Appendix F

Geosciences Report
APPENDIX F – GEOSCIENCES REPORT

TABLE OF CONTENT

1

SUMMARY & MAIN CONCLUSIONS................................................................. 1

2

REPORT REVIEW ............................................................................................ 3

3

INTRODUCTION .............................................................................................. 5

4

GEOLOGY........................................................................................................ 6

4.1 Geographical & Historical Geology .......................................................... 6

4.2 Dead Sea Transform (DST) – Arava Valley ............................................. 8

4.3 Stress fields versus time ........................................................................... 12

4.4 Rock properties .......................................................................................... 13

5

SEISMICITY .................................................................................................... 18

5.1 Seismicity – Objectives ........................................................................... 19

5.2 Historical Seismicity.................................................................................. 20

5.3 Seismic Hazard mapping ........................................................................... 23

5.4 Late Quaternary Seismicity of the Southern Arava ................................... 24

5.4.1 The marginal fault zone – Nahal Shehoret .......................................... 25

5.4.2 The central fault zone – Avrona Playa ............................................... 26

5.4.3 Gulf of Aqaba ...................................................................................... 28

5.4.4 Conclusions .......................................................................................... 28

5.5 PGA (Peak Ground Acceleration) and spectral analysis ....................... 28

5.6 Conclusions ............................................................................................... 34

6

HYDROGEOLOGY............................................................................................ 35

6.1 Introduction ................................................................................................ 35

6.2 Groundwater conditions in the Wadi Araba / Arava Valley and on its
eastern margin. ............................................................................................... 35

6.2.1 Lower Cretaceous (“Kurnub”) aquifer ............................................... 39

6.2.2 The Upper Cretaceous (“Judea”) aquifer ......................................... 40

6.2.3 The Neogene &Quarternary (“Arava Fill”) aquifer ............................. 40

6.2.4 Conclusions .......................................................................................... 45

6.3 Hydraulic conditions at the eastern margin. ......................................... 45

6.4 Dead Sea groundwater inflows ................................................................. 46
6.4.1 The Hydrogeology West of the Dead Sea ................................................. 46
6.4.2 The Hydrogeology East of the Dead Sea ........................................... 47
6.4.3 Groundwater Inflows from springs .................................................... 47
6.4.4 Groundwater Inflows from Shore Line ............................................. 48

6.5 Sinkholes hazard .................................................................................. 48
6.5.1 Sinkholes Hazard: Existing Models ................................................. 48
6.5.2 Detailed Description of the Dissolution Model ............................... 51
6.5.3 Consequences of the sinkholes hazard - Recommendations ...... 54

6.6 Incision of gullies hazard .................................................................. 54

6.7 Effects of climate changes on groundwater resources: ................... 55

6.8 Hydrogeology Conclusions ................................................................ 56

7 ENGINEERING GEOLOGICAL CONDITIONS AT THE DIFFERENT UPSTREAM WORKS .... 57
7.1 The Eastern Water Intake ..................................................................... 57
7.2 The North Water Intake and inferred pumping station .................... 63

8 CONVEYANCE ROUTES OPTIONS ............................................................ 71
8.1 Tunnel Alignment Option 0.1 .............................................................. 71
8.1.1 Introduction ..................................................................................... 71
8.1.2 Overview of the engineering geological conditions along the Alignment 0.1 ................................................................. 72
8.1.3 Rock mechanical properties ............................................................ 75
8.1.4 Access galleries ................................................................................ 77
8.1.5 Hydrogeological conditions ............................................................. 79

8.2 Tunnel/Canal Alignment Option 220.1 .............................................. 79
8.2.1 Introduction ..................................................................................... 79
8.2.2 Overview of the engineering geological conditions along the Alignment 220.1 ................................................................. 80
8.2.3 Rock mechanical properties ............................................................ 83
8.2.4 Access galleries ................................................................................ 85
8.2.5 Seismic hazard to canal part ............................................................ 86
8.2.6 Hydrogeological conditions ............................................................. 86

8.3 Other geological constraints to the tunnels of alignments 0.1, 220.1 and pipeline option (radioactive hazard excepted)................................. 86
8.3.1 Seismicity ......................................................................................... 86
8.3.2 Geothermic gradient and effects of temperature on the seawater conveyed in the tunnel ........................................88
8.3.3 Radioactive hazard ........................................................................................................88

8.4 Tunnel/Pipeline Alignment Option .............................................................................89
8.4.1 Overview of the engineering geological conditions along the pipeline alignment ................................................................. 89
8.4.2 Salt tectonics .............................................................................................................92
8.4.3 Seismicity ................................................................................................................ 92
8.4.4 Hydrogeological conditions ....................................................................................92

9 ENGINEERING GEOLOGICAL CONDITIONS AT THE DIFFERENT DOWNSTREAM WORKS ................................................................................. 93
9.1 Desalination Plant Area C for Conveyance Alignment Options 0.1 and 220.1 ................................................................................................................................................................................. 94
9.2 Desalination plant & Hydro Power Plant Area A .................................................... 100
9.3 Desalination Plant Area D related to the pipeline alignment option ............ 109

10 POTABLE WATER PIPELINE TRANSMISSION LINES ............................................. 110
10.1 Potable Water Pipeline Transmission Lines to Amman ........................................ 110
10.2 Potable Water Pipeline Transmission Lines to Ein Gedi and Jericho ...... 112

11 BRINE AND SEAWATER TRANSMISSION LINES ................................................. 115

12 BIBLIOGRAPHY – SOURCES OF DATA ............................................................. 116
Table of Figures

Figure 1: Schematic structural map of Middle East and surrounding areas ........................................ 8
Figure 2: Structural map of Middle East with basalt location .......................................................... 10
Figure 3: Structural relations between Dead Sea Transform and Pull-Apart structures (GARFUNKEL, Z., 1988) .......................................................... 11
Figure 4: Simplified drawing about sinistral and dextral motion along a strike-slip fault .......... 14
Figure 5: Simplified geological map of both sides of the Arava valley, crystalline rock in red colour, sedimentary in green colour ................................................ 14
Figure 6: Approximate mineralogical compositions of the more common types of igneous rocks.................................................................................. 15
Figure 7: Tectonic settings of the Araba valley. DEM image from Hall (1994) with fault interpreted from satellite images and fieldwork ........................................... 19
Figure 8: Instrumental Earthquakes (Ms ≥ 4) of the Dead Sea Transform region for the period 1900-2009. MALKAWI, A.I.H., NUMAYR, K.S. & BARAKAT, S., 1999 & Jordan Seismological Observatory) ........................................................................................................ 20
Figure 9: Historical Earthquakes of the Dead Sea Transform Region for the period 19AC-1900 (MALKAWI, A.I.H., NUMAYR, K.S. & BARAKAT, S., 1999 & Jordan Seismological Observatory) .... 21
Figure 10: Offset wall at the Tilah castle site (note one person as scale) ........................................ 21
Figure 11: Seismic source model consisting of seismogenic sources (UNESCO 2006) ........... 23
Figure 12: Morphological and morphotectonic map of the southern Arava valley with trenches, fault lines and seismic lines location ........................................................................ 24
Figure 13: Log of the southern wall of trench T-6 ........................................................................ 25
Figure 14: Log of the southern wall of trench T-17 ...................................................................... 26
Figure 15: Flower structures. On the left: positive “palm tree” transpression structure. On the right: negative “tulipe” transtension structure ................................................. 27
Figure 16: Log of the southern wall of trench T-18 ...................................................................... 27
Figure 17: Seismic hazard map for the Levant region using Ambraseys et al. (1996) peak acceleration attenuation relationship. PGA is assessed for a 10% probability of exceedance in 50 years and for Generic rocks ................................................................. 29
Figure 18: Spectral response zonation map in the North of Aqaba ............................................. 31
Figure 19: Spectral response zonation map in the South of Aqaba close to Eastern Water Intake ................................................................................................................................. 32
Figure 20: Dead Sea Transform location in Central Arava ............................................................ 33
Figure 21: Arava fault unique location based on geomorphological observations (Google Earth) ............................................................................................................. 34
Figure 22: Groundwater basins and flows based in the Middle East ......................................... 36
Figure 23: Israeli wells along the Arava valley, worth mentioning that some Israeli wells are located inside Jordan territory .................................................................................. 37
Figure 24: Geological cross section in the Zofar area, central Arava valley, western part (compiled by FLEISHER, E., FLEISHER, L. & FRESLANDER, U., 1997; Geophysical Institute of Israel) 38
Figure 25: Aquifer extension between the Red Sea and the Dead Sea .................................. 39
Figure 26: Hydrogeological model of Jordan side of Dead Sea (SALAMEH E., 2009) ...... 40
Figure 27: Piezometric, groundwater levelmap (GEOLOGICAL SURVEY OF ISRAEL, 2006) .... 42
Figure 28: Iso-salinity mapping and flow directions of Quaternary Alluvium Groundwater between the Red Sea and the Dead Sea (SALAMEH E., 2009) .................................................................43
Figure 29: Hydrogeological mapping (depth to water) of Quaternary Alluvium Groundwater between the Red Sea and the Dead Sea ..............................................................................44
Figure 30: Sinkholes localization map ................................................................................50
Figure 31: Dissolution model – Conceptual scheme ...............................................................51
Figure 32: Hydrogeological schematic section across the Elongated swarm of sinkholes in the Salem 2 site (SALAMEH E. & EL-NASER H., 2000) (location is given on Figure 30) ..............52
Figure 33: Water Intake locations on geological map and main structural features of the area...........................................................................................................................................57
Figure 34: Joints-fractures-faults directions represented on meridional stereographic net ..58
Figure 35: Seismic refraction profile No. 1 at the Eastern Water Intake ..................................59
Figure 36: Map showing the distribution of earthquake epicenters of the Gulf of Aqaba (A) 1983, (B) 1993 and (C) 1995 (Al-Zoubi, A.S., Heinrichs, T., Sauter, M. & Qabbani, I., 2006). ....60
Figure 37: Response spectral at the Eastern Water Intake .......................................................62
Figure 38: Location of North Water Intake, Available corridor and Arava fault on aerial photography (from Google Earth) ..........................................................63
Figure 39: Pumping station area associated to North water intake – Localization of geological and geophysical investigations on Aerial photography (from Google Earth) ........64
Figure 40: Liquefaction risk diagram (Curves relating to CRR to (N1)60 published over the past 24 years for clean sands and the recommended curve for M = 7.5) .................................66
Figure 41: Clastic dike photography ......................................................................................67
Figure 42: Basin effect & trapped seismic waves ...................................................................68
Figure 43: Response spectral at North Water intake location ...............................................69
Figure 44: Response spectral at Pumping station location associated to North water intake ..................................................................................................................69
Figure 45: Geological Strength Index table (MARINOS, P. & HOEK, E., 2000) ....................75
Figure 46: Joints-fractures-faults directions represented on meridional stereographic net at Access portal 220-3, main joint direction: N155° dipping 45°SW ........................................76
Figure 47: Joints-fractures-faults directions represented on meridional stereographic net at Access portal 220-3 ..........................................................77
Figure 48: Joints-fractures-faults directions represented on meridional stereographic net at Wadi Yutum (Access 220-1), main joint direction: N135° dipping 55°NE .......................84
Figure 49: Joints-fractures-faults directions represented on meridional stereographic net at Access portal 220-3, main joint directions: N35° dipping 85°SE; N142° dipping 85°SW; N130° dipping 5°NE. ........................................................................................................ Erreur ! Signet non défini.

Figure 50: Seismic refraction profile No. 2 (SRP2) at Wadi Yutum (Access 220-1) ...............85
Figure 51: Response spectral at for canal sections .................................................................86
Figure 52: Desalination plant areas locations on geological map ...........................................93
Figure 53: Desalination plant areas for alignment options 0.1 (West) and 220.1 (East) (image from Google earth) ..........................................................94
Figure 54: Aerial photography with localization of the performed investigations (Image from Google Earth) at the Desalination plant area for Alignment option 0.1 .................................95
Figure 55: Aerial photography with localization of performed investigations (Image from Google Earth) in the Desalination plant area for Alignment option 220.1 ........................................... 96
Figure 56: Response spectral at Desalination plant area C .................................................. 97
Figure 57: Probable normal faults localization (from aerial photography analysis) ........ 98
Figure 58: Topographical site effect conceptual scheme .................................................... 99
Figure 59: Aerial photography with potential site effect localization (Image from Google Earth) ........................................................................................................ 99
Figure 60: Limits of Desalination plant area A and localization of performed investigations (Image from Google Earth) ........................................................................ 101
Figure 61: T-X data of profile No. 8 at Desalination plant area A ....................................... 102
Figure 62: Georesistivity profile No. 2 ............................................................................. 103
Figure 63: Georesistivity profile No. 10 ........................................................................... 104
Figure 64: Clastic dike photography (LEVI, T., WEINBERGER, R., EYAL, Y., AIFA, T., LYAKOWSKY, V., PORAT, N., MARCO, S. & HEIFETZ, E., 2009). ................................................................. 105
Figure 65: Folded laminated formations into seisinite ....................................................... 105
Figure 66: Wave resonance into alluvial deposits ............................................................ 106
Figure 67: Best estimated response spectral at the Desalination plant & hydropower plant area A............................................................................................................. 107
Figure 68: High level DP (related to pipeline alignment) location on Aerial photography (Google Earth) ........................................................................................................... 109
Figure 69: Potable Water pipeline transmission line options on aerial photography (from Google Earth) ........................................................................................................ 110
Figure 70: Landslide areas location along the north transmission line option ................ 111
Figure 71: Fresh water pipelines schematic locations, sinkholes hazard areas ............. 113
Figure 72: Discharge works options in the Dead Dea ....................................................... 115
1 SUMMARY & MAIN CONCLUSIONS

The abundant literature related to the study area has been synthesised with a focus on the facts which may be relevant for the potential project works. This study is based on a desk review combined with site visits, field work, geomechanical and geophysical investigations. The key issues with respect to the potential project are the seismicity including earthquakes magnitude, slip rate per event, response spectra, liquefaction risk then the lithology and the related geomechanical properties and the groundwater conditions. The results of a project specific geological-geomechanical field investigation are also interpreted and incorporated in this report.

The earthquake hazard is treated from two points of view: (i) on fault, concerning the identification of active faults, where there is a risk of surface rupture, and (ii) off-fault, where there is risk of surface rupture, or where tremor-related effects might occur as liquefaction, rock falls, landslides and damage to infrastructure.

The project area stretching from the Aqaba Gulf to the north of the Dead Sea is dominated by the Dead Sea Transform (DST) is a fault zone with several branches. It comprises a major strike slip fault (AF) with the mean lateral slip rate (4 ± 2 mm/year) and a rift, corresponding to the Arava valley with its eastern shoulder reaching an elevation of 1000 m bordered by the Aqaba-Gharandal fault which is a normal fault with a slip component. In its southern part one observes proterozoic rock, typically granite and monzonite and mostly intensively fractured. In the northern part sedimentary rocks are observed they are predominantly sandstone, but marl, clay limestone also occur.

The branches of the main fault were active at different stages of the fault zone evolution. Possible activity of marginal faults has also to be considered in particular in light of evidence for young faults that became active in the Pleistocene to the west of the Wadi Araba/Arava Valley and in the Gulf of Aqaba/Eilat).

The absence of similar geomorphic analysis on the eastern margins of the Wadi Araba/Arava Valley makes the existence of young faults there a possibility that has to be tested.

Based on historic evidence of the last 2000 years and an extrapolation of instrumental data of the last 100 years, the mean recurrence interval of an earthquake Mw>7-7.3 is ≈10,000 year, but more recently seismologists believe the recurrence interval for an earthquake of this magnitude should be revised and reduced to 1000 year for the region, the best estimate for the 50 year probability of occurrence for a destructive earthquake (Mw>7) is 1.7%. The corresponding 500 years probability is 15.8%. The observed lack of significant earthquakes for more than 5 centuries implies that there is a deficit in seismicity, in which case the calculated 500 year probability is higher. Consequently, the potential occurrence of a coseismic slip of 1 to 3 m within the lifetime of the Red Sea Dead Sea conveyance system has to be considered. This means that any crossing of the Arava Fault is a major issue and that tremor related effects resulting from an earthquake of Mw>7 have to, be considered. Depending on the soil response earthquakes of this magnitude may be destructive.

Within the Wadi Araba/Arava Valley, amplification of the signal response may be expected to be around twice as high (some seismologist indicate they have calculated higher ratios) as the response at the rock basement. Therefore extensive paraseismic mitigation for works may be necessary at the surface within the Wadi Araba/Arava Valley.

The fill aquifer of the Wadi Araba/Arava Valley including the Quaternary and Neogene strata is the most important aquifer within the project area. It is constituted of alluvial heterogeneous deposits. It
is also very vulnerable and the risk of leakage of sea water from the conveyance conduit is a serious hazard for this aquifer which is crucial for the water supply of the area.

The eastern margin or shoulder of the WadiAraba/Arava Valley in its southern part comprises crystalline rock with relatively high hydraulic conductivities (from water tests and observations) so that at the” tunnel scale” a general aquifer has to be considered. This aquifer contributes to the recharge of the Arava/Arava fill aquifer and consequently the leakage hazard has to be considered. In its northern part, the tunnel passes through highly permeable sandstone which is part of the cretaceous aquifer and is also vulnerable. The groundwater discharge to the Dead Sea could not accurately be determined due to lack of available data and measurements. On the other hand the sinkhole hazard mechanism is well developed and the location where they are most likely to occur can be predicted, and if required mitigation can be undertaken.

On the Gulf of Aqaba/Eilat the planned works are the water intake and for two conveyance alternatives considered also a pumping station. If the eastern water intake is preferred, no serious geological problems are expected, while at the northern intake there is a serious risk of soil liquefaction in a seismic event, the geomechanical soil properties are poor, deep impervious cut-off walls will be required below any deep excavations to avoid locally fluidization and “boiling” problems during the construction. In addition an unfavourable response spectrum has to be considered and there is a risk where the conveyance crosses the Arava fault, which is also a major issue.

There are no severe geomechanical conditions to consider for the pipeline conveyance route, except the crossing of an area of salt mudflats where there is a liquefaction risk, which can readily be mitigated. But the crossing of the Arava fault is an issue. The pipeline route has been chosen in order to maintain the maximum practicable distance from the Arava fault and to cross it only once. This will require the excavation of paleoseismic trenches to exactly define the location of the Arava fault where specific design provisions will require to be adopted in order to avoid damage to the pipeline from multimetric coseismic slip. Since the pipe is buried, the risk of damage due to an earthquake is limited and may be mitigated. In addition the risk of leakage and the resultant contamination of the underlying aquifer, which is crucial for the area, also need to be addressed with appropriate design provisions.

For the tunnel-canal and tunnel options, no insurmountable geological difficulties are expected. The most crucial will be the risk of cataclastic rock, which could flow and jamb the tunnel boring machine but if these locations are previously accurately located this may be prevented by pre- grouting. If the project goes ahead further geotechnical investigation of the tunnel routes will be required comprising about 30 deep cored boreholes, up to 100 m dept.

In the area of the Dead Sea, the main works are the desalination plant and the hydropower plant. Different alternatives are considered. The hydrogeological conditions (deep water table) are favourable and the soil geomechanical properties are also generally good. However, the expected seismic response spectra are high and will require substantial paraseismic construction works.

The fresh water supply routes are also considered, only one route to Amman shows acceptable geological conditions.

In the case that it is desired to locate the brine and seawater outfall northward in the Dead Sea, this would be limited on the eastern side to about halfway up the total length of the Dead Sea. Further northward slope stability problems and unfavourable topography make this option impracticable.
2 REPORT REVIEW

The geosciences report has been reviewed by 5 peers and in addition comments were given by ERM and Amos Salomon of the Geological Survey of Israel on behalf of the Israeli SMU representative.

We are thankful of the reviewers for their contribution.

The comments and recommendations are given below.

Dr. J. Guttman, hydrogeologist of MEKOROT, considered the Geosciences report as very good work with a lot of data and information. He suggested that we should give more emphasis to the risk of contamination of the Arava aquifers in case of leakage from the pipeline option and the necessity to develop at the detailed design stage a contamination risk analysis for the existing wells and to design appropriate mitigation measures. He also corrected some discharge data at some springs. These suggestions and corrections have been incorporated in this version of the report.

Prof. Abdallah I. Husein Malkawi, Seismologist of the Royal Institute of Seismology and Professor at Jordan University of Science and Technology corrected the reported results of the UNESCO study. He also pointed out that herein the area acceleration maps there was a transposition of the work of Boorre and Ambrasey. These corrections have been incorporated in this version of the report.

Dr. Amos Shiran, Seismologist provided further insight into the Israeli codes and rules for paraseismic design. He also suggested we give more emphasis to the seismic deficit along the Arava fault. He also drew attention to the seismic induced tsunami risk in the Gulf of Aqaba/Eilat. These suggestions have been incorporated in this version of the report.

Dr. Shmuel Marco, Professor of Geology at the Department of Geophysics and Planetary Sciences in the Hebrew University. He considered that the authors of the geosciences report have done a commendable job. He commented that the report largely address almost all the relevant geological issues and present them in a clear manner with additional explanations aimed for non-specialists. He suggested more emphasis should be given to the deficit in seismological events along the Arava fault, the various branches of the Arava fault, the distinction between the effect of the coseismic slip and the consequences of the waves and the need at the detailed design stage to identify and map the active faults and fault branches crossed by the conveyance and at main works. He also provided some additional interesting references.

He suggested that further consideration should be given to the tsunami risk, seiche hazards, the headcut migration of incision gullies which may affect some infrastructure and the occurrence of the Dead Sea active fault and its branches close to the water transmission line to Jericho.

He also stressed that adhering to instructions, his review addresses the completeness of the geosciences-related hazards, the relevant data sources, and their proper integration in the report and that he refrains from expressing his opinion or judgment on the water conveyance project and the usage of the geological data in the decision processes, in which he had no involvement whatsoever.

Again all of these suggestions have been incorporated in this version of the report.

Dr. Salameh, hydrogeologist, Professor at the University of Amman. He was expecting full hydrogeological studies with groundwater modeling of the different aquifers of the project area for water supply. It has been clarified that this was not part of the scope of the studies. He also provided some corrections to the draft report.
Dr. Amos Salomon, geologist of the Geological Survey of Israel complained that the study and investigations were more focused on the eastern side of the Arava valley than on the western side, that the report did not address contradictions in the scientific knowledge between the scientists of the different countries and that it did not sufficiently reference the work of Israeli scientists and Israeli seismological rules. He also criticizes some conclusions taken from the Geological Survey of Israel. Finally he stated that the seismic risk in the Arava valley was not sufficiently stressed.

It is not the goal of this report to arbitrate academic discussions and differences of opinion where this has consequences on the geosciences-related hazards which could affect the proposed infrastructure works. We also note that the majority of the references which were used for this report are from authors working for Israeli scientific institutions. It is also obvious that since the works and infrastructures are overwhelming located in Jordan, the study and investigations were focused on the eastern Wadi Araba/Arava Valley. Nevertheless these comments have been addressed where appropriate and where possible in this version of the report.

