Bringing the Middle East India Deepwater Pipeline (MEIDP) closer to reality – findings of the 2013 reconnaissance survey

Authors: Ian Nash, Peritus International & Robert Hawkins, Fugro

1. Abstract

This paper presents the findings of the Middle East to India Deepwater Pipeline reconnaissance data acquired along the 3450m deep route from the 2013 geophysical survey with particular focus on the geohazard areas that have to be crossed including the Indian and Omani continental slopes, Owen Fracture Zone and the Indus Fan. Examples of data will demonstrate the challenges that need to be overcome in laying the pipe in these geohazard zones. The results of the survey will be discussed together with the process required to identify a feasible route and bring this project closer to reality.

2. Introduction

South Asia Gas Enterprise PVT Ltd. (SAGE) is evaluating options for installation of a pipeline across the Gulf of Oman through the Arabian Sea to Gujarat, India. The pipeline is sized to transport 1.1 BSCFD of processed, sales quality natural gas.

The proposed pipeline route is approximately 1200km long and it runs from Ra's Al Jifan / Al Ashkharah (eastern Oman), passing to the north of the Qalhat Seamount and south of the Dalrymple trough at the Owen Fracture Zone, to Navibandar (Gujarat, India). The majority of the route is deeper than 3000m water depth with the maximum water depth of 3450m on the Abyssal Plain.

A pipeline reconnaissance survey was carried out by Fugro OSAE in 2013 to investigate a feasible route between Oman and India. The primary objective of the survey was to investigate sections along the route that could present routing issues. These sections had been identified in a Desk Top Study completed in 2011. The data was then used for primarily engineering to identify a feasible route or routes.

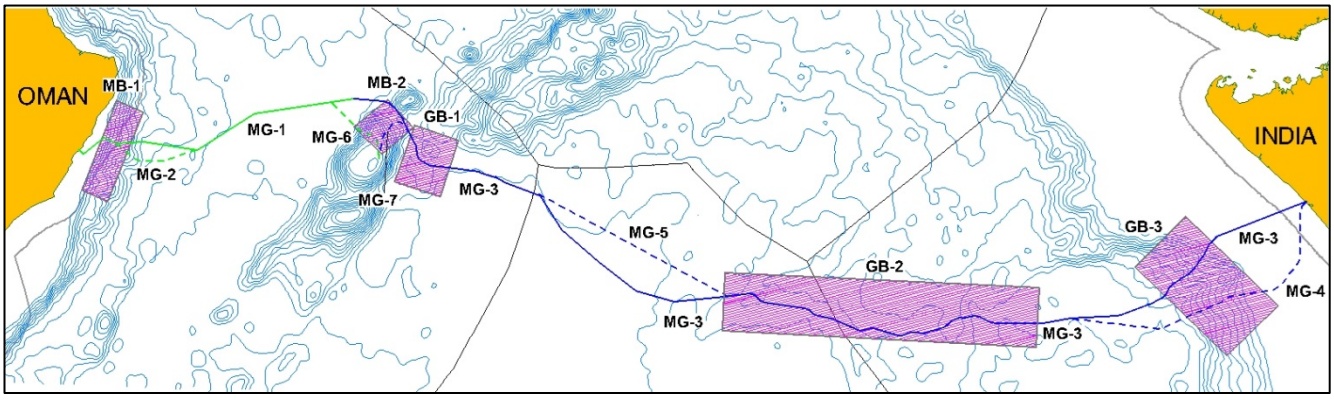

Figure 1 - MEIDP Geophysical Survey Campaign

3. Geological Setting

The Oman-Arabian Sea is part of a large and deep oceanic basin, which hosts several prominent topographical and geological/tectonic phenomena. The region of the Oman-Arabian Sea is made up by three tectonic plates; the Eurasian, Arabian and Indian Plates (Balakrishnan et al., 2009; Fugro William Lettis & Associates Inc., J33010-REP-IIDP-Y-0008). The Owen Fracture Zone and Murray Ridge delineate the boundary between the Arabian and Indian tectonic plates, which merges towards the north with the Katawaz and Himalayan Mountains. The Katawaz and Himalayan Mountains form the convergent plate tectonic boundary between the Eurasian and Indian plates. The Arabian Plate moves at a slightly higher rate towards the north than the Indian Plate, as such the Owen Fracture Zone currently accommodates a right lateral motion between the plates. The Arabian Plate collides with the Eurasian Plate and subducts beneath the Eurasian Plate. Sediments and rocks that were scraped of the subducting plate make up the Makran Accretionary Wedge, which forms a plate tectonic converging margin parallel to the Iranian and Pakistan coastline.

The Owen Fracture Zone and the Murray Ridge form a distinct topographic feature on the seafloor of the Oman-Arabian Sea. The Owen Fracture Zone and the Murray Ridge is made up by topographically high ridges, seamounts and deep troughs, such as the Qualhat Seamount and the Dalrymple Trough (Edwards et al., 2000). The troughs developed as a result of lateral extension along the Owen Fracture Zone, which also led to submarine volcanism along the Murray Ridge and Dalrymple Trough. Earthquakes indicate that the Owen Fracture Zone is still active. The Owen Fracture Zone also divides the Oceanic Basin into two parts: the Oman Abyssal Plain (or Oman Basin) to the west and the Arabian Abyssal Plain (or Arabian Basin) with the Indus Fan to the east.

The topography of the Owen Fracture Zone shields the Oman Abyssal Plain largely from influxes of terrigenous sediments coming from the Indus River and Fan system. As consequence, the sediment blanket on the Oman Basin floor is relatively thin and mostly derived from pelagic sedimentation and, to a lesser degree, sedimentation from submarine landslides and turbidity currents (Mullee, 1995). The Arabian Basin is largely dominated by sediments of the Indus Fan distributed through a channel and levee depositional system, which extends more than 1500 kilometres southward to the Carlsberg Ridge (Kenyon et al., 1995; Clift, 2002; Swift and Ross, 2002). Sediments in the Arabian Basin were mostly deposited by turbidity currents and submarine landslides derived from the Indus Canyon and Indian Continental Slope and to a lesser degree by pelagic sedimentation.

