. Hidden underneath the pile of sand is the worm' s tube.
	The Ordovician worm built very similar vertical burrows. If the burrows are spaced very closely, the sedimentary fabric is also called "piperock". But unlike *Arenicola marina*, that had to churn his way through the sediment, the Ordovician worm sat in his burrow and waited for the food to come to him. His helpers were the waves and currents that carried his food in suspension. The Skolithos worm liked high energy conditions. Skolithos trace fossils occur in various stratigraphic intervals of the marine Palaeozoic of southern Libya. But they are most common in parts of the early to mid Ordovician Hawaz and Ash Shabiyat formations. Here the piperock can become several tens of metres thick and makes a good local stratigraphic marker.
	The general tectonic stability of the shelf across North Africa through this period resulted in the deposition of broadly similar Cambrian and Ordovician successions across the entire region. Nevertheless, on a local scale tectonic movements have been certainly active. In Dor El Gusa, at the eastern Murzuq margin, the Hassauna and Hawaz contact is marked by a distinct angular unconformity. Intraplate uplift must have occurred here during the Late Cambrian or early Ordovician, but has not been reported from other parts of southern Libya.
	Despite its good reservoir qualities, the Hassauna is most probably of little relevance to petroleum exploration in Murzuq and Kufra. In most cases the unit may be too far away from the Silurian source rock, and vertical throws along steep faults are often too small to juxtapose Cambrian sands and Silurian source. But more importantly, there is a serious sealing issue in the Hassaouna. Although shales do partly occur within the unit, *regional* seals for the Cambrian appear to be absent in southern Libya.

	The story is very different for the Hawaz. The mid Ordovician sands are a proven reservoir in some of the Repsol Murzuq fields. As we will see later, Ordovician erosion has brought some of the Hawaz in direct contact with the Silurian source opening up a fascinating stratigraphic play type.
	When looking at well logs, isopach maps and seismic lines, one tends to forget that there are real rocks behind the data. Rocks that could be touched, studied and followed at outcrop over long distances. But what's the role of traditional fieldwork in a digital world like ours? Why bother stepping out of the air-conditioned office when you can overlay hundreds of fanciful maps and detailed datasets on a geographic information system with a few mouse clicks?
INTERVIEW Jonathan Craig	*Of course today in exploration we have a lot of technology, some very good technological tools, very high quality seismic data, very good modelling packages. But fundamentally the data that we use for exploration certainly in areas like the Sahara and southern Libya still relies fundamentally on the outcrop geology. It's the outcrops that we need to go to, to understand the facies, the facies distribution, and the thickness of the sedimentary sections, the distribution of the source rocks, the periods of uplift and tectonic activity. These are absolutely fundamental to our understanding.*
INTERVIEW Hussein Seddiq	*What we have in the surface is exactly what we have in the subsurface. So understanding the surface geology is a key issue. … No matter what you do in exploration, no matter how many wells you drilled you cannot know exactly everything unless you know the surface geology because that's the nice thing about geology. There you can see everything. You have a scale of things.*
INTERVIEW Belhadj	*There are so many models that are in three dimensions. You can see them, you can walk in the reservoir, you can see the relationship between the reservoir and the source rock. They are right there. All you have to do is you just have to compare the outcrop with the subsurface.*
INTERVIEW Klitzsch	*… I have a good example from Egypt. In Egypt an oil company wanted to drill at the southern Gulf of Suez, northern Red Sea area for oil in Cretaceous sands. And they found no Cretaceous sands, consequently they found no oil. If they had listened to field geologists they could have learned that the Cretaceous sands pinch out much further north, than they expected … But same thing in Murzuq Basin I think. If you do not understand the facies changes within the different formations and especially their directions you have a hard time to interpret your seismic I think. Or to interpret your drilling results. And let's face it. Fieldwork is cheap. So you always can learn, you can gain information that you can use in drilling.*
Part 6: ORDOVICIAN GLACIATION	
	The Ordovician years rolled by, with the sea comfortably ruling over southern Libya. A greenhouse climate, warm and cosy, which continued right through the Silurian and Devonian. If… yes, if there wasn't this short, peculiar interlude in Libya's geological history. For a s short while during the late Ordovician strange things happened. Things that struck most of Gondwana by complete surprise.
	It was suddenly getting cold. Seriously cold. The trilobites will not have liked it. We still don't know for sure what suddenly turned the air condition to cold and made southern Libya this giant natural fridge. Out of the blue, a giant icecap built up over the Saharan area. The average temperature fell to minus 50 degrees celsius. It has never been colder in southern Libya ever since.

	The following 5 million years decided the fate of the Murzuq and Kufra basins. As a petroleum province.
	In places the glacial Upper Ordovician sands of North Africa are full of oil --- or gas. Across the Sahara at least 5 billion barrels of oil equivalent have already been found in these strata. The black gold is stored in more than 50 fields that form a broad belt stretching from central Algeria into the northern Murzuq Basin. Here in SW Libya, at the eastern end of the belt, lie half of the discovered volumes. In the Mamuniyat Formation. The main reason why on the maps today this petroleum province ends in the northern Murzuq is --- that hardly anybody drilled further east.
INTERVIEW Beswetherick	*… To begin with we certainly didn't appreciate either the complexity of the CO stratigraphy or the changes of facies within particular units of the stratigraphy. So certainly understanding the reservoir system, we thought it would be easy and not one of our problems, and it was somewhat harder than we anticipated.*
INTERVIEW Jonathan Craig	*The Mamuniyat Formation because it is a glaciogenic unit is very complex. One of the key issues that we have in terms of field development very often is the continuity of the reservoirs. Like all glacial systems there is a great deal of heterogeneity in the system. And it is very difficult on the seismic data to be able to determine the individual facies.*
INTERVIEW Dr. Aziz	*And we see most our dry reservoirs due to the quality of the reservoir. I know it is not easy to have a 100% understanding of the Mamuniyat reservoirs. This is one of the main risks, really.*
INTERVIEW Jonathan Craig	*We know a great deal more about the Mamuniyat Formation than we knew maybe 10 or 15 years ago. A great deal of research work has been done, a lot of the outcrop work has been done in that period of time. So we now have a very clear understanding of the genetic relationships between the various depositional units. But at the field scale it is still quite difficult to predict what the lateral continuity of particular reservoir sands is going to be.*
INTERVIEW Jonathan Craig	*3D seismic is also proving the ability to improve our predictive capability. There is not a great deal of 3D seismic existing at this point in time within much of southern Libyan area. But that will certainly form one of the keys to improve predictions in the future.*
	The huge Gondwana landmass lay straight over the south pole during the late Ordovician. And the broad, uniform North African and Arabian shelf was an ideal platform to accumulate thick ice masses.
INTERVIEW Le Heron	*… The ice sheets were very large and continuous at their maximum extent. Very much like the modern East Antarctic Ice Sheet.*
	The Antarctic ice sheet covers almost 14 million square kilometres. In East Antarctica the ice sheet rests mostly on land, while large parts beneath the West Antarctic ice sheet would be seabed if the ice sheet were not there. On average the modern Antarctic icecap is 2 km thick, but in places the ice column measures four and a half kilometres. The late Ordovician ice sheet in Gondwana may not have been very different. Large areas covered by ice and great thicknesses means also great ice volumes. And this is the powerful control button that make glacial deposits so heterogeneous and the system so complex. A small change in climate can cause large volumes of ice to rapidly melt and raise sea

	level significantly. Likewise, buildup of additional volumes of ice on the icecap extracts the water from the world's oceans and lower the sea level. Climate, the size of the ice sheet, sea level, sedimentary facies and Ordovician reservoir quality are intrinsically coupled. It's worth taking a closer look at where the ice sheet was and how the late Ordovician glaciation worked.
	The center of the Gondwanan ice sheet lay just south of the Sahara, maybe in present-day Chad. From here the ice flowed outward into all directions. Rocks underlying the central parts of the ice sheet were eroded and the debris transported towards the ice margins. Here, the strata was deposited. Glacial sediments from the late Ordovician are preserved across Gondwana and have been discovered so far in South America, South Africa, Saudi Arabia, Jordan, Libya, Algeria and Morocco.
	Knowing where the edge of the ice sheet was at a particular time is important. Because this is where sediment is freed from the ice sheet and where the most significant sedimentary facies changes occur. So where was the edge of the glacier in North Africa?
INTERVIEW Le Heron	*We can say that the ice sheets terminated in northwestern Morocco where we have the chance of connecting the outcrops together in a depositional model. And they have appeared to have stopped there because there is a major break in bathymetry. So a big change from where you have sediments of perhaps 20 m or so in thickness being accommodated on the shelf to a rapid increase to about 400 m plus of sediments of differentiated turbidites. So in that particular case if you decompact the thickness of the Ordovician turbidites in northern Morocco you are talking about very deep water in that part of the world.*
INTERVIEW Le Heron	*For the more prospective parts of North Africa, that's to say in the central and eastern parts of Algeria and in western Libya the story is more complicated. Because the evidence for where we might find the limit of the ice sheet is now in the subsurface in the … northern part of the Ghadames Basin. … The further north you go in North Africa, the greater chance you have of truncation. Tectonic truncation by the Hercynian unconformity. So it is an open question at the moment.*
	The outward movement of ice within an ice sheet is concentrated in so-called ice streams. Most of the ice leaving the ice sheet passes through these large flow systems which can be 100s of kilometres long. Some ice streams flow at speeds of over 1000 m per year. In between the ice streams are zones of significantly slower moving ice, the interstream areas that in modern Antarctica account for 90% of the ice volume. Here flow velocities rarely exceed a few metres per year.
INTERVIEW Le Heron	*We now know based on a combination of fieldwork and the analysis of satellite imagery that a large and continuous ice stream up to 50 km wide was present in western Libya and eastern Algeria. And this ice stream probably extended towards what is now the southern Illizi Basin. So based on this finding and knowing what we do about modern ice sheets we would have expected similar ice streams to have been distributed unevenly over the North African area during the Late Ordovician glaciation. So it is likely that really at the ice maximum when the late Ordovician ice sheets were at their largest the region was divided into areas characterised by very fast flowing ice, these ice streams, separated by slower moving ice, interstream areas.*
	The ice streams were most healthy during peak glaciation times. Ice was constantly added to the ice sheet and a steady ice flow developed, fuelled by gravity. Dragging ice at the base of the stream carved huge valleys. Meltwater was not involved at this stage. Things changed completely during phases of rising temperatures. The ice stream movement stagnated. Parts of the ice began to melt. Huge amounts of meltwater were

	suddenly released and flowed within and beneath the ice towards the glaciers edges. Networks of tunnels developed cutting deeply into the substrate. Compared to the ice streams these channels were significantly smaller, but still sizable structures.
INTERVIEW Le Heron	*One of the most common features of the Ordovician glacial depositional system is the prevalence of large palaeovalley incisions. And the palaeovalleys themselves are of the order of 100-600 m deep in some cases. Generally between 4 and 6 km wide and particularly on the Gargaf Arch in the northern flanks of the Murzuq Basin we can see at least three generations of cross cutting palaeovalleys like this.*
INTERVIEW Le Heron	*Suggesting that we have at least three phases in Libya at least of ice sheet retreat.*
	So the main agents of erosion change during the course of a glacial cycle. Ice erosion by ice streams during peak glaciation times and meltwater erosion of smaller tunnel valleys during glacial retreat phases. The different origin of these two valley types means that also the sedimentary infill history will differ. And with this the reservoir characteristics. Distinguishing these features on seismic and in outcrop is therefore essential. In some areas today we find ice stream valleys with tunnel valleys superimposed.
INTERVIEW Le Heron	*And sure enough we see big basins that are carved by the ice streams and within those basins we see the tunnel valleys themselves. So we have to think of … incision on two orders of magnitude if you like. The tunnel valleys … a 100 m or so in depth, a few kilometres wide, sitting within the larger-scale fairways.*
	Let's concentrate on the tunnel valleys for a moment. Why should we bother so much about these?
INTERVIEW Jonathan Craig	*Tunnel valleys are a very interesting feature of the entire glacial depositional system that we have in southern Libya. … Not very much was known about them until a few years ago, and we still rely very heavily on using for example Pleistocene analogues from northern Germany, from the northern parts of the United States, from the UK. All of which give us a very good feel for what the geometry should be within the individual tunnel valleys. They are very, very important, because they often contain the best reservoir sequences.*
	While the Pleistocene tunnel valleys make a good comparison with the Ordovician palaeovalleys, finding real modern analogues is very complicated. Antarctica would be the place to search for, but despite the global warming debate, the East Antarctic ice sheet is currently very stable and is actually even growing. Not a good place for subglacial meltwater streams to form.
	Seen through the explorer's eyes, there are good tunnel valleys and bad tunnel valleys, depending on their position on the shelf and their detailed infill history.
INTERVIEW Le Heron	*… The valley systems are carved in different water depths. We can see that some of the valleys appear to be filled with mudrocks that were deposited in an outer shelf environment, for example. So we have to remember that these valleys are cut in areas that are naturally prone to poor-quality glacial deposits in the outer shelf region. And that some of them are cut in areas that naturally are prone to better-quality rocks, that's to say in the shallow marine setting and in braided fluvial environments. So we really have to bear those factors in mind as well.*
	A meltwater valley cut into the outer shelf, for example, could initially be infilled by high energy fluvial to very shallow marine sandstones and conglomerates with good reservoir properties. As the glacier gradually retreats and sea level rises, *deeper* water facies get deposited, such as shales interbedded with sandy turbidites. Finally

	hemipelagic fines infill the remaining accommodation space. A typical deepening and fining upward, backstepping sedimentary succession.
INTERVIEW Le Heron	*Thinking about the palaeovalleys themselves across the region we see a range of fills in North Africa and Arabia. On the Gargaf Arch in Libya some of the palaeovalleys contain a well-defined two-stage fill. At the base and the sides of the palaeovalleys we often see a very clean conglomeratic sandstone deposit which we can refer to as the initial fill of the palaeovalleys. This initial fill is onlapped by a secondary or main fill which constitutes really the main thickness of the palaeovalley sediments. In southern Libya the main fills to the palaeovalleys … consist of very well differentiated sands and mudrocks. And these contain sedimentary facies typical of underflows so we are talking about massive beds, channelized deposits, antidunes, rare parallel lamination. And also some rare intraformational conglomerates. If you look at the fill to palaeovalleys across the region as a whole really the fill styles are very variable. The fluvial deposits being recognised in Mauritania and Jordan for example, shallow marine deposits in Saudi Arabia and relatively deep marine debris flow deposits, very muddy in eastern Algeria in particular. In all cases however, we note that there are really these two well defined fill stages to the palaeovalleys.*
	And also the shape and distribution of the Ordovician palaeovalleys is variable. Sometimes they form rather isolated sinuous features, sometimes they form anastomosing interconnected networks.
	The complex relief and lithological heterogeneity within the tunnel valleys forms the basis for a collection of various potential stratigraphic traps.
INTERVIEW Le Heron	*… The fill of these valleys may be highly prospective. Because they may contain very clean sands and also viable stratigraphic traps for oil. Particularly when they are cut into mud rocks or diamictites on the shelf, or whether they contain sands that are bounded by mudrocks.*
INTERVIEW Jonathan Craig	*…We see certainly some potential for lateral seal for the edges of the palaeovalleys that would potentially give us some quite large stratigraphic traps.* *The topography that is associated with the glaciation is also a very important element in many of the fields that have been discovered. So we identify what are referred to as buried hills in some areas which are the prime structuration that gives us the closure for the trapping of the hydrocarbons.*
	Buried hills. Relict pre-glacial strata, mostly Hawaz sands, that survived mid or late Ordovician erosion. During the Ordovician glaciation these hills represented major highs and could not be covered by glacial deposits. Postglacial Silurian shales provide an ideal top seal and make the buried hills a successful trap in some of the Murzuq fields.
INTERVIEW Fello	*... They are good traps for oil accumulations. In palaeovalleys we usually don't have a good structure to accumulate the oil. So on 3D seismic it is very clear to investigate …within NC115.*
	And in parts of the Atshan area, erosion has penetrated even deeper. Locally the Silurian Tanezzuft sits here directly on the Cambrian. And the Cambrian is full of gas.
INTERVIEW Abdallah Khoja	*We have A1-NC151, producing gas from the Cambrian, from the Hassaouna as the reservoir.*
	The buried hill stratigraphic trap is a child of an erosional event that is still poorly understood. Sometimes during the mid to late Ordovician a huge relief was cut into the pre-glacial substrate creating an erosional surface referred to as the "Taconic Unconformity". This unconformity today separates the pre-glacial from the glacial strata.
INTERVIEW	*The origin of the Taconic unconformity remains a subject of considerable controversy.*