ERM raised some queries related to the boring tough rock with some uranium in it and the expected high temperature in the tunnel. The responses provided have been incorporated in this version of the report.
3 INTRODUCTION

The aim of the current report is to synthesise the engineering geological framework and conditions which are relevant to the potential project works. It comprises more specifically the geological stratigraphic and structural conditions, the seismic conditions, the geomorphologic conditions and the hydrogeological conditions.

It also includes the interpretation from an engineering geological point of view, of the site specific field investigations which have been performed specifically for the infrastructure considered in the Feasibility Study. The possible works considered in the Feasibility Study include large excavations close to Aqaba, long deep tunnels, open canals, related tunnel access portals, pipelines, a large pumping station, a hydropower plant and a desalination plant. For the results of the geotechnical site investigations we refer to the factual report: “Geotechnical and Geophysical Factual Report”.

The study area is located close to the Araba transform fault, which forms part of one of the most famous geological structures in the world and has consequently been thoroughly studied. Hundreds of papers related to the geosciences of this area have been written, sometimes with contradictory conclusions. In this report it is not the intention to outline the inconsistencies or to enter into academic discussion on issues that have no consequences on the conditions pertaining to the current study and the potential project works.

The report considers successively: the geological and structural conditions from an engineering geological point of view, the seismological conditions and the hydrogeological conditions. This is followed by a more detailed review of engineering geological conditions incorporating the results of the project specific geotechnical site investigation works.

The Red Sea – Dead Sea (RSDS) Water Conveyance System would be located in the Wadi Araba / Arava Valley which extends south-north trending, over a 165 km long section between the Gulf of Aqaba / Eilat and the Dead Sea. The Wadi Araba / Arava Valley is between 5 and 15 km width and is bordered:

- On the Jordan eastern side by mountains of the Arabian Plate
- On the Israel western side by hills of the Sinai sub-plate
4 GEOLOGY

4.1 Geographical & Historical Geology

The geological history of the Middle East and surrounding areas can be subdivided into three main stages, each one characterized by a distinct tectonic regime (32. Garfunkel, Z., 1988):

- **The Late Precambrian**\(^1\) Pan African orogenic stage which corresponds to the formation of the Arabo-Nubian Shield basement. This period is characterized by a high-temperature/low-pressure metamorphism\(^2\) followed by retrograde\(^3\) metamorphism. The main orogenic activity ended with emplacement of many end-or post-kinematic plutons\(^4\), which often intrude each other. This widespread plutonic phase marks the main consolidation stage of the crust in the area and thus signifies the end of the orogenic activity proper. The swarms of dykes observed close to Aqaba on the Jordan side have been formed at this time.

- **The Early Cambrian**\(^5\) to mid-Cenozoic platformal stage. During this stage an extensive veneer of mature platformal sediments accumulated over the area in several depositional cycles that were separated by periods of significant erosion. The main event was the formation of the passive continental margin of the Levant basin in early Mesozoic times.

- **The mid-Cenozoic**\(^6\) to Recent rifting and continental breakup stage during which the area was affected by important faulting, vertical and horizontal motion and volcanism related to the breakup of the Arabo-African continent and the separation of Arabia from Africa.

The Middle-East is characterized by a complex tectonic-geological context. This region can be divided into four geotectonic units (Figure 1):

- The Arabian plate which located in the east of the region This plate is affected by major geological features
  - The North Folded border linked to compression motion
  - The South border intruded by Early Miocene dykes\(^7\) linked to the Red Sea opening.

\(^1\) More than 542 million years ago.

\(^2\) Metamorphism is the solid-state recrystallization of pre-existing rocks due to changes in physical and chemical conditions, primarily heat, pressure, and the introduction of chemically active fluids.

\(^3\) Retrograde metamorphism involves the reconstitution of a rock via revolatisation under decreasing temperatures (and usually pressures), allowing the mineral assemblages previously formed to revert to those more stable at less extreme conditions. This is a relatively uncommon process, because volatiles must be present.

\(^4\) A pluton is an intrusiveigneous rock body that crystallized from magma slowly cooling below the surface of the Earth. In practice, “pluton” usually refers to a distinctive mass of igneous rock, typically kilometers in dimension, without a tabular shape. The most common rock types in plutons are granite, granodiorite, tonalite, and quartz diorite.

\(^5\) Early Cambrian : 542 to 513 million years old.

\(^6\) ~25 million years old.
• The African plate located in the southwest of the region.

• The Sinai sub-plate located between the African and Arabian plates and extending along the Dead Sea Transform Fault (DST).

• The Eurasian plate located to the north of the region.

These units are separated by 3 major tectonic discontinuities as follows:

• The **Bitlis/Zagros Thrust fault** which is the boundary between the Eurasian plate to the north and the Arabian plate/Sinai sub-plate to the south. This fault is linked to the Anatolian Faults observed in Turkey.

• The **Red Sea Rift** fault which extends from the Indian Ocean to the Gulf of Suez. The formation of the Red Sea started during the Eocene with the opening of the 150°-trending Red Sea rift between the Arabian and African plates along a 30° direction.

• The **Dead Sea Transform Fault** which extends from the Red Sea Rift to the North Bitlis/Zagros Thrust fault. This fault accommodates sinistral motion between the Arabian plate and the Sinai sub-plate which has occurred since the Middle Miocene (20 Ma).

The DST is a fault zone with several branches that were active at different stages of the fault zone evolution (Marco, S., 2007). Possible activity of marginal faults has to be considered in particular in light of evidence for young faults that became active in the Pleistocene west of the Arava Valley (Avni, Y., Bartov, Y., Garfunkel, K. & Ginat, H.,) and in the Gulf of Aqaba (Ehrhardt, A., Hübbscher, C., Ben-Avraham, Z. & Gajeński, D., 2005&. Makovsky, Y., Wunch, A., Ariely, R., Shaked, Y., Rivlin, A., Shemesh, A., Ben-Avraham, Z. & Agnon, A., 2008). The absence of similar geomorphic analysis on the eastern margins of the Arava makes the existence of young faults there a possibility that has to be investigated.

---

7 A **dike** is an intrusion into an opening cross-cutting fissure, shouldering aside other pre-existing layers or bodies of rock; this implies that a dike is always younger than the rocks that contain it. Dikes are usually high angle to near vertical in orientation.

8 A **thrust fault** is a type of fault, in the Earth's crust across which there has been relative movement, in which rocks of lower stratigraphic position are pushed up and over higher strata. They are often recognized because they place older rocks above younger. Thrust faults are the result of compressional forces.

9 A **rift** is a place where the Earth's crust and lithosphere are being pulled apart and in relation of extensional tectonics.

10 A **transform fault** is a fault which runs along the boundary of a tectonic plate. The relative motion of such plates is horizontal in either sinistral or dextral direction. Some vertical motion may also exist, but the principal vectors in a transform fault are oriented horizontally.
4.2 Dead Sea Transform (DST) – Arava Valley

The Wadi Araba/Arava Valley is the consequence of a change in tectonic regime in Mid-Tertiary times as the region was affected by rifting and continental breakup. This manifested itself in three ways (Garfunkel, Z., 1988):

- **Rifting and associated faulting** which produced new plate boundaries in the region. The boundaries along the Red Sea and the Suez rift were already formed 25-20 Ma ago (limit Oligocene-Miocene). The motion along the DST seems to have started later, perhaps in the Middle Miocene, according to Garfunkel & Ben-Avraham (Garfunkel, Z. & Ben-Avraham, Z., 1996). Igneous activity and local subsidence along the transform suggest it started some 18 Ma ago.
• **Widespread magmatic activity** which preceded and accompanied the rifting process. This magmatic event, mainly basaltic, has produced numerous high-level intrusions (dykes, sills11, ...) and extensive volcanic fields. This activity was much more widespread to the east (Jordan) of DST than to the west (Israel) of it.

• **Uplifting** which occurred in large areas along the new plate boundaries and raised them to elevations of 500-1000m and more above sea level. Uplifting was greatest around the Red Sea and most of it occurred during the Miocene, concurrently with plate separation, while in Israel the main uplifting is probably somewhat younger.

The new plate boundaries accommodated the separation between the Arabian and African plates. The Red Sea rift fault is essentially an extensional plate boundary. However, the DST has a very different trend which is almost parallel to the direction of the plate separation, with the motion being mainly lateral. The offset of rock bodies and structures shows a left lateral motion amounting to about 105-112 km but a small part of the motion was taken up by the Suez Rift.

This total amount of 105-112 km left-lateral motion along the DST is demonstrated by:

• Matching the sedimentary cover on both sides of the transform fault (BARTOV, Y., 1974; QUENNELL, A.M., 1958 & QUENNELL, A.M., 1959).

• Matching the lineaments of the central Negev-Sinai shear belt (Figure 2.1) which has yielded the most accurate value (BARTOV, Y., 1974 & QUENNELL, A.M., 1959).

• Further evidence from magnetic anomaly patterns across the transform (HATCHER, R.D., ZEIZ, I., REAGAN, R.D. & ABU-AMIS, M., 1981). However, across the northern segment of the DST ophiolite nappes, thrust onto the edge of the Arabian platform in the Late Cretaceous, are offset by just 80 km. Garfunkel explains this difference by the non-rigidity of the lands bordering that segment of the transform (GARFUNKEL, Z., ZAK, I. & FREUND, R., 1981).

Whereas the total slip, from the beginning of the DST formation is known, there are different motion velocity versus time is not well determined. Magnetic anomalies suggest an opening of the Red Sea of 75 km in the last 5 Ma, which is only a fraction of the total amount (GARFUNKEL, Z., BEN-AVRAHAM, Z. 2001 and the opening seems to have accelerated in the Middle or Late Miocene (LEPICHON, X. & GAULIER, J.M., 1988). These observations lead to a slip along the DST of about 40 km or less in the last 5 Ma (Plio-Pleistocene) which equates to 8km/Ma and thus most of the offset occurred earlier (JOFFE, S. & Garfunkel, Z., 1987) but approximately at the same rate 70 km/13Ma or 5.4 km/Ma. From Miocene to recent times, another phase of igneous activity produced mainly volcanic fields consisting of basalts (Figure 2) but on a regional scale, there is no proven relation between their extent and the DST (GARFUNKEL, Z., 1997).

---

11 A sill is a tabular pluton that has intruded between older layers of sedimentary rock or between beds of volcanic lava or tuff, this means that the sill does not cut across preexisting rocks, in contrast to dikes, which do cut across older rocks.
The morphology and internal structure of the DST resulted from its somewhat irregular shape. Along a large segment, which includes the Gulf of Aqaba / Eilat, Wadi Araba / Arava Arava Valley, Dead Sea and Jordan Valley, the predominantly lateral motion was associated with a small component of transverse separation. This produced the prominent structurally controlled transform valley which includes several basins that have depths in excess of 5-7 km (e.g. the Dead Sea and the Gulf of Aqaba) which are separated by narrower and shallower saddles (e.g. Gharandal saddle).

These basins, as well as the narrow Arava and Jordan Valleys, (Figure 3) are bounded by normal faults, which is typical of an extensional rift structure (KEAREY, P. & VINE, F.J., 1995). However, the presence of major strike-slip faults clearly demonstrates and confirms the transform character of the DST. Between the Gulf of Aqaba/Eilat and the Dead Sea the Arava Fault (AF) constitutes the major branch of the DST and takes up most of the slip.
At the very beginning of the Pliocene\textsuperscript{12} the renewed flooding\textsuperscript{13} of the Mediterranean produced a narrow bay that extended through the Yizreel Valley into the Jordan-Dead Sea-Arava Valley. The transform valley was filled by a thick marly and evaporitic series, consisting mainly by halite. The evaporate-rich series reached a thickness of a few kilometres in the Dead Sea basin. Continuing tectonic movements broke the connection between the transform valley and the sea. After that only lacustrine\textsuperscript{14} and fluvial, predominantly clastic\textsuperscript{15}, sediments continued to accumulate in the transform valley.

During the Late Pliocene the pattern of tectonic movements did not change and the same clastic sedimentation process continued (Garfunkel, Z., Zak, I. & Freund, R., 1981).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Structural relations between Dead Sea Transform and Pull-Apart structures (Garfunkel, Z., 1988).}
\end{figure}

\textsuperscript{12} From 5.3 million to 2.5 million years before present.

\textsuperscript{13} Following the Messinian salinity crisis during which the Mediterranean sea have been dried up.

\textsuperscript{14} Relating to a lake.

\textsuperscript{15} Clastic sedimentary rocks, were formed from rocks that have been broken down into fragments by weathering, which then have been transported and deposited elsewhere.
4.3 Stress fields versus time

The structural analysis, as part of the geological mapping, aims to identify the main trends of weakness zones, the kinematics and the relation to the main stress field. The objective is to identify fractures (faults, joints and lineaments), set trends in this case within the sedimentary deposits and granite rocks and to determine the structural effects of the Dead Sea Transform and rift formation in the project area. Paleostress analysis helps to define the geodynamic evolution of the project area and to determine whether some faults have been reactivated in the past and / or in recent times by comparing their mean trends with the trend of the regional stress field.

Analysis of fault kinematics for the reconstruction of past and present tectonic stresses is routinely done in neotectonic investigations. The standard procedures for brittle fault-slip data analysis and stress tensor determination are described by e.g. Angelier (1994), Dunne and Hancock (1994). A comprehensive description of the stress analysis methodology applied is given by Delvaux et al (1997) and Delvaux & Sperner (2003). Paleostress stages have been determined along the Arava valley by Eldeen et al. (2003). These paleostress directions are:

- **T1a**: NE-SW ($S_{H_{\text{max}}}$), defined from NE-SW late Neoproterozoic dykes;
- **T1b**: NE-SW ($S_{H_{\text{max}}}$) transtensional stress regime;
- **T2a**: N-S ($S_{H_{\text{max}}}$), defined from N-S late Neoproterozoic dykes;
- **T2b**: N-S ($S_{H_{\text{max}}}$) transpressional stress regime (only in Neoproterozoic basement);
- **T3**: E-W ($S_{H_{\text{max}}}$) strike – slip stress regime;
- **T4**: NW-SE ($S_{H_{\text{max}}}$) strike – slip stress regime;
- **T5**: N-S ($S_{H_{\text{max}}}$) transpressional stress regime;
- **T6**: E-W ($S_{H_{\text{min}}}$) extensional stress regime;
- **T7**: N-S ($S_{H_{\text{min}}}$) extensional stress regime;
- **T8**: related to Wadi Araba fault and DSS field which still active (NW-SE ($S_{H_{\text{max}}}$) (data provided from the World Stress Map, Muller et al, 1997; see also Heidbach, et al. 2008).

Time constrains for these paleostress T1 to T7 directions in the DST region are given in table below.
Summary of the time constraints for the determined paleostress directions in the Dead Sea Rift regions (reprinted after Zain Eldeen et al. 2002):

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Holocene (present-day stress field)</td>
<td>NW-SE $S_{\text{max}}$</td>
<td>ESE-WNW $S_{\text{max}}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post Pleistocene</td>
<td>T7: E-W $S_{\text{max}}$</td>
<td>T6: N-S $S_{\text{max}}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miocene /Pleistocene (DSS)</td>
<td>T5: NW-SSE to N-S $S_{\text{max}}$</td>
<td>NW-SSE to N-S $S_{\text{max}}$</td>
<td>NNW-SSE to N-S $S_{\text{max}}$</td>
<td>NNW-SSE to N-S $S_{\text{max}}$</td>
</tr>
<tr>
<td>Miocene (DSS)</td>
<td>T4: NW-SE $S_{\text{max}}$</td>
<td>NW-SE $S_{\text{max}}$</td>
<td>NW-SE $S_{\text{max}}$</td>
<td></td>
</tr>
<tr>
<td>Late Cretaceous (SAS)</td>
<td>T3: E-W $S_{\text{max}}$</td>
<td>E-W to ESE – WNW $S_{\text{max}}$</td>
<td>ESE-WNW $S_{\text{max}}$</td>
<td>E-W to ESE-WNW $S_{\text{max}}$</td>
</tr>
<tr>
<td>Late Neoproterozoic</td>
<td>T2: N-S $S_{\text{max}}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T1: NE-SW $S_{\text{max}}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It is important to emphasise that it is during the Neoproerozoic time that the stress field was the most important, inferring that the Proterozoic granite is strongly fissured in comparison to the Cretaceous formations. It affects the geomechanical properties of the granite, monzogranite, diorite ... and enhances (relatively permeable) its hydraulic properties.

4.4 Rock properties

As a result of the Arava strike-slip fault motion (Figure 4), the geological formations on both sides of the Wadi Araba / Arava Valley are completely different. Indeed, as described previously the offset of the rock bodies and structures shows a sinistral movement (or left lateral) measured to about 105 km (Figure 5).

---

Movement of strike-slip faults that offsets rocks can be described as dextral or sinistral. If the fault block across the fault has moved to the right, the motion is dextral. If it has moved left, it is sinistral.
Figure 4: Simplified drawing about sinistral and dextral motion along a strike-slip fault

Figure 5: Simplified geological map of both sides of the Arava valley, crystalline rock in red colour, sedimentary in green colour.

Crystalline (metamorphic and intrusive) rocks of Precambrian age are found on the east side for 60 km in the southern part of the rift valley. They typically consist of granite, granodiorite, monzonite, diorite and gabbro (Figure 6). They are cross-cut with impressive and abundant thick dykes. The composition of the dykes can be broadly subdivided into four major types: basalt, dolerite, andesite and trachyte (Figure 6). These formations have as a rule strong matrix geomechanical properties. The greater the quartz content the better these properties will be but on the other hand they are less ductile and consequently more fragile. The abrasivity also dramatically increases with the quartz content. The
The geomechanical properties of the rock body are dependent not only on the rock matrix properties but more significantly by the prevailing joint pattern. The crystalline rock massif is intensively jointed, the main joints or fractures have been filled during the Proterozoic time (Precambrian) with dykes. The main joint directions are: NNE, NNW, NW, NE and EW. This corresponds well to the observed lineaments. Mylonites are found locally at strike slip-faults. Mylonite is a deformed rock generated by the accumulation of large shear strain in ductile fault zones. There are many different theories regarding the formation of mylonites but it is generally agreed that crystal-plastic deformation must have occurred, and that fracturing and cataclastic flow are secondary processes in the formation of mylonites. Consequently mylonites generally develop in ductile shear zones where high rates of strain are focused. They are the deep counterparts of cataclastic brittle faults that create fault breccias giving crushed crystalline rock. The properties of mylonites are expected to be poor and that of cataclasts to be extremely poor possible comprising un cemented powder.

![Diagram of mineralogical composition](image)

**Figure 6:** Approximate mineralogical compositions of the more common types of igneous rocks.

Primary\(^{17}\), Secondary\(^{18}\) and Tertiary\(^{19}\) deposits are found above the crystalline basement rock from 60 km north of Aqaba to the Dead Sea. The Secondary is constituted mainly of sandstone, poorly cemented with cross bedded structures. Other rocks are dolomite\(^{20}\), limestone, marl and clay (Table 1).

---

\(^{17}\) Primary or Paleozoic era: 542 Ma - 251 Ma ago.

\(^{18}\) Secondary or Mesozoic era extended roughly 180 million years: from 251 million years ago to 65 Ma, when the Cenozoic era began.

\(^{19}\) Tertiary: 65 to 2.6 Million years ago.

\(^{20}\) Dolomite is the name of a sedimentary carbonate rock composed of calciummagnesiumcarbonateCaMg(CO\(_3\))\(_2\).
Table 1: Jordan Lithostratigraphic column

<table>
<thead>
<tr>
<th>Era</th>
<th>Symbol</th>
<th>Lithology (Jordan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td>AL</td>
<td>Alluvium undifferentiated</td>
</tr>
<tr>
<td></td>
<td>ALF</td>
<td>Alluvium (fan)</td>
</tr>
<tr>
<td></td>
<td>ALO</td>
<td>Early Holocene Alluvium Sediments</td>
</tr>
<tr>
<td></td>
<td>ALS</td>
<td>Aeolian Sand</td>
</tr>
<tr>
<td></td>
<td>ALM</td>
<td>Alluvial mudstone</td>
</tr>
<tr>
<td></td>
<td>PLG</td>
<td>Pleistocene Fluviatile gravels</td>
</tr>
<tr>
<td></td>
<td>PLF</td>
<td>Pleistocene Alluvial Fan</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>Pleistocene gravels</td>
</tr>
<tr>
<td></td>
<td>LM</td>
<td>Lisan Marl</td>
</tr>
<tr>
<td>Cenozoic</td>
<td>DC</td>
<td>Dana Conglomerate</td>
</tr>
<tr>
<td></td>
<td>URC</td>
<td>Umm Rim Ret Chert Limestone</td>
</tr>
<tr>
<td></td>
<td>MCM</td>
<td>Mus aqmar Chalk-Marl</td>
</tr>
<tr>
<td>Mesozoic</td>
<td>ASL/AHP</td>
<td>Amman Silifed Limestone / A/Hea Phosphorite</td>
</tr>
<tr>
<td></td>
<td>WG</td>
<td>Wadi Urm Ghudran</td>
</tr>
<tr>
<td></td>
<td>WSL</td>
<td>Wadi Aa Sir Limestone</td>
</tr>
<tr>
<td></td>
<td>FHVS</td>
<td>Fuhays-Hummar-Shu‘ayb</td>
</tr>
<tr>
<td></td>
<td>NL</td>
<td>Nu‘r Limestone</td>
</tr>
<tr>
<td>Paleozoic</td>
<td>KS</td>
<td>Kurnub Sandstone</td>
</tr>
<tr>
<td></td>
<td>DI</td>
<td>Dii Sandstone</td>
</tr>
<tr>
<td></td>
<td>IN</td>
<td>Umm Isrin Sandstone</td>
</tr>
<tr>
<td></td>
<td>BDS</td>
<td>Burj Dolomite - Slate (Undivided)</td>
</tr>
<tr>
<td></td>
<td>AK</td>
<td>Abu Khushayba Sandstone</td>
</tr>
<tr>
<td></td>
<td>SB</td>
<td>Salib Arkosic Sandstone</td>
</tr>
<tr>
<td>Precambrian</td>
<td>AM</td>
<td>Ahaymer Volcanic (Undifferentiated)</td>
</tr>
<tr>
<td></td>
<td>BA</td>
<td>AlBayda Quartz-Feldspar Porphyry (AM Suite)</td>
</tr>
<tr>
<td></td>
<td>QB</td>
<td>Quasyb Rhyolite (AM Suite)</td>
</tr>
<tr>
<td></td>
<td>FN</td>
<td>Fidan Syenogranite</td>
</tr>
<tr>
<td></td>
<td>HV</td>
<td>Hayylla Volcaniclastic</td>
</tr>
<tr>
<td></td>
<td>HT</td>
<td>Humrat Granite</td>
</tr>
<tr>
<td></td>
<td>AJ</td>
<td>Abu Jadda Granite</td>
</tr>
<tr>
<td></td>
<td>MM</td>
<td>Minhar Monzogranite</td>
</tr>
<tr>
<td></td>
<td>MN</td>
<td>Mulghan Monzogranite</td>
</tr>
<tr>
<td></td>
<td>U</td>
<td>Uff. Porphyric</td>
</tr>
<tr>
<td></td>
<td>HK</td>
<td>Hunayk Monzogranite - Uff Porphyric</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>Sabil Granodiorite</td>
</tr>
<tr>
<td></td>
<td>MU</td>
<td>Muha sid Quartz Diorite</td>
</tr>
<tr>
<td></td>
<td>HR</td>
<td>Huw ar h w-o-mica Granite</td>
</tr>
<tr>
<td></td>
<td>TH</td>
<td>Tabia Monzogranite</td>
</tr>
<tr>
<td></td>
<td>UA</td>
<td>Umm Saliya Granite</td>
</tr>
<tr>
<td></td>
<td>TN</td>
<td>Turban Granodiorite</td>
</tr>
<tr>
<td></td>
<td>RR</td>
<td>Abu Radmar Granodiorite</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>Dubheia Hornblendic</td>
</tr>
<tr>
<td></td>
<td>BT</td>
<td>Buseinat Gneiss Suite</td>
</tr>
<tr>
<td></td>
<td>AB</td>
<td>Abu Barqa Metasedimentary Suite</td>
</tr>
</tbody>
</table>

Their geomechanical properties are also dependent on the joint pattern affecting them. The joint directions are mainly NE and NS and they are vertical. NS joints are mostly open. Consequently the rock massif properties as inferred from the Bienawsky method are poor to fair. Previous investigations have highlighted the presence of U-enrichment in Cambrian sediments above the granitic basement. The mineralization is located in marine shales of Cambrian Burj Formation (Table 1). Uranium comes from the granitic basement. Indeed, uraninite crystals have been observed in the 200 m deep borehole drilled in Wadi Faddan. A few ancient Copper and Manganese mines are observed just 1 km to the north of Wadi Faddan.
Quaternary\(^21\) deposits are mainly located in the Arava Valley and close to alluvial outwash fans from the side wadis. Various facies\(^22\) of unsorted to sorted alluvium occur extensively in the Wadi Araba / Arava Valley: boulders, gravels, sand and clay with all intermediate facies. The most common is Aeolian sand (Als on the geological map), active Wadi sediments (Al), fine pelitic sediments forming mud flats (Alm) and also Pleistocene\(^23\) facies including gravels (Plg) and sand (Pls). Lisan marls occur in the northern part of the conveyance close to the hydropower plant area. SPT\(^24\) results in the Arava valley, close to the Gulf of Aqaba show low corrected N-Values (5 to 15) which indicate a potential risk of liquefaction. The most common facies here are silt and clay with sand beds and large scattered crystalline gypsum grains.

