

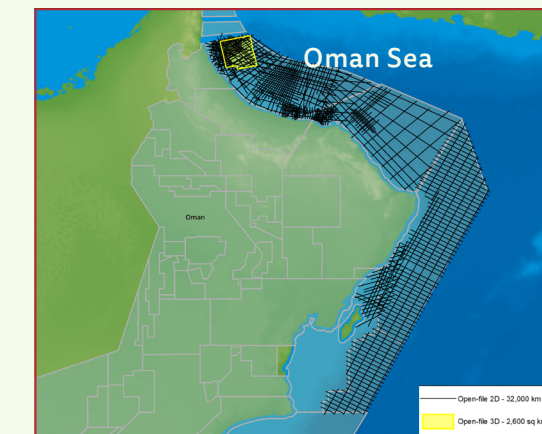
SEISMIC

FOLDOUT

OFFSHORE OMAN: STUNNING HYDROCARBON GEOLOGY FROM A CLOSING OCEAN

Figure 1: West to East Composite Line of 1990s Legacy Data, reprocessed in 2006 from the Oman Sea. Line length 200 km. Decollement surface in orange.

The Offshore Oman Sea lies east of obducted Oceanic crust, yet has a vast sedimentary sequence of Jurassic to recent clastics and carbonates that remains virtually unexplored. This basin contains extraordinary structures revealing compression and contemporaneous extension that has shaped the development of a hydrocarbon system. Little is known of the basin and yet, modern seismic reprocessing is poised to unlock the potential of this hidden gem.



Location map showing position of composite line.

Compressed Shelf

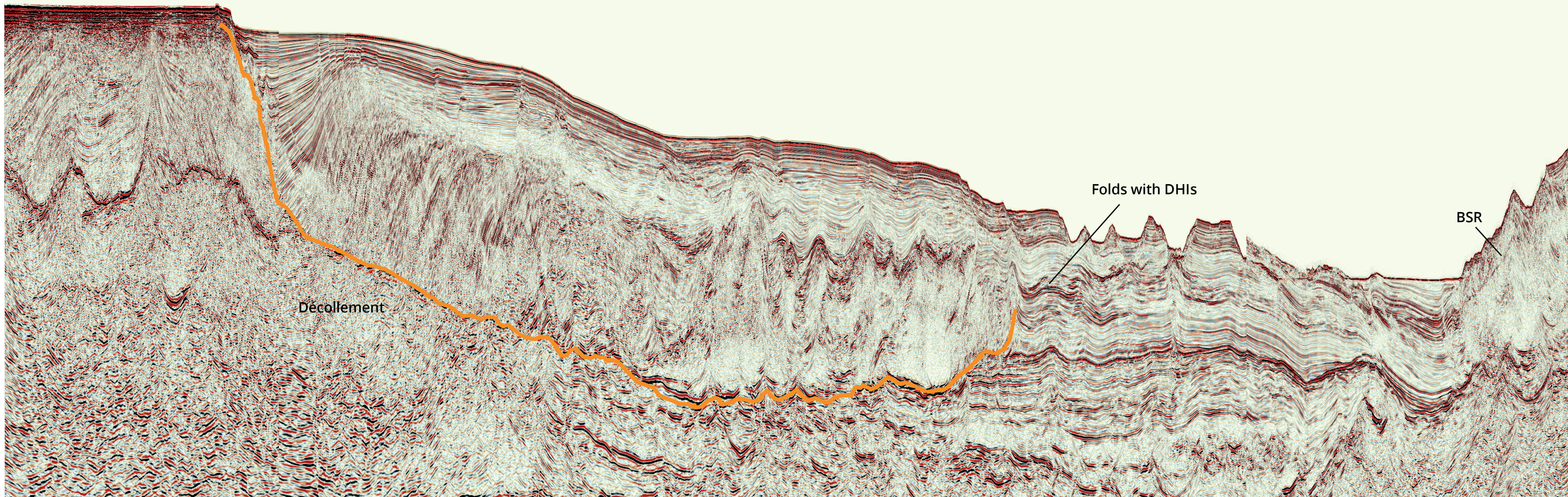
Extensional Zone

Gravity Slide

Toe Thrust Zone

Full Stratigraphic Section

Makran Accretion



OFFSHORE OMAN

Unexplored and tantalisingly prospective.

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The Eastern Oman Mountains are widely known as an ophiolite range of rugged and dramatic beauty, where one of Oman's two slices of obducted oceanic crust were emplaced on top of continental crust by thrusting in the Late Cretaceous. To the west of these mountains lie multiple, prolific oil and gas basins of extraordinary variety.