Jonathan Craig	*There are may different views. When we look at regional cross sections, when we look in the field, when we look at some of our regional seismic lines it is quite clear that that unconformity cross-cuts pre-existing structures. And there is certainly some significant evidence that there is a tectonic component to it. Having said that it has clearly also been considerably accentuated by glacial erosion associated with the northward progradation of the ice sheets which then re-excavated much of the unconformity surface. So certainly my opinion is that it is a mixture of both a primarily tectonic unconformity that has then extensively reworked by the ice sheets of the late Ordovician glaciation.*
	The assumed tectonic component must have been of intraplate character, responding to plate tectonic activities that took place several thousands of kilometres away, near Morocco. During middle Ordovician times here the Avalonia terrane split from Gondwana and drifted off. Nevertheless, tectonic intraplate stress could have been transferred as far as southern Libya. Pan-African and younger faults could have been reactivated, with the development of transpression or transtension depending on fault orientations and geometries. Towards the beginning of the glaciation, when the sea level had already markedly dropped, rivers might have deeply cut into the uplifted blocks. When the glaciers finally arrived, ice streams and subglacial meltwater added to this complex erosional puzzle.
START FILM 3	
	The glacial upper Ordovician strata of Libya is generally subdivided into two prominent lithostratigraphic units. The Melez Choqran Formation and the Mamuniyat Formation. For a long while things seemed rather simple.
INTERVIEW Le Heron	*In southern Libya the stratigraphy of upper Ordovician glaciogenic deposits has traditionally been considered as a layer-cake stratigraphy. The traditional model, that's to say the one that persisted for several decades has been that the mud prone unit, the Melez Chogran Formation, laid down at or near the start of the glaciation, followed by, stratigraphically a predominantly sandy deposit, the Mamuniyat Formation.*
INTERVIEW Le Heron	*It is fair to say I think that the simple stratigraphic model that this is assumed has really turned out to be a false concept. Certainly in the opinion of recent field parties down to that region. Basically it is now accepted that the stratigraphy is more complicated than this reflecting the various phases of incision and fill of tunnel valleys for example. And it is also accepted that there is a very mud-prone unit also within the Mamuniyat Formation. Really, due largely to the poor exposure of these mud-prone units, their interpretation has become and remains quite equivocal. Simply because they are not well exposed, people can come to their own conclusions. As opinion differs quite significantly among my co-workers.*
	The modern glacial concepts highlight the lateral discontinuity of upper Ordovician facies in southern Libya. Highly permeable sands may pinch-out within a few 100 metres, or might as well pass into poor-quality sands. And also the vertical facies stacking patterns are highly variable and hard to predict. A general depositional model helps to explain what controls this complexity. Once the Taconic depressions were cut, they gradually got infilled. The sea flooded the area and a green shale was deposited, the Melez Choqran. Marine conditions are indicated by the occurrence of brachiopods.

	Deposition of the shales was restricted to the deepest parts of the Taconic depressions. The Melez is absent in areas lying on higher ground. We also have got a fairly good idea at what stage of the glacial cycle the Melez Shoqran was deposited.
INTERVIEW Le Heron	*In my opinion the coarsening upward succession that we see within the … Melez Chogran Formation and within another mud-prone unit within the Mamuniyat Formation tends to suggest it was deposited during largely ice sheet advance.*
	So the glaciers were just in the build-up phase during Melez Choqran times. Icebergs breaking off from the glacial front drifted northwards. When the icebergs melted, pebbles and sand was set free and sank to the sea bottom. Here they were embedded as strange outsized clasts into the fine, hemipelagic Melez Choqran mud. Dropstones.
	When the sea-level eventually fell, the Mamuniyat times began. The Mamuniyat sandstones continued to infill the Taconic depressions - where they hadn't already been filled up. And the Mamuniyat did care for itself .Where necessary, ice streams and tunnel valleys eroded downwards into the ground to create new space for Mamuniyat sediments. In parallel with the glacial cycles, this erosion occurred in various phases. A cannibalistic system: Younger Mamuniyat eroding into older Mamuniyat – or into the Melez Choqran, or even the pre-glacial substrate.
	Zooming in, the Upper Ordovician consists of various different facies.
INTERVIEW Le Heron	*… On a glaciated shelf like North Africa during the late Ordovician we would expect to see a range of braided-fluvial through marginal marine to shelf through offshore facies. And that whole spectrum of depositional environments is something we also see in Libya.*
	So there is not ONE glacial facies --- there are MANY! And most of these facies are in fact only periglacial, so were laid down in front of the glacier rather than beneath the ice. In fact you might begin asking yourself, how we can be so sure there have been huge glaciers around at all.
	Well, let's start with the outsized clasts in the Melez Shoqran muds. Some critics might say the pebbles drifted around on floating wood and then fell down. Nice try, but wood was only invented many millions of years later. So we can keep them as glacial dropstones. Or take the palaeovalleys that are up to 600 m deep. Surely, these dimensions are too large to be created by a simple sea level fall.
INTERVIEW Jonathan Craig	*..Actually finding specific evidence of glaciation within that formation is actually extremely difficult. The evidence is very sparse. So again we tend to rely very much on analogues, modern analogues to identify the types of sediments and types of structures that we would expect to have a glaciogenic origin to them. …* *One of the key pieces of evidence that convinces us that there really is a glacial system here is the striated surfaces that we find within the formation. And these have a number of different origins. The majority of them seem to represent the scour at the base of the ice sheet as it moves northwards across the southern Libyan area. But clearly in some places the ice sheet was moving across unconsolidated sediment. And actually we have a broad package of sediments that is sitting beneath the ice sheet which is sheared. And*

	many of the striations are in fact related to shearing of the sediment column beneath the loading of the ice sheet itself. But that is one piece of evidence which gives us quite a good degree of confidence that this really is a glaciogenic system.
INTERVIEW Le Heron	*So we have here an example of one of these striated pavements. It's a hand specimen that comes from the Gargaf Arch in the Murzuq Basin. And you can see that there is a series of perfectly parallel grooves separated by ridges and a V-shaped cross section. This is just a typical hand specimen. If you can imagine this structure scaled up, scaled up to say a metre or so, for each ridge, a metre across, here, a groove, a meter, separated by more grooves, this is what you also find at outcrop. Very large-scale ridges and grooves. And scaling the structure up again you can also see similar features on satellite imagery. These at the very largest scale several kilometres or so in length are known as mega-scale glacial lineations.*
	And once you have the rough idea that the facies could be glacial, other observations suddenly begin to make sense.
INTERVIEW Le Heron	*... we see very unusual sedimentary facies, very high energy sedimentary facies. Thick bodies of sandstones, 40-50 m in thickness with continuous up building of megaripples if you like. Large, very large-scale crossbedding, which also includes huge clasts once more. So to me I would interpret these sorts of sediments as being deposited by very high energy sustained flows. In a glacial context what can give you these sorts of flows? Well, the answer is catastrophic collapse of the ice sheet, Jökulhaups we see in modern-day southern Iceland for example.*
INTERVIEW Le Heron	There are only a few things in life that could be more horrifying than a Jökulhaup. Jökulhaup is an Icelandic word that refers to the catastrophic release of meltwater from a reservoir within or underneath an ice sheet. Often triggered by melting ice, the flood erodes everything that comes in its way. In modern Iceland there are hundred ton boulders that got carried away. Huge clasts are ripped-up from the underlying substrate and are incorporated into the flow. But even a small rise in sea-level could trigger this deadly event. When the sea lifts the near coastal ice sheet from its substrate, water masses trapped near the glacier's base are suddenly freed and begin to move. The inhabitants of Ghat can consider themselves lucky that they missed these catastrophic flows by 445 million years.
	Talking about weird things in the Mamuniyat, here are more.
INTERVIEW Le Heron	*…we also see a range of other structures that should be interpreted in a glacial context, given what we know about the depositional setting of these rocks. And these structures include really fossil push moraines. And push moraines are basically as they sound. At the margins of a glacier or ice sheet when it moves forward it tends to disrupt, to deform and bulldoze if you like the sediments in front of it. So very much as you would see in an accretionary wedge for example near a subduction zone. It's the same sort of process scaled down. A series of folds, faults and so on.* *… We certainly see large-scale anticlines that rise about 30 m or so above the wadi floor. 30 m in amplitude, probably more. Fairly continuous belts of deformation over several kilometres. From a petroleum exploration point of view … we should be concerned with really in terms of their potential for guiding fluid flow in the subsurface altering and disrupting the continuity of reservoir units and so forth.*
INTERVIEW Jonathan Craig	*… in depositional terms it is the retreat which is important, in terms of … internal deformation in the reservoirs that we are dealing with then it is often the advance phase that creates the structures within the sedimentary section that we see, that act as barriers or baffles within the reservoir.*
	So where do we find good reservoirs within the complex Ordovician glacial depositional system? In tunnel valleys, ok. But where else?

INTERVIEW Le Heron	*Good reservoirs are probably deposited where the ice is closest to them. It's basically like any sedimentary system… where you are closest to the source of sediment you tend to have coarser grained hence more prospective sediments, such as sandstones.*
	A good place for a such ice proximal reservoir facies is right at the edge of the glacier.
INTERVIEW Jonathan Craig	*One of the keys in terms of exploration is identifying what we call ice contact fans. These are the big spreads of sand which are deposited in front of the retreating ice sheet. So when the ice front retreat stalls at what we call a grounding line, as it melts there is a great deal of meltwater being pushed out from the front of the glacial system and this deposits the big fan sands. And these are some of the key reservoir targets in the region. So from an exploration point of view it is very important for us to be able to identify first of all where the grounding lines are and then to be able to identify the exact position of these ice contact fans which are primary reservoirs.*
INTERVIEW Jonathan Craig	*The retreat of the late Ordovician glaciation and the ice sheets associated with it is probably one of the fundamental aspects of understanding reservoir distribution within the Mamuniyat Formation. Certainly the research work we have carried out suggests that the majority of the sands that act as the primary reservoirs within this system are formed during periods of retreat and particularly during periods of standstill of the ice sheet. When the ice sheet is degrading and there are considerable amounts of meltwater being flushed out of the ice sheets it's these that lead to the deposition of the main ice contact fans which are the primary reservoir.*
	So rapid meltwater flows are good. Likewise the turbulent coastal belt may help to sort out attractive reservoir-quality sands.
INTERVIEW Le Heron	*As the sea level was rising when the ice sheets retreated we tended to have very clean sands worked back onto the shelf producing really just tabular sand bodies, 10s of metres thick. That's one possibility for a good, clean sand.* *The other possibility which may not be recognized in Libya necessarily, nobody really knows, is the potential for very clean well-differentiated turbidites deposited immediately beyond the ice sheet at the shelf break. And we see examples of this sort of … prospective facies if you like in northern Morocco where we can see … differentiated turbidites up to 400 m in thickness. So it is something to always bear in mind.*
	Glacial processes and facies are the key to understanding reservoir quality in southern Libya. But this is not yet the end of the reservoir story. Because the end of sedimentation is the beginning of burial. -- And of diagenesis. Clearly, depth of burial plays another key role in controlling reservoir quality.
	Feldspars and some other silicate grains can't stand the heat and pressure in the subsurface. When these unstable grains come in contact with inflowing meteoric water, they become easily dissolved. From this, new minerals are generated and begin to block the pore network. At shallow depths kaolin forms. If burial continues, the kaolinite is later transformed into dickite. Most kaolinite and dickite simply replace the original grains and therefore are rather harmless for the reservoir.
	Not so the quartz overgrowth. When temperatures in the ground reach 80°C the quartz grains begin to grow. Larger grains means less room between the grains. An effective reduction in pore space, a problem increasing with depth. Another big pore blocker is siderite. This stuff is capable of infilling even large intergranular pores. At shallow depth it's the magnesium-poor siderite, at greater depth the magnesium-rich version.

	Outcrop samples therefore help us with the facies-side of the reservoir quality. For the diagenetic burial story, however, we need samples from the deep subsurface.
	And even desert weathering may change the petrographic composition of the Ordovician sandstones. In this outcrop near Wau El Kebir at the eastern Murzuq margin, a few hits with the hammer convert the sandstone back into a sand. Attacked by weathering, the cement has largely gone.
	This gives us a good excuse to play with some really exciting tools in the field. Let`s *rock* it! Using a rock drill the outer weathering zone is easily penetrated. The cores provide less weathered sample material for thin section and permeability study.
	Mamuniyat and Melez Shoqran together are up to 200 m thick. How long did it take to deposit all these sands and muds? How long did the glaciers actually rule over southern Libya?
INTERVIEW Le Heron	*The Ordovician glaciation is something that has always been argued about in terms of its length. Going back into the 1970s the estimates were of the order of 25-30 million years in duration for this glacial episode. So looking back to when Antarctic ice sheets began to grow about 40 million years ago that would be round about the same sort of length.* *However today we find ourselves in a position where … the length of the glaciation is thrown once more into controversy. In the mid 90s there were some suggestions by a group working in Liverpool under Pat Brenchley that the glaciation was of the order of 0.5 to 1 million years in duration. And this was continued quite recently by Owen Sutcliffe and co-workers to suggest that the glaciation was of the order of 200.000 years based on Milankovitch cyclicity that we see in Pleistocene glacial sediments. However, the cat has been thrown amongst the pigeons again, so to speak and really there were suggestions from American workers in the United States that the glaciation may have actually began 10 million years earlier than previously thought, so it's a controversial subject.*
INTERVIEW Le Heron	*Bearing in mind that the precise duration of the glaciation is still up for question we can say with some certainty that the maximum glacial conditions appear to have occurred during the Hirnantian. That's to say the last stage in the Ashgill, the very end of the Ordovician. And we can say this on the basis that the glaciogenic deposits contain a very characteristic fauna, known as the Hirnantia fauna. A series of brachiopods primarily which have been collected from the Melez Chogran formation in Libya and also in the equivalent succession in the Anti Atlas of Morocco, for example.*
	When a lot of ice is piled on a piece of land and the glaciers advance, the land begins to subside. Glacial loading. When the same glaciers retreat and finally disappear, the land rises. Glacial rebound. Unfortunately, loading and rebound are quite hard to identify in the sedimentary record. Much of the vertical movements may be counterbalanced by inverse-polarized glacio-eustatic sea-level changes so that shoreline shifts are hard to predict. During loading, the eustatic sea level falls as a lot of the oceans'waters is incorporated into the ice sheet. And during rebound, eustatic sea level rises due to the large quantities of glacial meltwater. And yet, we think we found something that points into the direction of a nice glacial rebound story also for southern Libya.