\(^{21}\) 2.6 Mia ago to present time.

\(^{22}\) Facies is a body of rock with specified characteristics, de facto a distinctive rock unit that forms under certain conditions of sedimentation.

\(^{23}\) The Pleistocene from 2.588 million to 12 000 years BP covering the world’s recent period of repeated glaciations.

\(^{24}\) Standard penetration test.
5 SEISMICITY

The seismicity of the study area is ruled by the Dead Sea Transform (DST), which is a prominent shear zone in the Middle East. As explained in paragraph 4.2, it separates the Arabian plate from the Sinai microplate, an appendage of the African plate, and stretches from the Red Sea rift in the south via the Dead Sea to the Taurus-Zagros collision zone in the north (Figure 1). Formed in the Miocene 16 Ma ago and related to the breakup of the Afro-Arabian continent, the DST accommodates the sinistral movement between the two plates (Freund, R., Garfunkel, Z., Zak, I., Goldberg, M., Weissbrod, T. & Derin, B., 1970&. Garfunkel, Z., 1981). The Wadi Araba / Arava Valley is the consequence of a major left-lateral strike-slip fault that accommodates the relative motion between the African plate and the Arabian shield. This is an “en echelon” fault with extensional jogs and associated pull-apart basins like the Dead Sea. A fraction of the global motion has been transferred to the Suez rift which separates the Sinai sub-plate from the rest of Africa.

The western margin of the Dead Sea basin is governed by a bimodal distribution of fault strikes, which form an orthorhombic pattern of zigzagging rift walls as conspicuously observed on the field (NS and EW strikes at the Dead Sea). The main observed faults and main inferred faults are shown on satellite images (Figure 7).

---

25 Describing parallel or subparallel, closely-spaced, overlapping or step-like minor structural features in rock, such as faults and tension cracks, those are oblique to the overall structural trend.
Figure 7: Tectonic settings of the Arava valley. DEM image from Hall (1994) with fault interpreted from satellite images and fieldwork.

The major DST strike-slip fault corresponds to an association of two faults, highlighted on the geological map (1:50 000 scale):

- The Arava fault(AF) with the mean lateral slip rate (4 ± 2 mm/year),

- The Aqaba-Gharandal fault, mainly observed near the Red Sea, is a normal fault with a strike component at a moderate slip rate (1 mm/year).

5.1 **Seismicity – Objectives**

The objective of the present analysis is not only to determine the potential surface movement at the fault during one event but also the levels of seismic risk at the proposed site locations for the various planned works and their alternatives, using a Probabilistic Seismic Hazard Analysis (PSHA). These levels are determined for 475 years (i.e. Operating-Basis Earthquake-OBE) return periods.
A PSHA has been carried out using the most recent earthquake catalogue of both historical and instrumentally recorded events (Figure 8 & Figure 9). We refer to the studies performed (Swiss Agency for Development and Cooperation (SDC), 2009; UNESCO, 2006) in that field, which employed well known international attenuation equations. The determined PGA is based on a return period of approximately 475 years (OBE) representing a probability of exceedance of 10% with 50 years exposure time.

5.2 Historical Seismicity

Historically, this 160 km-long fault has produced only a few large-magnitude earthquakes. The largest well-documented events occurred in AD 1068, 1212, 1293 and 1458 (Figure 8 & Figure 9). Other maps exist with some additional earthquakes with no impact on the seismicity assessment.

![Figure 8: Instrumental Earthquakes (Ms ≥ 4) of the Dead Sea Transform region for the period 1900-2009. Malkawi, A.I.H., Numayr, K.S. & Barakat, S., 1999 & Jordan Seismological Observatory)](image)

---

26 The Richter magnitude scale, also known as the local magnitude (ML) scale, assigns a single number to quantify the amount of seismic energy released by an earthquake. It is a base-10 logarithmic scale obtained by calculating the logarithm of the combined horizontal amplitude of the largest displacement from zero on a torsion seismometer output. So, for example, an earthquake that measures 6.0 on the Richter scale has a shaking amplitude 10 times larger than one that measures 5.0. Though still widely used, the Richter scale has been superseded by the moment magnitude scale, which gives generally similar values.

The moment magnitude scale (abbreviated as MMS; denoted as $M_w$) is used by seismologists to measure the size of earthquakes in terms of the energy released. It is based on the moment of the earthquake, which is equal to the rigidity of the Earth multiplied by the average amount of slip on the fault and the size of the area that slipped. The scale was developed in the 1970s to succeed the 1930s-era Richter magnitude scale ($M_r$). The MMS is now the scale used to estimate magnitudes for all modern large earthquakes.
The striking example of the left-lateral motion is the offset wall at the water tank at the Tilah castle site (Figure 10). We can consider that, since the wall was built, the fault must have slipped by at least 1.7 m and possibly as much as 2.7 m for a final slip estimate of 2.2 ± 0.5 m.

Amit (Amit, R., Zilberman, E., Enzel, Y., Porat, N., 2002) concluded from a study in the Eilat region (southern Arava Valley), that during the late Pleistocene, M6.7-M7 earthquakes displaced the surface by 1-1.5 m, and their average recurrence interval was 2800±700 years. In the Holocene, more frequent earthquakes (recurrence1200±300 years) were of smaller magnitudes (ML 5.9-ML 6.7), and displaced the surface by 0.2-1.3 m.
Based on historic evidence for the last 2000 years and an extrapolation of instrumental data of the last 100 years, and supported by the geological record for the last 40,000 years, Begin (Begin, Z., 2005) suggests that the mean recurrence interval of Mw>7-7.3 is ≈10,000 years for the Dead Sea area. Many seismologists (Salomon in its comment) believe the mean recurrence interval is much lower and could be of the order of 1000 year. Based on the assessment of the recurrence intervals, Begin (Begin, Z., 2005) suggested that the best estimate for the 50 year probability of occurrence for an earthquake of Mw>7, which may cause substantial damage is 1.7%. The corresponding 500 years probability is 15.8%. Therefore the authors use a probabilistic hazard assessment. It is commonly based on the assumption of Gutenberg-Richter (Poissonian) distribution of the earthquake magnitudes in the region. While this behaviour model may be correct, it has no memory and does not account for the actual slip history of the fault. Considering nearly a whole millennium with no significant earthquake according to Amit et al. (Amit, R., Zilberman, E., Porat, N., Enzel, Y., 1999) and Zilberman et al. (Zilberman, E., Amit, R., Porat, N., Enzel, Y. & Avner, U., 2005), and assuming the historic records are complete, substantial amount of stress has accumulated and the Arava is possibly ‘ripe’ for a major earthquake. Most of seismologists and structural geologists (oral communication of Begin 2009) confirm there is a deficit in seismicity. Many of the recent destructive earthquakes in the world filled “seismic gaps” (i.e., ruptured segments of faults that have not slipped in an unusually long time when compared with other segments along the same fault). The hazard map that shows the Arava and the least hazardous (Fig. 18) would be misleading if the “seismic gap” approach were taken. A simple way for calculating the slip deficit is presented by Garfunkel et al. (Garfunkel, Z., 1981). The assessment of the deficit is repeated with additional data by Salomon et al. (Salomon, A., Hofstetter, A., Garfunkel, Z. & Ron, H., 2003; Salomon, A., Hofstetter, A., Garfunkel, Z. & Ron, H., 1996) and Le Beon et al. (Le Beon, M., Klenger, Y., Amrat, A., Agnon, A., Dorbath, L., Baer, G., Ruegg, J.C., Charade, O. & Mayyas, O., 2008; Le Beon, M., Klenger, Y., Agnon, A., Dorbath, L., Baer, G., Meriaux, A.-S., Ruegg, J.-C., Charade, O., Finkel, R. & Ryerson, F., 2006).

According to the deficit in earthquake the 50 year probability of occurrence for an earthquake (Mw>7) and the 500 year probability are significantly higher than the calculated according the Poisson distribution law with “no memory”.

It is worth noting that Meghraoui et al. (Meghraoui, M., Gomez, F., Sbeinati, R., Van der Woerd, J., Mouty, M., Darkal, A., Radwan, Y., Layyous, I., Najjar, H.M., Darawcheh, R., Hiazi, F., Al-Ghazzi, R. & Barazangi, M., 2003) indicate that in the northern part of the DST a 6.8-7.0 mm/yrslip rate at depth would accumulate a slip deficit of 5.6-5.8 m on the locked upperpart of the fault, which exceeds the average estimated past coseismic movement. This implies that a large earthquake significantly larger than Mw>7 along the DST could occur and would induce severe damage to the region. Also Klenger et al. (Klenger, Y., Avonac, J.P., Abou Karaki, N., Dorbath, L., Bourles, D. & Reyss, J.L., 2000) from his geomorphologic observations does not exclude the possibility of larger Mw ≈7.6 earthquakes about every 6000 years and Mw 7 earthquakes about every 250 years. In any case the seismic behaviour of the northern DST involves long periods of seismic quiescence punctuated by infrequent large earthquakes, we refer to the three events interpreted as having occurred between AD 70 and 1170 (1100 year) followed by about 830 year without a major earthquake.
5.3 Seismic Hazard mapping

A seismic hazard model has been developed by the Royal Scientific Society of Jordan. This model is based on geology, the local and regional tectonic features and historical and instrumental seismic data. The final seismic source model (Jimenez, M.J., 2004) defines 18 seismogenic sources and, at least with respect to the project area under consideration, it is similar to the source model that was proposed in the UNESCO report in 2006 (Figure 11). The latter has the advantage of being accepted by the countries of the region (Jordan, Israel, Egypt, Saudi Arabia and Syria).

Figure 11: Seismic source model consisting of seismogenic sources (UNESCO 2006)
5.4 Late Quaternary Seismicity of the Southern Arava


Twenty different paleo-earthquakes have been reported between 0.045 and 0.001 Ma B.P. in the southern Arava segment (Amit, R., Zilberman, E., Enzel, Y., Porat, N., 2002). The cumulative normal slip versus time that was calculated from these events, shows that a constant slip rate of 0.5 mm/year can account for the total normal slip. This slip rate suggests that normal faulting is only about 10% of the total strike-slip motion in the last 45000 years (Salomon, A., Hofstetter, A., Garfunkel, Z. & Ron, H., 2003).

The studied fault zone may be subdivided into three subzones:

- Two marginal subzones (in white on Figure 12) located to the east and west of the central subzone. These areas are characterized by normal faults that trend northwest and north-northeast on both sides of the rift valley (Nahal Shehoret on the west, the other on the east, not yet investigated).

- A central subzone (in yellow on Figure 12), 5 km wide and characterized by sinistral faults expressed by push-ups and pull-aparts (Avrona Playa).

We also consider separately the Gulf of Aqaba.

![Figure 12: Morphological and morphotectonic map of the southern Arava valley with trenches, fault lines and seismic lines location.](image-url)
5.4.1 The marginal fault zone – Nahal Shehoret

The Israeli alluvial fan of Nahal Shehoret is dissected by sub-parallel normal faults arranged in a domino structure. The displaced alluvial surfaces are of Holocene and Pleistocene ages.

Eight trenches were excavated from west to east across several fault scarps in this zone. To the west, faults displace alluvial surfaces of Middle Pleistocene age and to the east, faults displace Upper Pleistocene and Holocene alluvial surfaces and Holocene playa deposits.

The total vertical displacements on these normal faults range from 0.5 m (trench T-15) to 7.5 m (trench T-6; Figure 13). Two types of faults are observed (Amit, R., Enzel, Y., Naomi, P., Hamiel, Y. & Zilberman, E., 2009):

- Older faults (exposed in trench T-8), typically multi-event faults, NNW oriented having been active since 0.080 Myr.
- Younger single-event type faults exposed in trenches T-5, T-6 (Figure 13), T-16 and T-17 (Figure 14).

![Figure 13: Log of the southern wall of trench T-6](image-url)
In conclusion, the westernmost part of the marginal fault zone was active until 0.080 Ma. A second set of faults was active between 0.037 and 0.005 Ma, during the late Pleistocene and the Middle Holocene (trench T-6; Figure 13). A clear trend showing a decrease with time in the amount of displacement is evident across this fault zone. An important observation is that the amount of displacement and the number of faulting events vary along a single fault trace (AMIT, R., ENZEL, Y., NAOMI, P., HAMIEL, Y. & ZILBERMAN, E., 2009).

5.4.2 The central fault zone – Avrona Playa

The central part is characterized by extension and compression structural features, such as grabens and push-up ridges. Flower structures typical of strike-slip faults are clearly defined in the subsurface (Figure 15).
Two environments were chosen for paleoseismic analysis. One is a Holocene alluvial fan of Nahal Shehoret (to distinguish from the marginal zone with the same denomination and previously considered) that is crossed by a graben structure (Figure 16). The other, located to the east, is the Avrona playa, across which push-ups, pull-aparts and normal faults occur (Figure 12). The analysis of paleoseismic trenches in the Avrona playa area concludes that at least six surface rupture have affected this area during the last 14000 years.
5.4.3 Golf of Aqaba

From a seismological point of view, the Gulf of Aqaba behaves differently; it is the link between the Red Sea and the DST of Jordan. Garfunkel (Garfunkel, Z. & Bartov, Y., 1977&. Ben-Avraham, Z., 1985) suggested that the Gulf of Aqaba is a transition between crustal spreading of the Red Sea and rifting without spreading of the DST. Eyal et al. (Eyal, M., Eyal, P., Bartov, Y. & Steinitz, G., 1981) studied the western margin of the Gulf of Aqaba (eastern Sinai) and they found a wide belt of strike-slip faults running more or less parallel to the Gulf with a left-lateral combined horizontal displacement of 24 km. They suggested a similar amount of horizontal movement on the eastern margin of the Gulf. In conclusion, the Gulf of Aqaba is regarded as a transition area between the divergent Red Sea and the DST. The region has been submitted recently to three earthquake swarms.

5.4.4 Conclusions

In accordance to previous studies in the southern part of Arava valley, Late Pleistocene sediments have been affected by M6.7-M7 earthquakes which have displaced the surface by 1 to 1.5 m with an average recurrence interval of 2800±700 years.

The Holocene sediments have been affected by more frequent earthquakes (recurrence 1200±300 years) but with smaller magnitudes (M5.9-M6.7), and displacements of about 0.2 to 1.3 m.

Based on historic evidence for the last 2000 years and an extrapolation of instrumental data from the last 100 years, and supported by the geological record for the last 40,000 years, the mean recurrence interval of Mw>7-7.3 is about 10,000 years for the Dead Sea. Based on the assessment of the recurrence intervals, the best estimate for the 50 years probability of occurrence for a destructive earthquake (Mw>7) is 1.7%. The corresponding 500 year probability is 15.8% (Begin, Z.B., 2005).

5.5 PGA (Peak Ground Acceleration) and spectral analysis

Instrumented data has become available from the beginning of the 20th century; hazard information of earlier earthquakes is given in terms of seismic intensities, which are not easily convertible to useful engineering parameters, such as response spectral values. The available catalogues (Ben-Menahem, A., 1991&. Amiran, D.H.K., Arie, E. & Turcotte, T., 1994) with the inferred estimates of the earthquakes magnitudes and hypocentral locations, the available instrumental data (Geophysical Institute of Israel online earthquake catalogue from 1900 to present) and magnitude-recurrence relations and appropriate attenuation model, can be used, by applying probabilistic seismic hazard analysis procedures, to obtain seismic hazard maps. Hazard analyses have been carried out in different ways by different authors, but for the purposes of the Feasibility Study, reference is made to the UNESCO document in which two PGA seismic hazard maps for generic rock have been produced, one based on the Ambraeyes (Ambraeyes, N.N., Douglas, J., Sarma, S.K. & Smitt, P.M., 2005) peakground acceleration attenuation relationship and the other based on Boore’s (Boore, D.M., Joyner, W.B. & Fumal, T.E., 1997) attenuation laws. Results of Ambraeyes are given in Figure 17.
“This seismic hazard mass has been preferred because resulting from the agreement between the different countries of the area. It looks this map, at least for the Arava Valley, doesn’t take into consideration the deficit in earthquakes that is observed. The corresponding accelerations may be higher”.

The computations have been carried out for PGA at a 10% probability of exceedance in 50 years. This probability corresponds to a return period of 475 years.

Figure 17: Seismic hazard map for the Levant region using Ambraseys et al. (1996) peak ground acceleration attenuation relationship. PGA is assessed for a 10% probability of exceedance in 50 years and for Generic rocks.
We prefer at the feasibility stage to consider Ambrasey’s attenuation laws.

The PGA is almost constant with a value of 0.17 g near the Arava strike-slip fault inside the Arava valley. At the Arava valley ends, close to the Dead Sea and close to Aqaba and on the Aqaba Gulf coast, it reaches 0.25 g.

This hazard is mainly contributed by magnitude 6.0-6.5 earthquakes. Evidently as mentioned above, larger earthquakes (M>7) may occur in the region, once in 1000 to 6000 years on average (Shapira, A., 1979) or once in 10000 year (Begin, Z.B., 2005), depending on the seismogenic zone as previously described. For performance based design more frequent events have to be designed for (serviceability limit states), so the fault zone may act as a wave guide, a trap of seismic energy. This phenomenon is predicted by theory and detected in field experiments (Gottschämmmer, E., Wenzel, F., Wust-Bloch, H. & Ben-Avraham, Z., 2002; Haberland, C., Agnon, A., EL-Kelani, R., Maercklin, N., Qabbani, I., Rümpker, G., Ryberg, T., Scherbaum, F. & Weber, M., 2003; Shtivelman, V., Marco, S., Reshef, M., Agnon, A. & Hamiel, Y., 2005; Wust-Bloch, G.H., 2002). The sectors of the conveyor within the Arava Valley are susceptible to increased amplitudes and vibrate longer time, hence increasing potential damage.

Since the instrumental data required for spectral characterization is not available the shape of the response spectra has to be inferred from foreign seismic areas.

This has been carried out by SDC (Swiss Agency for Development and Cooperation (SDC), 2009) together with the Royal society of Science. To obtain the spectral characterisation, it is required to obtain the thickness of the loose rock formations above the hard bed-rock, the shear wave’s velocity of these formations and a real earthquake spectrum. Therefore the authors performed a reflection seismic survey in the Aqaba area going from the Arava valley, north of Aqaba to the border with Saudi Arabia in the south. From this survey they acquired the thickness and the related shear wave’s velocities of the loose rock or less indurate formations for the various geological configurations of the investigated area. Real earthquake spectrum have been used, they are the spectra of Romania, Greece and Turkey, which, of the available spectra, are the most representative of the area under consideration. To obtain the final spectral responses, commonly used codes such as Eurocode EC8, SHAKE 2000 and 000155 have been used. It should be noted that the response spectra take into consideration the basin effect. The spectral response for the Aqaba areas is given on Figure 18 & Figure 19.
Figure 18: Spectral response zonation map in the North of Aqaba
Figure 19: Spectral response zonation map in the South of Aqaba close to Eastern Water Intake

Arava fault location accuracy, fault unicity.

The DST is a fault complex of which the Arava fault is the most active, but is not the unique active, fault. Other questions relevant to the works of the project are:

- Is its location accurately known throughout the project area?
- Are there indications that the AF could be separated into several branches?

The DST has been investigated in several places with reflection seismic surveys and paleoseismic trenches and by satellite views, aerial photography’s, gravimetric, magnetic survey and geomorphologic features.
Based on a major collective work (68 authors; WEBER, M. ET al., 2009), after a significant seismic reflection survey could enhance the knowledge of the DST complex. It could be shown that on the major part of the Wadi Araba / Arava Valley, the active Arava fault is probably unique without branching. However several subsidiary faults run parallel to the active Arava fault (Figure 20) they are:

- **A fossil, and now inactive, Arava Fault** (AF) occurs one km to the east of the active Arava fault.

- **Al Quwayra fault** (AQF) occurs 9km to the east of the active Arava fault.

- **The Western fault** (WF) and **the Eastern fault** (EF) are located 4 km and 9 km respectively to the west of the active AF and both are now considered inactive.

- **The Zolar fault** (ZF) and **the Barak fault** (BF) can be observed to the west of the main Arava fault and belong to the dominant active faults.