To the south-east lies the Indian Ocean where the Omani continental shelf has a hydrocarbon province, shaved slim by the transform fault that eased the Indian continent on its northward Early Tertiary fly-by to its collision into Asia. The consequences of that geo-drama could not be more significant for humanity or more studied, as befits the formation of the Himalayas and significant removal of CO₂ from the atmosphere which facilitated the ice ages that arguably evolved the human species into consciousness. Yet, perhaps just as importantly, on the way north the Indian Plate blocked the exit of the Oman Sea creating a restricted marine basin – ideal for depositing an Early Tertiary source rock and clipping the edge of Oman, depositing the Semail Ophiolite onto it. To the north-west of Oman lies the Oman Sea where a far less well-known story unfolded in the last 80 million years as the normal passive margins to the Neo-Tethyan Ocean were caught in a plate tectonic vice. Here, as Africa and the Arabian Peninsula rotated into Asia and the ocean disappeared, the oceanic crust was first obducted on both sides creating mirroring mountain ranges in Oman and Iran, until subduction began, and the basin acquired a more familiar destructive margin geometry with subduction verging eastward under Iran and Pakistan in the Makran subduction zone.

It is to the Oman Sea, or Sohar Basin, that we have turned first because of the incredible geology that is illustrated on existing legacy seismic data, which we can now reveal has huge potential for image uplift on reprocessing. In the Oman Sea, south of the Straits of Hormouz that provides marine access to the Arabian Gulf, there lies a wide, shallow shelf with over 8 km of Cretaceous and Tertiary sediments, that leads through a steep slope down to 4,000m water depth and the jaws of the Makran subduction zone. The thick sedimentary section, found at depth on the Omani side of the Makran

accretionary prism (Figure 1 – main panel) is the stage for extraordinary hydrocarbon geology to play out, where access to modern seismic data allows us to see a hitherto little imagined engine of hydrocarbon generation, migration and entrapment that has hardly been considered by industry to date. Here we have new possibilities for exploration in a little-known basin with amazing geology and a friendly, sophisticated government to facilitate commercial business.

Geological Knowledge of the Oman Sea: Structures and Sources

Although there has been relatively little published this century on the geology of the Oman Sea, in just the last two years three key papers have been published: Ali et al., 2020, concerning the northern, UAE area of the Gulf offshore Fujairah; Levell et al., 2021, focusing on the Omani part of the Sohar Basin; and Ninkabou et al., 2021, focussing on the southern, relatively more stable part of the Oman Sea.

Each of these excellent papers draws upon onshore outcrop and well data integrating beautifully with the seismic and the limited wells drilled in the offshore.

The three wells in the Sohar Basin are key to understanding just how unexplored this basin is. Two of these wells were drilled 50 years ago, in very shallow water at the shelf margin. Both are remarkably well located for the time, and target tilted fault-blocks at the point of regional migration loci. Both are reported to have encountered shows, and found significant reservoirs in the Tertiary at least, reaching final depth in Late Cretaceous shales. The bounding fault for these structures appears to be an extensional fault which is active today and is perhaps the most likely reason for the lack of success of these wells.

The foldout line (Figure 1) shows a composite traverse across the Oman Sea and is a good foil for discussion of the geology of the basin. At the far western end (left) of this line many structures can be observed in the Miocene to Cretaceous section. These are mostly thin-skinned thrusts and compressional structures, folds, inverted anticlines, and strike-slip flower structures formed in post-ophiolite obduction by the contraction of the basin. Compression continued after the start of Makran subduction and thin and thick-skinned structuring was coeval creating features such as what Levell et al. call the Daymaniyat anticline (see Figure 7 in their paper). Peak deformation appears to have been at the end of the Miocene. But that is not the last of the structural strangeness, as, when subduction started in the mid-Tertiary, the slope angle significantly increased