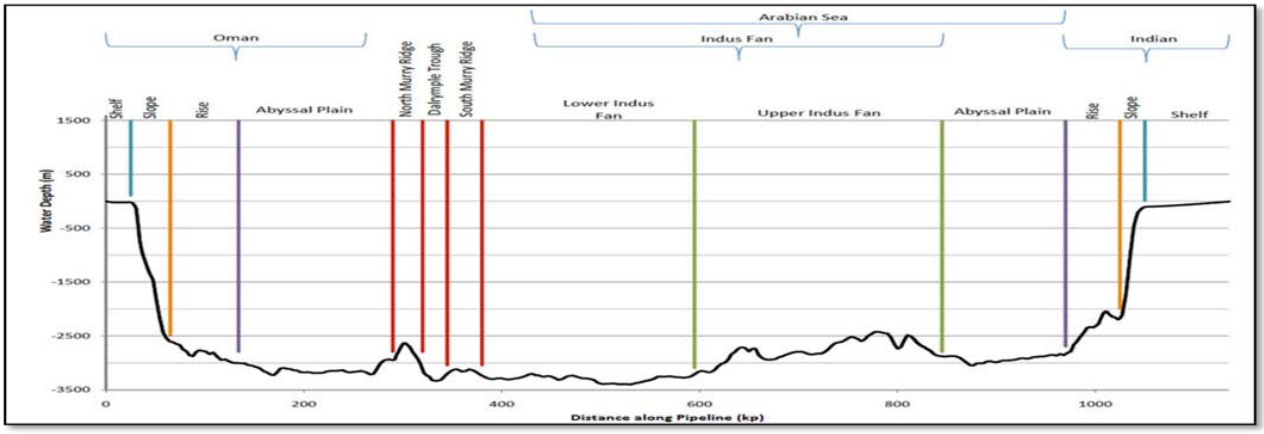

Figure 2 – MEIDP Route Profile

Sea level changes and climate were and are the main factors controlling the influx of terrigenous sediments into the Oman-Arabian Sea (Prins and Postma, 2000). In approximately 45 million years, the Indus Fan has been built upward and outward into the Oman-Arabian Sea through a complex system of switching distributary channels and fan lobes (Kolla and Coumes, 1984; Clift et al., 2002). In the proximal part of the Indus Fan sediments have accumulated up to several kilometres thick (Naini and Kolla, 1982). Some sediments in the Oman and Arabian basins derived from mass flow deposits from the continental shelves and steep slopes. During sea level low-stands, the shelves were shallower or (partially) exposed and dominated by carbonate sediments and reefs. Sediments from the continents were transported over the shelves through deeply incised channels and canyons on the steep continental slopes and into the deep basin areas. The slopes were and may still be (partially) controlled by faults, such as the Masirah fault zone on the Oman margin and faults on the margin of Kathiawar Peninsula (Gujarat, India).

4. Objectives of the Reconnaissance Survey

Prior to the reconnaissance survey in 2013, a Desk Top Study was carried out in 2011 to assess the shallow geological conditions along the route including an evaluation of the fault crossings and the generation of a seismotectonic model for the region. An additional study investigated the metocean conditions along the route.

The study identified that there were four areas that required investigating before a feasible pipeline route could be considered. These areas were:

1. Omani Continental Shelf and slope
2. Owen Fracture Zone
3. Indus Fan
4. Indian Continental shelf and slope.

In addition, the potential site of an offshore compression facility located on the plateau of the Qalhat seamount, dictated the need for possible routes from the abyssal plain to the top of the seamount, which added a fifth area of investigation. The objective of the reconnaissance survey was to investigate these five areas (blocks) and the potential route corridors between them.

The survey included the acquisition, processing, interpretation and reporting of appropriate hydrographic, geophysical, geological and geotechnical data as required to:

- Establish seabed topography
- Evaluation of seabed and shallow sub-seabed geological and geotechnical parameters
- Identify and map potential geological features, geotechnical phenomena and environmental constraints that may have the potential to influence the pipeline routing, construction or operation of the proposed pipeline development.

5. Vessel & Geophysical Survey Equipment

The reconnaissance survey was executed by Fugro OSAE based in Bremen, Germany using the MV Fugro Gauss survey vessel between 18 April 2013 and 21 June 2013. The survey commenced at the Indian landfall and then finished at the Oman landfall just ahead of the SW Monsoon. In total 1780km of route corridor survey on seven route segments and 26,207km^2 of block surveys in five feature areas were performed.

MV Fugro Gauss is a dedicated hydrographic and geophysical survey vessel The primary equipment that was used for the survey was the hull-mounted multi beam echo sounders and sub bottom profiler.

The bathymetry data (seabed topography) was acquired using a hull-mounted high resolution Kongsberg EM122 multi-beam echo sounder capable of operating to full ocean depth. In the shallower section of the route, bathymetry data was acquired using a hull-mounted high resolution Kongsberg EM710. According to the manufacturers specifications the acquisition depth ranges from 2m to 2000m.

The shallow seabed soil conditions were investigated using a hull-mounted Innomar SES-2000 sub bottom profiler. The parametric acoustics provide excellent resolution and good penetration into the seabed at low frequencies. Onboard Fugro Gauss the “deep” version of the SES 2000 SBP is installed. This system provides a water depth range of 5–6000m. The sediment penetration is up to 150m, with a vertical resolution of up to 15cm.

6. Findings from the survey

6.1. MB-1 – Omani Continental Shelf and Slope

The seabed surveyed in Box MB-1 (Omani Continental Shelf and Slope) is dominated by large canyons and channels coming down the slope and extending seawards from the Continental shelf. This survey covered the outer 3km of the shelf and the continental slope which is about 30km wide. The shelf is generally very flat, although there are some features that show up in the multibeam data. These features may be either outcrop of rock or outcrop of hardground, sometimes covered by a thin layer of soft sediment, comprising calcareous clayey sand and/or calcareous sandy clay/silt. The water depth at the shelf break is relatively constant at 90-100m.

The multibeam data shows a large amount of small channels and gullies at the shelf break. As the channels continue down the slope, they merge into larger channels and canyons and at the foot of the slope the majority of them have merged into four major canyons. One of the largest canyon complexes is seen in the south. It comprises three large tributaries at the foot of the slope and is

almost 6km wide at the edge of Box MB-1. Further upslope where it divides it is almost 9km wide. The water depth at the canyon mouth at the edge of Box MB-1 is 2900 m. Along the slope there is evidence of slumping and sliding, however slump scars are almost entirely found within the channel walls. No slump scars have been detected in the areas in between the canyons and channels. At the foot of the slope there are several slump scars on the sea ward side.