INTERVIEW Le Heron	*At the end of the glaciation we know that there appear to have been several strange effects upon the stratigraphy, upon the pre-existing rocks, that were deposited during the height of the late Ordovician glaciation. On the Gargaf Arch, the northern margin of the Murzuq Basin, we see evidence of extensive growth faulting, halfgrabens basin development and so on that appear to have their masterfaults roughly parallel to the pre-existing structural grain. That's to say a NW-SE oriented structural grain. So there is the possibility … that deep basement faults were reactivated as the ice sheet withdrew from the platform back onto the shelf.*
Part 7: DISCOVERY OF THE ELEPHANT OIL FIELD	
	The glaciers went away -- and never returned. The Ordovician sands gradually subsided into the ground. And waited. Waited for precious goods to arrive. When these finally came they stayed. Until, yes, until the day when the drill bit struck…
INTERVIEW Vince Withams	*... We hit some sand, and they sent the chippings up. I remember that very clearly. So we got the chippings. Ian Hodgins who was the wellsite geologist at that point gave me the privilege, and it was a privilege, of basically looking at the chippings under the fluorescence. So I put the tray of chippings into the machine, and there was the first indication that we had oil. It glowed, it fluoresced. He was edging me from behind, saying "So is there any fluorescence?" and I said "Yes, there was". So that was the first indication that things were looking reasonably good.* *… The first core came up at one o'clock in the morning. I remember that very well. And, as the core came out, it was just dripping oil. And I remember the driller at that point. A Croatian guy I think. He basically said "This is sweet oil". I remember those words. And we knew that the porosity was good. … I remember the Korean, Joon Zoon, next to me at that point, was standing to attention. Taking everything very seriously. And he didn't mutter a word through the whole proceedings. I remember that.*
	The Ordovician had delivered. An elephant was born. The Elephant Oil Field, discovered by Lasmo and partners is a giant. With more than 1.2 billion barrels in place it is still the biggest discovery made in Libya during the last 30 years -- and it is also the biggest oil field in the Murzuq Basin today.
INTERVIEW Vince Withams	*Nobody came out at the time. There was lots of discussion in the canteen at the well site by everybody about what we actually had found. We realized it was big. I mean it was a huge bump. …* *I remember the guys back in Tripoli wanted to know everything. And Mike Buck who was the General Manager at that point was on holiday in Paris with his wife and some friends. And he was told of the news while in a restaurant in Paris. And basically made a first toast. And he cut his holiday short. …*
INTERVIEW Vince Withams	*The day I left the site I remember… walking up this little hill to get away from the noise and just to experience the beauty of the desert. And I was sitting on top of that hill and said, look …and thinking myself how this area is going to change in the next few years. …That I remember very clearly, in the silence of the desert.*
	The Lasmo exploration team was delighted. And with every piece of information that arrived, the excitement kept growing. Only one man did *not* take part in the celebrations. Lasmo Grand Maghreb's key geologist had disappeared. Calls to his mobile phone remained unanswered. Where was he?
INTERVIEW	*On the day of the Elephant discovery I sadly was on holiday in Pembrokshire, having*

Beswetherick	*discovered that I was going to be posted to Pakistan in a month time. So I had a mobile phone to keep in contact with Tripoli and London but the mobile phone did not receive a signal in Pembrokshire. And it was only three days later, after the discovery that I went somewhere where the signal was obtained that I had 19 messages. And several of them were, we have cut a core in the top of the Elephant discovery and it is 100% sandstone and 100% oil dripping. So by the time I found out about it we cut 100 m of core I think. All sandstone, all oil-dripping. So very excited. But sadly on the day, I was on holiday walking along the coast of Pembrokshire.*
INTERVIEW Jonathan Craig	*… Although there was initially excitement in the office, certainly, it was several days before it really began to dawn on us this was a very, very important discovery that we have made. And obviously as that began to dawn on people in the office the level of excitement became tremendous. It was a huge discovery for us. And one that was in very many ways to change the face of the exploration portfolio that we held in Libya at the time, but also in very many ways to change the face of the company Lasmo that was involved in drilling that major discovery in the first place.*
INTERVIEW Beswetherick	*Strangely when it was announced to the press the Lasmo shareprice dropped about 2p, on concerns about the expense of developing such a big discovery. That was disappointing. But NOC and indeed our partners Eni and the Korean consortium were very excited by a big discovery. I think the Elephant discovery turned the spotlight onto the Murzuq Basin.*
INTERVIEW Jonathan Craig	*The discovery of the Elephant field is one of those classic stories in exploration history. When Lasmo took the block in the Murzuq Basin, NC174, which ultimately contained the Elephant discovery we recognized very clearly at that time that there was likely to be a working petroleum system in the region. We had a lot of evidence that we were going to encounter the late Ordovician system as the reservoir. We knew that the basal Silurian hot shale was a working source rock in the region. So we had very considerable hopes for the block when we acquired it.*
	In fact Lasmo was lucky that the Elephant was still there. It wasn't virgin territory that the company started to explore in the early 1990s. Others had been looking around that area a few years earlier. And discovered various large fields north of NC174. The proven oil finders of the Romanian company Rompetrol smelled the Elephant --- but in the end let it go.
INTERVIEW Dr. Aziz	*Elephant field which was discovered by Lasmo has been part of NC115 concession. In time of exploration stage we can see that part of Elephant, can see it on 2D seismic. But people were still thinking if they have the possibility to drill this well or not. The topographical problems where this field is located on the escarpment, what we call the Messak escarpment.*
INTERVIEW Dr. Aziz	*More or less 200 m higher than our gravel area, or where we have our main fields; A, B and H.*
INTERVIEW Dr. Aziz	*… And then they considered the mob demob of the equipment and other things. Then they said, maybe we can postpone to drill this one. We are still not sure if we have a discovery or not. And in this area we had a lot of problems with the seismic. Today we there also have a lot of problems, if you see the seismic data in this escarpment area. That's why all these risks were evaluated and then decide not to move to this area. Except that later on we may have decided this area still keeping to our side.*
	Keeping it in reserve was certainly a good plan. Exploration agreements with NOC, however, meant that Rompetrol finally had to relinquish this part of their concession. For once, the Elephant had successfully escaped the hunters. Nevertheless, soon others were on the scene to continue the search.
INTERVIEW Meijrab	*The attraction came when Libya introduced the EPSA III in the late 1980s. And then*

	the Murzuq Basin was opened for licensing round. The NC174 was just at the southern boundary of NC115 where there were those major 3 oil fields discovered by Rompetrol. So that part of the basin attracted different European operators. Among them Lasmo …. And they succeeded in sanctioning an exploration commitment with the Libyan NOC.
INTERVIEW Beswetherick	*… We were encouraged by the large Rompetrol discoveries although we knew very little at the time. … We also saw that the Bulgarians, Boco had made some smallish discoveries and the Brasilians had made one small discovery out of 8 wells. So we recognized the petroleum systems that we thought should be there but we didn't really understand at the time what were the critical factors controlling prospectivity.*
INTERVIEW Jonathan Craig	*We went through a very detailed and full exploration program that involved us in acquiring 2D seismic data over the vast majority of the block, and then in succession drilling 4 wells.*
INTERVIEW Meijrab	*There were plenty of prospects and a really huge anticlinal and fault bounded traps.*
INTERVIEW Beswetherick	*…. We discovered two small fields with the first well, A1, which was the North Scorpion prospect, and also a small field with the C1 well, which was the camel prospect. B1 well had good oil shows but poor reservoir, and the D1 well was the only one which was absolutely dry. The results encouraged us in that we obviously had a petroleum system capable of working but the fields were much smaller than we originally mapped. We were encouraged to try and drill more wells. Management was encouraged by the results but disappointed that we hadn't found any good sized field.*
INTERVIEW Meijrab	*…The disappointment …actually made the company a bit aware of – where is this potential now. Is there a good understanding about basic play elements like the oil charge, the migration pathway, the source kitchen situations. So those questions started to arise. In the beginning they thought the play is very simple. But later on after the drilling of the second well we understood that still many basic questions have to be answered related to the reservoir, the source rock, the migration – the play fairway indeed, the main one which is the CO play.*
INTERVIEW Beswetherick	*After the first drilling campaign a decision was made by the management to farm out an interest in the block by all of the partners, reducing their interest, the two main partners, to a third each. And the Murzuq block and indeed the Sirt acreage was farmed out to Agip.*
INTERVIEW Jonathan Craig	*… We decided to continue with the exploration program and acquired additional seismic data in order to firm up some more leads, and identified a couple of new prospects at the same time. And we decided that we would drill probably two more wells in the basin before making a final decision.*
INTERVIEW Beswetherick	*…. All of the prospects were examined or re-examined and ranked. Also we recognized a very big structure, Elephant, the Elephant structure, half of which lay outside the original NC174 block. So an extension was applied to cover the rest of the prospect. We decided to drill a prospect called Ostrich first, because it had a lower technical risk. And it was also surrounded by six other features of a similar size. It wasn't particularly big.*
INTERVIEW Jonathan Craig	*The fifths well that we drilled was also dry. And at this point in time I think it is fair to say that we were all very concerned and worried about the future prospectivity of the block. There was one very large structure remaining on the eastern side of the block that became known as the Elephant structure. And many people think it was called the Elephant structure simply because it was a very large structure on the block. Actually it was named the Elephant structure because there is a superb … prehistoric a rock carving of an Elephant that was identified and found in the wadi that underlies the well location.*
INTERVIEW Meijrab	*The F1-NC174 was a discovery with a certain fear. The decision to drill that prospect*

	because of the size of the trap. The size was really substantial. It's a large fault-bounded trap, about 35 square km in area and with a huge vertical displacement on the fault. But the main risk on that prospect was the charge, the migration route. They were not identified and lack of control. So people decided to drill that prospect because of its size. And that was really some kind of encouragement. They took the risk of migration despite that risk there was some encouragement from senior geologists in the company to drill that prospect.
INTERVIEW Jonathan Craig	*So it was with some trepidation that we drilled what was intended to be the final well on the block. The structure quite frankly was just too large to leave behind…. So it was really the last hope on the block. And as has happened so many times in exploration when you drill the last hope on the block it's the one that gives you the huge discovery that you have been waiting for during the entire exploration history. And that's exactly how it happened in his case.*
INTERVIEW Jonathan Craig	*Obviously when a discovery of the size of the Elephant field is made in a basin it changes everybody's perception of the petroleum potentiality of that particular region. And it was very clear from the discovery that the potential to find significant quantities of hydrocarbons in the Murzuq Basin had been improved considerably. And that created a great deal of interest in the industry. And many, many companies started to look at exploration in the southern Libyan basins from that point forward. It was really one of the turning points in exploration in southern Libya.*
INTERVIEW Jonathan Craig	*Clearly in the past there had been the majority of focus on the Sirte Basin and on the Mesozoic system. There had of course been other discoveries within the Palaeozoic system. But this again really changed the face of exploration. And everybody at this point recognized that the Palaeozoic, and in particular the deeper Palaeozoic was one of the areas where future reserves were likely to come from for Libya.*
	The Elephant oil is stored in the glacial Mamuniyat sandstone. In fact all other commercial fields discovered in Murzuq are also reservoired in this unit or the underlying pre-glacial Hawaz sands. Where did all the oil originally come from? What is the source of the southern Libyan "black gold"?
START FILM 4: **Part 8: SILURIAN HYDROCARBON SOURCE ROCK**	
	The sea came - and went, mountains formed - and collapsed, glaciers appeared - and melted: The only continuity in our planet's history is --------- CHANGE.
	When the late Ordovician glaciation came to an end, more than 50 million cubic kilometres of ice were transformed back into water. Sea level rose by 150 m. The latest Ordovician – Early Silurian postglacial sea level rise is one of the most intense eustatic flooding events. Enormous amounts of coastal land suddenly were drowned. Within a few million years the coastline was pushed inland many hundreds of kilometres. A large shelfal sea developed across North Africa and Arabia. Only Egypt stayed what is used to be, land, and formed a huge Peninsula.
	The modern Barents Sea in the Arctic Ocean may be a small-scale analogue for what

	happened during the early Silurian in North Africa. Covered by ice sheets during the Pleistocene, the Holocene sea level rise transformed the Barents area into a large shelfal sea. Today the ice sheets have long gone but the Arctic cold still has a firm grip on the area. The winters are tough. Surface waters are greatly cooled down and sink into the depth of the sea - as if to hide from the unfriendly forces of nature. Other, slightly less cold water masses rise to the surface and take over the vacant place in the winterly frontline. The rising waters are bringing with them precious nutrients from the deep. Food for tiny plants --- the phytoplankton. As spring arrives, enormous amounts of Russian and Scandinavian meltwater enter the Barents Sea. The light fresh water forms a stable layer on top of the sea water. The highlight of the year. Because now, undisturbed by the winterly vertical circulation, the phytoplankton can finally concentrate on what they like most: Food! Abundant light and great amounts of nutrients in the upper water layer generate a large phytoplankton bloom. Organic material that eventually sinks to the sea bottom in large quantities. As the summer approaches, the nutrients are finally all used up and the party is over. --- Until it starts allover again, in spring of the following year. The seasonal phytoplankton dance of the Barents Sea gives us a first idea that some cold-water ecosystems are capable of producing large amounts of organic matter.
	The intense Silurian transgression in North Africa stopped all sands and coarse detritus already the river mouths. Only muds and some silts were able to exit onto the shelf where they built up piles of hemipelagic mud. Rarely, sand packages were mobilized by storms or gravitational instability at the coast and were transported onto the shelf as tempestite or turbidite mass flows.
	Despite the enormous rise in eustatic sea level, the northern Gondwanan shelf was initially not easy to conquer for the sea. It was surely not a flat platform or ramp. Not at all. The glaciers had left behind a chaotic battlefield. A complex network of lows and highs dominated the shelf. Valleys and mini-basins, carved out by ice and meltwater. Hills that had escaped erosion or that were newly formed by glacial fans or other glacial sediment dumps.
	Clearly, a good understanding of the Ordovician glacial system can just be an advantage for the study of the basal Silurian shales. What is the regional distribution pattern of the palaeovalleys? Where are they completely infilled with glacial sediment, and where underfilled, where have they left some room for the Silurian transgressive muds?
	During the initial transgression only the low-lying areas, the palaeodepressions were flooded by the sea. Many of the highs were islands at that time. Or they were covered by so little water that they were still in the turbulent wave zone, where only sandstones were laid down or non-deposition prevailed.
	The lows gradually filled up with mud. --- A very special mud. The fuel for numerous of Saharan and Arabian oil fields. The Silurian “lower hot shale”. The basal part of the Tanezzuft Formation. The black mud contains up to 18% organic matter of marine type II kerogen. It was formed during an anoxic event that occupied much of the early Llandovery time at the very beginning of the Silurian.
	During this time, the early days of the Silurian transgression, the palaeohighs acted as efficient flow barriers, preventing the establishment of large-scale water circulation. In addition, meltwater coming from the waning glaciers formed a light freshwater cap, sitting on heavier saltwater. Lack of circulation and lack of vertical water movements blocked out any oxygen supplies to the basal water levels. Quickly these waters turned