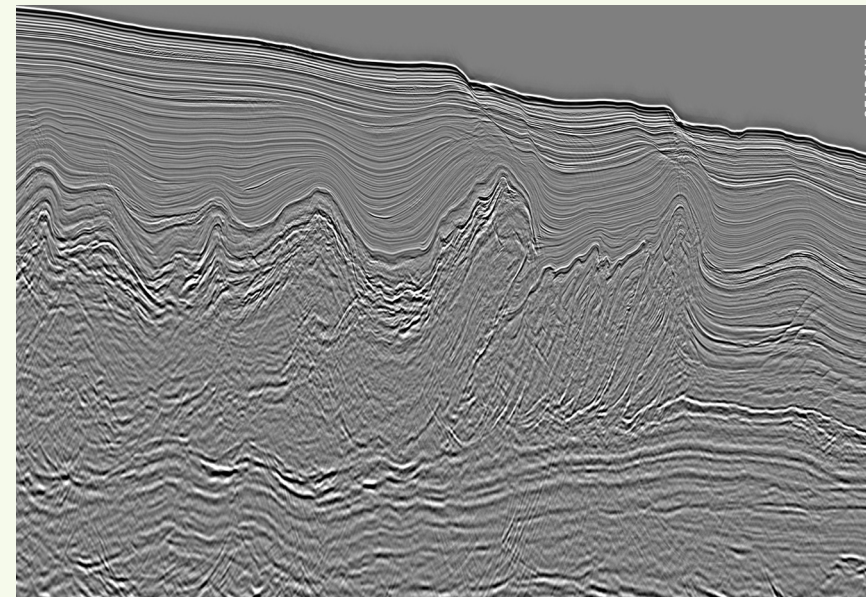


Figure 2: 2021 Reprocessed line over toe-thrust zone showing imbricate thrust structure of toe thrusts and imaging of the Cretaceous pre-decollement section. Line length 26 km.

and a large part of the thick Cretaceous and Palaeocene slope (some of which was deformed and folded by compression) began to move downslope under gravity sliding towards the subduction trench. The diachronous decollement surface appears on the basin floor to be at Palaeocene level age, contemporaneous with the eastern closure of the Oman Sea and the development of a restricted marine basin and is a candidate source rock of Pabdeh Formation age. However, up-slope Cretaceous sediments are also entrained in the slide.

The couplet of up-dip extension and sediment loading with a down-dip contractional toe-thrust set at the end of decollement is clearly seen on Figure 1. The mid-slide area shows drape over pre-slide compressional folds caught up in the slide. These are often associated with bright reflectors in the Pliocene.

Biogenic gas is evident in the Makran system to the east, expressed as gas hydrate 'Bottom Simulating Reflectors' (BSRs). Where BSRs can be confidently picked to the west of Makran, one can calculate a geothermal gradient at the BSR of around 35°C/km (whilst in the Makran accretionary prism this drops to 20–25°C/km). The nature of the decollement surface is uncertain, and

it would be speculative to consider this as a candidate potential source rock. Yet below this lies a thick sequence of Cretaceous and Jurassic section that has not been drilled offshore, of similar age – if not depositional setting to the super-prolific Cretaceous and Jurassic source rocks of the northern Arabian Gulf.

Seismic Reprocessing 2021–2022

It is frustrating that on legacy 1990s to mid 2000s data the sub-decollement surface cannot be mapped or examined, and it is for this reason that late last year Searcher was awarded a contract by the Ministry of Energy and Minerals, Oman (MEM) to reprocess and promote as a multi-client product. Initial reprocessing with a modern processing sequence including deghosting and multiple elimination, have been extraordinarily successful in revealing the sedimentology of the pre-decollement section and the structural detail of thrusting complexity in the toe-thrust area (Figure 2).

Whilst exploration of the toe-thrust area has been successful in many basins globally, for example the Rovuma Basin (Mahanjanr and Franke, 2014), this has never been attempted in the Oman Sea.

To the north of the seismic line in Figure 1 (main foldout panel), the toe thrusts of the gravity slide collide with the opposite verging thrusts of the Makran accretionary prism. However, here we see the first structures outboard of the last toe thrust as simple, large anticlines in the Miocene to Pliocene as a soft-kick event associated with direct hydrocarbon indicators – flat events and positive (far-near)*far angle responses. These structures are particularly interesting because they sit where a continuous sequence can be observed from the oldest sediments lying on Oceanic crust (Jurassic and Triassic) right through to recent sediments. It is here that the Early Cretaceous older source rocks can feed directly into the shallower play systems. Experts picking natural oilslicks from satellite data have found many repeating slicks in this area; however, note the presence of active ports and shipping lanes (Clermont Blaizot, personal communication).

Unexplored and Tantalisingly Prospective

There are very few remaining thick clastic sections in moderate water depth remaining on earth that are so little known, so incredibly under-explored, and have such tantalising indications of the presence of hydrocarbons. It is perhaps ironic that the imaging power being unleashed through broadband extension of deghosted data, that had always been needed to conduct efficient and successful exploration, is only now becoming available. However, this new imaging is constantly revealing new geological marvels – and here that will surely lead to a new province for exploration success in the beautiful Sultanate of Oman.

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References provided online.