![Figure 20: Dead Sea Transform location in Central Arava](image)

On the other hand, to the north and close to the Dead Sea, there are conflicting interpretations regarding the location of the Arava fault and a single unique location has not been established.

When the trace is unique its location may be considered as well established, mainly based on geomorphologic evidence and aerial views (Figure 21). The most probable location of the Arava fault is shown in Drawings No. 111201, 111202 and 111203 included in Appendix H. However, an enhanced location (accurate to within a few metres) would require paleoseismic trenches to be undertaken.

At the Dead Sea itself, there are contradictory observations: geomorphologic studies locate the fault at the eastern border of the sea but a reflection survey indicates its location in the middle of the sea. A resolution of the location of the Arava fault within the Dead Sea is not necessary for the determination of the project configuration and is only pertinent to the design of the discharge works to the Dead Sea.
Figure 21: Arava fault unique location based on geomorphological observations (Google Earth)

5.6 Conclusions

*It will probably not be possible within the frame of the ongoing project to exclude the potential occurrence of a coseismic slip of 1 to 3 m within the lifetime of the Red Sea Dead Sea conveyance system. This means that any crossing of the Arava Fault is a major issue.*

*The spectral response is established for different zones and will be specified for each work type and area.*
6 HYDROGEOLOGY

6.1 Introduction

The groundwater conditions are relevant to the project in the following respects:

- impact on design and construction where the ground water table is close to the land surface;
- where there could be a risk of soil liquefaction;
- where an aquifer is used for water supply and/or irrigation purposes and there is a risk that leakage from the conveyance might contaminate the aquifer with seawater;
- where the location of the tunnel conveyance with respect to the groundwater table results in a risk of draining groundwater from the aquifer into the tunnel both during construction and during operations;
- determination of the maximum external hydrostatic pressure that could be applied to the tunnel lining;
- location of groundwater resources for the construction works;
- estimation of the risk of groundwater contamination along the conduit route or downstream of the tunnel route in case of leaking;
- the contribution of ground water flow to the Dead Sea water budget at the current stage and attempting on various Dead Sea levels;
- assessment of sinkhole hazard in the Dead Sea area.

It should be noted that only limited groundwater data is available and/or has been made available to the study team. However, detailed hydrological studies are not essential for the Feasibility Study stage of the project development.

6.2 Groundwater conditions in the Wadi Araba / Arava Valley and on its eastern margin.

Groundwater resources of the Middle East are subdivided into groundwater basins on the basis of natural administrative boundaries (Figure 22). Only three basins need to be considered for the RSDS conveyance project: (1) The North Wadi Arava basin and (2) The South Wadi Arava – Red Sea basin and the Dead Sea Basin (JMWI, PWA & IHS, 1998).
The groundwater resources of the Wadi Araba/Arava Valley represent a major water resource. The Arava valley forms a regional drainage basin to which both surface water and groundwater flow, and through which the water is drained to the final drainage basins. The thickness of the Arava fill sediments, between the bordering faults, is up to a few thousand meters, becoming thinner at the topographic high near the Gharandal saddle. This topographic saddle (or divide) also governs the flow regime of groundwater along the Arava towards the Dead Sea to the north of the Gharandal saddle and south of it towards the Gulf of Aqaba.

Surface water between the Red Sea and Dead Sea is exclusively generated in the form of flash floods which develop sporadically and may reach high volumes for short durations. They contribute significantly to the recharge of the underlying aquifers.

Regional aquifers on both sides of the rift valley drain across the valley margins into the local alluvial aquifers which, as mentioned above, in turn are directly recharged through flash floods or via alluvial fans developed along the margins of the valley.
In the northern basin, only in the upper 250-300 m' of the Arava fill section c water of good quality is found. In the southern basin the section that contains good quality water is found between 350-450 m depth. Deeper saline water and brines are found.

The morphotectonic setting of the region and more specifically its main faults has created a hydrogeological regime through which deep confined aquifers merge and mix with shallow aquifers (, WEBER, M. et AL., 2009). Therefore, groundwater of varying quality is found and exploited throughout the valley and along its margins. The freshest water is used for direct irrigation and in some cases, after some minor treatment, also for domestic consumption.

Brackish water encountered, mostly in the southern part of the rift valley, is desalinated and used for the municipal water supply.

The wells in the Arava Valley exploiting groundwater for use in Israeli are shown Figure 23. In recent years an increasing number of well shave also been drilled to exploit groundwater in the Wadi Araba for use in Jordan (These are not shown on the Figure 23).

Figure 23: Israeli wells along the Arava valley, worth mentioning that some Israeli wells are located inside Jordan territory.
Three aquifers are exploited along the margins of the Arava valley. These aquifers are:

- The Lower Cretaceous aquifer (known as “Kurnub” on Figure 24)
- The Upper Cretaceous aquifer (known as “Judea” on Figure 24)
- The Neogene& Quaternary aquifer located in the valley proper (jointly known as “Arava Fill” on Figure 24).

These aquifers are described below and a typical cross section is shown in Figure 25.

Figure 24: Geological cross section in the Zofar area, central Arava valley, western part (compiled by Fleisher, E., Fleisher, L. & Frieslander, U., 1997; Geophysical Institute of Israel)
6.2.1 Lower Cretaceous ("Kurnub") aquifer

The Lower cretaceous (Kurnub Group) is composed of sandstone with clay interbedded. The Turonian and Cenomanin formation (Judea Group) are composed of dolomite, limestone with clay and shale interbedded.

In the southern part (south of the watershed), below the Kurnub formations there are sandstone layers of the Paleozoic age containing brines.

The Lower Cretaceous contains water that is mainly "fossil". High artesian pressures in this aquifer give rise to leakage into the overlying upper Cretaceous beds (called the Judea Group in Israel) and into the permeable Neogene and Quaternary alluvial strata. The water is somewhat brackish and is characterized by high sulphate content. This aquifer represents a major water resource for the southern area of the region.
6.2.2 The Upper Cretaceous ("Judea") aquifer

In the western side, the aquifer is composed of limestone and dolomite. The major water is mainly "fossil water". In places where the wadis are cutting through the permeable formation, fresh water from floods can recharge the aquifer but the related amount is very small and randomly.

In the Eastern side this aquifer is also composed of limestone and dolomite and is recharged from the underlying Kurnub, also from floods running over its outcrops in the wadis draining towards the Arava valley and from lateral flow of overlying aquifers on the eastern valley shoulder. Available data refer to hydraulic conductivity values ranging between \(10^{-2}\) (highly fractured) to \(10^{-4}\) m/s (HARZA JRV GROUP, 1998).

The water in this aquifer is also typically slightly brackish and is characterized by high sulphate content and is also a major water resource for the southern area of the region.

6.2.3 The Neogene & Quarternary ("Arava Fill") aquifer

This aquifer consists of alternating alluvial clay, sand and some conglomerate beds. Numerous facies changes are observed which form an aquifer system comprising sub-aquifers of limited extend. Apart from the very shallow sub-aquifers, the alluvial aquifer system is confined to a certain degree over most of its area.

The average depth to the water table is about 70 to 80 meters, but the range extends from standing water at the surface to a maximum of 137 meters depth (Figure 26; Salameh E., 2009; Geological Survey of Israël, 2006).

According to the Israeli wells, in the northern basin the productive thickness is between 200-300 m and in the southern basin it is between 350-450 m. Below this depth the water contains brines.

![Figure 26: Hydrogeological model of Jordan side of Dead Sea](image_url)
Previous geophysical and drilling surveys indicate that the fill aquifer could exceed 400 meters thickness. This aquifer is the main water supplier of the central and north Arava region.

The groundwater elevations are shown on Figure 28. Heterogeneities of lithologies can lead to high variations in hydraulic conductivity with clay sediments ranging from $10^{-6}$ to $10^{-9}$ m/s whilst sands range from $10^{-9}$ to $10^{-5}$ m/s.

Close to Aqaba, the GWL is shallow and the groundwater gradient 0.1% (from data of observation wells). Typical well discharge rates are 75 m$^3$/h and the water quality is fair. The main areas of recharge are the wadis which are acting as drainage axes from the crystalline massif. In the southern half of the Arava valley, the main contributor to this aquifer are the eastern escarpments of the valley. The ascendant movement of groundwater from lower formations is linked to faulting (Harza JRV Group, 1998) and also contributes to the recharge.

The water in the alluvial aquifer system, which contains a significant meteoric component, is generally of low salinity and is therefore of prime importance to agriculture but unfortunately in the last 10-15 years irrigation return flow become a major source of salinity and nitrate.

Brackish to saline groundwater is sporadically encountered and is utilised for both industrial and domestic usage. The average salinity of water is 2500 µS/cm but higher values are observed locally (6500 µS/cm at JTM latitude 300000; Figure 28). This high salinity area is manifested by a 20 km$^2$ mud flat located 25 km at the north of the International Airport of Aqaba. The clayey silt infers a high evaporation with associated precipitation of gypsum and halite. Subsequently at each flash flood these minerals are redissolved and additional minerals are imported increasing the salinity. Regardless of salinity, water is always of the Ca-chloride type which is considered to be the fingerprint of marine derived brines developed along the valley since Neogene times.
Figure 27: Piezometric, groundwater level map (GEOLOGICAL SURVEY OF ISRAEL, 2006)
Figure 28: Iso-salinity mapping and flow directions of Quaternary Alluvium Groundwater between the Red Sea and the Dead Sea (Salameh E., 2009)
Figure 29: Hydrogeological mapping (depth to water) of Quaternary Alluvium Groundwater between the Red Sea and the Dead Sea.
6.2.4 Conclusions

As can be concluded from the above considerations groundwater in the Arava Fill aquifer can be found at shallow depths (up to 100 m) throughout much of the Wadi Araba / Arava valley. This aquifer is not protected and in the event of leaks from the conveyance system (conduit, canal or tunnel) this would create a serious potential hazard to groundwater. Due to localised hydrological links between the Arava Fill and the Upper Cretaceous aquifers, continuous leaks or a major spillage could affect all water resources in the area. The first to be affected in case of a leak would be the many shallow wells operating along the Arava Valley on the Jordanian side. The heterogeneity in water quality of the Fill Aquifer will make the detection of such leaks difficult with usual resistivity methods or grids.

In the case, the pipeline option should be preferred, a detailed hydrogeological investigation would be required (determination of accurate groundwater levels hydraulic conductivity, dispersion parameters) in order to predict the impact of a leakage, failure or spillage of the conduit on the aquifer and to define the best preventive measures and remediation techniques.

At the detailed design stage, it will be important to spot and to map the sensitive places where randomly leakage of sea water from the conveyance may reach the groundwater and the wells. I recommended adding a map with the conveyances alternatives and the well fields downstream so that actions can be planned to capture the randomly leaked water before it arrives to the wells. In places where hydraulic connection is possible a flow and transport model is worked out in order to get the travel time and the concentration of the contaminated plume that may reach the wells. Monitoring wells will be drilled between the conveyance and the sensitive well fields, when necessary between the conveyance and sensitive production wells, a hydraulic drawdown will be generated so that the contaminated water in case of leakage is pumped and will never reach the production well.

6.3 Hydraulic conditions at the eastern margin

The Proterozoic rock of the eastern margin doesn’t bear a significant aquifer, therefore only limited data are available and notwithstanding low hydraulic conductivity values could be expected one observes:

- This massif is strongly fissured and two deep cored boreholes drilled under the project specific geotechnical site investigation program, one of them two hundred metres deep, shows cracks within the granite over their full depth with traces of water circulation;

- The water tests carried out in these boreholes indicate relatively high hydraulic conductivities of around $10^{-7}$ to $10^{-6}$ m/s, corresponding to a high fracture hydraulic conductivity;

We consequently have to consider the massif is bearing slightly permeable discontinuous aquifers. They are interconnected with the Arava fill aquifer and contributing to its recharge via alluvial fans and wadis which may act as drainage axes. Locally intensively fractured rock and cataclastic rock (uncemented mylonite) corresponding to faults are assumed to be strongly water bearing.
Because of the topography (elevations of up to 1,000m) the cracks can be suddenly filled to considerable elevations during heavy rainfall. This would result in brief high hydrostatic pressure which would act on the tunnel lining if it is not drained.

6.4 Dead Sea groundwater inflows

The groundwater inflow is one of the terms of the Dead Sea water mass balance. In order to be able to estimate the range of the groundwater inflow to the Dead Sea as accurately as possible each of the different origins or aquifers must be considered. The Dead Sea lies in the central part of the Syrian-African Rift System. It is located in the lowest topographical-structural segment of the rift, and serves as a drainage basis for all the hydrological systems in its vicinity; both surface and subsurface. The hydrogeology on both sides of the Dead Sea is very different both in the characteristics of the aquifers and in the water flowing through them.

6.4.1 The Hydrogeology West of the Dead Sea

The western catchment area of the Dead Sea is between the water divide on the mountain and the Dead Sea. Although there is a certain match between the subsurface and the surface water divide, they are not identical (Arad, A. & Michaeli, A., 1967). The total area of the Judea desert basin is more than 750 km². The general direction of the groundwater flow in the regional aquifers is to the northeast, towards the Dead Sea.

The amount of rain is 100 mm/yr in the vicinity of the Dead Sea to larger amounts (500 mm/yr - 600 mm/yr) close to the Hebron mountain. The western Dead Sea groundwater system consists of two main aquifers: the Upper Cretaceous Judea Group Aquifer and the Quaternary alluvial costal aquifer (Arad, A. & Michaeli, A., 1967; Yechieli, Y., Ronen, D., Berkovitz, B., Dershowitz, W.S. & Haddad, A., 1995). The coastal aquifer consists mainly of clastic sediments, such as gravel, sand and clay deposited asfan deltas and lacustrine sediments, such as clays, aragonite, gypsum and salts (Appendix C).

The alternations between gravel and clay subdivide the aquifer into several subaquifers that differ in their groundwater levels and chemical composition. The transmissivity of the aquifer ranges between $3 \times 10^4$ m²/s and $10^3$ m²/s, depending upon the aquifer’s thickness (Annex C).

This aquifer is bounded by normal faults, which set Cretaceous carbonate rocks of the Judea Group against Quaternary alluvial and lacustrine sediments. The recharge of the aquifer is mainly through lateral flow from the Judea Group aquifer, which is replenished in the highlands 10 km -30 km to the west and by flash floods.

Due to the scarcity of observation boreholes penetrated into the deeper sub-aquifers, the monitoring of the water levels and the interface location is limited to the upper subaquifer.
6.4.2 The Hydrogeology East of the Dead Sea

The eastern Dead Sea groundwater system consists of three main aquifer systems: the upper aquifer system – Quaternary- Tertiary alluvial coastal aquifer, the Middle aquifer system – Upper Cretaceous carbonate rocks known as Amman-Wadi Sir aquifer, and the lower aquifer system – Lower Cretaceous and older sandy aquifers (Appendix C).

The upper aquifer system is similar to the coastal aquifer at the western side of the Dead Sea (see previous section). The Middle aquifer system is the most important aquifer in Jordan. Groundwater flow in this aquifer is directed from there charge area at the high rainfall zones of the highland towards the Dead Sea. The lower aquifer system is composed of two groups, the Ram Disi and the Kurnub Groups that extend over almost all Jordan. Source of recharge of unknown extent may be by downstream seepage from overlying aquifers (Salameh E., 2009). Groundwater in these aquifers is considered as of fossil origin, recharged at times of higher rainfall. The deep aquifer system is being continuously drained to the Dead Sea. The groundwater discharge to the Dead Sea was estimated to be approximately 400 MCM/yr, most of it in the form of undetected discharge below the shoreline.

Contrary to this estimation, Salameh and El-Naser (1999, 2000a,b) argued that the total natural discharge of groundwater on the eastern side from deep aquifers to the Dead Sea is 90 MCM/yr. However, they claim that a high volume of groundwater (~500 MCM/yr) is drained to the Dead Sea due to the rapid drop of the Dead Sea.

6.4.3 Groundwater Inflows from springs

There are a number of thermal springs which are very saline, with Cl\(^{-}\) content up to 200 g/L, at a temperature of 40 to 44°C (44°C means 600 m depth circulation) containing bromine, hydrogen, sulphide and ammonia. These are mostly located on the west side of the Dead Sea and the total yield of the thermal springs on the west side has been estimated to be around 10 Mm\(^3\)/y (Harza JRV Group, 1998). The water quality will not be affected by changes in the Dead Sea level but the discharge may vary marginally. A sea level rise will reduce the gradient but, owing to the deep circulation origin of this water, the gradient (current groundwater gradient between 0.005 and 0.002) decrease will be negligible. Hot springs on the east side of the Dead Sea discharge water at a similar temperature to the springs on the west side, evidence of an equally deep circulation, but from a completely differently source (east shoulder aquifer).

Other springs correspond to the base of a water bearing layer above an underlying impervious layer. Their outflow is independent of the Dead Sea level. On the west side they are the groundwater resurgences of the Judean aquifer which is composed of a succession of aquifers and aquicludes. The groundwater abstraction and springs together yield between 90-95 MCM/yr. Actually, the spring discharge is around 60-65 MCM/year. The abstraction in wells located near the mountain axes at the basins that flow to the springs is today around 30 MCM/yr. Additional 1 MCM/yr is pumping from the spring itself for local uses.

This spring water is largely captured and used and so does not contribute significantly to the groundwater inflow to the Dead Sea. Similar springs are observed on the east side where the total discharge is not known but it looks significantly lower than on the west
side. The inflow to the Dead Sea from surface water springs is considered together with the next groundwater inflow.

As the Dead Sea level decreases, additional spring lines may appear. Their occurrence is confirmed by lush vegetative growth on the newly emerged shore and they may contribute, as further explained below, to the sinkhole hazard.

### 6.4.4 Groundwater Inflows from Shore Line

Sub-surface springs related to the fresh water aquifers occur on both sides of the Dead Sea. In this case the groundwater gradient will increase significantly with a fall in the Dead Sea level and decrease with a rise in the Dead Sea level resulting in corresponding changes in the flow from these springs. The water balance studies have indicated that the residual inflow to the Dead Sea has increased with a fall in the Dead Sea level. The residual inflow is closely related to the groundwater inflow below the shore line and the outflow at the additional spring lines, but flow measurements supporting this relationship are conspicuously lacking. However, due to aquifer overexploitation, the gradient increase will not be as large as might be expected from the changes in piezometric gradients. The additional fresh water losses due to the Dead Sea water level decrease are estimated to be 1 Mm³/y (Harza JRV Group, 1998), while in their water balance Harza has assumed that the contribution from groundwater is as large as 400 Mm³/y as already mentioned here above.

In fact the hydrodynamic system is quite complex, as evidenced by Salemeh (Salameh E. & El-Naser H., 2000). The sudden drop of the Dead Sea level triggers a seaward movement of the fresh/salt water interface which, combined with the inferred increase in groundwater gradient, generates a large movement of the fresh\textsuperscript{27} water body. This amount was estimated independently by Harza (Harza JRV Group, 1998) and Salameh (Salameh E. & El-Naser H., 2000), it ranges around 420 Mm³ per metre additional sea level drop.

We may compare this with the recharge of the aquifers which is 57 Mm³/y (JMWI, PWA &IHS, 1998).

This component of the water budget is significant and its amount as estimated by Harza looks exaggerated. In the Dead Sea budget the groundwater inflow has been calculated as the balance between the other terms and made variable with the Dead Sea level decrease or increase.

### 6.5 Sinkholes hazard

#### 6.5.1 Sinkholes Hazard: Existing Models

Sinkholes are large collapsed openings at the subsurface. Sinkholes pose a serious hazard and are a major problem in the Dead Sea area. Sinkholes have been identified throughout a large region around the shoreline of the Dead Sea and most alarmingly over the last few

\textsuperscript{27} In fact brakish water.
years in the resort areas, along the highway and at the sites of Israeli and Jordanian potash plants (Figure 30).

A number of different conceptual models for sinkhole development have been postulated; all of which relate sinkhole formation to the rapid decrease in Dead Sea level.

The first model called the “flushing model” is based on the assumption that turbulent groundwater flow (turbulent because of the raised groundwater gradient within a thin water bearing layer) erodes and transports fine insoluble fractions such as clay, silt and fine sand. After time subsurface cavities are generated, expanding upwards and appearing on the surface (. ARKIN, Y., AND Gilat, A., 2000).

The second model is based on the assumption that salt of evaporitic (halite) beds are dissolved by flowing fresh water passing through pre-existing cracks or at the contact with pervious water bearing layers, thus generating salt caverns. These cause the collapse of the overlying strata and finally appear on the surface as sinkholes. (. ABELSON, M., BAER, G., SHTIVELMAN, V., WACHS, D., RAZ, E.,CROUVI, O., KURZON, I., AND YECHIELI, Y., 2003). This second model is slightly adapted and the salt dissolution would be inferred from a seaward migration of the fresh/Dead Sea water interface with the fall in Dead Sea level (. SALAMÉH E. & EL-NASER H., 2000. CLOSON D. & ABOU KARAKI N., 2007).
Research based on borehole information and geophysical tools reveals that the formation of sinkholes results from the dissolution of a ≈10,000 year old salt layer buried at a depth of 20–70 m below the surface. The salt dissolution by groundwater is evidenced by direct observations in test boreholes. These observations include large cavities within the salt layer and groundwater within the confined subaquifer beneath the salt layer that is under saturate with respect to halite. Moreover, the groundwater brine within the salt layer exhibits geochemical evidence for actual salt dissolution (Na/Cl =0.5–0.6 compared to Na/Cl = 0.25 in the Dead Sea brine).

For a clear understanding we refer to the geology of the Dead Sea: the upper tens of meters along the Dead Sea shores consist of the late Pleistocene Lisan Formation.

**Figure 30: Sinkholes localization map**
B., EHRlich, A., and NathAN, Y., 1974; Sneh, A., 1979) and Holocene Formation composed of alternating clastic material (clay, sand, and gravel) deposited in fan deltas, with intercalations of lacustrine sediments (clay, aragonite, gypsum, and halite). The relative abundance of fine-grained layers within both formations increases eastwards. The sinkholes develop within the sediments of the Holocene Formation and are confined to a narrow strip that stretches up to several hundred meters away from the shoreline.

The sinkholes are concentrated on the west side of the Dead Sea, the north being excluded, and in the vicinity of the evaporation ponds of Arab Potash Company on the east side shoreline (Figure 30). There are indications that the locations where sinkholes occur is controlled by active faults.