	into a dead zone. Organic matter arriving on the sea floor could no longer be oxidised and was preserved.
	And there must have been a lot of organic matter. Some people say, there was a giant upwelling zone in front of the northern Gondwanan shelf margin, pumping up great volumes of nutrients that formed the basis for rich marine life.
	A typical modern example of a coastal upwelling zone is the Mauritanian upwelling system in the Atlantic. Here northeasterly trade winds push the coastal waters seawards, which are replaced by cool bottom waters rich in nitrate and phosphate. The nutrients feed large quantities of phytoplankton that forms the basis for zooplankton and fish. The Mauritanian upwelling system is active almost throughout the year and produces large amounts of organic matter.
	The early Silurian black organic muds were deposited across North Africa and Arabia, and probably as far away as South America and India. Not as a continuous layer, but restricted to the earliest Silurian palaeo-depressions. A mosaic of hot shale patches, surrounded by higher areas that the hot shales couldn't reach.
INTERVIEW Abdallah Khoja	*If we have a very deep low so we have a very thick shale. … So the hot shale has followed the pattern of the palaeolows at that time, the palaeotopography.*
	On seismic sections from the Murzuq and Kufra basins we clearly see the hot shale onlapping against the margins of the palaeodepressions. The hot shale is marked by strong seismic amplitudes as sound waves travel much slower through organic matter than through normal, organically lean shales.
	And there is also another very useful fingerprint that the hot shale leaves behind wherever it goes. The hot shale is markedly enriched in uranium and can therefore be easily detected on gamma-ray wireline logs. How does the uranium get into the hot shale? In all seawater there are traces of uranium. In fully oxygenated waters, the uranium is dissolved as U^{6+}. Under anoxic conditions, however, the U^{6+} is reduced to U^{4+}, precipitates and is incorporated into the sediment. Sediment that also accumulates and preserves large amounts of organic matter. And the data we have show that uranium, gamma-ray and total organic carbon concentrations are nicely interlinked in the Silurian hot shale of North Africa and Arabia: The higher the organic matter content, the more uranium is fixed in the sediment. So once this relationship is empirically established it is easy to approximate the TOC using uranium or even total gamma-ray data from wireline logs.
	Using the characteristic gamma-ray hot shale kick at or near the base of the Silurian, the hot shale patches can be nicely mapped out.
	Based on an analysis of all existing wells in the Murzuq Basin, we have identified a large, elongated hot shale basin that extends from the northeastern part of concession NC115 into NC174 and NC58 where our data suddenly end. The hot shale basin was surrounded by large scale highs where the hot shale has not been deposited. When investigated in more detail, the hot shale distribution is even more complex and may change abruptly within a few 100 metres.
	Silurian Tanezzuft outcrops occur in many areas around the Murzuq and Kufra basins. However, due to the shale's softness, in most cases only the middle to upper parts of the Tanezzuft are exposed, protected from erosion by the overlying Akakus sandstones. Only in a few outcrops, erosion has not completed it's job properly. It is here where the

	basal Tanezzuft is exposed. And yet, for a long time the only “hot shale” in the Murzuq and Kufra outcrops was cooked Tanezzuft under the camp fire. Till 2004 none of the numerous field parties visiting the Libyan desert ever discovered the Silurian hot shale at outcrop. A time of wild speculations. Were the Kufra and Murzuq margins possibly palaeohighs during the early Silurian and the hot shale absent? This would have had immediate source implications for blocks away from the basin centre. Or was the hot shale hiding somewhere and just fooled the geologists? The hunt was on. And only a few years ago it became clear that the hot shale was indeed hiding behind a weathering zone several metres or even a few 10s of metres thick. Oxidation during desert weathering commonly penetrates deeply into the ground and destroys any organic matter in the shales. The black colour is lost and reddish-greenish tones take over. As a consequence the hot shale at outcrop looks identical to any ordinary organically lean shale.
	Technology had to be called in to help. Remembering the characteristic uranium enrichment of the hot shale in the subsurface, a portable gamma-ray spectrometer was dragged around the outcrops. The big question: Did weathering also steal our uranium or can we possibly use it to identify the hot shale radiometrically at outcrop. Uranium values in the first test section in the Ghat area were disappointing. 4.1 ppm, 5.2 ppm, 3.9 ppm. Typical values of a normal shale. The second section. 19.2 ppm!!! A significant uranium enrichment was detected. Then 17.5, followed by 45.8 ppm. The hot shale gamma-kick was found and the field team greatly excited. Uranium-enriched intervals were also found in various other sections – always at the base. ---- Proof that the uranium hadn’t moved. Finally, a tool was found to map the hot shale around the Murzuq and Kufra basins.
INTERVIEW Fello	*The main technique we used is called gamma-ray spectrometer. This technique measures radioactive material which is present in the exposure. …If the result of this reading is more than 8 ppm that means we have high concentration of radioactive material, that means the hot shale. And if less than 8 ppm that means we have a normal shale or a cold shale. …This technique helps to distinguish between the hot shale and the cold shale.*
	A reliable tool but heavily depending on the presence of basal Tanezzuft outcrops. And the Ghat hot shale also demonstrated that large parts of the western Murzuq margin were certainly not a palaeohigh during the earliest Silurian. Otherwise the hot shale would not be there.
	A glacial reservoir with a very complex sedimentary architecture. An extremely patchy Silurian source rock. The traditional layer cake stratigraphic model is dead. Today the real challenges in Murzuq and Kufra exploration have become clear. But during the early 1990s, things still looked quite straightforward.
INTERVIEW Beswetherick	*The initial exploration phase involved defining the petroleum systems. It seemed to be a very simple petroleum system. A CO sandstone … overlain by a source rock which was also a thick shale section so it was also the seal. The system seemed very simple, but in fact was more complicated than we anticipated. Those complexities revolved around the complexity of the CO stratigraphy mainly. Understanding the CO facies at the top of the CO section. And that’s the reason for many failures in the Murzuq Basin. The sandstones are not in a good reservoir facies. The other issue involved the sourcing and the charging of these prospects. It was very difficult to define the Silurian source*

	kitchen. And the prospects with the highest risks, for example Elephant, should not have been sourced when we did our auto-contouring. And yet the ones with the lowest risk, some of them were dry or they had a small oil column on. I think what this said is that we didn't fully understand the source kitchen story, migration story and thus didn't appreciate the risk. We were too confident in our understanding of the model. If we had recognized more uncertainty we would have possibly had a more open mind.
	Uncertainty and risk are essential parts of the hydrocarbon exploration game. We try to reduce uncertainty by working out models based on existing data that help us to predict the geology over large regional areas. When there is new data, we compare it to our model. After we have done this we are either happy, because the model worked well, or we simply refine or change the model. The traditional scientific approach.
	And yet, something seems to have gone wrong with this approach over many years in the Kufra Basin. In the 1980s and early 1990s it was widely assumed that the Kufra Basin lacked any prospectivity because there was no Silurian source rock. The Kufra had been written off. And it had been written off on the basis of just 2 wells --- in a basin as large as Germany. The wells A1- and B1-NC43 had been drilled in 1978 and 1981 by Agip Name in the northern part of the Kufra Basin. The basal Silurian hot shale was indeed absent in these two localities. But how about the other 1 million potential localities in the basin? Even in a Silurian layer cake model, a layer extending over 400.000 km^2 cannot be characterised by just two data points.
INTERVIEW Meijrab	*In such a vast basin two wells cannot tell the world about the source rock. It's not fair in Kufra Basin to downgrade the basin because of source rock based on only two wells in such a vast, huge-sized basin like Kufra.*
	And from the mid 1980s onwards, new drilling results became available from the Murzuq Basin that showed clearly that the Silurian hot shale had a patchy regional distribution. Still, the Kufra verdict wasn't changed.
	It took nearly until the new millennium that Kufra got a second chance. A new depositional model showed that the presence of the basal hot shale is fully independent of the total Tanezzuft thickness. A shallow borehole produced graptolites proving the early Llandovery anoxic event at the eastern Kufra margin. Uranium-enriched shales were found in a basal Tanezzuft outcrop section. And high amplitude basal Tanezzuft reflectors onlapped onto palaeohighs on seismic. And there seems to be indications that the hot shale even produced hydrocarbons in the Kufra. A recent survey in the northern part of the basin appears to have documented local hydrocarbons micro-seepage. And in the southeastern portion of the Kufra Basin in Sudan, bedouins seem to use the oil from natural seeps to treat camel diseases.
INTERVIEW Belhadj	*…The fact that there is reports of seepage in the southern part of Kufra Basin in Sudan makes the area exactly similar to Murzuq Basin. Because Murzuq Basin number one was attracted by these seepage, that was found in the southern area of the Gargaf, these little towns of Gutta, Bergen and Shati. And I think now there is seepage in the southern part of the Kufra Basin in Sudan. So this makes the two basins quite similar in many, many ways.*
	The Silurian world class source rock has finally arrived also in the Kufra Basin. The question no longer is, *if* there is a source rock but *how much* and *where*.
	Southern Libya has never looked better than today. And things are happening fast. The first Murzuq field was brought onstream only in 1996. In addition, a string of discoveries in the past few years has finally proven the great petroleum potential of the Murzuq Basin.

INTERVIEW Hussein Seddiq	*Although it was among the latest basins where we have discovered oil among the sedimentary basins of Libya. But now I think the contribution of Murzuq Basin is more than the contribution of Ghadames…. So I think for the time being we are producing something like 350.000 barrels per day and our target is that production is maybe tripled in the next two or three years.*
Part 9: EXPLORATION HISTORY SOUTHERN LIBYA	
	Large parts of the Murzuq Basin are now licensed out and are being actively explored. To the pioneers of Libyan exploration this busy activity may seem as a deja-vu. Because already half a century ago, in the late 1950s, there was a time when oil companies flocked into the Murzuq Basin in great numbers, in the search of their bonanza.
	It all began in 1956 when a French Consortium operating in eastern Algeria near the Libyan border discovered the large Edjeleh field in the Illizi Basin. Inspired by the discovery, several American and European companies came to Libya to explore the Ghadames and Murzuq basins. The first concessions in Murzuq were awarded in 1957, mainly in the northern and eastern parts of the basin. It didn't take long and the first discovery was made in the Atshan area, located in a transitional position between the Murzuq and Ghadames basins. In 1958 Esso's well B2-1 tested here oil and gas. Although uncommercial, the Atshan discovery proved that the Silurian-sourced play *works* in the Murzuq Basin. The Atshan field consists of stacked oil and gas pools distributed over 5 different reservoir horizons between the Upper Ordovician and the Carboniferous. A leaking fault must have provided a nice conduit for the oil and gas to travel to the various reservoirs.
	Meanwhile in the neighbouring eastern Algerian Illizi Basin, more commercial discoveries had been made, all in Upper Silurian and Devonian reservoir horizons. Hoping to find similar fields, the companies operating in western Libya now specifically targeted this mid Palaeozoic reservoir play in Murzuq.
INTERVIEW Jonathan Craig	*There was a general feeling that …the deep Palaeozoic was probably too difficult. There was certainly a feeling that reservoir quality was going to be an issue, that it had been deeply buried. And there was very little understanding about what the source rock system might be.*
	The attempts to make the Siluro-Devonian reservoir work in northern Murzuq failed at the time. Maybe because the Tanezzuft Shale had effectively sealed most migration attempts of Silurian-sourced hydrocarbons into higher levels. New ideas were needed. For example taking the reservoir risk and indeed search a bit deeper in the stratigraphic column.
INTERVIEW Boote	*…Gulf also made a discovery around this time, the A1-68 which discovered oil in Ordovician sandstone reservoirs, sealed by basal Silurian shales, the Tanezzuft Formation. This turned out to be a key discovery but was pretty much ignored at the time.*
	It was busy years for the young petroleum industry in Libya. The companies came with great hopes and invested into their luck. By 1960 70% of the land area of Libya was placed under license, including all of the Ghadames and northern Murzuq, but none of

	the Kufra Basin.
	There was still little data around. The creativity of the oil company geologists was needed. Some play concepts were simply copied from neighbouring areas, others newly developed. Conventional ones and really crazy ones. It was clear, the geologists needed to talk to each other. They needed a forum to exchange ideas and data.
INTERVIEW Hammuda	*And the Petroleum Exploration Society which is…the pre-Society before the Earth Science Society - it was established in 1958 - and was an international group of geologists with local geologists together formed this Society. And from that time on more information was accumulating every year.*
INTERVIEW Klitzsch	*And the main fellow who pushed that was Pierre Burollet. …He was also the first one who initiated to publish a lexicon of stratigraphy… In 62 or 63 the first Sahara Symposium took place in Tripoli. … And there it was probably the first time when results of oil companies became public. And it created an atmosphere of open exchange, of relatively open exchange of surface geology information. Not necessarily subsurface. Subsurface exchanges were in the normal terms. You offered a certain well and you got another well in exchange. But surface geology was relatively open exchange.*
INTERVIEW Klitzsch	*…I was the one who got the award for the best paper. Which was very interesting because at that time I spoke much worse English than now. And as you can hear my English is not the best. But it was mainly due to the fact that I was the one who first understood or at least to publish and talk about it that there was a definite change in structural behaviours, structural setup towards the end of Silurian. In other words what we in Europe would call Caledonian. And the place to see that and the place where I understood it is northern Dor El Gusa at the eastern edge of Murzuq Basin.*
INTERVIEW Klitzsch	*And I must say, the position I had within DEA was an excellent position because I had a head geologist or exploration manager in Hamburg, which not only tolerated scientific work of this type of interpretation and publication, who also encouraged it. He was a scientist and was happy that his men work scientifically. And he was happy to go with us to the desert. And we took him several times to southern Libya. Even to Tibesti and to northern Niger. And I remember the first trip he was called back to Hamburg at the third day. And this had one consequence. On the next trip we turned off the radio. We told him it was broken. And so we made our two weeks in the desert without having the order for him to come back.*
	It was characteristic during this phase that companies didn’t rule out any region without having actively explored it. Also in the Murzuq.
INTERVIEW Boote	*There was further drilling to the south. And indeed a number of wells have been drilled in the Niger extension of the basin, in the extreme southern part of the basin. But all with general lack of success.*
	Despite a few uncommercial discoveries, companies soon lost interest in the Murzuq. And this did not even have to do much with the Murzuq itself but with some interesting geophysical results from northern Libya.
INTERVIEW Klitzsch	*And meanwhile oil companies had undergone quite a bit of gravity and magnetometric surveys and found out that the area between Achetabya and Benghazi which we now call the Sirte Basin is an area with a very distinct subdivision and graben and horst structures, with deep graben floors. And so the consequence was to concentrate more in that area. And within one of the first wells a large oil field was found. … And this was the end of at least intensive exploration in other areas.*
	The Bahi field in the Sirte Basin was the first commercial discovery of Libya, found by Oasis in April 1958 by their well A1-32. In that same year six other discoveries were

	made in the Sirte, nearly half of them were declared commercial. And all this during a time when in western Libya there were still no commercial finds in sight.
	The Murzuq had lost the race. Exploration in the following 30 years now concentrated mainly on the Sirte Basin.
INTERVIEW Klitzsch	*I believe the reason that Murzuq basin was not considered to be very attractive in the early days has of course several reasons. One of it is, big oil fields have been found in Sirt Basin. The first wells that found oil in the Murzuq Basin or bordering areas did not find much. The test results were in the order of a few hundred barrels maximum while in the Sirte Basin it was several thousands. … The second reason is the distance to a harbour or to the Mediterranean is drastically bigger than from Sirte Basin. And the third reason is … the Hamra or Ghadames Basin, was under exploration relatively early. … It is the area east of the successful oil exploration of Algeria and southern Tunisia. So Edscheleh for example, is at the Libyan border. And there was no reason why there should be no oil in the Ghadames Basin. Ghadames Basin underwent a very intensive seismic interpretation – it was full of seismic lines. It was difficult to find your way across Hamra Basin. I went several times from Ghadames to Al Aweinat. And lost my way several times because of that. But whatever oil was found, in Ghadames Basin was little oil. There was no big field, not at all. Nothing, even until today there is no big fields in Ghadames Basin. And it is a similar basin as the Murzuq Basin. It is Palaeozoic. It is similar deep, but closer to the sea, not successful. So why should people go to the Murzuq Basin. I think that is the whole reason. We tried very hard to get our company, which was DEA at the time, to drill Jebel Ati, which is even further south, the southern part of Murzuq Basin. A very large, 80 km long and 10-15 km wide anticline … But this was impossible to convince any management. I think other companies had the same problem. We were not the only geologists that were interested in the Murzuq Basin but we had no success in convincing management.*
INTERVIEW Boote	*During the seventies, exploration was pretty much dormant. Until Braspetro moved in the late 70s and followed through with a very aggressive exploration program drilling wildcats in many parts of the basin. Again that was unsuccessful.*
	And also Occidental tried their luck in Murzuq at that time. But these efforts were not rewarded either. Until this point, the Kufra Basin had been hardly looked at. Not a single well had been drilled. But this was to change. In the mid 1970s AGIP NAME carried out a full-scale exploration program in Kufra. An enormous amount of outcrop, aeromagnetic and 2200 km of seismic data were collected. But two dry holes brought also this campaign to an end.
	In the 1970s and early 1980s, geological concepts and technology were not yet fully developed to make explorers believe in the prospectivity of southern Libya. But most of all, they lacked one thing: luck!
INTERVIEW Abdallah Khoja	*At that time before 1980 it was considered as frontier area and that the exploration costs will be very high. So the people were not encouraged to work there and to explore that area. Plus the reservoir pressure at that time. The wells never flowed to the surface. So that was another negative point at that time. Plus the cost of the barrel of oil at that time did not encourage people to explore that area.*
	Undeterred by the past failures eastern European companies stepped onto the Murzuq scene in the 1980s. The Bulgarian Boco and Romanian Rompetrol explored large areas of the basin and understood quickly that it was in fact the Ordovician sands that were the most rewarding target.
INTERVIEW Dr. Aziz	*We have three companies working in the basin at that time. Rompetrol, Boco and Braspetro. These companies had huge blocks. The smallest one was for Rompetrol with 25.000 sq km.*