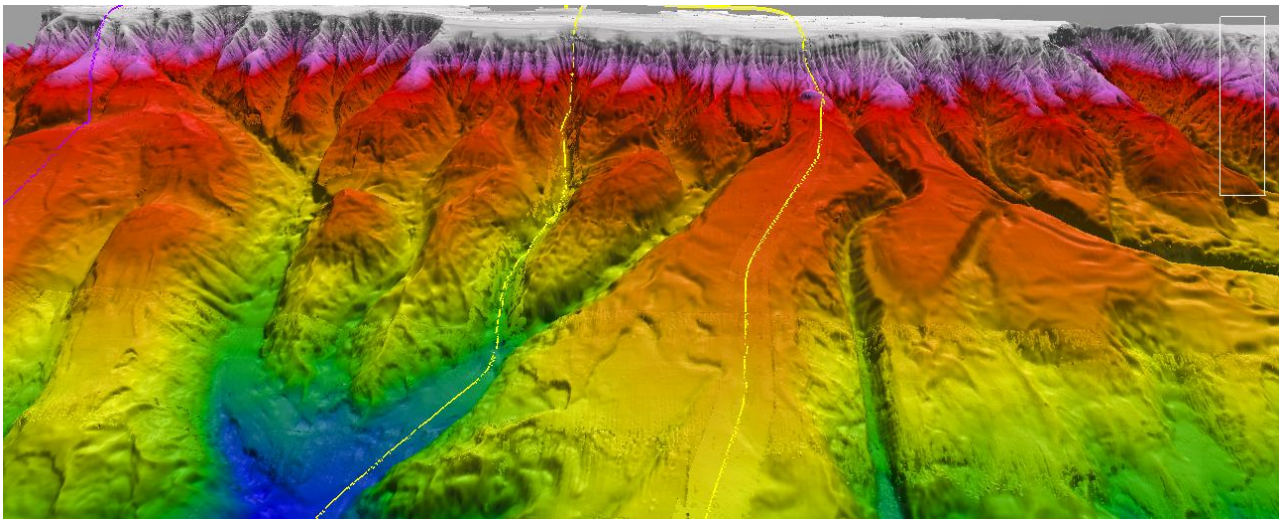

Figure 3 – Omani Continental Slope Canyon Systems

The Oman Continental slope and Abyssal Plain have a thinner sequence of sediment than its Indian counterpart to the east. The Continental slope in Oman is not as steep and not as wide as on the Indian side. Furthermore the continental slope in Oman shows less slump scars along the slope than its Indian counterpart. The fact that there are less slump scars along the slope does not automatically mean that there occur less slumping processes present, but it means that only the amount of sediment transport is less. On the flat shelf, there are large areas where the underlying rock or hardground is outcropping or sub-cropping. The soft sediment cover, probably comprising calcareous clays sand/sandy clay/silt varies in thickness, but is generally less than 2m. The soft sediments to the south-west are only about 4-5m thick. The rock surface is rather flat where it is not covered by soft sediment and shallow gullies are cut into the surface. To the south-east of the shelf a large “fan-like” channel complex emerging from the shelf break is seen. The channels are generally filled with coarser sediment.

6.2. MB-2 – Qalhat Seamount

The main feature surveyed in Block MB-2 is the Qalhat Seamount which is located in the south-east of MB-2. The survey covered the northeast and northwest slopes, parts of the plateau and the deep sea basin away from the seamount to the north. The seamount rises from a water depth of 3000m in the deep sea area to about 300m at the shallowest point on the plateau, a rise of 2700m. The plateau covered by this survey, is dipping slightly towards the north from approximately 500m in the south to about 700m in the north over a distance of about 28km. Deep canyons and gullies dissect the slopes and there is evidence of a number of slump and slide features. The north western slope is slightly steeper and narrower than the eastern side. The western slope shows the highest slope gradient, 34˚ which is almost at the top of the plateau.

Further downslope the gradients are slightly less, between 20˚ and 26˚ on the steep sides of the canyons to about 10˚ in the flatter areas in between. The highest gradient on the north eastern slope, 33˚ occurs in the lower end of a large canyon. In general, the gradients are around 20˚ down the east slope with increased values up to 33˚ towards the foot of the slope with the highest gradients in the canyon walls. The upper slope has gradients between 25˚ and 29˚.

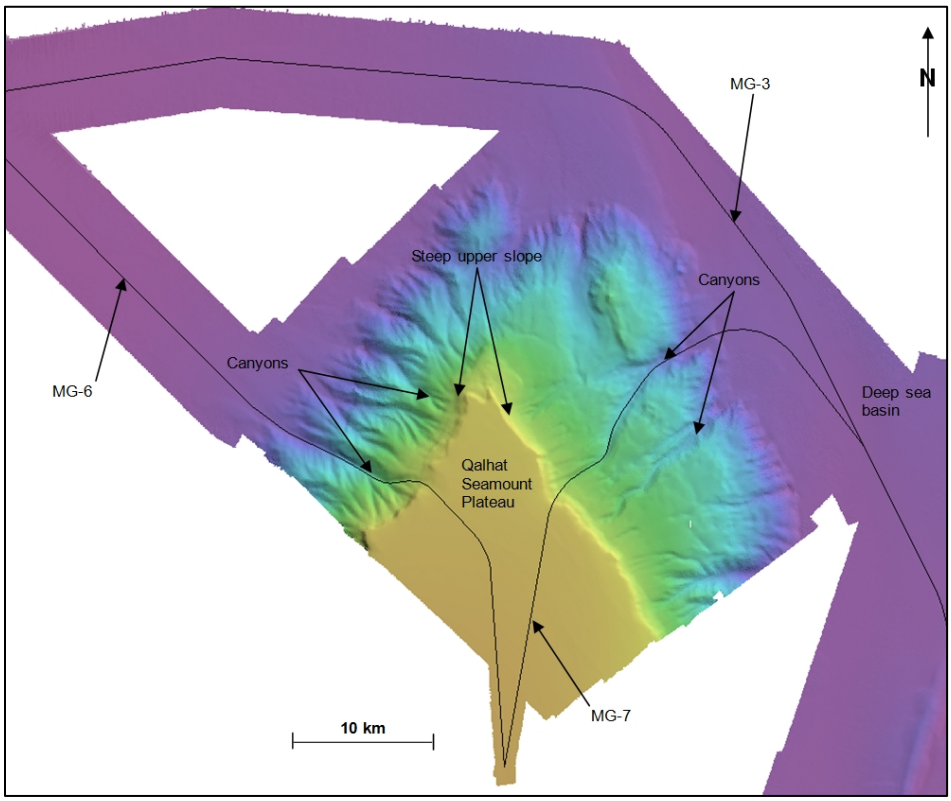

Figure 4 – Qalhat Seamount

The history of the Qalhat Seamount is not completely known. There is no clear evidence on the composition of the underlying basement, it has never been sampled. However, there is a small buried seamount, the Little Murray Ridge volcanic seamount under the Oman basin (Gaedicke et al. 2002; Mouchot 2009) and together with a strong magnetic anomaly in the vicinity of the seamount and a typical flat morphology, it's strongly suggested that the Qalhat Seamount is a volcanic guyot (Edwards et al 2000; Fournier et al. 2011). Palaeocene sediments onlap onto the Qalhat Seamount (Edwards et al. 2000, 2008; Gaedicke et al. 2002) indicate that it is older than Palaeocene.

6.3. GB-1 – Owen Fracture Zone

The aim of the survey in Block GB-1 was to investigate the Owen Fracture Zone. Two main structures were identified in this block, a central part which comprises the westernmost extension of the Upper Indus Fan complex as well as the east flank of the Qalhat Seamount, and the deep basins of the Dalrymple Trough in the north. In the far south-east is the deep sea area of the Arabian Abyssal Plain.

A distinct fault crosses the area in an almost north-south direction into the south end of the Dalrymple Horsetail and at its extension, the Dalrymple Trough. The deep basins in the north are about 24km wide in total. South and west of the Dalrymple Trough, there is a complex pattern of faults and ridges which are associated with the Dalrymple Horsetail. However, all faults seen in the area are associated with the Owen Fracture Zone that crosses the site in a SW-NE direction. In the south-east, an elevated arch bending towards the north-west comes in from the south. To both sides of this elevated area, meandering channels linked with the Upper Indus Fan can be seen. The channel to the west, bordering the distinct fault in the west, is almost entirely filled with sediments and barely visible.

Two extensional basins in the north, forms the deepest part of the surveyed block. Water depths ranges from 3350m to 3590m in the basins. A deep, narrow canyon extends from the south-western basin, along an almost N-S trending major fault – the Owen Fracture. The approximately 200m deep canyon is 1.3km wide where it starts and 2.6km where it connects to the western extensional basin, south-west of a threshold that marks the southern tip of the pull-apart basin.