6.5.2 Detailed Description of the Dissolution Model

Yechieli et al. (YechielYoseph, Meir Abelson, Amos Bein, Onn Crouvi, 2006) has shown and explained the dissolution phenomena with respect to chlorides and the subsequent sinkholes formation as being of water of geothermal origin and of fresh water flow coming from the Dead Sea basin aquifers. His conclusions are derived from investigation boreholes and seismic survey. Indeed in all cases below the investigated sinkholes a halite layer was found. The phenomena are best illustrated with his conceptual schemes shown in Figure 31 & Figure 32.
**Figure 32: Hydrogeological schematic section across the Elongated swarm of sinkholes in the Salem 2 site (. SALAMEH E. & EL-NASER H., 2000) (location is given on Figure 30).**

The Mineral-2 borehole penetrated a cavity in the salt layer with water that exhibits a clear signal of salt dissolution (Na/Cl = 0.6). Much less-saline water (Cl = 120 g/L and also lower Na/Cl values (0.33) were found in the nearby Mineral-1 borehole. The sinkholes develop along a presumed fault. The characteristics of thermal spring water are 120g Cl/l and 40°C.

It appears that the sinkhole formation is linked to the shrinking of the Dead Sea, as implied by the coincidence between the accelerated rate of the declining level of the Dead Sea and the abrupt appearance of the sinkholes during the late 1980s, reaching recently a sinkhole occurrence rate exceeding one thousand per year. The early model suggesting that the declining lake level triggers piping processes has to be abandoned. The salt dissolution phenomena is the trigger for the sinkholes.

The rapid declining lake level controls a unique change in the position of the Dead Sea brine - groundwater interface. The interface along the Dead Sea coast retreats seaward because of the rapid shrinkage of the Dead Sea. Following the interface shift, the salt layer, which originally was saturated with the Dead Sea water over its entire extent, is gradually invaded by fresh groundwater and/or unsaturated thermal water. These waters are confined beneath the halite layer, showing a piezometric head several meters higher than the water level in the upper subaquifer level which is close to the Dead Sea level. The inferred groundwater head forces the water to flow toward the salt layer through adjacent gravel layers, faults, and cracks.

Once the groundwater, under saturated with respect to halite, reaches the salt layer, dissolution takes place and increases steadily to form a karst system with high hydraulic conductivities. Cracks and faults when encountered within the solid salt layer allow the flow of the unsaturated water and enhance the dissolution process. Water flow within the salt layer expands mainly vertically and upward because, and this is crucial, it is controlled by the higher heads below the salt layer than above it. Because of the limited thickness of the salt layer, the dissolution process forms a “short circuit” and allows circulation of water from lower to higher aquifers. The preferential dissolution along the cracks and faults forms...
a dynamic cavity system, which develops rapidly into a linear (because essentially along main faults) cluster of collapse sinkholes (. Salameh E. & El-Naser H., 2000).

The entire process is enhanced further due to the steady increase in the flow gradients caused by the declining Dead Sea, which in turn intensifies the flow and dissolution capacity of the salt layer with relatively unsaturated water. The cavity formed in the salt layer grows to a point where the overlying ceiling layer yields and collapses to create a sinkhole.

It is worth to note that:

• There are no sinkholes along the northwestern and northern shorelines of the Dead Sea (Figure 9). This is in agreement with the fact that no salt layer was found along the northwestern part of the Dead Sea coast (shown with test boreholes and seismic-refraction profiles).

• The absence of sinkholes along the eastern coastline, down to the Lisan Peninsula. This might be attributed to the steep relief of the eastern flank of the lake, which follows a fault escarpment inferring that the eastward extension of the salt layer is limited or not even present. There is a lack of field data to confirm this. On the other hand sinkholes were found in the southern part of the eastern coastline (. Taqieddin, S.A., Abderahman, N.S., and Atallah, M., 2000).

• The sinkholes started to develop once the Dead Sea level dropped below 400 m bmsl. Recent studies suggest that such lake levels and lower ones did exist during the last several thousand years (. Bookman (Ken-Tor), R., Enzel, Y., Agnon, A. & Stein, M., 2004). They show that the Dead Sea water level over the past 4000 years was intermittently below 400 bmsl, for ~2800 ears, and a water level as low as the present level was reached some 3400 ears ago. Therefore, one would expect to find fossil sinkholes along the Dead Sea coast or even that the present sinkholes actually evolved over paleo-cavities that formed in the past. In fact, very few paleokarst features are found. It may be expected that at that time the Dead Sea level drop was much slower than now so that the water head difference between the lower subaquifer below the salt layer and the upper subaquifer above the salt layer was limited and the inferred water flow and dissolution capacity moderate, and insufficient to trigger cavern formation and upper layer collapse.

• Sinkholes are mostly observed following alignments corresponding to preexisting cracks.

• The rate at which the sinkhole swarms propagate raises questions concerning future trends and possible changes in time and space. It appears that the process leading to the formation of sinkholes could continue as long as the groundwater heads remain higher than the level of the salt layer. The hydrogeological framework and the distribution pattern of the salt layer indicate that with time and further decline of the Dead Sea level, the western margins of the salt layer will gradually protrude above the regional fresh water table. Consequently, dissolution at the present sinkhole sites would cease. Unfortunately the water head of geothermal origin will
not decrease and this water, which is salty (120 /l) but under saturated, will retain its dissolution capacity.

6.5.3 Consequences of the sinkholes hazard - Recommendations

The sinkhole hazard raises questions regarding the risk we would have below the desalination plant and other infrastructure related to the Project and concerning the future trends of the sinkhole hazard after the Red Sea -Dead Sea conveyance is in operation.

The selection of the location of the penstock outlet and desalination plant is crucial. If at these locations the risk of sinkhole hazard would be high, mitigation works would be required such as Cl\- saturated water injection upstream of the infrastructure works or, alternatively, fresh water withdrawal in order to allow the fresh/salt water interface to move landwards. In both cases, if properly designed, the dissolution phenomena would cease. The design will require an appropriate geotechnical and hydrogeological investigation program. The program would include pumping tests, piezometric wells, and conductivity logging in addition to the usual soil investigation program.

Concerning the future trends of the sinkhole hazard after the Red Sea - Dead Sea conveyance is in operation, this will depend on whether the Dead Sea level is stabilized or raised. If the level were raised, the groundwater flow will be reversed meaning that a flow of under saturated water will be directed from the sea to the land and that gradually the salt/fresh water interface will progress landward. Since the water is under saturated in respect to chloride content and there is flow, further dissolution phenomena and inferred sinkholes may not be totally excluded but, because the flow rate is limited, the dissolution capacity is reduced (under saturated water but with a high salt concentration) at least the dissolution phenomena occurrence will be dramatically reduced.

The sinkhole hazard model corresponds to that outlined in the sub-studies (Appendix C).

6.6 Incision of gullies hazard

The lowering Dead Sea water level, which during the last several years occurs at approximately 1 my-1, has accumulated more than 30 m since the early 20th century. The rapid lake retreat causes large-scale environmental deterioration, including soil erosion, land degradation, incision of gullies and rapid head cut migration in addition to the development of collapse sinkhole fields. The incision of gullies and head cut migration upstream in the region is a major source of hazard (e.g., Ben Moshe et al., 2008; Bowman et al., 2007). The process already inflicted significant damage to bridges, lifelines, and other infrastructure and it is likely to increase in the future. Clearly this is one of the problems that the water conveyor is meant to solve.
6.7 Effects of climate changes on groundwater resources:

The effects of climate changes have been thoroughly studied within the frame of the subsidies. Analysis and results are given in Appendix A.

The main trends of the global warming consequences on the groundwater resources are as follows:

1. an increase in annual mean temperatures equivalent to between 0º and 0.5º C per century over the Eastern Mediterranean between 1901 and 2005 is observed, equivalent to 0.5º-0.7º C per decade for the period 1979-2005, with greater warming in spring and summer than in autumn and winter.

2. In Jordan the observed changes in precipitation over the latter half of the 20th century is a decline ranging from 5-20%, the most significant on the eastern shoulder of the Arava valley.


4. Climatic projections have been performed by various scientific institutions versus the different emissions scenarios. The projections are a temperature increase for the project area, for the 21st century ranging from 2 to 6+0.5°C, mainly during the summer months.

5. There is a consensus that the whole area will become significantly drier during the same period, for the study area a decrease of the rainfall between 10and 20%.

6. Run off changes. The results of the modelling studies highlight the fact that runoff responses to climate change will vary from one river basin to another, indicating that caution must be employed when using regional climate change projections to infer information about potential changes at sub-regional scales. Nonetheless, the results from the studies indicate that changes in runoff of tens of per cent might be anticipated as a result of plausible changes in temperature and rainfall.

7. Groundwater recharge. It is depending on the evapotranspiration, which would increase per 1% per 1°C temperature rise. It is reasonable to assume that groundwater recharge rates will be reduced by an amount comparable to that by which runoff decreases, although recharge will also be affected by factors such as the intensity and frequency of precipitation, and any changes in the properties of the land surface that might alter infiltration rates. Nevertheless some study show that a 16% decline in rainfall could result in a reduction in annual groundwater recharge of 30%, and that the decline could be as high as 50% when such a reduction in precipitation is combined with a projected increase in mean temperature of 6º C.

8. Globally it means an increased deficit between the supply and the demand in Jordan.

9. Mores specifically to the project area, in case the pipeline option would be preferred any leakage of Red Sea water from the conveyor as it transits through the Wadi Araba will have adverse local impacts on groundwater. Where groundwater levels are falling and/or groundwater is becoming more saline as a result of lower rainfall and reduced runoff, any such leakage will exacerbate existing climate change impacts. Lower levels of freshwater infiltration are also likely to reduce the potential for recovery from such events through the dilution and dispersal of minerals derived from the Red Sea water. The conveyor therefore has the potential to increase salt stress where it might already be increasing, while climate change might exacerbate the adverse impacts of leakage.
10. Reduced rainfall over the Dead Sea and reduced surface runoff in the Red Sea basin and Jordan River catchment will act to reduce input to the Dead Sea by an amount that could exceed 100 MCM/yr by the mid-late 21st century, offsetting the input from the RSDSC. The greatest impacts on the operation of the RSDSC would most likely be realised towards the middle of the century and beyond. While the shift towards a more arid climate is likely to have some impact on the rate at which Dead Sea levels rise for a given inflow from the RSDSC, this impact might be small over the 25 year period during which levels would rise to the target level. Subsequently once the target level is reached, further input from the RSDSC would be required to maintain the level of the Dead Sea, in order to compensate for the continued abstraction of water from the Jordan River and the imbalance between inflow and evaporative losses.

6.8 Hydrogeology Conclusions

In the Arava, the main aquifer is the fill aquifer, including the Quaternary and Neogene strata. It is constituted of alluvial heterogeneous deposits. It is also very vulnerable and in the case of leakage of the conveyance conduit is a serious hazard for this aquifer which is crucial for the water supply of the area. In case the pipeline option would be decided, a detailed investigation will be required in order to accurately define the groundwater conditions and to design a preventive system and a remediation system in case the pipeline would leak or be damaged. The system could be of an impervious membrane below the pipes with a drainage and pumping system of the leaked saline water and a permanent pumping below the membrane to create a hydraulic sink so that in case of the membrane failure, the sea water can’t reach the water abstraction wells.

The eastern margin or shoulder of the Arava valley in its southern part is made of crystalline rock with relatively high hydraulic conductivities (from water tests and observations) so that at the “tunnel scale” a general aquifer has to be considered. This aquifer contributes to the recharge of the Arava fill aquifer and consequently the leakage hazard has to be considered. In its northern part, the tunnel runs through highly permeable sandstone part of the cretaceous aquifer and also vulnerable.

The groundwater discharge to the Dead Sea could not accurately be determined. But at the other hand the sinkhole hazard mechanism is well determined, their occurrence location can be predicted and if required mitigation can be undertaken.
7 ENGINEERING GEOLOGICAL CONDITIONS AT THE DIFFERENT UPSTREAM WORKS

7.1 The Eastern Water Intake

The eastern water intake is the selected intake location for alignment options 0.1 and 220.1 and for one pipeline option. The pumping station location for pipeline option and alignment option 220.1 is located close to it. The intake is located in a small wadi about 5 km to the south of Aqaba. This location is presently occupied by the old Aqaba thermal power plant.

Figure 33: Water Intake locations on geological map and main structural features of the area.


Kind of rocks

The described wadi is located inside a granite (high quartz content and fragile) body. This body is intensively fractured and cross-cut by andesitic (medium quartz content and consequently medium ductile) dikes. The intense fracturation is related to the convergence and junction of two main faults, the NS trending Aqaba-Garandal fault, which is a normal fault and a strike-strip fault (Figure 33). It is suspected that southward the strike strip movement is transferred to the pre-existing Aqaba-Gharandal fault and the vertical movement of the normal fault to the pre-existing strike-strip fault. This fault having consequently to the south a combined normal and strike slip behaviour. The granite body is thus intensively fractured due to the more fragile characteristic of the granite. One also observes at the faults transfer zones a 600m wide mylonitic belt.

The granite is mostly homogeneous, the joint pattern is given in Figure 33, and preferential joint directions are not clearly identified. Nevertheless one main joint direction appears and is N0) dipping 42°W. The rock quality at the outcrops is poor to fair, the RMS score is 50, corresponding to an equivalent friction angle of 40° and 0.2MPa cohesion.

Figure 34: Joints-fractures-faults directions represented on meridional stereographic net
The Eastern intake location has been investigated:

- one 180 m long refraction profile, EW trending at the north of the existing power plant, profile 1 of Appendix G2 of the factual investigation report.

- two 180 m long seismic refraction profiles, also east west trending inside the wadi at the east of the power station: SRP2 and SRP3 of the factual investigation report.

- two cored boreholes CBH1 and CBH2 of respectively 18 and 28 m depth

From investigations results (Figure 35), interpretation is, from top to bottom:

- Anthropogenic and alluvial deposits up to 10 m deep (pink to red colour). This first layer consists in sandy gravel with pebbles, boulders. The internal friction angle is estimated to be 36°.

- Intensively weathered and fractured granite (yellow to green colour; 30 m thick; RQD$^{28} = 0$; VL$^{29} < 2600$ m/s), andesitic dykes, with a best estimated equivalent friction angle of 40° and 0.2 MPa cohesion.

- Sound granite VL=5000 m/s from elevation -20 m (blue colour).

![Figure 35: Seismic refraction profile No. 1 at the Eastern Water Intake](image)

The groundwater level has been observed close to elevation zero, indicating the hydraulic conductivity is high. In the central part of SRP1 and SRP3, one observes in its central part a dome shaped structure (Figure 35), elevating the sound granite of 10m to elevation -10.

---

$^{28}$ RQD = Rock Quality Designation is the borehole core recovery percentage incorporating only pieces of solid core that are longer than 100 mm in length measured along the centerline of the core. In this respect pieces of core that are not hard and sound should not be counted though they are 100 mm in length. RQD is used as a standard parameter in drill core logging together with Total Core Recovery (TCR). RQD has considerable value in estimating the most used rock mass classification systems: Rock Mass Rating system (RMR) and Q-system.

$^{29}$ VL = Longitudinal waves velocity.
corresponding to locally less fractured granite. Inferring from the longitudinal wave’s velocity, the excavation works until elevation 0 could be performed mechanically, the tunnel portal has to be supported until a rock depth of at least 10 m. The hydraulic conductivity has been determined with 4 Lugeon tests, as could be expected the hydraulic conductivity is relatively for fractured granite, ranging between $10^{-6}$ and $7 \times 10^{-5}$ m/s. It has to be taken into consideration for the groundwater lowering.

**Seismicity**

The seismicity is that of the southern part of the Arava valley. The PGA\(^{30}\) of the area has been determined using Boore (. **Boore, D.M., Joyner, W.B. & Fumal, T.E., 1997**) and Ambraseys (. **Ambraseys, N.N., Douglas, J., Sarma, S.K. & Smit, P.M., 2005**) attenuation laws. The calculated values are respectively 0.22-0.25 and 0.17-0.19 g. No site effect has to be taken into consideration.

This area was also characterised in the last 30 years by the incident of swarm earthquakes (**Figure 36**). Among these, the most significant are (. **Malkawi, A.I.H., Numayr, K.S. & Barakat, S., 1999**):

- The 1983 swarm with a maximum local magnitude of 4.85 with the epicenters concentrated in the northern tectonic block of the Gulf of Aqaba.

- The 1995 swarm which had a maximum moment magnitude (Mw) of 7.3 where the epicenter of the main event was located 80 km to the south of Aqaba City. This earthquake was the main shock of the earthquake sequence that possibly extended up to 1998 (**Figure 36**).

![Figure 36: Map showing the distribution of earthquake epicenters of the Gulf of Aqaba (A) 1983, (B) 1993 and (C) 1995 (. Al-Zoubi, A.S., Heinrichs, T., Sauter, M. & Qabbani, I., 2006).](image-url)

\(^{30}\) PGA: 10% probability of exceedance in 50 years for a generic rock.
A summary of the characteristics of these swarm episodes are listed in Table 1. Waveform inversion of this event suggests a nearly pure strike-slip mechanism with about 1.6 m of left-lateral slip along 80 km fault zone striking N20E (Klinger, Y., Avonac, J.P., Dorbath, L., Abou Karaki, N. & Tisnerat, 2000). The intense microseism activity that shows off at the northern tip of the Gulf of Aqaba is mainly due to the aftershocks sequence that follows the main shock. Seismological results show that the rupture of the 1995 event originated in the vicinity of the 1993 event, which didn’t affect the intake area and propagated to the north, where the major movement release of two subevents took place, 20 and 40 km away, respectively. Studies indicated that the source mechanisms of the major events in the two swarms are different. The 1995 (November 22nd) earthquake has a predominantly left lateral strike-slip mechanism. At the same time the 1983 (Figure 36-A) swarms indicated that the seismic activity migrated from north to south, whereas the 1995 swarms (Figure 36-C) showed end to end migration of energy sources from south to north.


<table>
<thead>
<tr>
<th>Aspect</th>
<th>1983 swarms</th>
<th>1993 swarms</th>
<th>1995 swarms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inception date</td>
<td>21 January</td>
<td>3 August</td>
<td>22 November</td>
</tr>
<tr>
<td>Duration (days)</td>
<td>22</td>
<td>148</td>
<td>more than 6 months</td>
</tr>
<tr>
<td>Total no. of events</td>
<td>249</td>
<td>272</td>
<td>1236 until Dec. 31 1995</td>
</tr>
<tr>
<td>Largest M&lt;sub&gt;L&lt;/sub&gt;</td>
<td>4.85</td>
<td>5.34</td>
<td>Mw = 7.3 (M&lt;sub&gt;L&lt;/sub&gt;=6.2; Ms= 6.3)</td>
</tr>
<tr>
<td>Total released energy</td>
<td>1.97 x 10&lt;sup&gt;19&lt;/sup&gt;</td>
<td>2.11 x 10&lt;sup&gt;20&lt;/sup&gt;</td>
<td>1.349 x 10&lt;sup&gt;22&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

The swarms having affected the eastern water intake area show that this block is intensely fractured and its faults are active, they are the adjustment response of a large movement along the Dead Sea Transform fault.

The response spectral for this area has been calculated and for a Mw 6-6.5 is proposed on Figure 37. Considering an eigen frequency for a pumping station of 4 Hz (period of 0.25 s), one should have to consider an acceleration of 0.5 g.
Figure 37: Response spectral at the Eastern Water Intake

**Tsunami/seiche hazard:** The small seiche (defined as a standing wave in an enclosed or partially enclosed body of water) that was triggered by the Nov. 22, 1995 earthquake (Wust et al., 1997) demonstrated that this source of hazard must be considered in relation to coastal installations.

**Conclusions**

The Eastern water intake and its inferred pumping station are located inside an intensively fractured granitic body at a wadi mouth. The subsoil conditions are fair: mostly intensively fractured granite below the wadi deposits which are mainly coarse sand and gravel.

The area is seismic but no site effects are expected. The spectral response is two times lower than at the Northern Water Intake.

The granitic body is cross cut by a series of faults which regarding the recent seismic swarms having affected it are still active.

Tsunami risk has to be taken into consideration.
7.2 The North Water Intake and inferred pumping station

The north water intake is located in the centre of the valley of Arava along the Israel-Jordan border inside the no man’s land. This location is one of the two intake alternatives of the pipeline option. This intake consists of an underground water transfer structure.

Social and economical constraints (project of hotels construction) don’t allow that the conveyance could pass everywhere. Consequently, if this alternative is preferred, the conveyance must run parallel to the Israel-Jordan border (and parallel to the Arava fault) on a distance of 4 km (Figure 38).

Figure 38: Location of North Water Intake, Available corridor and Arava fault on aerial photography (from Google Earth)

For the geological conditions appraisal, we consider the area including the intake itself, the inferred pumping station, and the conveyance route between the two works, stretching on a length of 12.5 km.

These construction works are located in the lowest part of the Wadi Arava where active wadi sediments are found. They grade laterally and in depth into the feeding fans. Fine pelitic sediments lie over the normal wadi sediments.

This area of ephemeral standing water has formed a mud flat (Alm on the geological map) through which has threatened the modern, usually dry water course down to the coast. Stream and beach deposits represent the most superficial phase. The wadi Arava collects the
water of the different contributory wadis from both banks, which may be submitted to flash floods. The risk of damage with flash floods is then high and specific protection works would be needed.

The related area has been investigated with 6 boreholes with SPT tests: BH-PL1 of 10m depth and BH-A, BH-B, BH-C, BH-D and BH-E of about 30 m depth. three test pits (TP-PL1 to TP-PL3) were also performed and 10 geo-resistivity profiles (tomography): GR1 to GR10. Most of the investigations are focused on the pumping station area (Figure 39).

![Figure 39: Pumping station area associated to North water intake – Localization of geological and geophysical investigations on Aerial photography (from Google Earth).](image)

Previously in the Harza study, two boreholes (b7a and b8a) with SPT tests were performed up to a depth of 20m. The Geological Survey of Israel has also performed paleoseismic trenches at the Avrona playa area adjacent to the pumping station area (AMIT, R., ENZEL, Y., NAOMI, P., HAMIEL, Y. & ZILBERMAN, E., 2009). Several faults have been identified from these paleoseismic trenches (Figure 39).

**Kind of deposits**

As a rule, the investigations show alluvial deposits mainly constituted by clay, silty clay and silty sand. Fine sediments (clay and silt) look overwhelming. At the pumping station the investigation boreholes as well as georesistivity profiles show that the alluvial deposits are affected by facies changes, so that laterally the soil conditions may sudden change from sand to clay to silt, making any correlation between boreholes and/or georesivity tomographies, hazardous and not reliable. Results of geophysical research indicate that the thickness of the
Plio-Quaternary sediments in the south part of Arava valley ranges from 1210 m to 1390 m (SWISS AGENCY FOR DEVELOPMENT AND Cooperation (SDC), 2009)

**Hydrogeological conditions**

At the pumping station area, the groundwater level is at 7 meters depth, corresponding to elevation 16. The inferred groundwater slope amounts 1.6 0/00. No tests for the determination of the hydraulic properties have been performed but it may be expected that very locally the hydraulic conductivity may reach 10-4 m/s; this means that pervious bodies will be found requiring pumping during the excavation works and deep wall deepening to avoid fluidization.