INTERVIEW Dr. Aziz	*Myself I joined Rompetrol in the exploration stage in 1984 as a trainee geologist in the exploration department. From there we started.*
	Between 1982 and 1985 Rompetrol discovered various large fields in their concession 115 and laid the foundation for the oil boom in the region today.
INTERVIEW Beswetherick	*Rompetrol I think had reserves of 500 million barrels in the A-field. Repsol bought the Rompetrol interest and found that there was indeed a lot more oil than they originally thought was in these fields. And Repsol went about drilling new prospects, shooting new seismic, 3D, the quality of seismic data over NC115 is excellent, because of the flat sand plain.*
	While lack of funds prevented the Romanians to develop their own discoveries, they were indeed the first company in Murzuq to earn money from their activities. After the transfer of the Shahara field to Repsol in 1994 the reserves were re-estimated to be more than 1 billion barrels in place. Development was completed in 1999 and today the field produces about 160.000 barrels per day.
INTERVIEW Fello	*So when Repsol joined NC115 so they found … three major oil fields which are called A field, B field and H field. But now we discovered and we developed the whole NC115. So at the moment we have four main fields A, B, H, M fields, and we have also small structure which is called L structure, O structure and we have another small structure called G (J?), F, C structure.*
INTERVIEW Dr. Aziz	*Some of them are under development, the other ones are planned to develop very soon, other ones are postponed, depending on the sizes of the field and the relation to the service facilities. But we make our plans to reach our production quota. And we are now in a good production level.*
INTERVIEW Dr. Aziz	*I can say we have a very good rate of success. It means that a lot of new discoveries…achieved recently which gives us more interest points in the basins.*
INTERVIEW Beswetherick	*I am surprised that onces Rompetrol had made the discoveries in the NC115 block that more companies didn't look at the basin. And looking back there was a prolific source rock there, a world-class source rock, there was a good reservoir system. It is surprising that it wasn't recognized earlier.*
	Following the Shahara giant oil field discovery in 1984, it took another 13 years for the oil industry to land the next commercial discovery. In 1997 Lasmo eventually found the giant Elephant field. Since then various other fields have been discovered in the Murzuq Basin by Repsol, Total and partners.
INTERVIEW Boote	*During this period the central and southern parts of the basin were largely ignored. There was very little drilling there. But ultimately, roundabout 2000 or so, people started to think about the area and gradually moved down. Repsol drilled a well in the central part of the basin and Hunt drilled several wells in the Niger extension. Again, these were unsuccessful.*
INTERVIEW Boote	*In 2004/2005 Libya had the first of the EPSA INTERVIEW rounds which really triggered off a new round of exploration in this area. And now we wait to see the results.*
	Looking back at 50 years of trial and error exploration in Murzuq, activity can be split up into various phases. The presence of a working petroleum system was proven very early on. In the following 30 years, the basin was largely forgotten, as interest had shifted into the Sirte Basin. From a historical perspective, was it probably a mistake to have overlooked the great potential of the Murzuq for so long?
INTERVIEW Jonathan Craig	*I am not sure if I would consider it a mistake to have overlooked the evidence, if you like, the evidence was very clear. I think it was much more a question of priorities. There were other places that we wanted to explore first that were nearer to facilities*

	that were nearer to centres of population, nearer to the coast, so we had a better export route. So I think it was rather a question of priorities. And I think we recognized that there was good evidence that there were other petroleum systems around. But we simply had other priorities at that time.
START FILM 5 **Part 10: SILURIAN DELTAIC PROGRADATION**	
	After the early Llandovery anoxic event had ended, the oxygen returned to the shelfal sea. The sea level was still rising fast so that the earlier glacial flow barriers eventually were flooded. Large-scale water circulation systems began to operate, mixing the ocean waters and eliminating the anoxic water masses across the shelf. The hemipelagic muds that were now deposited were healthy and green, containing only negligible amounts of organic matter. They represent the bulk of the Tanezzuft Formation. Up to 500 m of Tanezzuft shales formed in Murzuq. In the Kufra Basin the unit is markedly thinner and usually is no more than 100 m thick. Why so little in Kufra? Kufra lies on the proximal part of the North African shelf, close to the early Silurian sandy coastal zone. By mid Llandovery times, the coastline began to shift northwestwards and quickly reached the Kufra Basin. The end of hemipelagic Tanezzuft muds and the beginning of deltaic sandstone deposition. The Akakus sands. The Murzuq Basin was overrun by these sands only later, allowing extra time to pile up more mud here. At first glance it is hard to believe that the coast line began to shift seawards at all during the mid Llandovery, because the postglacial sea level rise at that point in time was still in full swing. Rising sea level – yes. But outweighed by far by a huge pile of sand parked in the North African river mouths that was now actively pushed by more sand into the sea. Throughout Silurian times numerous rivers transported enormous amounts of sand from the Gondwanan hinterland towards the North African coast. The early Llandovery transgression still managed to trap these sands in the river mouths, where they backstepped unwillingly onto the coast. By the middle Llandovery, however, so much sand had been accumulated in the coastal belt that huge deltaic fans began to form in Kufra, shedding the sediment into the sea. Layer by layer the delta system built out onto the shelf. A prograding deltaic front developed that must have stretched over more than 2.000 kilometres.
	There is no deltaic system on earth today that only comes close to these dimension. On a scaled-down level, however, the present-day largest delta of the world may give us an idea of how such a long deltaic coastline may have functioned. The Ganges Delta in Bangladesh and India is 350 km long and is fed by 240 individual rivers, the largest of them being the Ganges and the Brahmaputra. The general architecture of the Silurian Akakus delta may have not been very different to the Ganges system. Numerous rivers draining the huge Gondwanan hinterland may have joined forces and formed the deltaic Akakus front.

	The general northwestward movement of the Akakus delta was occasionally interrupted by third-order sea level cycles that pushed the shoreline slightly back towards the land. In the Ghat area a series of three to four shallowing upward sedimentary packages formed, separated by pronounced flooding surfaces. A sedimentary architecture interpreted as parasequence in the sequence stratigraphic model. In general, Akakus times in the Murzuq Basin must have been rather peaceful for the inhabitants of the Silurian sea. Abundant trace fossils speak of luxurious times with plenty of oxygen available at the sea bottom. The king of all traces is undoubtedly Cruziana.
INTERVIEW Seilacher	*Cruziana is the burrow of a trilobite. And it is made by the legs, burrowing strangely, not away from under the body but towards the midline. So actually, the sediment was carried together under the body. This means the animal did not want to get burrowed for protection but it wanted to loosen the sediment and filtrate the sediment and process under the dorsal shield which was just on top of it. And here we can see the details of the claw formula. They have five raw claws. And when they are larger we can see that there is a notch in the middle of each claw.*
	The trilobites were not alone. The sand must have been also full of worms, leaving behind an amazing labyrinth of simple-structured Arthrophycus tunnels. In some Akakus beds, Cruziana and Arthrophycus traces are intensely interwoven. Scenes of a fierce hunt? Not at all. In reality, the two animals hardly got to meet each other.
INTERVIEW Seilacher	*This is two generations of burrows. First you have here the trilobites coming from very shallow above. And then the deeper burrowing worms here they came up with sedimentation and crossed it. And then they searched out the old trilobite burrows and if they could went along them.*
	Akakus life must have been good. --- With probably one exception. Climbing up the Akakus escarpment in Wadi Tanezzuft, the cliff in the lower part exposes a mysterious unit with strangely patterned surfaces. The imprints appear to originate from gas bubbles that got trapped in biomats. Usually there is little room for biomats in healthy ecosystems because they make a perfect dinner for many sea creatures. The wide occurrence of these mats indicates that the ecosystem might have turned sick for a few million years.
	In fact it was a second anoxic event that had struck. An event that terrorised the North African-Arabian shelf for a short while during the late Llandovery to early Wenlock. Offshore the sandy delta zone, in the Ghadames Basin, a stinky black mud was deposited during this event. The so-called "upper hot shale". A unit that is absent in the Murzuq and Kufra basins because the sandy delta sediments had already overrun them at that time.
Part 11: DEVONIAN UPLIFT AND FLUVIAL SANDS	
	The Akakus delta slowly worked its way through to western Algeria. But before it could reach Morocco, the early Devonian arrived. The sea had suddenly enough and withdrew. The end of the Akakus deposition. It happened at a time when sea levels dropped worldwide. --- But there was also something else that kept Libya quite busy during those days.

	Part of the Murzuq started moving --- *upwards*.
	We still are not quite sure why these movements took place. Certainly, Libya was not involved in any nearby plate collisions at that time. According to some specialists the tectonic stress could have originated from Morocco. The Armorica terrane that includes parts of present-day France seems to have broken away from NW Africa during the early Devonian. The Tectonic stress that resulted from this divorce may have travelled thousands of kilometres into the southern Libya intraplate, triggering the uplift. As it did in the western Algerian Reggane Basin and the Mauritanian-Malian Taoudenni Basin.
	In the Murzuq Basin, uplift and eustatic sea level fall joined forces. Hungry as they were they took a huge bite into the ground and removed part of the Akakus sands that had just been deposited. In other areas they wanted more, cutting away all of the Tanezzuft, including the precious Silurian source rock. In the northeastern Murzuq erosion took out even the uppermost Cambro-Ordovician layers. The erosional event is known in North Africa as the Caledonian unconformity.
INTERVIEW Hammuda	*The most prominent tectonic events that shaped Libya are the Caledonian.*
INTERVIEW Belhadj	*The Caledonian really had uplifted the centre of Murzuq Basin. … The Caledonian provided a new palaeohigh.*
INTERVIEW Klitzsch	*… The most obvious place to see the Caledonian unconformity is in northern Dor El Gusa, at the eastern edge of Murzuq basin.*
INTERVIEW Klitzsch	*The Akakus pinches out towards the south, towards central Dor El Gusa. between Tadrart Sandstone and Tanezzuft Shale. And later, even further south Tanezzuft Shale pinches out and the Cambro-Ordovician is directly overlain by the Tadrart, by Lower Devonian strata then. …*
	The unconformity's early Devonian age matches quite well with that of the real Caledonian Orogeny in Laurasia, which inspired the geological pioneers in North Africa to choose the same name. But in fact there is no genetic link between the two compressional activities. Gondwana is far away from anything at this time.
	The Caledonian erosion was just one of various phases when the thoroughly deposited sand grains were ripped out of their beds and set alive once again. Taconic, Caledonian, Hercynian, Austrian, Alpine. Attacks on the quartz particles were numerous.
INTERVIEW Belhadj	*These sands were re-deposited, in fact were re-deposited on margins and depocenteres where the depocentre is in the outcrop.*
	Some grains that found their final resting place today in the Mesozoic Nubian Sandstone have been recycled three times since their first deposition in the Cambro-Ordovician. The North African shelf – a cannibalistic system.
	The Caledonian uplift changed the structural architecture of Libya. Before the Caledonian the Early Palaeozoic substrate of Libya is thought to have been dominated by NNW-SSE trending structures. Ridges and troughs controlled the facies and thickness distribution in southern Libya on a 100s of kilometre scale. These trends are often hard to detect within individual concessions but operate more on a basin-wide scale.
INTERVIEW Jonathan Craig	*We see some evidence that there was onlap onto particular palaeo-arches, some of the big broad N-S palaeo-arches, but essentially it was one series of continuous linked sag basins that ran across the whole of the North Gondwanan margin.*

INTERVIEW Klitzsch	*Gargaf was part of a NNW-striking high during Silurian and this is the high you can see at Mouri Ide. At Mouri Ide along the track down to Chad there is Silurian directly on basement …*
	The vast majority of strata in the Murzuq and Kufra basins dip only gently towards the respective basin centres. The dip angle is very low --- often it's really nearly flat-lying.
INTERVIEW Klitzsch	*But even this flat lying strata evidently had undergone structural differentiation. To find out that these structural differentiations can be mapped can be shown on maps was interesting … And what we had on the preliminary geological maps showed basins and areas between basins.* *But what I found out already in the first field campaign was that a basin …was not necessarily a basin all the time. There were highs and there were lows during different times and changing during the times.*
	Part of the early Palaeozoic pre-Caledonian action is captured in stone at the eastern margin of the Murzuq Basin.
INTERVIEW Klitzsch	*In northern Dor El Gusa you see a very strong unconformity of Ordovician strata with an angle of about 15 or even more degrees, overlying steeply dipping pre-Ordovicians, Cambrian or Infracambrian we don't know….*
INTERVIEW Klitzsch	*The uplift happened probably as early as Cambrian or early Ordovician. It's one of those very early structural elements.*
INTERVIEW Klitzsch	*So this is the old structural setup and it changed towards the end of Silurian, we suddenly got a totally different structural setup. The NW direction became common and we got sedimentation of Devonian and Carboniferous in troughs and later in Permian or Triassic time in troughs which had a different direction of strike. And different centres as well.*
	So the early Devonian Caledonian uplift marked an important change in the tectonic regime of southern Libya. As the area was partly uplifted and eustatic sea level fell, the Gondwanan feeding rivers quickly invaded the former marine deltaic zone. --- The Tadrart sands arrived.
	Wide bundles of shallow river channels covered the low lying areas of southern Libya. Every day the braided systems kept pushing their sandbars further downstream. The movement is preserved in the monotonously dipping tabular crossbeds. The Tadrart rivers were rather unreliable guys. The channels frequently became clogged and alternative routes were established. New bars formed – and soon they had been eroded again. The water discharge varied from extreme floods to weak trickles. And there was no space for fines here. The strong currents swept the muds out of the braided river basin, leaving behind a nicely cleaned Tadrart sand.
	The crossbeds piled up and today form towering walls in the Akakus Mountains, a national park of stunning beauty. Textbook-like. The lower Tadrart is massive, fluvial strata everywhere. But then the sea must have remembered the good times it once had in southern Libya. It wanted to come back. Several attempts to reclaim the territory were only shortlived and each time the river sands managed to strike back. Several cycles developed in the upper Tadrart with alternating marine and fluvial facies.