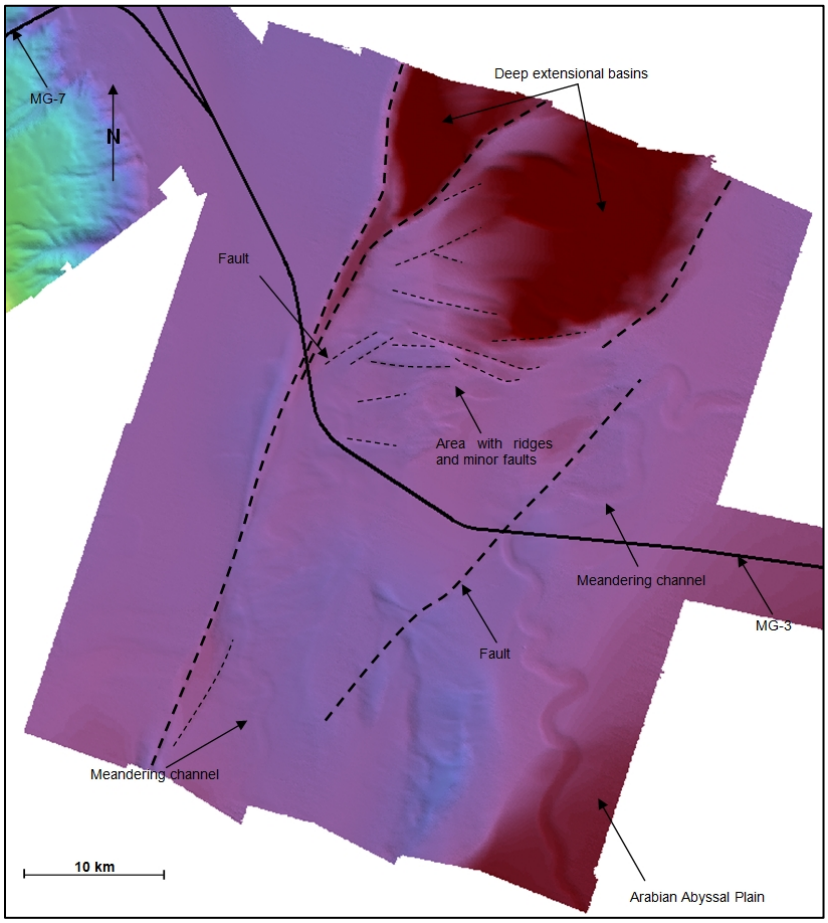

Figure 5 – Survey Block GB1

The seabed sediments in Box GB-1 have been interpreted to comprise soft to very soft calcareous clay/silt. The soft sediments are generally deposited by turbidity currents, mass wasting events

and pelagic sedimentation. However, the channel systems found in box GB-1 are most likely to have been inactive for a long time.

There are two structures that influence the sedimentation in the GB-1 box. Firstly, the proximity to the Qalhat Seamount and secondly, the Owen Fracture Zone crossing the area. The influence in the sediment regime from the Qalhat Seamount comprises slumped material extending across the area. The sediments flow down the steep sides of the seamount and come to rest in quieter environments. The flow of sediments from the sides of the Qalhat Seamount may be responsible for the infill of the meandering channel east of the Owen Fracture crossing the area. The channel itself is possibly the westernmost extension of the Indus Fan complex. The Owen Fracture Zone, together with the two Murray Ridges to the north-east, prevents much of the sediment coming from the Indus River from reaching the Oman Abyssal Plain in the west. Sediments and typical seabed features such as meandering channels and channel levees of the Indus Fan complex are seen in the east and south-east of Box GB-1, i.e. east of the crossing N-S extensional fault.

6.4. GB-2 – Indus Fan

The seafloor in the survey area of Box GB-2 is characterized by two topographical main structures: 1) channel/levee systems of the Indus fan which are dominating the central part of the box, 2) deep sea basins in the easterly and westerly sections of GB-2.

The water depth in the survey area ranges from 2120m at the central northern edge of the box to approximately 3180m in the deep sea basins in the western and eastern section of the surveyed area. Also within these deep basins, channel systems could be observed.

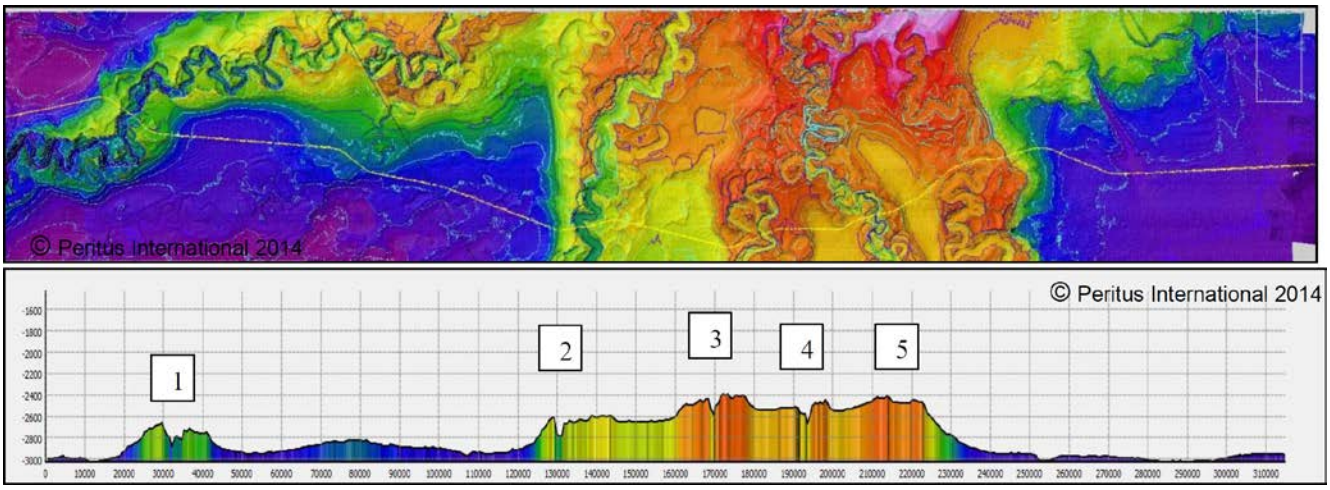

Figure 6 - Indus Fan Channel and Levee System

The channel/levee system is characterized by central channels with a series of adjacent terraces and numerous abandoned channel loops, which are partially refilled by the overspill sediments from the active canyon parts. The channels follow a meandering flow pattern with in general N-S direction. The main channel/levee complex in the centre of the surveyed box is approximately 95km wide and comprises three separate channel systems on the north, one of which subdivides to form a fourth channel in the southern half of the block. Each of the systems covers a 10km to

15km broad corridor across the box area, intermitted by more even seafloor sections. The third channel of the four distinguishable systems has an average base width of around 200 m in most of its southern half with minimum base width of around 100 m whereas the middle one is the narrowest with the steepest channel flanks. Slope gradients up to 35° could be detected. It seems that this channel is the most active one in the area at the time. The vertical relief across these channels ranges from a few tens of metres to 260m from the top of the highest levee to the base of the channel. The sedimentary levees are the result of overspill sediments generated by turbidites floating down the channels. These fine grained overspill sediments are deposited to both sides of the canyon and are in general well stratified. If a channel transports a high amount of turbidites these two processes, erosion and deposition, form a steep incised canyon flanked by pronounced levees. If the slope gradient along the pathway of such a channel comes below a critical value of around 1 degree, the channel starts meandering and forms typical loops. Due to shifts in the pathway of the channel, the loops can become abandoned. These loops become infilled with pelagic sedimentation and mass wasting events.