**Geomechanical properties**

They are appraised from standard penetration tests. Between 10 and 20 m depth, the N (number of blows) varies within an interval of 2-20, corresponding to an unconfined compression strength interval of 0.03-0.3 MPa (Peck, R., Hanson, W. & Thornburn, T., 1957) or for clay and silt undrained shears strength of 0.015-0.15 MPa. For sand one should consider a friction angle of slightly less than 30°.

**Liquefaction**

Soil liquefaction describes the behaviour of soils that, when loaded, suddenly suffer a transition from a solid state to a liquefied state, or having the consistency of a heavy liquid. Liquefaction is more likely to occur in loose to moderately saturate granular soils with poor drainage, such as silty sands or sands and gravels capped or containing seams of impermeable sediments. During loading, usually cyclic undrained loading as earthquake loading, loose sands tend to decrease in volume, which produces an increase in their pore water pressures and consequently a decrease in shear strength, i.e. reduction in effective stress. The most susceptible deposits to liquefaction are young (Holocene-age, deposited within the last 10,000 years) and consists of sands and silts of similar grain size (well-sorted), in beds, meters thick, and saturated with water. Idriss has developed a simplified procedure to evaluate the liquefaction risk during an earthquake (Idriss, I.M. & Boulangar, R.W., 2004) using the N values of SPT results. This method, for earthquakes with a Mw magnitude between 7 and 7.5 has been applied and the obtained CSR (cyclic stress ratio) ranges between 0.2 and 0.25. The red ellipse on Figure 40 indicates an area corresponding to the field conditions which are observed on the site area and belongs to that part of the diagram with obvious liquefaction risk.
Adjacent to the northern intake, in 2009 during excavation works for buildings paleo-
liquefaction events have been observed. As consequence, clastic dykes are observed
(Figure 41). Sedimentary dikes or clastic dikes are vertical bodies or intrusions of sediment
into an overlying sedimentary rock. They can form a shallow unconsolidated sediment
composed of alternating coarse grained and impermeable clay layers the fluid pressure inside
the coarser layers may reach a critical value due to a (sudden) pressure increase e.g. from an
earthquake. Driven by the fluid pressure the sediment breaks through overlying layers and
forms a dike, corresponding in this case conspicuously to a liquefaction process.

Water escape is essential for a sedimentary layer to compact as more and more sediment is piled on top of it. If
the layer above the sand or the silt is impermeable, the water gets trapped and can’t escape. This is a stage
where essentially the overburden of rock is being supported by the water itself, not by the rock grains and this is
unstable. During an earthquake, the slight fractures it causes in the upper impermeable layer allow the water to
explosively move up the fractures carrying some of the sand or silt with them. When the water has found a way
to escape from its overpressured prison, the clastic injection ceases and the water flows through the injected
sand from the sand below to the surface above.
Seismicity

In the south part of Arava valley, the strike-slip Arava fault position is well identified. From various paleoseismic investigations (Le Beon, M., Klingler, Y., Amrat, A., Agnon, A., Dorbath, L., Baer, G., Ruegg, J.C., Charade, O. & Mayyas, O., 2008) a series of cross faults (or conjugated faults) have been located (Niemi, T., 2009; Amit, R., Enzel, Y., Naomi, P., Hamiel, Y. & Zilberman, E., 2009). Their most probable location is shown on Figure 39. For most of them, there are indications (even archaeological) of recent activity. The seismicity has been estimated and therefore the PGA of the area has been determined using Borre and Ambraseys attenuation laws. The calculated values are respectively 0.23 and 0.18 g.

The fault activity is in discredit of this location for the pumping station, close to the Arava fault and close to the Avrona playa where at least six surface rupture have affected this area during the last 14000 years (Amit, R., Enzel, Y., Naomi, P., Hamiel, Y. & Zilberman, E., 2009).

Site or basin effects

In addition to the direct expectable seismic activity itself we have to consider site effects. Indeed destructive earthquakes have demonstrated that damages are often more severe over unconsolidated deposits than on firm rock. Since river valleys or wadis are often the site of recent alluvial deposits as we have below the Arava valley and also prime locations for the development of urban areas, local amplification is a major concern in earthquake-prone regions. Macroseismic surveys of major earthquakes have led to the conclusion that in soft deposits with SPT value of 5, the damage potential of the earthquake must be increased by 2 degrees on the MM or MSK/EMS scale (in particular cases, an increment of 3 degrees is observed).

PGA: 10% probability of exceedance in 50 years for a generic rock.
Basically, site effects are associated with the phenomenon of the seismic waves travelling into soft soil layers. It is explained firstly by the lower velocity and density between unconsolidated sedimentary layers and the underlying rock (impedance contrast). For conservation of energy, this requires larger amplitudes and higher velocities of the seismic waves in the sediments: 

\[ c = \rho_1 \omega_1 u_1^2 = \rho_2 \omega_2 u_2^2 \]

with \( \rho_1 \) the rock density, \( \rho_2 \) the sediment density, \( \omega_1 \) the wave length in the rock material and \( \omega_2 \) the wave length inside the sediments and the wave velocities in the respective media.

Secondly, for a structure composed of sub-horizontal layers, body waves which travel up and down are the chief inputs. However surface waves generated by the structure are also trapped. Resonance patterns are created when trapped waves interfere (Figure 42). The shape and frequency content of such waves depends on the geometry and physical properties of the structure. Of course the degree of complexity of predicting a seismic response increases with the complexity of the structure. Resonance prolongs the duration of shaking, induce large amplifications. The main source of these phenomena is the development within the sedimentary basin of surface waves including the vertically polarized elliptical Rayleigh waves and horizontally polarized Love waves.

![Figure 42: Basin effect & trapped seismic waves](image-url)

The Swiss agency for Development and Cooperation together with the Royal society of Sciences performed a reflection seismic study, including the determination of the shear wave’s velocity. They were able to determine the spectral response including the basin effect. The related response spectral diagrams are shown on Figure 43 representative to North Water Intake location and Figure 44 representative of the pumping station area associated to North Water Intake. The works (pumping station, conveyance and the water intake to a certain extent) are buried, they have no eigen frequency and follow the response spectral.
Figure 43: Response spectral at North Water intake location

Figure 44: Response spectral at Pumping station location associated to North water intake
Conclusions

At northern water intake, at the related pumping station and at the conveyance between both works, the subsoil conditions are poor and heterogeneous: mostly slightly consolidated clay, and silt but also sand. This last would require special care when excavating below the groundwater table in order to avoid fluidization phenomena.

Poor conditions mean that the geomechanical properties may be as low as to have to consider at some places for clay undrained shear strength of 0.015 Mpa.

The considered area is also located at the wadi collecting various wadis which may undergo severe flash floods.

The area is also highly seismic and adjacent to the Arava fault. Basin effect which increase the earthquakes amplitudes (spectral response two times higher than at eastern intake with a similar expected seismicity magnitude, before site effects) are considerable, the liquefaction risk can’t be denied. Consequently the probability of damages linked to destructive earthquakes during the lifetime of the works is far of negligible.

In final conclusion, the fault activity at this considered area is in discredit of the northern intake. In addition, geotechnical properties of alluvial soils are poor and hydrogeological conditions are in discredit of underground structure (problems of pumping during the excavation works).

Tsunami risk has here also to be taken into consideration.
8 CONVEYANCE ROUTES OPTIONS

8.1 Tunnel Alignment Option 0.1

8.1.1 Introduction

This route starts at level 0 and descends progressively with a slope of 0.2% (2 m/km) till elevation -326, stretching on a length of 163 km. The main advantage of this alternative is that the sea water is conveyed by gravity, requiring thus not any pumping.

The route is located inside the eastern shoulder of the Arava valley and consequently on its total length in tunnel.

The tunnel route has been selected in order to fulfil a certain number of constraints or when it was not possible to fulfil all of them to find the best compromise.

These constrains are:

- To minimize the tunnel length, for cost evidences but also to minimize the hydraulic head losses;

- To minimize the tunnel lengths crossing mylonitic zones and the faults more specifically the strike slip ones. Their crossing requires mandatory advance drilling campaign and may require specific action. These operations increase the tunnelling cost and are time consuming;

- To locate the route at a reasonable distance of the Arava fault, which is active and not to cross it because a one to three meter slip during the lifetime of the conveyance route has to be considered;

- To limit the intersection number with the Aqaba-Gharandal fault to one, because this mainly normal fault is also active and that the vertical displacement for three hundred year is estimated to be 30 cm;

- To limit as far as possible the tunnel depth below the mountains of the eastern Arava valley margin, because a large depth may trig high hydrostatic pressure, will increase the earth pressure which may cause front bursting during the tunnel excavation. It also increases the underground temperature not only requiring more ventilation but also diminishing the reverses osmosis efficiency which is in inverse ratio to the to desalinate water temperature;

- In the northern part of the route to cross the wadis below the land surface;
8.1.2 Overview of the engineering geological conditions along the Alignment 0.1

The route is in tunnel from km 0 to km 163.0. The geological conditions along the alignment are summarised hereafter, more details are shown on drawings No. 111201, 111202, 111203 and longitudinal sections No. 111204, 111205, 111206.

The sources which have been used for the geological setting as described hereafter are the geological maps, the satellite and aerial photography’s analyses, field observations at the wadis cutting the eastern margin and two deep boreholes, one (BHAQ1) close to the Wadi Yutum in the south, 170.5 m deep and the other (BH-Q1) at Wadi Faddan in the north of 180.5 m depth. In wadi Yutum a seismic refraction survey has been performed.

The geological cross sections are the best interpretation, but conspicuously in the case this option would be preferred, the final tunnel design and route optimization would require an extensive geological investigation mainly made of boreholes up to 1000 m depth., for a 163 km long tunnel and 5 access galleries 37 investigation boreholes will be required. By lack of data, the groundwater levels are best estimated from extrapolation and using common expected groundwater gradients versus the aquifer type.

From km 0 to km 2.0: Very faulted and fractured granite (AJ), cross-cut by a lot of dykes. Ground Water Table (GWT) is located at maximum +30 masl; exceptional sudden increase at +100 masl is expected.

From km 2.0 to km 4.4: Very faulted and fractured granite (AJ), cross-cut by a lot of dykes. GWT is located at maximum +40 masl; exceptional sudden increase at +300 m asl is expected.

From km 4.4 to km 5.0: Crushed (mylonitic) granite with difficult excavation and support conditions. High pressure water inflow is expected. Probable continuous water table expected at + 40 masl.

From km 5.0 to km 18.6: Granite, some granodiorite cross-cut with abundant metric andesite dykes. Most NS trending faults located at the west of the route are avoided. At km 13 cross-cut of a major E-W trending fault which may behave as draining fault. Water problems may be expected there. Probable GWT is located at maximum +40 masl, exceptional sudden increase at +600 masl is expected. Locally from BHAQ1 borehole RQD values (<30% even <5%) are found until 170 m depth with traces of water circulation. The cores observation indicates the rock is intensely fractured. Six Lugeon (water) tests have been performed between 40 and 167 m depth, the obtained hydraulic conductivity ranges between $10^{-5}$ and $10^{0}$ m/s, which is surprising high for deep granite but conform to the observed fracturation. It also means the crystalline rock at least at this location is water bearing. The rock matrix unconfined compression strength varies inside a 30-800 MPa interval (average 350 MPa).

At km 14.0: Tunnelling cavity No. 0.1 at Wadi Yutum is not needed.

---

23 Deep from a geotechnical point of view.
From km 18.6 to km 31.5: Granite and monzonite. The plagioclase and feldspar content is higher, the rock is less abrasive but the geomechanical properties are slightly diminished when faults are crossed. This type of rocks is more ductile and consequently there is probably less cracks expected. Abundance of dykes mainly constituted of andesite and rhyolite. Non continuous water table has to be expected. Average GWT is +50 masl; exceptional sudden increase at +900 masl is expected.

At km 31.0: Tunnelling cavity No. 0.2 at Wadi Al Murtadi. Protection works for access portal have to be foreseen because there is a flooding risk as consequence to flash floods. The entrance portal has to be located 2 m higher than the highest expected flash flood level. The corresponding platform, made of earth fill, has to be large enough (at least 1000 m³) for the access gallery construction works and protected at its foot with gabions to avoid erosion.

From km 31.5 to km 42.6: Mainly granodioritic lithology (less ductile rock). Average GWT is +60 masl; exceptional sudden increase at +900 masl is expected. Several EW faults are crossed, a strike slip fault is crossed between km 41.2 and km 41.8, the rock may be mylonitic and excavation support problems may be expected.

From km 42.6 to km 51.2: Mainly monzogranite lithology. The plagioclase and feldspar content is higher, the rock is less abrasive but the geomechanical properties are slightly diminished when faults are crossed. This type of rocks is more ductile and consequently there is probably less cracks expected. Average GWT is +80 masl; exceptional sudden increase at +700 masl is expected.

From km 51.2 to km 63: Mainly granodioritic lithology (less ductile rock). Average GWT is +75 masl, exceptional sudden increase at +400 masl is expected.

At km 49.0: Tunnelling Cavity No. 0.3 with associated access portal located outside wadi. Protection works (digue) have to be foreseen in order to protect the installation for tunnel works against wadi bed changes after flash floods.

From km 63 to km 69: The deep geology of this section is not clearly defined. The probable lithologies are sandstone or granite. The lithological limit is uncertain. Average GWT is +100 masl. In sedimentary formations, severe water problems may be expected locally through permeable lithologies (sandstone/limestone; open joints) and close to faults.

From km 69 to km 74: Mainly in sandstone with other sedimentary formations as dolomite, limestone, shale. The tunnel is below the water table and severe water problems may be expected locally through permeable lithologies (sandstone/limestone; open joints) and close to faults. Average GWT is +125 masl.

At km 74.0: Tunnelling cavities No. 0.4. The associated access portal is located in a small wadi. Consequently, there is a flooding risk as consequence to flash floods. The entrance portal has to be located 2 m higher than the highest expected flash flood level (defined by H. Garros). The corresponding platform, made of earth fill, has to be large enough (at least 1000 m³) for the access gallery construction works and protected at its foot with gabions to avoid erosion.

From km 74.0 to km 80.5: Exogene Rhyolitic lithologies. No GWT is expected.

From km 80.5 to km 82.2: Gneissic and meta-sedimentary formations. Average local GWT is +125 masl.

From km 82.2 to km 100.4: Mainly granitic and granodioritic lithologies (less ductile rock). Average GWT is +125 masl; exceptional sudden increase at +300 masl is expected. Several faults (3 directions: NW-SE / NE-SW / NNE-SSW) are crossed. Water inflow problems may be expected close to fault crossing.
At km 96.5: Tunnelling cavities No. 0.5. The associated access portal is located in a small wadi. Consequently, there is a flooding risk as consequence to flash floods. The entrance portal has to be located 2 m higher than the highest expected flash flood level (defined by H. Garros). The corresponding platform, made of earth fill, has to be large enough (at least 1000 m²) for the access gallery construction works and protected at its foot with gabions to avoid erosion.

From km 100.4 to km 115.0: The conveyance crosses a particular area named “Wadi Az Zabda structure” (Barjous 1987). This area forms a triangle shape located between the Dead Sea Transform (DST) Fault and the Al Quwayra Fault zone. This area, where sedimentary rocks (Neocomian (KS) to Coniacian (WSL) aged) outcrops, is highly fractured and deformed either by faulting and folding. Two major fault trending NW & NE are noticed. Small scale folds are the structural features dominating in this area.

Indeed, this area is located close to the Gharandal Saddle which probably corresponds to a compression zone between two extensional pull-apart structures (Dead Sea and Gulf of Aqaba). The length of this compression zone along the conveyance is unknown but one observation is that the structural fracturation/faulting is well marked in sedimentary rocks. However, it is possible that the compression zone start at km 88 (Gharandal Saddle).

At km 115.0: The conveyance crosses the Al Quwayra Fault Zone. This one is a set of faults striking N to 5°N and extends over a distance of several hundreds of kilometres. This fault has a sinistral strike-slip movement. A total sinistral displacement of 40 km has been reported (Barjous, 1987). The system is also associated with vertical displacement up to 2.2 km.

This fault constituted the western boundary of a mountainous ridge facing Wadi Arava close to km 115. This ridge comprises mostly Ahaymir Volcanic (AM) and continues to the north up to a point where it is cut by the E-W trending Salawan fault.

From km 115.0 to km 139.0: Tunnel in granite and granodiorite. No major problems are expected.

At km 123.0: Tunnelling cavities No. 0.6.

At km 139.0: Tunnelling cavity No. 0.7 at Wadi Faddan is not needed.

From km 139.0 to km 149.5: Mainly granitic rocks like those observed in the borehole BH 270 m (in Wadi Faddan). This lithology is probably present up to km 149.5 where a normal fault takes place. This granite is covered by a thin layer made of primary sandstone and schists (BDS). The granite seems to have a high content of Uranium. Radioactive problems are expected (Radon particles). The alignment is located above GWT from km 143 to km 149.5. From BHQ1 borehole RQD values are low. The average is only 30%, between 80 and 180 and even 0% in the upper part of the granite. Until 180 m depth traces of water circulation are observed some are suspected to contain uraninite, which is an uranium mineral. The cores observation indicates the rock is intensely fractured. Nine Lugeon (water) tests have been performed between 88 and 179 m depth, the mean obtained hydraulic conductivity is \(10^{-6} \text{m/s}\), which is high for deep granite but conform to the observed fracturation. It also means the crystalline rock is water bearing. The rock matrix unconfined compression strength varies inside a 30-400 MPa interval.

From km 149.5 to km 163: Sedimentary rocks (mainly carbonate and sandstone). The conveyance is probably above de GWT (-180 masl) and 220-C lining scheme will be used.
8.1.3 Rock mechanical properties

For underground excavations and rock slope stability, the rock mechanical properties evaluation is based on empirical methods such as Bieniawski or Barton, normally based on close examination of samples from deep core drilling. It provides a single “number” (RMR or Q) summarizing the rock quality at the tunnel depth. From this RMR value an equivalent shear strength and internal friction angle are determined and derive from the RMR value a behaviour law equivalent to the Mohr Coulomb criteria for soil medium.

The rock behaviour law is parabolic and based on two well known parameters: m and s which determination is based on the RMR value.

In case the number of deep core drilling are not sufficient, Hoeck (MARINOS, P. & HOEK, E., 2000) has provided another double entry table (joint quality vs fracturing pattern) that could be used to infer this “number” without boring but requiring strong geological expert judgment. Although less reliable than actual boring (or even exploratory adits), it is the only tool available at this stage. An example of the table developed by Hoeck is shown in Figure 45.

Figure 45: Geological Strength Index table (MARINOS, P. & HOEK, E., 2000)

This table provides a range of GSI value. The GSI or Geological Strength Index is the classical RMR (Rock Mass Rating) from Bieniawski but without the correction factor related to the tunnel orientation and water occurrence.
The GSI values have been determined and are shown on the geological longitudinal cross section.

The joint pattern has been defined at several locations, which are at the wadis crosscutting the eastern shoulder of the Arava valley. They mostly are representative of the access galleries and it is assumed of the tunnel there.

Figure 46: Joints-fractures-faults directions represented on meridional stereographic net at Access portal 220-3, main joint directions: N155° dipping 45°SW
8.1.4 Access galleries

The geological cross sections of the access galleries are also attached to the longitudinal section. From field inspection no specific difficulty, related to the slope stability (static) raised at the tunnel and access galleries portals.

8.1.4.1 Access 0-2

- Length: 3000 m
- Slope profile - Geology (drawing No. 1112013):
  - From 0 to 200 m: Alluvial deposits (Alf)
  - From 200 to 2600 m: Quartz Diorite (MU)
  - From 2600 to 3000 m: Monzogranite (MN)
- Location (drawings No. 10-402 and No. 111201):
  - The access start outside of the wadi along the western mountain bank
  - The junction cavity is located at km 31.0

8.1.4.2 Access 0-3

- Length: 1315 m
- Slope profile - Geology (Drawing No. 1112013):
  - From 0 to 100 m: Alluvial deposits (Alf)
o From 100 to 1315 m: Monzogranite (TH-RA)

- Location (Drawings No. 10-403 and No. 111201):
  o The access start in the Arava valley along the western mountain bank
  o The junction cavity is located at km 49.0

8.1.4.3 Access 0-4

- Length: 2410 m
- Slope profile - Geology (Drawing No. 1112013):
  o From 0 to 200 m: Alluvial deposits (Alf) and marls (LM)
  o From 200 to 1150 m: Limestone (GN-TT) and conglomerate (DC)
  o From 1150 to 2410 m: Sandstone (IN-AK-SB) or igneous rocks
- Quantities: 174450 m³ of excavation.
- Location (Drawing No. 10-404 and No. 111202):
  o The access start in the small wadi located to Southwest.
  o The junction cavity is located at km 74.0

8.1.4.4 Access 0-5

- Length: 2660 m
- Slope profile - Geology (Drawing No. 1112013):
  o From 0 to 200 m: Pleistocene gravels and sand (PLG & PLS)
  o From 200 to 1450 m: Sandstone (AK) or Rhyolite (QB)
  o From 1450 to 2660 m: Volcanic rocks (MR-QB-MC)
- Quantities: 192540 m³ of excavation
- Location (Drawings No. 10-404 and No. 111202):
  o The access start along a road in gravel alluvial deposits
  o The junction cavity is located at km 96.5

8.1.4.5 Access 0-6

- Length: 3040 m
- Slope profile - Geology (Drawing No. 1112013):
  o From 0 to 50 m: Alluvial deposits (Alf-AI)
  o From 50 to 600 m: Limestone (WG-WSL-ASL/AHP)
  o From 600 to 3040 m: Volcanic rocks - Rhyolite (AM-BA)
- Location (Drawings No. 10-405 and No. 111203):
  o The access start along the road to Namla (located to the north of Petra)
  o The cavity is located at km 123.0
  o Topographical (High overburden) problems may be expected.
8.1.5 Hydrogeological conditions

The route is the last kilometres excluded, always below the water table and the risk of leakage is inexistent. The tunnel could be draining at a rate depending on its design and hydraulic rock properties. When passing below irrigated areas as Wadi Faddan, in order to avoid undesirable water abstraction, the lining design has to be adapted to limit the drainage at an acceptable amount.

8.2 Tunnel/Canal Alignment Option 220.1

8.2.1 Introduction

This route starts at level +0, the water is pumped up via a penstock to elevation 220. Further it descends progressively with a slope of 0.2% (2 m/km) till elevation -314, stretching on a length of 169 km.

The route is located for a significant part (3 segments of a total length of 118.6 km) inside the eastern shoulder of the Arava valley and consequently predominantly in tunnel. Two canal segments of 21.4 and 29 km complete the conveyance route.