	But the final winner was the sea. Marine sands, siltstones and shales of the Early Devonian Ouan Kasa Formation mark the end of the fluvial Tadrart times.
	The Tadrart surely makes a nice potential reservoir. There is only *one* little problem. --- And that is that the Tadrart today is completely absent in the central and northern parts of the Murzuq Basin. Eroded by a middle Devonian uplift event underneath the so-called mid-Eifelian unconformity.
	Following the Early Devonian Caledonian tilting, the Tadrart and Oun Kasa were deposited on top of the erosional surface. During the middle Devonian, another intraplate uplift event struck. Short-lived but very effective. The central and northern parts of the Murzuq were pushed up and the Ouan Kasa and Tadrart taken out. The mid-Eifelian even eroded through the Caledonian unconformity and helped to remove more of the Akakus and Tanezzuft.
Part 12: MIDDLE DEVONIAN TO CARBONIFEROUS SAND-SHALE ALTERNATIONS	
	When the middle Devonian erosional event was over, the sea came back. It often is surprising to see how innovative and exciting nature can be. And on the other extreme – also how boring sometimes. Throughout the middle Devonian to late Carboniferous, nature in southern Libya had only one thing in stock: Monotonous eustatic sea-level oscillations. Sands and shales, deposited from shoreface to storm wave base. The sand-dominated parts of the cycles during the sea level lows, the shale-dominated packages usually during the sea level highs. Only during rare occasions, the siliciclastics paused for a short while --- and carbonates formed. Time went by, formation names changed: Awaynat Wanin during the Middle to Late Devonian; Marar, Assedjefar and Dembaba during the Carboniferous The depositional pattern, however, stayed the same.
	At the northwestern Murzuq margin, the Middle Devonian to Carboniferous sandstones form prominent ridges on a huge desert plain. Old ridges around Al Awaynat, younger ridges along the road towards Ubari. Very easily accessible from the asphalt road connecting the two towns. A paradise for the lazy geologist who hates to leave his air-conditioned car for too long. The basinward dipping Palaeozoic strata have created a superb cuesta morphology. The hard Tadrart and Akakus sandstones form the large ridge of the Akakus Mountains. The soft Tanezzuft shales a wide wadi, that is also home to the town of Ghat. The Cambro-Ordovician sandstones in the extreme west make another gentle ridge.
	There are some nice sands in the Upper Palaeozoic. Could they be alternatives to the traditional Ordovician reservoirs?
INTERVIEW Jonathan Craig	*What is particularly interesting is that there are other possibilities in southern Libya that still require quite a lot of work and a lot of exploration to understand and to*

	recognize whether or not there are working petroleum systems. Two that are of particular interest is the Devonian system. We already have some hydrocarbons encountered within the Devonian but generally rather small amounts. But there is no reason why the Devonian and indeed some of the later Silurian sands shouldn't work in that region.
INTERVIEW Dr. Aziz	*In one of the areas that we have we call the C structure, yes we have, the main structure is within the Devonian, what we call the BDS, basal Devonian sandstone. And I am sure that … in some areas it should be the main reservoir within Murzuq Basin.*
INTERVIEW Belhadj	*You have to consider the Carboniferous, too. Because the Carboniferous is also capable of producing in Atshan area. But the most important thing is that the Devonian hot shale, Frasnian is not present in Murzuq Basin. So what you have to see is that your source rock has to be Silurian.*
	In most parts of the Murzuq, the Devonian and Carboniferous sands are separated from the Silurian source rock by the Tanezzuft shales, a very effective seal. The only way up for the hydrocarbons is along faults.
INTERVIEW Meijrab	*So you really depend on the faults. And you want the faults to play as conduits for migration of oil to go to the Devonian on top of that thick Silurian section.*
INTERVIEW Meijrab	*At the same time you have to be careful about the side seals. You need another strong side seal to have the oil migrated to your reservoir.*
INTERVIEW Belhadj	*We can use the Atshan field discovered by Esso in 1959 - I think it is an example and it is a school to understand if we really want to explore the Devonian and the Carboniferous.*
INTERVIEW Jonathan Craig	*And as far as we can determine at the moment it requires that we have some juxtaposition of the Devonian reservoirs against one of the other carrier beds in order to charge the Devonian structures. And that's one of the main reasons why the relatively few of them that have been tested have worked successfully so far.*
Part 13: THE HERCYNIAN COLLISION AND FORMATION OF GONDWANA	
	Towards the end of the Carboniferous, earth prepared for a change. The continents once again came together for one of their rare re-unions. The legendary supercontinent of Pangaea ruled the world.
	Southern Libya stayed out of any trouble. The nearest collisional zone was in NW Africa where Gondwana crashed into North America. The most intense deformation of the so-called Hercynian Orogeny was concentrated over the north-west coast of Morocco and Mauritania. The compressive stress once again was transmitted far inside the plate interior. But when it arrived in southern Libya --- there wasn't that much left of it. While the Hercynian created spectacular angular unconformities in the Ghadames Basin of NW Libya, the effects in Murzuq and Kufra appear to be more on the subtle side. But in reality, they were an important step on the basins' way to adulthood.
INTERVIEW Jonathan Craig	*Certainly in broad regional terms one of the prime effects of the Hercynian unconformity was to accentuate both N-S and E-W trending arches, so that really at that stage in the geological history we began to differentiate and separate the individual basins as we see them today. So the separation of the Murzuq Basin from the*

	Kufra Basin, the Murzuq Basin from the Ghadames Basin certainly appears to become prominent in the Hercynian period. And then it has been periodically reactivated throughout of the rest of the geological history. And again the Alpine deformation has been the final phase in that history if you like, in determining the uplift of some of these arches, separating the main basins.
	Prior to the Hercynian collision, the northwest African shelf appears to have been actively dragged down, accumulating several kilometres of sediment. Soon the Silurian source rock was buried under a big pile of strata. The organic matter matured and hydrocarbons were generated that migrated into pre-Hercynian traps. When the continental collision happened, some of these traps were damaged and a lot of these pre-Hercynian generated hydrocarbons escaped to the surface and were lost. Complications that mostly affected parts of Morocco and Algeria. And what about southern Libya?
INTERVIEW Boote	*From the modelling we have done we don't believe there was a significant amount of hydrocarbon generation in pre-Hercynian, in this area at least.*
	The most obvious effect of the Hercynian in southern Libya was that it had lifted the area out of the sea. The sea had to go and rivers and lakes were the new masters of the Murzuq and Kufra. And they liked it so much that they dumped their red sands and muds here for more than 150 million years, until the Late Cretaceous.
START FILM 6: **Part 14: MESOZOIC EXTENSION AND CONTINENTAL DEPOSITION**	
	The post-Hercynian continental redbeds are informally known in North Africa as the "Nubian Sandstones". Nubian outcrops cover the large central parts of both the Kufra and Murzuq basins today. The spectacular canyons in Jebel Bin Ghenihma at the eastern Murzuq margin are a Nubian open-air museum. Typical fluvial-dominated strata. Planar and trough crossbeds, channels. Some overbank and lacustrine muds. That's essentially it. The Nubian is no longer an official name used in Libyan stratigraphy. But it is rather practical nervertheless. Officially the Nubian is represented by three units. The Triassic Zarzaitine Formation The Jurassic Taouratine Formation and the Upper Jurassic to Lower Cretaceous Messak Formation. Of these the Messak is the most attractive in the field. In Murzuq it forms a huge cliff stretching over 300 kilometres across the open desert. A nice little challenge for pipeline planners…
INTERVIEW Fello	*The escarpment is very, very close to NC115. It looks like a boundary between NC115 and NC174. So this escarpment is quite high.*
	During the Late Cretaceous and Early Tertiary, the sea made its last appearance in southern Libya. Around Cenomanian-Turonian times, global sea level had climbed to a Phanerozoic record high.

	A large trans-Saharan seaway formed, connecting the Tethys with the Atlantic Ocean. Part of the seaway ran along the western Tibesti margin, flowing gently around the Murzuq island. Falling sea level interrupted the seaway in the Santonian to Masstrichtian, but it got re-established during the Paleocene. Carbonates and marls dominated the facies. When the Oligocene came, the sea had to withdraw from southern Libya. ---- Since then, it was never seen again here. It also marked the end of sedimentation in southern Libya.
	Although rather unspectacular, the Nubian Sandstone is critical for the Palaeozoic petroleum plays in Murzuq and Kufra. And this is purely related to its thickness and role as overburden material. In the central parts of the southern Libyan basins, the Nubian gets up to 2 km thick. The Silurian source rock would not have expelled its precious organic juice without the Nubian overburden.
	Huge sedimentary thickness means, there was a lot of space that waited to be infilled. Space created by two main phases of increased subsidence. The first extensional event affected the whole of North Africa. After Pangaea's best days were over, the supercontinent broke apart. From the late Permian onwards Turkey and other blocks separated from northern Gondwana. Deep rift grabens opened up all along the North Africa margin. The extensional stress also affected southern Libya where the ground began to subside rapidly.
	The second extensional event in southern Libya started in the Early Cretaceous. A complex zone of rift grabens formed across North and Central Africa. The birth of the Sirte Basin. Break-up days of western Gondwana, shortly before the North and South Atlantic became united.
	The enormous accommodation space created in southern Libya by the extensional events was soon filled up. The Silurian source rock got buried. Deeper and deeper. Eventually, temperatures and pressure were too much for the organic matter stored in the hot shale. Chemical bonds cracked and hydrocarbons formed. Enormous amounts of hydrocarbons, many billions of barrels – as simple modelling shows. The peak hydrocarbon generation phases in both the Murzuq and Kufra basins must have occurred sometime between the Jurassic and Tertiary. The question in southern Libya is not, how much oil once was generated. The question is rather how much and where is it preserved?
	While the general mechanism and timing today are well understood, there are unfortunately some very important details that we still haven't properly figured out. Details that are critical to the hydrocarbon play and continue to cost us a lot of money when they have once more fooled us again.
INTERVIEW Jonathan Craig	*In terms of the geology in the petroleum system probably the thing that remains the biggest challenge for us is getting a proper understanding of the distribution and maturity of the source rock. But in particular understanding migration pathways between individual prospects and the source kitchen. This has been a fundamental problem all through the exploration history, of the Murzuq Basin in particular but I am*

	sure the same will apply in the Kufra Basin. And it's one of the things that we focus particular attention on in terms of trying to understand the risks and uncertainties associated with exploration in the southern Libyan basins.
INTERVIEW Beswetherick	*We never quite understood if the kitchen was in the centre of the Murzuq Basin or maybe migration had come from a different area, for example out towards the Atshan arch towards Algeria. The oil was fairly light although it had very low aromatics, indicating possibly water washing. The B1-NC174 well encountered a very good source rock section and we had this analysed for various maturity parameters, especially the GC-MS maturity parameters, and the maturity given by that Tanezzuft hot shale was precisely what we had modelled. Just entering the oil window. So the thermal story seemed to be correct. And what seemed to be more of a mystery was, where exactly was the oil migrating from? Because if you had a kitchen in the centre of the Murzuq Basin, the oil should have had difficulty migrating into structures like Elephant or A1-NC115 indeed, from our auto-contouring which was done once we had restored the maps back for any Cretaceous tilting. So it was really the migration model that we had the greatest uncertainty about.*
	Today there is a lot of evidence for short-distance migration. Local source kitchens from where hydrocarbons migrated over a few kilometres or a few 10s of kilometres into the trap. But what about longer migration distances in southern Libya?
INTERVIEW Boote	*…I am inclined to think the migration distances are relatively short. …And that is because of the character of the Ordovician sandstones.* *The periglacial sandstones, the Mamuniyat sandstones are very heterolithic, have a lot of complexity within them. And they don't look to me as if they make a good … lateral conduit. The Hawaz sandstones are rather poorer quality, however they are more continuous in fact. They are broken up by the deep erosional incision. And again, it is difficult to imagine long distance migration through them. However, that said I do feel it is possible under certain circumstances lateral migration over significant distances might be possible. We know that the glaciers advanced and retreated in a roughly north to south direction. And this would suggest that the channels and the main sand fairways associated with glacial deposition have a very strong N-S alignment.* *Where the alignment is conveniently oriented with respect to structural dip it's quite possible…* *some of these sands may have focused migration in particular directions.* *And in those situations it may have been possible that lateral migration might have been quite significant.*
Part 15: ALPINE UPLIFT AND EUROPE/AFRICA COLLISION	
	By the mid Tertiary most of the source kitchens in Murzuq and Kufra must have been shut down. Tectonic forces had pushed up the Silurian hot shale. After it had left the oil window the source rock cooled down and stopped generating hydrocarbons. The phenomenon was studied in greater detail only a few years ago in the Murzuq Basin.
INTERVIEW Abdallah Khoja	*We have a lot of inversions in the area. …The margin has been inverted so we have shallow depth for the hot shale. And this has been inverted lately, after the maturation. In the northern part we have now some fields at a depth of 2000 ft only. …And this*

	could have been inverted at a certain time, maybe Alpine time, and that brings the …reservoir in a shallow depth.
	What had happened? Afroarabia and Eurasia had collided. Numerous Alpine foldbelts formed all along the collisional zone. The Atlas in NW Africa and the Zagros north of Arabia are the most prominent ones. Libya itself was not directly involved in the crash. Once again, the central Sahara stayed out of trouble. Nevertheless, intraplate stress managed to reach southern Libya. In terms of stress propagation and tectonic impact in Murzuq and Kufra, the Alpine was not too different from the earlier Hercynian compression.
INTERVIEW Jonathan Craig	*In fact the effects of both of those tectonic events are very strong as we move towards the west into Algeria, into Morocco. But in fact the overall effects decline very quickly as we move eastwards and southwards. So by the time we come into the southern Libyan basins then we don't see significant effects from either of those particular events.*
	Certainly, the Late Cretaceous to Tertiary Alpine compression did not create major folds or thrusts in southern Libya. Nevertheless, this tectonic event was of great importance to the Murzuq and Kufra petroleum systems, and this was related to uplift and the reactivation of existing faults.
	At the present-day basin margins there are Cambrian rocks today at surface. Based on what we know about the basins' tectonic history, there once were several kilometres of other strata on top of this. So exposure of the Cambrian today means that several kilometres of strata must have been uplifted and eroded here. Part of this uplift might have been Hercynian. The rest must be Alpine.
	In fact, when looked at in greater detail, there was another compressional event in the Cretaceous that contributed to the overall uplift. The so-called Austrian event of the mid Cretaceous, the Aptian.
INTERVIEW Boote	*It's quite clear that the whole western part of Libya was uplifted and unroofed in middle Cretaceous times… An enormous amount of sediments was stripped off.*
	During the Austrian many of the rift grabens that had formed during the Early Cretaceous in North and Central Africa were inverted. The continental stress field controlled by the Africa-Europe plate approach, the opening Atlantic and the Sirte rifting had changed. In some parts of southern Libya it was probably already the Austrian event that marked the end of local hydrocarbon generation.
	The Austrian and Alpine uplift of the basin margins of up to 3 kilometres has huge implications for regional hydrocarbon prospectivity. In some areas close to the present-day basin margins the Silurian may have been deeply buried until the Early Cretaceous. Local source kitchens might have generated hydrocarbons here until Alpine uplift shut them down in Late Cretaceous or Early Tertiary times. Structures could have been charged using completely different migration routes than in scenarios with hydrocarbon charge coming from the basin centres. Clearly, we still lack a lot of data to substantiate these uplift and migration models on a quantitative basis. The key question is "How much and when were the different regions of the southern Libyan basins uplifted?" If we only had thermometers in the rocks that could tell us the detailed history of the