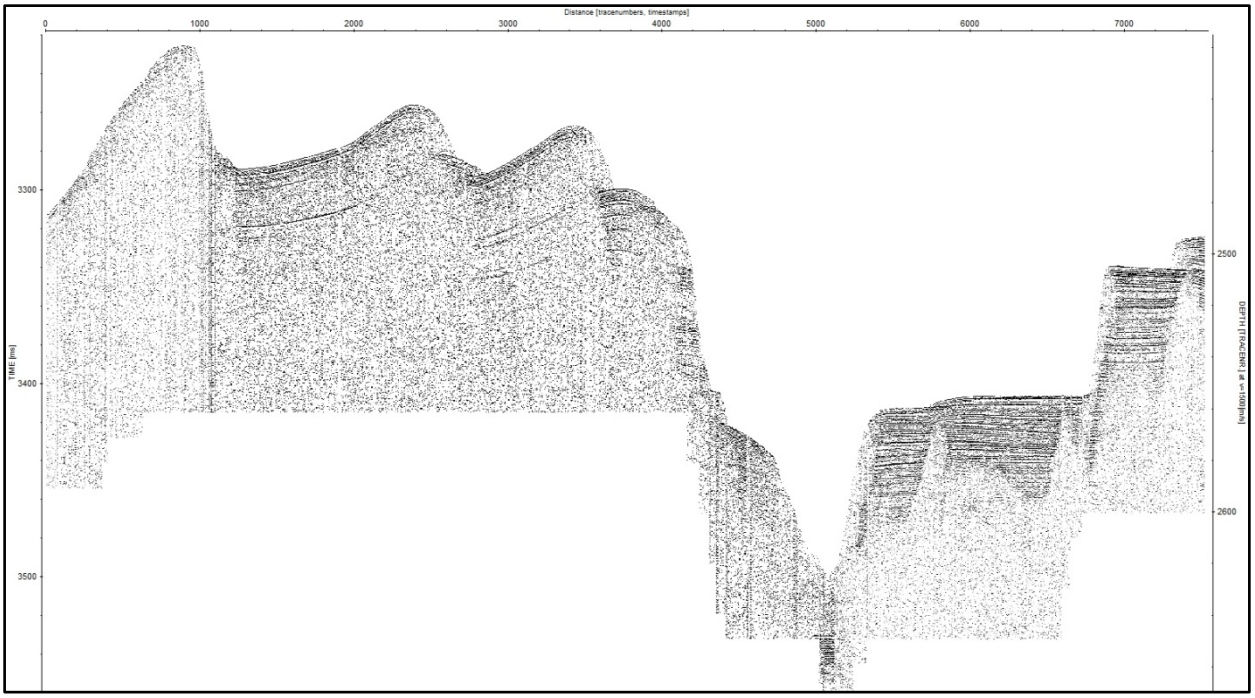

Figure 7 – Sub-bottom Profile data showing active meandering channel terraces of cut off loops

6.5. GB-3 – Indian Continental Slope and Shelf

The seabed in the survey area of Box GB-3 consists of a narrow shelf section at the eastern edge of the box and a broad area covering the continental slope in the middle and western part of the survey area. The surveyed Indian continental shelf is in general flat and featureless with low relief. The water depth ranges from 70m at the eastern extent of the survey block to around 150m at the shelf break. The seafloor gradient is in general less than 1°. The shelf area is nearly continuously covered by soft sediment such as very soft to soft calcareous clay/silt. Only small areas of isolated pinnacles of palaeo-coral reefs and areas of probably outcropping dense clayey sands occur along the shelf break with higher acoustic reflectivity.

Towards the open sea the continental slope becomes the dominating morphological feature. The water depth ranges from 150m at the shelf break to around 2500m at the base of the slope. The block is divided in to two halves by a major canyon feature that cuts deeply into the continental slope approximately half way through the block. In the northern half of the block, the upper slope area is dominated by numerous smaller canyons, steeply incised into the shelf break. Down slope in a water depth of approximately 800m to 1000m most of these smaller canyons join together to build up broad and deep canyons with a NE-SW orientation. The south western part of the box area is dominated by numerous medium sized canyons with a nearly parallel orientation. In-between all of these canyons the seafloor shows staggered head walls of mass wasting events. A few of these head walls have a very sharp edge, which is an indication for the younger age of these dynamic events. The surface of these deposits shows a rough, partially terraced morphology, which is a result of intensive mass wasting processes. The terraces represent slide planes of sediment packages (landslides), which became unstable for some reason (earthquakes, slope gradient, superimposed sediments). Most of the material flows into one of the canyons and from there it is transported towards the abyssal plain.

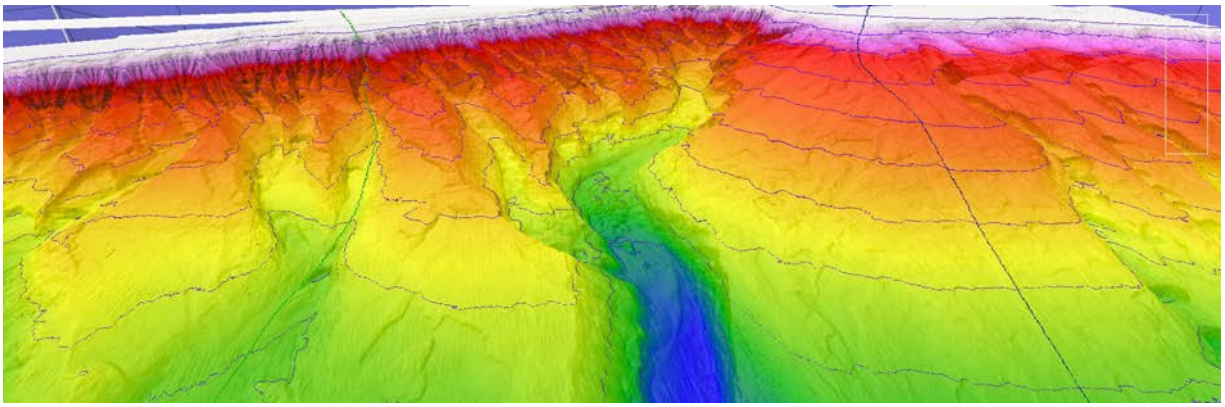

Figure 8 – Indian Continental Slope and Canyon Systems

In the lower slope area, with water depths greater 2000m, the seafloor has an undulating topography with a relief of 50m to 200m. This hummocky appearance is a result of a huge amount of sediment avalanches, which came to deposition in areas with a decreasing slope gradient.