The tunnel route has been selected in order to fulfil a certain number of constraints or when it was not possible to fulfil all of them to find the best compromise. They are the same as for 0.1 alternative and are given hereafter. They are:

- To minimize the tunnel length, for cost evidences but also to minimize the hydraulic head losses;

- To minimize the tunnel lengths crossing mylonitic zones and the faults more specifically the strike slip ones. Their crossing requires mandatory advance drilling campaign and may require specific action. These operations increase the tunnelling cost and are time consuming;

- To locate the route at a reasonable distance of the Arava fault, which is active and not to cross it because a one to three meter slip during the lifetime of the conveyance route has to be considered;

- To limit the intersection number with the Aqaba-Gharandal fault to one, because this mainly normal fault is also active and that the vertical displacement for three hundred year is estimated to be 30 cm;

- To limit as far as possible the tunnel depth below the mountains of the eastern Arava valley margin, because a large depth may trig high hydrostatic pressure, will increase the earth pressure which may cause front bursting during the tunnel excavation. It also increases the underground temperature not only requiring more ventilation but also diminishing the reverses osmosis efficiency which is in inverse ratio to the to desalinate water temperature;
8.2.2 In the northern part of the route to cross the wadis below the land surface;

- To be able to locate the access galleries at a reasonable elevation and distance of the tunnel, in any case never exceeding 3 km length. Access shafts have to be avoided.
- The obligation not to have any surface infrastructure in the Dana reserved area

8.2.2 Overview of the engineering geological conditions along the Alignment 220.1

This alternative can be subdivided into five main parts (plan views No. 111201, 111202 & 111203; longitudinal sections No. 111210, 111211 & 111212).

The sources which have been used for the geological setting as described hereafter are the geological maps, the satellite and aerial photography’s analyses, field observations at the wadis cutting the eastern margin and two deep boreholes, one (BHAQ1) close to the Wadi Yutum in the south, 170.5 m deep and the other (BH-Q1) at Wadi Faddan in the north of 180.5m depth. In wadi Yutum a seismic refraction survey has been performed.

The geological cross sections are the best interpretation, but conspicuously in the case this option would be preferred, the final tunnel design and route optimization would require an extensive geological investigation mainly made of boreholes up to 800 m depth., for 118.6 km tunnel and 2 access galleries 25 investigation boreholes will be required. By lack of data, the groundwater levels are best estimated from extrapolation and using common expected groundwater gradients versus the aquifer type.

- The first part in tunnel from km 0 to km 65.0:

  From km 0 to km 2.0: Strongly faulted and fractured granite (AJ), cross-cut by a lot of dykes. Ground Water Table (GWT) is located at maximum +30 masl, exceptional sudden increase at +100 masl is expected.

  From km 2.0 to km 4.4: Strongly faulted and fractured granite (AJ), cross-cut by a lot of dykes. GWT is located at maximum +40 masl, exceptional sudden increase at +300 masl is expected.

  From km 4.4 to km 5.0: Crushed (mylonitic) granite, even cataclastic, with difficult excavation and support conditions. High pressure water inflow may be expected. Probable continuous water table expected at + 40 masl.

  From km 5.0 to km 18.6: Granite cross-cut with abundant metric dykes. Most NS trending faults located at the west of the route are avoided. At km 13 cross-cut of a major E-W trending fault which may behave as draining fault. Water problems may be occurring. Probable GWT is located at maximum +40 masl, exceptional sudden increase at +600 masl is expected. Locally from BHAQ1 borehole RQD values (<30% even < 5%) are found until 170 m depth with traces of water circulation. The cores observation indicates the rock is intensely fractured. Six Lugeon (water) tests have been performed between 40 and 167 m depth, the obtained hydraulic conductivity ranges between 10^{-5} and 10^{-6}m/s, which is surprising high for

Deep from a geotechnical point of view
deep granite but conform to the observed fracturation. It also means the crystalline rock at least at this location is water bearing. The rock matrix unconfined compression strength varies inside a 30-800 MPa interval (average 350 MPa).

At km 14.0: Tunnelling cavity No. 1 at Wadi Yutm. Protection works for access portal have to be foreseen because there is a flooding risk as consequence to flash floods. The entrance portal has to be located 2 m higher than the highest expected flash flood level. The corresponding platform, made of earth fill, has to be large enough (at least 1000 m²) for the access gallery construction works and protected at its foot with gabions to avoid erosion.

From km 18.6 to km 31.5: Granite and monzonite. The plagioclase and feldspar content is higher, the rock is less abrasive but the geomechanical properties are slightly diminished by faults crossing. This type of rock is more ductile and consequently probably less cracks are expected. Abundance of dikes mainly constituted of andesite and rhyolite. Non continuous water table has to be expected. Average GWT is +50 masl, exceptional sudden increase at +900 masl is expected.

At km 31.0: Tunnelling cavity No. 2 at Wadi Al Murtadi. Protection works for access portal have to be foreseen because there is a flooding risk as consequence to flash floods. The entrance portal has to be located 2 m higher than the highest expected flash flood level. The corresponding platform, made of earth fill, has to be large enough (at least 1000 m²) for the access gallery construction works and protected at its foot with gabions to avoid erosion.

From km 31.5 to km 42.6: Mainly granodioritic lithology (less ductile rock). Average GWT is +60 masl, exceptional sudden increase at +900 m asl has to be considered possible. Several EW faults are crossed, a strike slip fault is crossed between km 41.2 and km 41.8, the rock may be mylonitic and excavation support problems may be expected.

From km 42.6 to km 51.2: Mainly monzogranite lithology. The plagioclase and feldspar content is higher, the rock is less abrasive but the geomechanical properties slightly diminished when faults are crossed. This type of rock is more ductile and consequently probably less cracks are expected. Average GWT is +80 masl, potential exceptional sudden increase at +700 masl is expected.

From km 51.2 to km 63: Mainly granodioritic lithology (less ductile rock). Average GWT is +75 masl, exceptional sudden increase at +400 masl.

At km 49.0: Tunnelling Cavity No. 3. Protection works have to be foreseen.

From km 63 to km 65: The deep geology of this section is not clearly defined. The lithologies are probable: sandstone or granite. The lithological limit is uncertain. Average GWT is +100 masl. With Sedimentary formations, severe water problems may be expected locally through permeable lithologies (sandstone/limestone; open joints) and close to faults.

- The second part in channel from km 65.0 to km 86.4:

The channel crosses 14 wadis, for which containment works have to be foreseen. The most important location where huge flash floods are expected is the Wadi Rakya, which divides into two streams which have to be crossed by the canal alignment, and the Wadi Burq. These two wadis may require large containment and canal protection works. Specific protection to avoid the formation of sand bars in the canal has to be foreseen. The canal route has been investigated with 10 test pits (TP1 Z1 to TP10 Z1) and two boreholes (BH1-Z1 and BH1-Z2) with SPT tests. The canal is built on alluvial fans and aeolian sands. For this latter, the sand is very
well sorted and the average size is 0.29 mm. Proctor curves (3 performed) are wide spread with an optimum moisture content between 6 and 11.2%. The N of the SPT tests is always much larger than 50. It means high geomechanical properties.

The geomechanical properties are best estimated: internal friction angle of 35° for aeolian sand and 40° for alluvial deposits, which are well graded.

- The third part in tunnel from km 86.4 to km 116.0:

From km 86.4 to km 100.4: Mainly granitic and granodioritic lithologies (less ductile rock). Average GWT is +125 masl, exceptional sudden increase at +300 masl is expected. Several faults (3 directions: NW-SE / NE-SW / NNE-SSW) are crossed. Water inflow problems may be expected close to fault crossing. 

From km 100.4 to km 116.0: The conveyance crosses a particular area named “Wadi Az Zabda structure” (Barjous 1987). This area forms a triangle shape located between the DST Fault and the Al Quwayra Fault zone. This area, where sedimentary rocks (Neocomian (KS) to Coniacian (WSL) aged) outcropping, is highly fractured and deformed either by faulting and folding. Two major fault trending NW & NE are noticed. Small scale folds are the structural feature dominated this area.

Indeed, this area is located close to the Gharandal Saddle which probably corresponds to compression zone between two extensional pull-apart structures (Dead Sea and Gulf of Aqaba). The length of this compression zone along the conveyance is unknown but one observation is that the structural fracturation/faulting is well marked in sedimentary rocks. However, it’s possible that the compression zone starts at km 91 (Gharandal Saddle).

- The fourth part in channel from km 116.0 to km 145.0:

The channel crosses 9 wadis, for which containment works have to be foreseen. The canal is mainly built on alluvial fans, aeolian sands and alluvium, but mostly on coarse fan deposits. Between km 119 and km 125, the canal is locally built on sedimentary rocks.

Specific protection to avoid the formation of sand bars in the canal has to be foreseen.

The canal route has been investigated with 15 test pits (TP1Z2 to TP15Z2), 4 boreholes (BH1Z2, BH3Z2, BH4Z2, and BH5Z2) with SPT tests. The fan deposits are coarse, well graded with a medium size of 22 mm. Proctor curves (3 performed) are wide spread with an optimum moisture content between 7 and 9%. The N of the SPT tests is always much larger than 50. It means high geomechanical properties which are best estimated: internal friction angle of 45° for the fan deposits.

At km 138.0 and km 143.0: The conveyance route crosses Salawan fault and Dana fault.
The fifth part in tunnel from km 145.0 to km 169.0:

This tunnel part is slightly moved to the east in order to pass below the valley close to km 161.0. The conveyance is probably above de GWT (~180 masl) and 220 lining scheme will be used. Tunnel located mainly in sedimentary rocks (mainly carbonate and sandstone). The conveyance crosses the Burj Dolomite Shale Formation (BDS) which is known for its high content of Uranium. Few mining excavation and exploration have been done close to the km 146. Mitigation measures are required for radon when tunnel excavating and identification of rock debris contains uranium. These wastes have to be stored separately.

8.2.3 Rock mechanical properties

For underground excavations and rock slope stability, the rock mechanical properties evaluation is based on empirical methods such as Bieniawski or Barton, normally based on close examination of samples from deep core drilling. It provides a single “number” (RMR or Q) summarizing the rock quality at the tunnel depth. From this RMR value an equivalent shear strength and internal friction angle are determined and derive from the RMR value a behaviour law equivalent to the Mohr Coulomb criteria for soil medium.

The rock behaviour law is parabolic and based on two well known parameters: m and s which determination is based on the RMR value.

In case the number of deep core drilling are not sufficient, Hoeck (MARINOS, P. & HOEK, E., 2000) has provided another double entry table (joint quality vs fracturing pattern) that could be used to infer this “number” without boring but requiring strong geological expert judgment. Although less reliable than actual boring (or even exploratory adits), it is the only tool available at this stage. An example of the table developed by Hoeck is shown in Figure 45.

This table provides a range of GSI value. The GSI or Geological Strength Index is the classical RMR (Rock Mass Rating) from Bieniawski but without the correction factor related to the tunnel orientation and water occurrence.

The GSI values have been determined and are shown on the geological longitudinal cross section.
Figure 48: Joints-fractures-faults directions represented on meridional stereographic net at Wadi Yutum (Access 220-1), main joint direction: N135° dipping 55°NE

Figure 49: Joints-fractures-faults directions represented on meridional stereographic net at Access portal 220-3, main joint directions: N35° dipping 85°SE; N142° dipping 85°SW; N130° dipping 5°NE
8.2.4 Access galleries

The geological cross sections of the access galleries are also attached to the longitudinal section. From field inspection no specific difficulty, related to the slope stability (static) raised at the tunnel and access galleries portals.

8.2.4.1 Access 220-1

- Length : 610 m
- Slope profile - Geology (drawing No. 1112013):
  - From 0 to between 30 and 50 m : Alluvial deposits (Al)
  - From (30)50 to 610 m: Granite (AJ). The weathered or deconsolidated granite doesn’t exceed 10 m (see refraction profile of Figure 50: Seismic refraction profile No. 2 (SRP2) at Wadi Yutum (Access 220-1).

![Figure 50: Seismic refraction profile No. 2 (SRP2) at Wadi Yutum (Access 220-1)](image)

- Quantities : 47910 m³ of excavation
- Location (drawings No. 10-402 and No. 111201):
  - The access start in Wadi Yutum just at the exit in the Arava valley
  - The cavity is located at km 14.0

8.2.4.2 Access 220-2

- Length : 2020 m
- Slope profile - Geology (drawing No. 1112013 :
  - From 0 to 100 m : Quartzitic Diorite (MU)
  - From 100 to 2020 m : Monzogranite (MN)
- Quantities : 158650 m³ of excavation
- Location (drawings No. 10-402 and No. 111201):
  - The access start at the entrance of wadi Al Muthadi
  - The cavity is located at km 31.0
8.2.5 Seismic hazard to canal part

The risk of canal damage when embanked is that of a building with an Eigen frequency roughly estimated of about 0.5 Hz (period of 2 s). For canal section, in regards of lithologies, the best estimated response spectral is given on Figure 51. According to this figure and a period of 2 s, the correspondent acceleration is 0.2 g.

![Response Spectral for Pleistocene gravel](image)

**Figure 51: Response spectral at for canal sections**

8.2.6 Hydrogeological conditions

The route is likely always above the water table and the risk of leakage is a crucial issue because the Arava fill aquifer is a major resource of the region water supply. Impermeability of the conveyance has to be ensured and monitored.

8.3 Other geological constraints to the tunnels of alignments 0.1, 220.1 and pipeline option (radioactive hazard excepted)

8.3.1 Seismicity

The PGA according the Ambraseys acceleration attenuation relationship is 0.2g. But underground structures like tunnels are less sensitive to seismic damages compared to surface structures as buildings and bridges, because tunnel structures are constrained by the surrounding ground and, in general, can not be excited independently of the ground or be subject to strong vibratory amplification. Another factor contributing to the lower

---

35 Taken from the most similar geological setting of the Aqaba region and determined by the Swiss Agency of Cooperation and the Royal Institute of Sciences.
vulnerability of tunnel to earthquake is that the amplitude of seismic ground motion tends to reduce with depth below the ground surface.

An earthquake generates two types of waves:

- **Body waves** travelling within the earth’s material. Those waves may be either longitudinal P waves or transverse shear S waves. They can travel in any direction in the ground and are the first to arrive ground deformation coming from the longitudinal waves is limited but relatively more important for the shear waves.

- **Surface waves**, they include the Love waves moving material back and forth in a horizontal plane perpendicular to the wave movement direction; the Rayleigh waves moving the material in an elliptical path in a plane parallel to the wave direction. Their velocity is much lower than the body waves and their arrival is delayed but their amplitude is much higher and causes the surface to undulate and shake from side to side. They are the most destructive but absent at a certain depth.

Adequate design and construction of seismic resistant tunnel structures, however, should never be overlooked, as moderate to major damage has been experienced by many tunnels during earthquakes. The greatest incidence of severe damage has been associated with large ground displacements due to fault rupture through a tunnel, land sliding (especially at tunnel portals) and soil liquefaction. Fault rupture can and has had very damaging effects on tunnels. Tectonic uplift and subsidence can have similar damaging effects to fault rupture, if the uplift/subsidence movements cause sufficient differential deformation of the tunnel.

In cases where the tunnel structure is stiff relative to the surrounding soil some damage has been observed and the effect of soil-structure interaction must be taken into consideration.

Other critical conditions that warrant special seismic considerations include cases where a tunnel intersects or meets another tunnel. Under these conditions, the tunnel structure may be restrained from moving at the junction point due to the stiffness of the adjoining structure, thereby inducing stress concentrations at the critical section.

Consequently in our case the risk of tunnel damage is limited:

- to the portals because in the case of earthquakes they may be affected by surface waves and landslides;

- to the intersections of the tunnel and the access tunnels, therefore their seismic design and analysis should be based primarily on the ground deformation approach (as opposed to the inertial force approach); i.e., the structures should be designed to accommodate the deformations imposed by the ground ;when possible, they should be structurally independent.

- to faults movements, their amplitude would be limited since the tunnel does not cross the Arava fault. Nevertheless some minor movements may affect mainly the lining complex and its impermeability. After each earthquake (Mw>5) a remote inspection will be required.
In addition the proposed lining complex will include a Precast Concrete Tunnel Lining. Due to the jointed construction and resulting inherent flexibility, PCTLs are able to accommodate ground shaking with little or no damage compared to stiffer forms of lining. PCTL systems have been used extensively in seismically active locations, including Japan, Iran, Taiwan, Mexico, Turkey, and are generally specified for bored tunnel construction in seismic areas. In case of earthquake only the inner lining could be damaged.

8.3.2 Geothermic gradient and effects of temperature on the seawater conveyed in the tunnel

This problem has been highlighted from observation of high overburden along the layout of alternative 0.1. The geothermal gradient in Jordan is reported to range from 3.6 - 4.5°C/100 m. (Saman, J., 1999). Considering a geothermic gradient of 4°C per 0.1 km, a table of temperature increase has been developed. It is at km 14 that the highest rock temperature would be reached 60 to 65°C at the tunnel. In case of risk of main water inflow, the TBM will bore in closed way if only dropping is expected, the workers will work under a canopy provided by the lining. The human interventions have to be limited to a minimum. We mention the Alpine tunnels and more recently the Gothard tunnel, bored at 2000 m depth faced successfully similar temperature hazards.

8.3.3 Radioactive hazard

Radioactive minerals are naturally present in Precambrian igneous rocks especially below the Dana Reserve (between km 144 to km 149.5). U-rich minerals have been observed in the deep borehole performed in wadi Faddan (BH-Q1). In addition, few Uranium mining exploration surveys have been performed in the past. They are located on geological map (see on drawing No. 111203).

Radon may be generated and special caution is required during the excavation works. The radioactivity level of the rock fragments has to be measured. In the case it is considered as radioactive waste the project needs to find particular waste disposal area fulfilling the IAEA rules for rad waste management. The uranium concentration is not known, only evidences of hexavalent uranium minerals have been observed in one of the boreholes of the geological investigation we performed. Hexavalent uranium minerals are mostly yellow; they are called secondary uranium minerals since they are the alteration of primary minerals as pitchblende (black color). In our case they coat granite cracks as a result of water circulation along these cracks. It is not known if the water is leaking from the upper layered sedimentary formations (shales) or by hydrothermally convection from a deeper in uranium enriched body. The uranium content has been estimated to 30ppm and would not exceed 300 ppm (Jamal Alali November 2006, Oil shale, availability, distribution, and investment opportunity - Recent Trends in Oil Shale, 7-9 Amman, Jordan). Also referring to similar uranium deposits, its content will likely not exceed a few percent. In the worst case the total spoil would be 2 Mton. If the tunnel alternative is preferred, the required additional investigations could allow having a better idea of the uranium content that could be found in the spoil and could be classified as inert, very low radioactive waste or low radioactive waste. We assume the second is the most likely (VLRW). With a Geiger counter it is then possible to sort out the VLRW from the inert spoil and to sort the VLRW in an adequate storage which design is similar to that of a hazardous industrial waste. For the handling Uranium itself is only slightly radioactive. However radon, a radioactive gas, is released in very small quantities when the rock containing the uranium is mined and crushed. Radon, one of the decay products of uranium and radium, occurs naturally in most
rocks and minute traces of it are present in the air which we all breathe. But at the relatively high concentrations associated with uranium, radon is a potential health hazard. Consequently special precautions are taken during the tunnel excavation process to protect the health of the workers. These precautions include:

- Efficient dust control, because the dust may contain radioactive constituents and emit radon gas.
- Limiting the radiation exposure of workers in mine, mill and tailings areas so that it is as low as possible, and in any event does not exceed the allowable dose limits set by the Health Code.
- The use of radiation detection equipment, if necessary a sas is foreseen behind the TBM.
- Good forced ventilation systems to ensure that exposure to radon gas and its radioactive daughter products is as low as possible and does not exceed established safety levels.
- Imposition of strict personal hygiene standards for workers because if uranium oxide is ingested it has a chemical toxicity similar to that of lead oxide.

By uranium contaminated groundwater hazard. For alternative 0.1, according to the geological profile given in the appendix H (drawing No. 10-1206) the tunnel in the uranium zone (pk 135 to pk 150) is partly below the water table and partly above. When below, the tunnel will be bored in closed mode so that no water inflow is possible.

8.4 Tunnel/Pipeline Alignment Option

8.4.1 Overview of the engineering geological conditions along the pipeline alignment

This alternative can be subdivided into 2 main parts (tunnel & pipeline)(plan views No. 111201, 111202 & 111203; longitudinal sections No. 111221, 111222 & 111223).The geology can be summarised:

The pipeline investigation investigations are 10 boreholes BHPL1-10, ten meter deep and twenty test pits (TPL1-TPL20).

- The first part in tunnel from km 0 to km 25.5:

  From km 0 to km 2.0: Strongly faulted and fractured granite (AJ), cross-cutted by a lot of dykes. Ground Water Table (GWT) is located at maximum +30 masl, exceptional sudden increase at +100 masl is expected
From km 2.0 to km 4.4: Strongly faulted and fractured granite (AJ), cross-cut by a lot of dykes. GWT is located at maximum +40 masl, exceptional sudden increase at +300 masl is expected.

From km 4.4 to km 5.0: Crushed (mylonitic) granite, even cataclastic, with difficult excavation and support conditions. High pressure water inflow may be expected. Probable continuous water table expected at + 40 masl.

From km 5.0 to km 17.9: Granite cross-cut with abundant metric dykes. Most NS trending faults located at the west of the route are avoided. At km 13 cross-cut of a major E-W trending fault which may behave as draining fault. Water problems may be occurring. Probable GWT is located at maximum +40 masl, exceptional sudden increase at +600 masl is expected. The tunnelling cavity No. 1 is located at Wadi Yutum (km 14). Protection works for the entrance gallery and access infrastructure as cofferdams have to be foreseen to avoid their destruction during flash floods. The cores observation indicates the rock is intensely fractured. Six Lugeon (water) tests have been performed between 40 and 167 m depth, the obtained hydraulic conductivity ranges between $10^{-5}$ and $10^{-6}$ m/s, which is surprising high for deep granite but conform to the observed fracturation. It also means the crystalline rock at least at this location is water bearing. The rock matrix unconfined compression strength varies inside a 30-800 MPa interval (average 350 MPa).

From km 17.9 to km 20.0: Undifferentiated Yutum granitic lithology, strongly faulted and fractured. This igneous body is cross-cut with abundant metric dykes and by 3 main faults. This granitic body is a part of the xenolithic belt.

From km 20.0 to km 22.1: Monzogranite to monzonite. The plagioclase and feldspar content is higher, the rock is less abrasive but the geomechanical properties are slightly diminished by faults crossing. This type of rock is more ductile and consequently probably less cracks are expected than in granite. Abundance of dikes mainly constituted of andesite and rhyolite.

At km 22.1: The conveyance alignment crosses the Aqaba-Gharandal fault, which is a normal fault with associated offset motion expected.

From km 22.1 to km 25.5: Alluvial fan made of silt, sand, gravels, igneous cobbles and boulders. This type of deposits is strongly heterogeneous. The last 1500 m are in covered trenches.