	cooling and uplift in Murzuq and Kufra. But we are lucky. Hidden in the rocks there are quite a few palaeo-thermometers that may help to collect this data.
INTERVIEW Lisker	*There is a number of techniques that can be used to constrain the maximum palaeotemperature and as well the maximum depth that a rock experienced in…its past. These techniques mainly base on either radioactive decay or on organic maturity. And these techniques are in the first order of fission track analysis but there is as well vitrinite reflectance, illite crystallinity analysis and fluid inclusion analysis. All of them refer to different temperatures, they have a different temperature sensitivity*
INTERVIEW Lisker	*The application of fission track in apatite is particularly helpful in the context of exploration geology because it is as well the oil window and that is a very practical coincidence.*
	So let's look at the fission track method for a moment. Fission track works with small apatite grains that form in basement rocks but are also recycled into sandstones. Apatite typically contains radioactive uranium. Uranium fission fragments shooting through the mineral damage the apatite's crystal structure, leaving behind tracks of a typical length. If the apatite is buried deeply enough with temperatures exceeding 125°C, the fission tracks disappear after a while and the apatite crystal structure is fully repaired. But below 125°C the radiation damage is only partially repaired. The tracks survive, although they are shortened. So: The longer the apatite grain has stayed cooler than 125°C the more tracks one will find in the apatite today. It is the amount of tracks that tells us when this particular strata cooled down enough to pass through the bottom of the oil window. But there is more: The number of shortened tracks and their detailed length distribution reveals for how long the strata stayed within the oil window. Because at temperatures lower than in the oil window, that is lower than 55°C, repairing of tracks stops altogether and they retain their original, typical track length.
	So the technique requires quite a bit of track counting and measuring of track lengths under the microscope. But it's certainly worth the effort. The initial results from a pilot study sound promising.
INTERVIEW Lisker	*If you consider the two major uplift stages in southern Libya, that are the Hercynian and the Alpine uplift we do have to estimate different amounts for each stage. It seems as far as we know today that the Hercynian uplift was more significant for the Gargaf Arch – we calculate an order of three or four kilometres of uplift at the time whereas the younger, the Alpine uplift perhaps comprises 400-2.500 m. This is of course very much different over the whole area. The more one moves towards the basin centre the lower are the uplift amounts.*
INTERVIEW Lisker	*Our knowledge about the evolution of the Kufra Basin is even less well constrained than the one about the southern Ghadames Basin, the Gargaf Arch and the Murzuq Basin. However, we were able to analyse as well two samples from the vicinity of the Kufra Basin…. And it seems that in general the evolution is rather similar as in the area between Ghadames and Murzuq Basin. That means as well an early Hercynian uplift stage and a late Alpine uplift stage both with dimensions comparable to the area further in the west.*
	Vitrinite and other maturity data from the northeastern margin of the Murzuq Basin had already inspired some re-interpretations of conventional basin-center-based source kitchen models.
INTERVIEW Boote	*The Mesozoic-Palaeozoic section on the north side of the Atshan Saddle gives us a clue*

	for the Rompetrol petroleum province. A simple comparison of well maturity profiles in the area shows something in the order of 2500 to 3000 m of sediments were stripped off this area. *This is in fact the missing kitchen for the Rompetrol oil province and the Atshan gas field*
	So we clearly need more data. Ideally we want a system of fission track traverses, including both outcrop and subsurface samples. An integration with results of other palaeotemperature techniques would give us an even better picture of what really happened in the past 100 million years.
	And the samples? In which lithologies do we actually find our fission track apatites?
INTERVIEW Lisker	*We do find sufficient yields in granites or in gabbros.*
INTERVIEW Lisker	*Sandstone samples can yield very sufficiently apatite as well but as an average only every third sample perhaps works. That means two thirds of the samples do not yield sufficient apatite for an age determination or a complete measurement of all the data that you really need.*
INTERVIEW Lisker	*Nevertheless sandstones belong to our standard samples because sandstones are very abundant and a very widely distributed rock type among the Palaeozoic rocks of Libya.*
	If you collect fission track samples, think BIG! Several kilograms of rock are needed --- per sample! In the outcrops it's easy. Just take a big chunk. In the subsurface a collection of cuttings over a 100 m interval would do.
	The other important contribution of the Alpine movements in southern Libya is the reactivation of faults. The main fault of the Elephant field is a classical example for long-term structural growth in the Murzuq and Kufra basins.
INTERVIEW Jonathan Craig	*Surprisingly the structure of the Elephant field is actually very simple. It's a very large tilted fault block with a very steep reversed fault on one side of it and then a very long dipping fault block. So nothing particularly complex at all about the structural configuration. Actually working out the timing in terms of when the structure developed is not that easy. It's clear that there were multiple periods of movement on the bounding faults.*
INTERVIEW Beswetherick	*Most of the faults in the Murzuq Basin are of that nature and they probably follow a Pan-African trend. There is nearly always a fair degree of structuration during Caledonian times. And you can see sometimes the Silurian black shale onlapping fault blocks, and certainly thinning of these Silurian shales onto these fault blocks. There seems to be very little effect during the Hercynian movements, but there is again structuration during the so-called Alpine movements in Tertiary times. And indeed some of these faults are structures at the surface, like Elephant where you can see wadis deflected around the structure.*
INTERVIEW Jonathan Craig	*But this clearly hasn't affected the integrity of the trap which contains the hydrocarbons in the Elephant field.* *Because this is clearly a particularly young structure, or at least it has a young phase of history to it, certainly prior to drilling it one of the risks that was considered to be an important risk is that the structure could be breached and we might have had leakage of hydrocarbons to the surface. What the Elephant discovery proved was that certainly in this particular case that this was not the situation. And there seems no reason to think that other faults that we see that extend all the way to the surface may not have very similar histories and that they could also be responsible for trapping hydrocarbons at depth against the faults.*

	So there are surely quite a few faults in the Murzuq Basin that locked the oil in their traps despite fault movements. On the other hand, there are other fields where there is clear evidence for leakage along faults.
INTERVIEW Boote	*The Atshan Gas Field for example shows quite clear examples from leakage from the Ordovician reservoir up into several thin units ending in Carboniferous.* *There is evidence in both the Rompetrol area and also in the Boco region of oil leaking upwards into the Devonian. This is Silurian sourced oil and it has leaked up from the basal part of the Silurian, or possibly from Ordovician reservoir underneath, up through the shales, through a fault or some gap in the seal, up into the Devonian sands. So it is vertical leakage we are looking here. Now, in the Boco area also what really is a quite fascinating story of charge and then spillage. There are two types of fields in the Boco area. One is the fairly substantial high relief buried hills, palaeotopographic traps and the other ones are on a more platform area much lower relief features. So we have the high relief features and the low-relief features. When we look at the high relief features they all have quite substantial oil columns of 60-70 m or so, and very thin residual oil columns, sometimes none. But on the low-relief features you quite often see thin oil columns and very extended residual oil columns. … And that's because those structures have been tilted after charge. Now, the high-relief features weren't affected by that tilting. You can move them around and the geometry of the trap is simply retained. It's very robust. It simply retains the oil. But if you start tilting a low-relief feature it's very susceptible to tilting. And a lot of the oil that may have been present there originally is tilted out. And now we see extended residual oil columns in those accumulations. And we also see signs of migrated oil to the north. On the flanks of the Gargaf Arch. In a number of water wells. And that oil in my opinion is leaked up from the Boco area. Because of that late period of tilting.*
	The Elephant seals, the Atshan leaks. So is there really any chance to predict whether a particular fault that you see on your seismic is a sealing or leaking fault?
INTERVIEW Jonathan Craig	*The answer is probably that they seal or leak at different times in their geological history. So it is extremely important to understand the phases of tectonic activity and what the sense of movement was on the fault at those various different periods of tectonic activity. So one of the keys for understanding whether we have a potential trap or a potential leak is to understand in some considerable detail not only the geometry of the faults but their history and timing.*
	Structural traps may be extremely successful, like in the Elephant discovery. On the other hand, their individual effectiveness is still hard to predict which has caused some bad surprises in Murzuq drilling in the past. So let's look briefly at stratigraphic trap alternatives.
INTERVIEW Boote	*There are a lot of dry holes in the basin. Of course the question is: Why? When one looks at the trapping style of the fields discovered by Rompetrol, Repsol and Lasmo a quite interesting story begins to emerge. On the one extreme you have pure stratigraphic traps, these are buried hills.* *With middle Ordovician sandstones sealed by Silurian shales. And you can rock and roll that structure around and it is still going to retain its hydrocarbons. Then you have combination traps, a mixture of structural and stratigraphic traps. And these two are pretty robust, as long as the Silurian shale seal is not broken by faulting.* *And then you go right to the other extreme of pure structural traps, such as the one discovered by Lasmo, the Elephant field. Where you have to rely on a cross-fault seal. …The Ordovician reservoir is displaced against Carboniferous shales. That in a way is a unique case. You just get the right juxtaposition of sealing shales against the reservoir and it works at Elephant.* *But it requires a fairly unique combination. … Just a little bit more up or down then the*

	reservoirs might be offset against Devonian sands, Carboniferous sands and the oil leaks out. And it is my view that most of the old wells, the ones that were drilled in the 60s and 70s were drilled on prominent structures. Big faults, which were not sealed across the fault. And this is why I think those earlier wells failed. I think the message for the future that comes from the Rompetrol discoveries is, that the structures that really are going to survive in an environment of constantly changing uplift, unroofing, reburial, jostling, rocking and rolling are the palaeotopographic traps, buried hills traps. Those I think we should be looking for in the southern and central parts of the Murzuq Basin.
Part 16: TERTIARY VOLCANISM	
	The Tertiary was a tough time for southern Libya. The basins were uplifted and individual blocks tilted, old fractures broke up again. Deposition had largely stopped. And from the Eocene onwards there was another attacker getting ready.
	Coming from the deep, hot magma was injected into the southern Libyan body. During various phases volcanoes grew out of the ground. Some of them, like the Emi Koussi in northern Chad are still active. The Emi Koussi is one of seven major volcanoes in the Tibesti Mountains. The volcano is dominated by two nested calderas that are 12 by 15 kilometres in size. The Emi Koussi is the highest point in the Sahara, it's southern caldera rim lies 3415 m above sea level.
	200 km north of the Tibesti lies the isolated volcanic field of Wau-en-Namus. Dark basaltic tephra extends 10-20 km around the volcano, which makes a stark contrast to the surrounding light-coloured Eocene carbonates. Wau-en-Namus – the "mosquito crater" in direct translation from Arabic. Because inside the 4 km wide caldera crater there are mosquito-infested lakes that fringe the central volcanic cone. Certainly not a good place for camping.
	Another 200 km further north lies the huge volcanic field of Harudj. The Harudj consists of 150 volcanoes with heights ranging between 100 to 400 m. A surreal landscape full of basaltic pyroclastic cones, lava flows and explosion craters. The Harudj volcanoes are quite young and were formed mainly during the Pliocene to Holocene.
	East and west of the volcanic Tibesti-Harudj axis, the volcanism also partly extends into the Murzuq and Kufra basins. Series of dykes, craters and feeder channels occur in various places around the two basins and may also have affected parts of the subsurface. The volcanism made best use of the existing fault systems and preferentially poured its hot rock melt into these zones of weakness.
	The Tibesti's twin brother is the Hoggar in Algeria. Volcanism here, west of the Murzuq, was very similar and occurred around the same time.
	And even at the eastern margin of the Kufra Basin there was Tertiary volcanism. Various ring dykes are scattered along the Egyptian border, the most prominent ones are Jebel Arknu and Jebel Uweinat. The circular structures represent deep levels of Eocene to Oligocene volcanoes. The upper parts of these volcanic structures have already been eroded, and left are just the characteristic circular feeder channels. --- More evidence for massive Alpine uplift and

	erosion along the margins of the Kufra Basin.
	At Jebel Uweinat large, weathered granite blocks are stacked on top of each other like potatoes. It seems the piles could collapse any moment. The subvolcanic rocks here were first studied by Hassanein Bey who explored the Kufra area in 1923. The murderous heat made the expedition travel mostly during the nights. Hassanein Bey was fascinated by the Jebel Uweinat ring dyke. He managed to bring back a few samples for laboratory study, which wasn't that easy as the petrographer F. W. Moon learned later from Hassanein Bey. "As the explorer explains, there was not the freedom of transport he would have desired for making larger collections of full-sized specimens, nor did he wish to incur displeasure of those who formed his escort by seeming to do anything that might appear in any way suspicious, such as the constant breaking and collecting of stones."
	For a long time the intraplate volcanism in the Tibesti and Hoggar was explained by hot spots. The evidence for this, however, seems rather poor. Therefore an alternative model was proposed, in which the compressional stress originating from the Africa-Europe collision has reactivated deep-seated Pan African faults. These may have provided suitable conduits for the magma of the volcanoes. So the geodynamic reasons for the Tertiary and Quaternary volcanism in southern Libya are still very much unclear. Likewise, its implications for the Palaeozoic petroleum systems clearly need further study.
INTERVIEW Jonathan Craig	*I think the role of volcanic episodes in the maturity, generation and migration story across the whole of the North African region is a complex one and a poorly understood one. … Clearly where we are close to volcanic intrusions there is going to be a significant local effect, but it is a local effect. We do recognize that there is some overall increase in heat flow at a regional scale that is associated with that volcanic activity. But it is actually very difficult to demonstrate that that has a significant impact on the generation history of the source rock.*
	But not all craters in southern Libya are of volcanic origin. At the northeastern edge of the Kufra basin we find two large wounds in the desert. Two extraterrestrial rock bodies had visited southeast Libya during the Cretaceous or Tertiary and made a rather hard landing. Oil geologists found their impact craters and named them in honour of their respective employers. With a diameter of 11 km the Oasis structure is the larger one of the two meteorite craters. The BP structure 80 km to the north is just 3 km wide.
START FILM 7: **Part 17: PLEISTOCENE-HOLOCENE CLIMATE HISTORY AND**	

WATER RESOURCES	
	The Sahara has been a desert for many million years. But there were also brief exceptional times. During several periods in the Quaternary, the Sahara suddenly turned green. Times of a wet climate. Rivers and lakes formed, and provided the basis for vegetation and human settlements. During these wet phases, the Sahel zone expanded northwards into the Sahara and brought precious subtropical rain. At the same time, the Mediterranean climate belt shifted southwards, attacking the desert also from the Mediterranean side. High rainfall filled the groundwater basins and lakes developed, such as the Lake Fezzan. During a wet phase 30.000 years ago, there were people living in Libya down to 20° latitude. But areas south of this point remained uninhabited. During the Neolithic, 12.000 years before present, the final wet phase began. Once again the Sahel zone was on the move and entered Fezzan. People following the water settled down in the Saharan mountains and valleys. The Neolithic rain eventually ended 3500 years ago, when the subtropical zone shifted back to its real home in the south.
	The people have long left. But their carvings and paintings are a constant reminder of a lost world. A world that seems so unreal today in the boiling desert heat. And there is something else that the Green Sahara has left behind. Water. Large parts of the groundwater from the Quaternary wet phases are still stored underneath the Sahara. The water fuels numerous oases all over southern Libya – fragile islands of life in an ocean of rock and sand.
INTERVIEW Klitzsch	*The lakes near Ubari or the lakes in northern Chad , the lakes in northern Sudan like Mertsch for example they are in morphological depressions and they are probably remaining parts of the exposed groundwater… And the longer the time lasts that the area is dry, in other words the dry desert period of the Sahara goes on, the water table will decrease and the water will disappear some when.* *Wau Anamus is a different case because this has something to do with volcanism and it may be older groundwater which by volcanic activity, heat flow or whatever, is kept at surface. The water in the bigger lake in Wau Anamus is very hot. At surface it is in the order of 15-20 degrees, because of high evaporation. But 20-30 cm below that it is very hot. I tested it, I went there to swim. And my dog, at that time I had a dog in my early years in Libya, my dog followed me and learned swimming in Wau Anamus.*
	The water in southern Libya is reservoired in multiple aquifers ranging from Cambro-Ordovician all the way up to the Nubian.
	Life in the Sahara today depends on the fossil groundwater from the Quaternary wet times. And also the Great Man Made River project uses this valuable resource and pumps it to the costal towns in northern Libya. Water is life. We have to be grateful to nature for this gift. But let's put our oil explorer hat on for a moment. And suddenly things look surprisingly different.