7. Implications from Pipeline

7.1. Omani Continental Slope

Two route options are considered feasible to cross the Omani Continental slope, based on initial inspection. A northern route utilises a broad promontory between two major canyons to ensure a smooth descent onto the abyssal plain. A southern route utilises one of the canyon systems to route the pipeline to the abyssal plain. The slopes encountered by the northern route are generally less than 10° with a maximum slope at the shelf break of 20° as the pipeline passes into one of the numerous small gullies that characterise the shelf break. The southern route descends more quickly initially experiencing maximum slopes near the shelf break of around 30°, however once fully in the canyon system the general slopes are less than 10°. It is likely that the seabed on both pipeline routes will require modification in the form of trenching to smooth the transition into the small gullies at the shelf break. The northern route may require some gravel berm support as it

moves from its initial gully onto the promontory in approximately 700m water depth. The southern route whilst similar in average slope to the northern route, experiences much greater variation in slopes locally and may require span supports at numerous locations.

7.2. Qalhat Seamount

Two routes are considered feasible to ascend and descend the Qalhat Seamount, based on initial inspection. A north western route (ascent) utilises a straight gully feature to allow a smooth ascent from the abyssal plain to the flat top of the seamount. A north eastern route utilises the northern most canyon systems on the eastern side to descend back to the abyssal plain. The slopes encountered by the north western route are generally less than 12° with a maximum slope midway down the gully of 22°. The north eastern route descends initially within the gully system where the general slopes are less than 12° with the maximum slopes near the shelf break and at the base of the seamount of around 25°. It is likely that as the seabed on both pipeline routes will require modification in the form of trenching to smooth the transition into the small gullies at the shelf break. The north eastern route may also require trenching in specific locations to protect the pipeline from impingement by debris flows from tributary canyons and gullies and improve the profile at the base of the seamount.

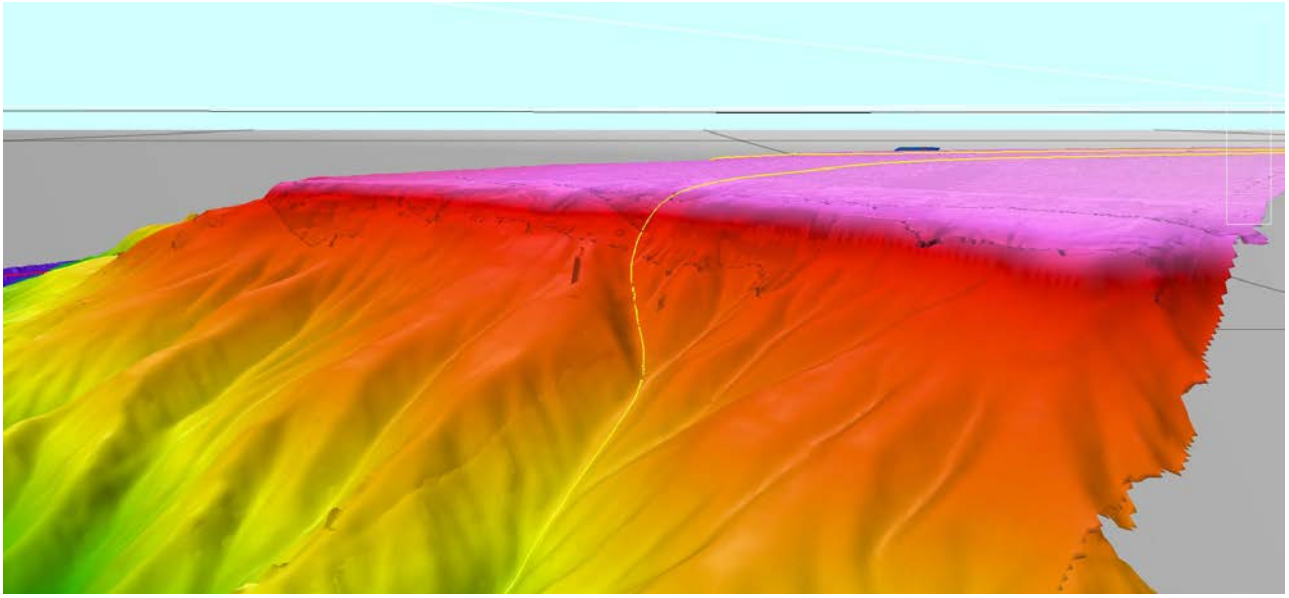

Figure 9 – North West Route Crossing the Qalhat Seamount Headwall

7.3. Owen Fracture Zone

The preliminary pipeline route determined during the survey activity passes north of the Qalhat Seamount and turns crosses the NNE-SSW trending Owned Fracture Zone in a NW-SE direction to traverse the fault line south of the deep Dalrymple Trough at the end of the Horsetail feature and north of the bathymetric high. This route has been used to perform an initial bottom roughness assessment of the pipeline, to determine the stress state and spanning condition of the pipeline in the areas of the Owen Fracture Zone. It is clear from the assessment made that the initial goals of the routing to: minimise spans; avoid areas of steep slopes; avoiding water depths greater than 3400m and give flexibility to the pipeline to accommodate a potential movement of the fault have been achieved. The spans associated with the canyon of the Dalrymple Horsetail are relatively minor, having height less than 0.35m and lengths less than 70m. The maximum

span height and length are associated with the relic channel of the Indus fan on the eastern edge of Block GB-1. At the pipeline crossing of the relic channel the anticipated installation span length is 120m with a height of 1.0m. The exact nature of optimum intervention has yet to be defined however given the size and nature of the spans predicted from the bottom roughness assessment it is most likely that vortex shedding stakes will be used for the spans. Remediation will also be required in the immediate vicinity of the main plate boundary fault, as it is clear that the flexibility afforded to the pipeline by the free span will be beneficial in accommodating fault movements. Spans associated with the irregular seabed caused by the displaced blocks may best be remediated by mechanical supports or mattresses. The long span associated with the relic channel may best be remediated by shoulder lowering using mas flow excavation techniques, providing the soils are suitable.