	To say it straight away: The water is the enemy of the oil. Locally the Quaternary water may have flushed out *part* of our precious black gold. Clearly the end of a love affair.
INTERVIEW Klitzsch	*If you take Jebel Ati. We were interested in Jebel Ati and one of our ideas was it might be flushed and it's only 100 or 120 km … from areas where water infiltrates.*
INTERVIEW Abdallah Khoja	*Water flushing is a serious problem for the migration of oil in the periphery of the basin, especially in the western part of the Murzuq Basin where we have a lot of water flooding from Algeria. …*
INTERVIEW Belhadj	*The head of the water table in Algeria is higher …, so that I think the freshwater is flushing or running towards the low areas.*
INTERVIEW Abdallah Khoja	*So that water can flush and migrate downdip towards the east and the north of the basin… And that has created a lot of problems for the oil migration and can be even a secondary migration, by flushing.*
INTERVIEW Jonathan Craig	*There is very clear evidence from the wells that have been drilled that we do have fresh water entering the reservoirs, particularly around the margins of the basin. So we see a very clear salinity profile as we move out into the basin which tells us that there is flushing of fresh water that is occurring. It is an issue in terms of understanding the prospectivity, particularly of the more marginal parts of the basins. It's something we need to be very aware of and to take account of and to incorporate into the risking of individual prospects.*
INTERVIEW Belhadj	*…We need to know the behaviour of the fresh water movement and how it is being moved from one place to another. …*
INTERVIEW Belhadj	*…We really have to address the fresh-water flushing by means of porosity, permeability, movement directions and diagenesis.*
INTERVIEW Belhadj	*... It can be a barrier, a seal. So maybe if we can identify some zones that have really diagenesis that can prevent freshwater flushing that area, that is probably one of the new innovative ideas that we can really put our fingers on and maybe we can start working on.*
Part 18: CONCLUSIONS AND REMAINING POTENTIAL OF MURZUQ AND PROSPECTIVITY OF KUFRA	
	We have learned so much since the beginning of hydrocarbon exploration in southern Libya.
INTERVIEW Klitzsch	*When we worked in the field in the late 50s, early 60s we thought it was easy to make predictions. Even after we found out that structural setups had changed several times during earth history. … We thought that within the basin the facies is not changing much. But as I learn now… from drilling results it is not all that easy. In other words our way of predicting things was probably too simple.*
	We started off with some basic geological concepts and have kept refining them continuously until today. Who knows, maybe in 20 years time geologists will laugh about the funny models that we use in exploration today. But it's all part of the fact-finding process. And so are the dry holes in Murzuq and Kufra.

	Despite the over 3 billion barrels of oil that have now been discovered in the northern Murzuq Basin so far, statistically only every sixth well has been a discovery.
INTERVIEW Jonathan Craig	*Yes there have been quite a number of wells drilled in the Murzuq Basin. And indeed many of those have turned out to be dry.*
INTERVIEW Jonathan Craig	*There are certainly wells that in hindsight when we have acquired more seismic data we have come to realize that they were not drilled on structure. There are other wells which have encountered low quality reservoirs, tight reservoirs. And those are for a number of different reasons. Some of them because of the depth of burial that's involved. Some of them related to very rapid facies changes that we see within the main glacial system that is the key reservoir. Certainly quite a number of them have failed because they have turned out not to be connected to a particular source area and therefore they have not been charged with hydrocarbons.*
INTERVIEW Belhadj	*Or the survey was probably a little off. Because we were in the field and we have looked at one of the wells that is about 800 ft off-structure. Because now using GPS it is very precise. So I think there is a lot of reasons combined together. So I think if we need to do good work in Libya we need to establish a new project that resurveys all the wells, especially the dry wells. And I think we will be surprised that we missed some structures.*
INTERVIEW Jonathan Craig	*So it is very important when we look at the wells that have been drilled that we understand in some detail what the reasons were for a particular failure in a particular place. Because they very often vary from well to well.*
INTERVIEW Belhadj	*Those wells that had been drilled dry they are not really a waste. Because those wells have really conducted a very good information that we can study.*
	Since the big discoveries in the northern part, exploration in the Murzuq Basin has moved on. Suddenly also the central and southern portions of the basin have entered the spotlight, areas that have been hardly looked at in the past.
INTERVIEW Boote	*To my mind this region, the central and southern part of the Murzuq Basin is extremely exciting. With the potential for very large petroleum reserves. Which may in fact be as much or more than has already been discovered in the northern part of the basin.*
INTERVIEW Hussein Seddiq	*With more seismic we do and more drilling I think production will extend to these areas and we see we have a very bright picture in ten years from here.*
INTERVIEW Jonathan Craig	*Well, there are many reasons why southern Libya is attractive to oil companies these days. First of all it is one of the few remaining areas in the world which is truly underexplored. And it is underexplored in an area which is immediately adjacent to some very large fields. So of course this makes it very attractive. We know that the petroleum system works in the northern part of the basin, and there is no reason why it shouldn't work in the southern part. And given that we have got large structures there, there is at least the potential to find some very big fields. And that makes it extremely attractive.*
INTERVIEW Beswetherick	*The prospectivity of that area I think will primarily depend on the location of the source kitchens and the migration story. The Silurian shale section certainly thins towards the south, but we know it is developed quite a way down south in the Murzuq basin. The prospectivity will mainly depend on whether or not there is an access to a mature source kitchen in that area.*
	We earned our academic degree proudly in the northern Murzuq Basin, studying the Palaeozoic petroleum system here in great detail. Now the time has come where need to proof that we have learned our lessons, are able to apply our knowledge successfully.

	The Kufra Basin seems to be the ideal challenge.
INTERVIEW Jonathan Craig	*There is no doubt that the depositional systems between the Kufra and the Murzuq Basin are actually almost identical. So very, very similar indeed. So we recognize in the field in the Kufra Basin that we have the Ordovician, late Ordovician glacial system present, the Mamuniyat equivalent. So there is no doubt that the reservoir is there. We see very clearly on the seismic data that we have that there is a lot of structuration. So very clearly we will be able to develop prospects. If there is an area of uncertainty it again relies on the distribution and indeed the maturity of the early Silurian hot shale, the primary source rock. We know that it occurs. We have identified it in shallow boreholes. So it is certainly present but it appears to be patchy. Much as it is in the Murzuq Basin. If there is one potential difference between the two basins, it's to do with the later history of the two basins and the amount of burial of the source rock and the level of maturity. It's a complex story in the Murzuq Basin. The source rock had been buried more deeply that it is today and much of the basin has been uplifted in the Cretcaeous and Tertiary. We know that present-day quite significant parts of the Kufra Basin, the basal Silurian hot shale would not be mature as it is today. But we think again that it was probably buried more deeply in the past. So one of the keys is to understand how much burial there was in the past and when the basin was uplifted and when the basin margins were uplifted.*
	Our geological concepts for Kufra are ready, based on the Murzuq analogue. It's the hard data in Kufra that is still in short supply. From a data point of view, there was more data available in Murzuq in the 1960s than from the Kufra Basin today.
	The two wells in Kufra are not too impressive when compared to the well density in Murzuq. But even the more than one hundred Murzuq wells are dwarfed by the number of wells drilled in areas like the North Sea or the Gulf of Mexico. There is certainly room for more in southern Libya.
INTERVIEW Beswetherick	*I think there are more oil fields out there in southern Libya. I think the recipe is, yes, look at the petroleum system, do all the science, do all the risking, but ultimately, if there is a big structure there, it's probably worth drilling. In an area with a world-class source rock and a good reservoir and a simple system the way to find some more big fields is to drill wells.*
	We are on a good track. If we continue our efforts as in the previous 10 years, our understanding of the regional geology will improve further. And there are some questions that we have to particularly concentrate on.
INTERVIEW Jonathan Craig	*I think there are a number of very significant challenges that remain for us to address in terms of understanding properly the geology of the southern Libyan basins. All of us still have a tendency to rely on lithostratigraphy as being the prime way to divide up the stratigraphic column. And it is very clear that we need to do a considerable amount of biostratigraphic work within the lower Palaeozoic in particular, so that we can make chronostratigraphic correlations across the basin. Where we have very heterogeneous reservoirs it is very easy to miscorrelate one sand to another, or indeed to miscorrelate one shale unit to another. So we remain in a situation for many of the basins where using lithostratigraphic terms is not helping us.*
INTERVIEW Belhadj	*The type sections that are present now are not really the representatives of the subsurface. We really need to revise those type sections. And I think we need to form some sort of a committee that is really responsible for this kind of type sections and naming formations for the nomenclature because I think it is important to speak the same language between all the companies. We really have to unite the names of the formations, the age of the formations. We cannot just everybody go on and change*

	whatever.
INTERVIEW Abdallah Khoja	*This is a big challenge even for NOC Exploration Department. We are currently working to nominate a committee for the formation nomenclatures and for the stratigraphic subdivisions. And this task is going to be started next year to establish a good columnar section and good stratigraphic and biostratigraphic subdivision for all the formations.*
	And of course geological systems are known for their bad habit of not paying attention to national boundaries.
INTERVIEW Hussein Seddiq	*There is some efforts being done in the past in geosciences to integrate the geology of the different Palaeozoic basins. We have seen some publications to this regard. But that's maybe just the beginning. That's the minimum. I am sure if we join forces with NOC and Sonatrach and other scientific institutions in Egypt and Morocco of course with the help of known universities … I am sure we can do better and we can understand exactly the things related particularly related to petroleum exploration.*
	And a better age control over the strata means also a better basis unravelling the complex structural history of southern Libya.
INTERVIEW Jonathan Craig	*One of the other main areas that we need to continue to put focus on in exploration terms is improving the quality of the seismic data. Clearly when you are exploring for Palaeozoic reservoirs these generally tend to be quite hard, deep rocks. They are often very difficult to image. There have been significant improvements over the years. We have new seismic processing algorithms that allow us to improve the resolution quite considerably but that's another area in which we need to continue to work. And clearly progressively we will need as an industry to move towards 3D datasets rather than 2D datasets. So that we can be quite clear about the geometry of the prospects and the structures that we drill.*
	Despite the digital age we live in today, hydrocarbon exploration is still done by people. It's not a secret that even the best computers require human input to produce realistic results. Garbage in, garbage out. A well-trained workforce is the basis for exploration success.
INTERVIEW Hammuda	*The problem is to convince oil companies to take more students. To invest into human resources. Because this is the most important. And I know most of the students in the Society … are my … graduates. And I am very proud of their contributions. Because whenever they are given the chance to continue their education they exert a great effort in order to succeed and accomplish success in their profession.*
	And geologists need to talk to each other. To inform each other about recent findings and to discuss strange and not-so-strange ideas. For this, they need a forum.
INTERVIEW Hammuda	*The ESSL has been very keen on this topic of exchange of geological and exploratory information. They are pushing very hard and they are getting the support of the NOC to hold Symposia from time to time and to have field excursion to different parts of these basins. … I urge all oil companies to cooperate with ESSL and with NOC to promote exploration efforts and also to have some chance of publishing this information.*
	Petroleum geology is teamwork. A co-operation of geoscience experts. Within organizations, but also across organization boundaries.
INTERVIEW Hussein Seddiq	*When it comes to geology, cooperation is a necessity, it is a must. You cannot differentiate scientific research in universities or educational institutions from work carried out in exploration companies. Because universities…only see surface geology, they don't know exactly what happens in the subsurface. Companies have access, because they are drilling wells which is very costly and universities cannot do, seismic is also very costly and universities cannot do but oil companies can provide. So*

	combining the data from exploration companies related to subsurface with some geological fieldtrips …carried out by academic institutions this two together will give you a good picture of the geology. And this is the beauty of geology. Combining forces will lead at the end to something fruitful for both parts.
	Predictive geological concepts can only be generated when all players work together. A good compromise between confidentiality and open exchange is of benefit to everyone --- and without it even this film could not have been made.
INTERVIEW Hussein Seddiq	*Some people may think geology is just monopolized to oil companies. But this is not true.*
INTERVIEW Hussein Seddiq	*Knowing the geology, even if we don't have oil and gas it's in itself is a very important issue. This should shed more light on the African continent, understanding the geology of Africa.*
INTERVIEW Hussein Seddiq	*…Even children in schools - they start if they go to the field and see different kinds of rocks, they start and look at its beauty. And of course look at some fossils and so on. We like people to give attention more and more to the educational part of geology.*
	The geology of southern Libya is the key to billions of barrels of oil. But apart from that, it is also much more. The geology of southern Libya is part of our own history. About a world that kept changing restlessly. The geology of southern Libya is about time. Time that keeps moving on. It cannot be stopped. All that remains is memory. A memory of wild action, fossilized in fascinating rocks of the Murzuq and Kufra basins. Lastly, the geology of southern Libya is also about the people, who helped to unravel the Sahara's geological secrets. People who got hooked by the desert's beauty and its amazing geological story.
INTERVIEW Jonathan Craig	*I have been very fortunate that I have been able to work in the Sahara and in southern Libya for the vast majority of my career as an exploration geologist, probably for the last 20 years or so. And as I have travelled around the world it's actually the geology of southern Libya which has brought me time and time again back to going out into the field and looking at the rocks. It's some of the most fantastic geology in the world. And it has been a real thrill to spend that time in the field with Libyan colleagues who have a huge knowledge of the geology of the region, to be able to take out with us young geologists, starting out in their career and then being able to inspire them with the geology of their own country. So I found my times in Libya doing fieldwork in Libya to be some of the best times of my life.*
	Petroleum geology is not mathematics. There is often no right or wrong, no black and white. We geologists know how to deal with uncertainty. We are allowed to think the unthinkable. A good knowledge of the regional geological story is the basis from which we operate. But at the end of the day our creativity is judged by only one thing. ------ The drillbit.
END: TEXTSCREENS	
	Presented by the Academy of Graduate Studies (Tripoli) [left screen side] and the Earth Science Society of Libya [right screen side]

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Modern facies analogues:

Formation	Age	Depositional Setting	Modern Analogue
Marar Fm.	Carboniferous	cyclical changes between deeper and shallow marine	on a much faster scale: high and low tides North Sea
Ouan Kasa	Lower Devonian	shallow marine	Any muddy shelf, e.g. deeper parts of the North Sea
Tadrat Fm.	Lower Devonian	braided river	Brahmaputra (India) (analogue of Cambrian in Hassi Messaoud) Platte River (USA)
Akakus Fm.	Silurian	prodeltaic to deltaic	Nile delta, Niger Delta (Tertiary to present progradation, see USGS Report 99-50-H, Tuttle et al. 1999)
Tanezzuft Fm.	lower Silurian	hemipelagic to prodeltaic	Falkland Shelf
Tanezzuft Lower Hot Shale	uppermost Ordovician - lowermost Silurian	anoxic mud	Upwelling SW Africa, Black Sea / Mississippi Delta, Baltic Sea, north Wales postglacial example
Mamuniyat Fm.	upper Ordovician	sandy glacial marine	Iceland (Skeidir Sandur; braid delta in big glacial valley), modern Norwegian glaciers
Melez Choqran Fm.	upper Ordovician	muddy glacial marine	Iceland
Hawaz Fm.	lower to mid Ordovician	sandy deltaic to shallow marine	North Sea; sand beaches, wadden sea
Hassaouna Fm.	upper Cambrian	sandy deltaic	North Sea; sand beaches, wadden sea