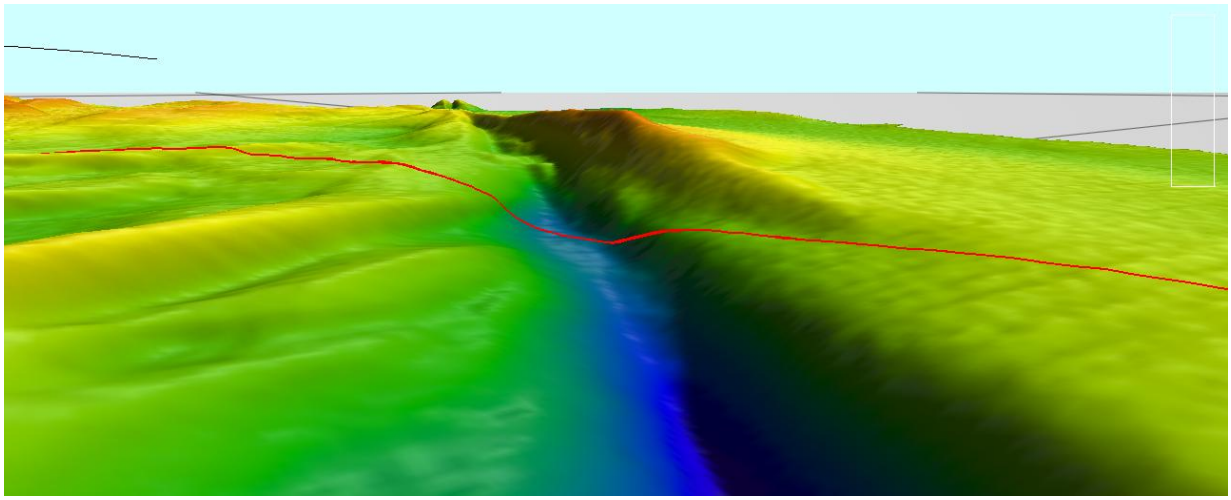

Figure 10 – Fault Crossing at the Dalrymple Horstail

7.4. Indus Fan

The pipeline route across the Indus Fan runs predominantly from west to east. Given the general E-W nature of channel 1, the route tracks this channel in the deepwater basin to its north in approximately 3050m water depth for 24km until a suitable crossing is afforded in a NW-SE direction. After crossing Channel 1 the pipeline route passes into the deepwater basin south of channel 1 and traversing ESE for 85km in this deep basin area crossing several infilled relic channels and channel loops in water depths between 2840m and 2940m before climbing to 2590m water depth over the final 3.5km to reach the N-S orientated channel 2. Channel 2 marks the start of the main N-S trending of the Indus Fan within Block GB-2 which contains 4 main channel features (channels 2-5). In the southern, deeper water part of the block, Channels 2-5 are spaced between 20km-30km from each other, diverging slightly as they meander their way from north to south. The exact nature of optimum intervention has yet to be defined however given the size and nature of the spans predicted from the bottom roughness assessment it is most likely that vortex shedding stakes will be used for spans requiring remediation in the immediate vicinity of the base of the channels. Spans associated with the irregular seabed caused by the channel flanks and extinct channel loops may best be remediated by mass flow excavation or mechanical trenching equipment. Mechanical supports or mattresses may be used where span heights are small and where the foundation soils are adequate.

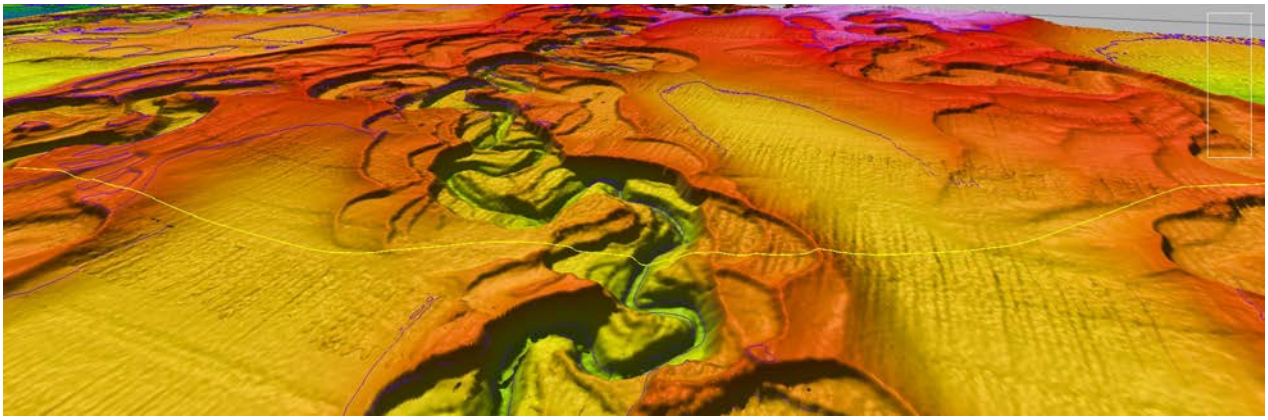

Figure 11 – Indus Fan Channel 4 Crossing

7.5. Indian Continental Slope

Two route options are considered feasible to cross the Indian Continental slope, based on initial inspection. A southern route utilises a broad promontory south of the main central canyon feature to allow a smooth ascent from the abyssal plain to the continental shelf. A northern route utilises one of the smaller canyon systems to the north of the main central canyon feature to route the pipeline to the continental shelf. The slopes encountered by the southern route are generally less than 5° with a maximum slope at the shelf break of 15° as the pipeline passes into one of the numerous small gullies that characterise the shelf break. The northern route climbs gently within the gully system where the general slopes are less than 10° with the maximum slopes near the shelf break of around 28°. It is likely that as the seabed on both pipeline routes will require modification in the form of trenching to smooth the transition into the small gullies at the shelf break. The northern route may also require trenching in specific locations to protect the pipeline from impingement by debris flows from tributary canyons and gullies. The southern route is very smooth and is unlikely to require significant span support or intervention, however evidence of surface slides on this route will need to be assessed in more detail before required intervention can be determined.

8. Conclusion

The geophysical reconnaissance survey covered several geological regimes. The Oman shelf is dominated by outcropping rock and hardgrounds with coral structures only covered by a thin blanket of fine soft sediments probably consisting of very soft to soft calcareous sandy clay/silt. Complex gully and channel systems dominate the Oman slope down to the continental rise where several generations of slump deposits were found.

The Oman Abyssal Plain comprises of smooth featureless seabed covered by fine soft pelagic sediments, such as very soft to soft calcareous clay/silt. The Qalhat Seamount located at the Owen Fracture Zone, the tectonic plate boundary between Arabian Plate to the west and Indian Plate to the east, is a flat topped volcanic guyot with steep slopes. The flat plateau is covered by soft fine sediments and consolidated sediments / hardgrounds with outcrops of the rock basement at its rim.

The route also crosses several faults at the Owen Fracture Zone and the associated Dalrymple Horsetail. The Upper Indus Fan is dominated by large channel-levee systems that originated from turbidity mass movements. This large historical sediment input of the Indus River has also dominated the sedimentation processes at the Indian Continental Shelf and Slope and has led to extensive historical mass movements, such as turbidity currents, slumps and slope creeping, and development of canyon systems at the slope. Outcropping rock and coral reef structure were also found at the Indian shelf break.

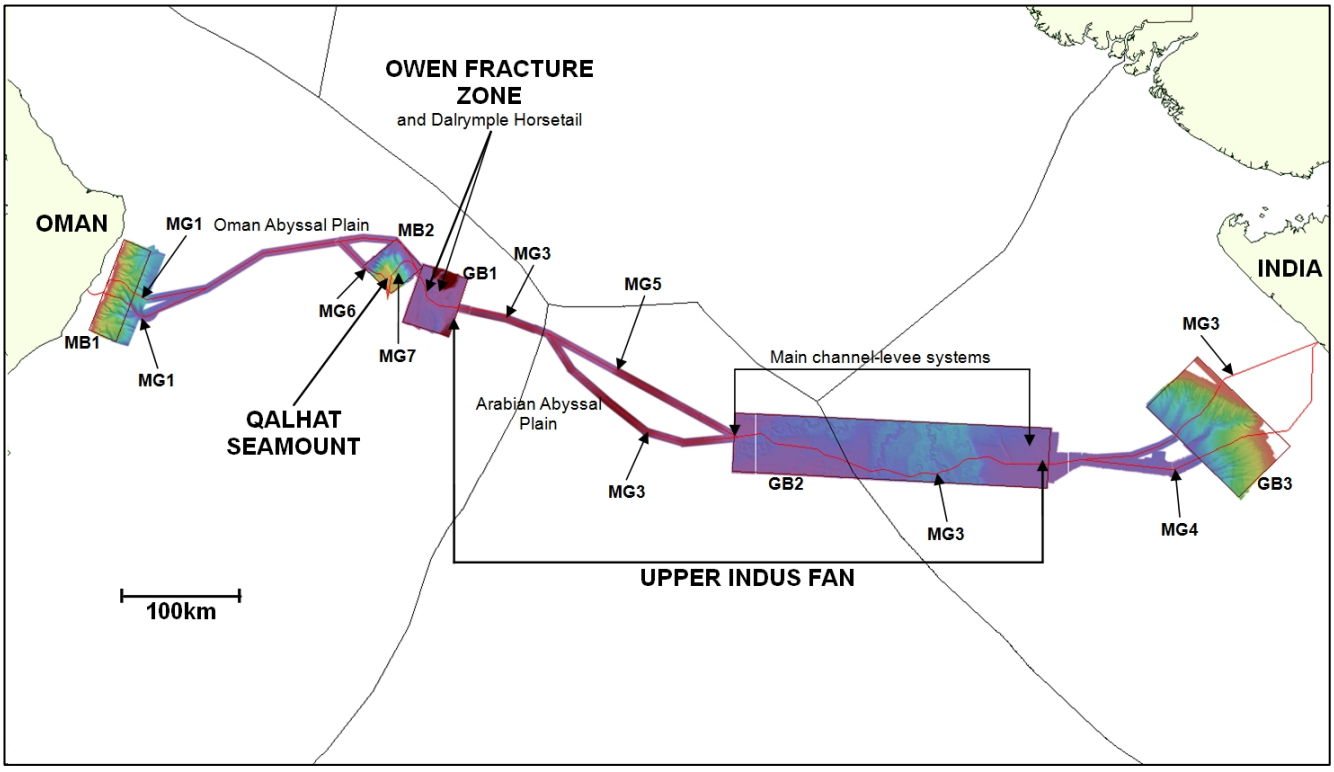

Figure 12 - Overview of main geological features

The objectives of the reconnaissance survey were achieved. Preliminary pipeline engineering analyses has determined that routes through the five areas are feasible and within the route corridors between these areas.

To bring the project even closer to reality a more detailed geotechnical survey will have to take place on the identified route together with detailed geotechnical and seismic surveys to allow a full geohazard and engineering assessment to be made.

9. Acknowlegements

The authors would like to thank SAGE Pvt Ltd. for allowing this paper to be written, their respective colleagues at Peritus International, the offshore Fugro team that carried out a successful and safe survey and the Fugro teams that prepared the initial Desk top Studies.

10. References

Balakrishnan, T.S., Unnikrishnan, P. and Murty, A.V.S. (2009), "The Tectonic Map of India and Contiguous Areas", Journal of the Geological Society of India, Vol. 74, No. 2, pp. 158-170.

Clift, P.D. (2002), "A Brief History of the Indus River", in Clift, P.D., Kroon, D., Gaedicke, C. and Craig, J. (Eds.), The Tectonic and Climatic Evolution of the Arabian Sea Region, The Geological Society, London, Geological Society Special Publication, No. 195, pp. 237-258.

Edwards, R.A., Minshull, T.A. and White, R.S. (2000), "Extension across the Indian-Arabian Plate Boundary: the Murray Ridge", Geophysical Journal International, Vol. 142, No. 2, pp. 461-477.

Edwards, R. A., Minshull, T. A., Flueh, E. R., Kopp, C., 2008. Dalrymple Trough: An active oblique-slip ocean-continent boundary in the northwest Indian Ocean. Earth and Planetary Science Letters 272, 437-445.

Fournier, M., Chamot-Rooke, N., Rodriguez, M., Huchon, P., Petit, C., Beslier, M.-O., Zaragosi, S., 2011. Owen Fracture Zone: the Arabia-India plate boundary unveiled. Earth and Planetary Science Letters 302, 247-252.

Fugro Engineers BV (2011), Desk Study Report, Geology and Geohazard Route Assessment South Asia Gas Enterprise (SAGE) Pipeline Oman to India, J33010-REP-IIDP-Y-0002 Rev C

Fugro OSAE (2013), Marine Pipeline Route Survey for the Middle East to India Deepwater Pipeline, Survey Report, Volume 3, Geophysical Survey Results – Area Surveys.

Fugro William Lettis & Associates Inc. (2011a), “Seismotectonic Study for the Middle East to India Deepwater Pipeline”, Report No. 79110002, Document No. J33010-REP-IIDP-Y-0008 rev B, dated 1 February 2011.

Gaedicke, C., Prexl, A., Schlüter, H.-U., Roeser, H. , Clift, P. 2002. Seismic stratigraphy and correlation of major regional unconformities in the northern Arabian Sea. In: The Tectonic and Climatic Evolution of the Arabian Sea Region (Eds P. Clift, D. Kroon, C. Gaedicke and J. Craig), Geological Society of London, Special Publication, 195, 25-36.

Kenyon, N.H., Amir, A. and Cramp, A. (1995), “Geometry of the Younger Sediment Bodies of the Indus Fan”, in Pickering, K.T., Hiscott, R.N., Kenyon, N.H., Ricci Lucchi, F. and Smith, R.D.A. (Eds.), Atlas of Deep Water Environments: Architectural Style in Turbidite Systems, Chapman & Hall, London, pp. 89-99.

Kolla, V. and Coumes, F. (1984), "Morpho-acoustic and Sedimentologic Characteristics of the Indus Fan", Geo-Marine Letters, Vol. 3, No. 2-4, pp. 133-139.

Mouchot, N., 2009. Tectonique et sédimentation sur le complexe de subduction du Makran pakistanais. Unpublished PhD thesis, Cergy Univ., France, 364 pp.

Mullee, J.E. (1995), “Oman-India Pipeline Route Survey”, in 27th Annual Offshore Technology Conference, 1-4 May 1995, Houston: Proceedings, OTC Paper 7676.

Naini, B.R. and Kolla, V. (1982), "Acoustic Character and Thickness of Sediments of the Indus Fan and the Continental Margin of Western India", Marine Geology, Vol. 47, No. 3-4, pp. 181-195.

Prins, M.A. and Postma, G. (2000), "Effects of Climate, Sea Level, and Tectonics Unraveled for Last Deglaciation Turbidite Records of the Arabian Sea", Geology, Vol. 28, No. 4, pp. 375-378.

Swift, S.A. and Ross, D.A. (2002), “Interpretation of Seafloor Characteristics in the Western Arabian Sea: Final Report to the Office of Naval Research”.