- The second part in pipeline from km 25.5 to km 175.7:

From km 25.5 to km 44.5:

- **Lithology on geological map:** AL
- **Geotechnical Survey (GS) Item:** TP3(PL)-TP4(PL)-TP5(PL) / BH-PL 2
- **Lithologies from GS:** Mainly sandy alluvial deposits
- **ASTM:** SW-SC-SP
- **Groundwater level:** +26.21 m at km 36.
From km 44.5 to km 52.0:
- **Lithology on geological map**: ALM
- **Geotechnical Survey (GS)** Item: TP7(PL) / BH-PL 3
- **Lithologies from GS**: Silty clay to clayey silt with minor silty sand
- **ASTM**: SM-SC-SW
- *The groundwater level is close to the surface.* High risk of liquefaction.

From km 52.0 to km 83.9:
- **Lithology on geological map**: ALS
- **Geotechnical Survey (GS)** Item: TP8(PL)-TP9(PL)-TP10(PL) / BH-PL 4 / GR3
- **Lithologies from GS**: Mainly Aeolian sand deposits with minor alluvial sand. There is loose sand (50%) and silty-clay cemented sans (50%)
- **ASTM**: SW-SC-SP
- **Groundwater level**: +100.00 m at km 66 and +88.35 m at km 73.

From km 83.9 to km 86.0:
- **Lithology on geological map**: ALM
- **Geotechnical Survey (GS)** Item: TP11(PL)
- **Lithologies from GS**: Fine grained sandy silt to clayey silt
- **ASTM**: SW-SC-SP

From km 86.0 to km 93.0:
- **Lithology on geological map**: Sedimentary rocks (Limestone). Geological properties are unknown but probably rippable.
- **Geotechnical Survey (GS)** Item: /
- **Lithologies from GS**: /

From km 93.0 to km 156.0:
- **Lithology on geological map**: AL-ALO-ALS-PLG
- **Lithologies from GS**: Alluvial coarse deposits uncemented or slightly cemented.
- **ASTM**: GW-GC-GP
- **Groundwater level**: +117.17 m at km 110 and -164.77 m at km 140.

From km 156.0 to km 168.5:
- **Lithology on geological map**: ALS
- **Geotechnical Survey (GS)** Item: TP18(PL)-TP19(PL) / BH-PL 9
- **Lithologies from GS**: Loose to very loose Aeolian sand.
- **ASTM**: SW-SC-SP
From km 168.5 to km 173.9:

- **Lithology on geological map**: Lisan Marl (LM)
- **Geotechnical Survey (GS) Item**: TP20(PL) / BH-PL10
- **Lithologies from GS**: Described lithologies seem to be similar to Aeolian sand.
- **ASTM**: /
- **Groundwater level**: -321.53 m at km 170.

From km 173.9 to km 175.7:

- **Lithology on geological map**: AL-ALF
- **Geotechnical Survey (GS) Item**: TP1(i7)-TP2(i7)-TP3(i7)-TP4(i7)
- **Lithologies from GS**: Silty clay to clayey silt
- **ASTM**: SW-SC-SP
- **Groundwater level**: -394.92 m at km 175.

### 8.4.2 Salt tectonics

Actively rising salt diapirs are common in the Jordan Valley and the Dead Sea Basin (Al-Zoubi and ten Brink, 2001; Larsen et al., 2002). The rising rates are detectable by InSAR (Shimoni et al., 2002; Weinberger et al., 2006) and past deformation is ubiquitous in the vicinity of the Sedom diapir, the only exposed one (Levi et al., 2006; Marco et al., 2002). Hence, long-term deformation of the surface has to be accounted for.

### 8.4.3 Seismicity

The PGA according to Boore (1997) acceleration attenuation relationship is 0.15 g. But since the pipe is buried it is less sensitive to seismic damages compared to surface structures because buried pipes are constrained by the surrounding ground and, in general, can not be excited independently of the ground or be subject to strong vibratory amplification.

Nevertheless it is submitted to the body waves and surface waves with higher amplitudes and causing the surface to undulate and shake from side to side. It requires adequate design.

More crucial is the pipeline section crossing the Arava fault with a potential slip of to several meters. It is between PK83.9 and 85.7 and more probably close to PK 85. At this location there is an uncertainty on the fault location and it may be there separated into several branches. Paleoseismic trenches will be required in order to accurately fix in number and locations the special design able to afford the coseismic slip.

### 8.4.4 Hydrogeological conditions

The route is likely always above the water table and the risk of leakage is a crucial issue because the Arava fill aquifer is a major resource of the region water supply. Impermeability of the conveyance has to be ensured and monitored.
9 ENGINEERING GEOLOGICAL CONDITIONS AT THE DIFFERENT DOWNSTREAM WORKS

Initially three locations had been considered for the desalination plant mainly based on topographical conditions, one of them (zone B) was excluded because it would have inferred huge excavation works and is located above an aquifer without any geological barrier. So only 2 locations are still further considered:

- **Zone A**: low level (-350 m) location close to the Dead Sea, this area includes also the hydropower plant location.

- **Zone C**: at the eastern side of the Dead Sea just at the northern boundary of the Dana natural reserve.

- **Zone D**: more southward of zone A in the Arava valley and only to be considered for the pipeline option combined with the high level desalination plant.

![Desalination plant areas locations on geological map](image)
9.1 Desalination Plant Area C for Conveyance Alignment Options 0.1 and 220.1

Introduction

Two platforms (-30 m and +185 m) are still under consideration relative to both alignment options (Figure 52). The lithological conditions are quite similar for both sites. The substratum is mainly made of marl and limestone (estimated friction angle of 30° and undrained shear strength of 0.5 MPa). The continuous water table is expected to be found at about -320 m. The main difference between the two platform location conditions are related to the seismic risk and geomorphologic features.

Several Trial pits (8) and Seismic Refraction profiles (5) have been performed in each area. Locations of these investigations are shown on Figure 54 and Figure 55.

Figure 53: Desalination plant areas for alignment options 0.1 (West) and 220.1 (East) (image from Google earth)
**Desalination plant location for Alignment option 0.1**

From Investigations results, we can summarize the geological conditions as follows:

- The observed formations in the rial pits are very variable. From clay (TP-i8-3) to limestone (TP-i8-2), all intermediate lithologies (marl, clayey marl, marly limestone) are observed. Talus deposits are also observed close to the area limits (TP-i8-4; TP-i8-5; TP-i8-8).

- Seismic Refraction profiles indicate that:
  - fair rock ($v > 2500$ m/s) is observed at minimum 30 m below the ground level
  - the thickness of very poor rock/soil ($v < 1500$ m/s) ranges from 2 to 8 m deep except in profiles No. 2 and No. 5 where the depth could reach 12 and 25 m respectively.
  - Fracturation axes are observed in profiles No. 2 (close to the south eastern end of the profile) and profile No. 4 (in its central part).

![Aerial photography with localization of the performed investigations](image_url)

*Figure 54: Aerial photography with localization of the performed investigations (Image from Google Earth) at the Desalination plant area for Alignment option 0.1*
Desalination plant location for Alignment option 220.1

From Investigations results, we can summarize the geological conditions as follows:

- The observed lithologies in trial pits are mainly marly to dolomitic limestone (TP-i9-1; TP-i9-2; TP-i9-4; TP-i9-6; TP-i9-7; TP-i9-8) but clay may be also observed in the central part of the area in association with large gypsum grains (TP-i9-3; TP-i9-5).

- Seismic refraction profiles indicate that:
  - fair rock (v > 2500 m/s) can reach 15 m thickness (profile No. 2 close to end of profile) and 20 m depth (profile No. 4 in its central part) below the ground surface. In other profiles, the good rock is located much deeper (more than 30 m for profile No. 1 and more than 40 m for profiles No. 3 & 5).
  - The thickness of very poor rock/soil (v < 1500 m/s) is often 10 m but it can reach 20 m as in profiles 4 and 5.
  - Fracturation axes are observed in profiles No. 2 (close to the southern end of the profile) and profile No. 5 (in the central part).

- Geomechanical properties for the desalination plant locations of both alignment options.

No results of specific geomechanical tests are available, but from the visual inspection of wells, the observed landslide and the measured longitudinal waves velocity, the best estimate of the friction angle is about 40° and a shear strength of 1 MPa for the fair rock, for the overlaying poor rock, the friction angle should be limited to 32° with no shear strength.

Figure 55: Aerial photography with localization of performed investigations (Image from Google Earth) in the Desalination plant area for Alignment option 220.1
Seismicity

The Arava fault is passing just at the east of the area C (Figure 53). Obviously the risk of destruction will be higher close to the fault. It can be argued that from a seismological point of view, the area look to be quiescent since more than 400 to 500 year, the last serious event is that of the 14th century causing a wall displacement of 2 m in the water tank of a Byzantine fortress (Tilah Castle) located a few km to the north of the considered area exactly on the Arava fault. The seismicity has been estimated. Therefore the PGA of the area has been determined using Boore (Boore, D.M., Joyner, W.B. & Fumal, T.E., 1997) and Ambraseys (Ambraseys, N.N., Douglas, J., Sarma, S.K. & Smit, P.M., 2005) attenuation laws. The calculated values are respectively 0.25 and 0.20 g for generic rock.

The desalination plant area of Alignment option 0.1 seems to be also affected by two normal faults which are indicated on the geological map (Figure 57).

In this case also, from the survey and the study of the Swiss Agency for Development and Cooperation together with the Royal Society of Sciences performed, as far as the areas with topographical effects are avoided, the response spectral the closest to the field conditions we have at this location is shown on Figure 56.

If we consider the Eigen frequency of the desalination plant between 3 and 4 Hz (period of 0.25-0.33 s), the corresponding acceleration is 0.5 g.

![Response Spectral for Rock](#)

**Figure 56: Response spectral at Desalination plant area C**

---

PGA : 10% probability of exceedance in 50 years for a generic rock.
Figure 57: Probable normal faults localization (from aerial photography analysis)
Site effects

About site effects, the rock soft layers effect and basin effect have here for the geological conditions we have with relatively dense rock as came out from the refraction seismic survey, not to be considered. At the other hand a topographical site effect is possible (Figure 58). With this effect the waves are focused on the top of a convex hill.

![Figure 58: Topographical site effect conceptual scheme](image)

In the particular case of desalination plant area C, several potential topographical site effects are observed (Figure 59). These areas have to be avoided for the construction of the desalination plant.

![Figure 59: Aerial photography with potential site effect localization (Image from Google Earth)](image)
Conclusions

Geomechanical properties of the sound bedrock are fair, while the conditions of the upper meters are poor. The groundwater table is at large depth. Even some marl is expected below the construction area, since no significant less permeable layers are shown between the surface and the deep aquifer, at the plant itself the surface must be made impermeable in order to avoid any contamination (from chemicals and sea water). For both locations a serious seismic risk exists. The seismic risk is probably higher for the desalination plant area of alignment option 0.1. Site effects are possible and more marked for the desalination plant area of alignment option 0.1. But in any case, all platforms will require heavy paraseismic construction, but nevertheless significantly less than at the A location.

9.2 Desalination plant & Hydro Power Plant Area A

Introduction

The desalination plant area A is located close to the evaporation pounds of Arab Potash and Dead Sea Works. From the geological map, this area is made of alluvial formation (Alf – Al; Figure 52)

Several investigations have been performed in this area (Figure 60):

- 11 boreholes, 10 of 10 m depth (BHi7-1-BHi7-10), all with standard penetration tests (SPT) and one of 50 m depth.
- 10 Seismic Refraction profiles (i7SR1-i7SR10), 240 m length,
- 20 Georesistivity tomographies (i7GR1-i7GR20), 240 m length.
Figure 60: Limits of Desalination plant area A and localization of performed investigations (Image from Google Earth)
**Investigation survey results**

Lithogological data from boreholes are as follows:

- Until 10 m depth, yellow to brown, medium to fine grained sand is observed. Some small clayey silt intercalations are observed. No water table was observed.

- In borehole i7-BH-11, 50 m deep, one observes fine sand till 10 m depth and deeper the alluvial deposits become coarser with gravels and boulders of limestone. The water table is observed 12 m below the ground level (approximately -350 masl).

Results of seismic refraction profiles give for the total concerned area, homogenous longitudinal wave’s velocities of 650 m/s translating that till a multi-metrical depth and the full considered area one has from a compaction point of view, a homogenous body. There are no evidences that a refracted horizon has been reached (excepted at the end geophones of the array; Figure 61). It means that the thickness of this homogenous body should be at least 70 m thick and the aquifer is reached at this depth (from end geophones information). It also means that no groundwater has been found till that depth.

![Figure 61: T-X data of profile No. 8 at Desalination plant area A](image)

Otherwise a refractor with a longitudinal wave velocity of 1500 m/s should have been identified on several geophones. It is in contradiction with the regional available piezometric map and with the results of the observed groundwater level of the 50 m deep borehole, where it is found at 12 m depth, corresponding to an elevation of – 360 m. The evaporation pounds with the water level elevation estimated at – 400 is at 5 km of the deep borehole. The inferred groundwater gradient is 40m/5000 m or 0.8 % which is quite high and unlikely for a sandy aquifer.
Considering the water table is at 70 m depth (at elevation - 420 m), the corresponding groundwater slope is 2‰ which is more likely. Lessing better we consider the groundwater in the current conditions at 70 m depth (elevation - 420 m) which is in agreement with the depth obtained of the regional water table depth (see Figure 29: Hydrogeological mapping (depth to water) of Quaternary Alluvium Groundwater between the Red Sea and the Dead Sea.) and the occurrence of locally perched water tables\(^\text{37}\) as could be observed in the deep borehole.

The interpretation of the georesistivity profiles, allow distinguishing two areas:

- The first area is located at the north, central-east and southern boundary\(^\text{38}\) with high conductivity or low resistivity (\(\rho = 4\) to \(5 \Omega\).m) up to 30 m deep (Figure 62). This low resistivity may be interpreted as occurrence of large amount of clay interbedded in the sand or the occurrence of some damp salty layers of sand.

- The second area is located at the eastern and southern part of the investigated area with high resistivity (\(\rho = 150\) to \(>450\Omega\).m) in the upper 20 m (Figure 63). The latter certainly corresponds to dry sand or silty sand.

It is important to notice that no salt even in traces has been observed in the cores of the 50 m deep borehole. The first interpretation looks then the most likely.

![Figure 62: Georesistivity profile No. 2](image)

---

37 A perched water table (or perched aquifer) is an aquifer that occurs above the regional water table, in the vadose zone. This occurs when there is an impermeable layer or even a relatively impermeable layer (aquitard) above the main /aquifer.

38 At the southern boundary what could have been interpreted as a deep conductive layer is in fact a lateral and southern conductive body.
The SPT results give after correction (, Skempton, A.W., 1986) at 10 m depth, a N value between 32 and 54. and closer to the surface between 30 and 40, the corresponding angles of friction are between 45° and 50° at 10 m depth and at least 45° at 1 m depth (. SCHMERTMANN,J.H., 1975). These values are high but may be expected for dry sand.

**Seismicity**

The proximity of the Arava and Khunayzir faults, both potentially destructive makes this area very sensitive to earthquakes. The seismicity has been estimated; therefore the PGA of the area has been determined using Boore (, BOORE, D.M., JOYNER, W.B. & Fumal, T.E., 1997) and Ambraseys (, AMBRASEYS, N.N., DOUGLAS, J., SARMA, S.K. & Smit, P.M., 2005) attenuation laws. The calculated values are respectively 0.25 and 0.20 g for generic rock.

**Liquefaction risks**

At 8km of the study area spectacular clastic dikes (Figure 64) have been observed in similar geological formations as we have here, they testify liquefaction phenomena as previously explained (Figure 40).

At the other hand, even considering the occurrence of a perched aquifer, taking into consideration the results of the SPT tests with N values after correction always above 30 and meanly around 40 and applying the simplified method of Seed and Idriss, there is clearly no risk of liquefaction until an earthquake of Mw =7.5.

---

**Figure 63: Georesistivity profile No. 10**

PGA: 10% probability of exceedance in 50 years for a generic rock.
Figure 64: Clastic dike photography


Site or basin effect

Also a few km at the west, laminated formations folded to give seismsites are observed in similar formations as at the site. They are a consequence of earthquake events. The biggest seismite until now observed in the world has been found in this district (Figure 65).

Figure 65: Folded laminated formations into seismite
As described, seismite can be a consequence of earthquake events but site effects (rock/sediment and resonance) can increase earthquake capability. Indeed, wave resonance can be observed in sediments following few parameters:

- Thickness of sediment layer
- Geotechnical properties of these sediments and particularly the density.

The site configuration is typical of that one which generates basin effects (Figure 66). This site effect may increase the magnitude of one unit.

From the survey and the study of the SDC (SWISS AGENCY FOR DEVELOPMENT AND COOPERATION (SDC), 2009) together with the Royal Society of Sciences performed, the response spectral the closest to the field conditions we have at this location is shown on Figure 67.
Figure 67: Best estimated response spectral at the Desalination plant & hydropower plant area A

If we consider the Eigen frequency of the desalination plant between 3 and 4 Hz (period of 0.25-0.33 s), the corresponding acceleration is 1.1 g and the Eigen frequency of the hydropower plant between 5 and 6 Hz (period of 0.15 – 0.2 s), the corresponding acceleration is between 0.9 and 1.1 g.

**Sinkhole hazards**

As described below, the desalination plant area A is located near the Dead Sea but outside of established sinkhole areas. Indeed, sinkholes are mostly observed on the western side of Dead Sea. They are large collapsed openings at the subsurface. Sinkholes were identified throughout a large region and most alarming when occurring the last years in the resort areas around the highway at the west bank and at the sites of Israeli and Jordanian potash plants. At area A the subsurface is consisting in Quaternary formations under which the Lisan marl formation with, sand, pebbles some clay but also halite. The investigations indicate no halite above 50 m depth and with the seismic refraction survey performed on a large area, no any halite body (which should have a high longitudinal waves velocity) hasn’t been identified in the upper 80 m.

Even the risk of sinkholes can’t totally be excluded at this location their occurrence chance is limited as long as the wells withdrawing groundwater for irrigation purposes at the Jordan side are in operation. Indeed the sinkholes generation requires a fresh or brackish groundwater flow through the cracks inside the halitic body.

Fresh or brackish water inflow should be considered and may trig dissolution phenomena generating sinkholes as observed in the north. The best way to prevent sinkhole formation is to withdraw the groundwater before entering the desalination plant area.
**Conclusions**

At desalination alternative A and hydropower plant location, the subsoil conditions are fair to good, high frictions angles may be expected. The next layers are mainly made of sand to at least 50 m depth. Locally the clay may become predominant; this has to be taken into consideration for the settlements analysis. The groundwater table is found at 70 m depth, but local perched ground water tables may be expected, they may be very shallow (10 m depth).

The area is highly seismic and adjacent to a destructive fault. Basin effect which increases the earthquakes amplitudes and consequently a considerable spectral response is expected with for the works high accelerations to consider as high as 1 g. At the other hand the risk of liquefaction is very low even negligible.

The risk of sinkholes can’t totally be excluded at this location but their occurrence chance is very limited since no halite layers are found in the upper 50 m and probably in the upper 80 m. The available data about the groundwater table conditions are questionable; more observation wells have to be drilled in order to have a good control of the groundwater hydraulics which is the best way to fully exclude the sinkholes formation.
9.3 **Desalination Plant Area D related to the pipeline alignment option**

Desalination plant at km 143 and elevation : -90 m.

**Location**

![Aerial photography of desalination plant location](image)

*Figure 68: High level DP (related to pipeline alignment) location on Aerial photography (Google Earth)*

One borehole has been performed there: BH PL08. One observes 5 m eolian sand above at least 5 m of alluvial deposits. The SPT values rising from 20 near the surface to 70 at 10 m depth. The inferred geomechanical properties are high and a friction angle of 40° may be taken into consideration.
10 POTABLE WATER PIPELINE TRANSMISSION LINES

There are three potable water transmission lines, one for Amman, one for Israel and one to the territories under the Palestinian Authority. For the transmission line to Amman, three alternatives are considered. No specific field survey has been performed; the conditions assessment is inferred from geological maps, aerial photography’s analysis, satellite images analysis and some field inspection (only South 3 and North 2 alternatives to Amman and options to Jericho and Ein Gedi.\textbf{(Figure 69&Figure 71)}

10.1 Potable Water Pipeline Transmission Lines to Amman

The pipe to Israel is limited to supply Ein Gedi, at the Dead Sea and there are three options to the Under the Palestinian Authority Territories. That to Ein Gedi may be considered as a part of one option to Jericho.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{potable_water_pipeline_transmission_lines.png}
\caption{Potable Water pipeline transmission line options on aerial photography (from Google Earth)}
\end{figure}
South Alternative No. 1

Before reaching the eastern plate, the pipeline should be buried in sandstone rock, with no excavation stability problem. No significant risk of landslides has been observed.

North Alternative No. 2

A significant part of this route is located inside marly formations, the slope also is most of time very high so that the risk of landslide is important and significant landslides areas could be observed from aerial views and field inspection (Figure 70).

In addition to that, the route part along the Dead Sea and the part rising up are located in a seismic area with potential site effects as resonance along the Dead Sea and topographic effects in the rising part.

Even if the route of this alternative is shorter than that of the 2 other alternatives there is a chance that the costs of the required paraseismic devices and of the landslide prevention measures, will offset the saving induced by the shortest length of the pipe.

Figure 70: Landslide areas location along the north transmission line option
Alternative No. 3

The geological conditions are very similar to those of alternative 1: until the plateau mostly sandstone with no stability or excavation problems, no landslides and even a gentler slope when leaving the Arava valley.

Transmission to Amman: Conclusions

Alternative 2 has to be excluded because located for a significant part along unstable slopes. Regarding geological conditions, alternatives 1 and 3 are similar, 3 is slightly more favourable than 1. In this case elevation (highest point) and length criterions are largely prevalent on the geological conditions criterion.

10.2 Potable Water Pipeline Transmission Lines to Ein Gedi and Jericho

There are three potential routes for the fresh water transmission of desalinated water from the Red Sea – Dead Sea Project desalination plant to Jericho as follows:

- **Option West 1** - A pipeline around the south west end of the Dead Sea parallel to, but separate from, the proposed transmission main to Israel and onward up the west coast of the Dead Sea approximately paralleling the existing road and northwards beyond the Dead Sea to Jericho and beyond.
- **Option West 2** - Combine the water transmission to Palestinian Authority with that to Israel in a single pipeline as far north as Ein Gedi with an extension northwards to Jericho and beyond as above.
- **Option East 1** - A pipeline around the south east corner of the Dead Sea northwards up the east coast of the Dead Sea and thence north west across the Jordan River to Jericho and beyond.

These three alignments are shown schematically on Figure 71.
All three alignments are of similar length but by combining some 60 km of the alignment in a single pipe to carry water to both Israel and Palestinian Authority, Option West 2 will be preferred.

Geological conditions for options West 1 and West 2. The crucial issue is that the pipe routes pass on almost the total length of the Dead Sea through known sinkhole zones requiring special design and specific investigations to identify the areas with high risk of sinkholes. (red dashed lines circumvent the sinkhole zones on Figure 71. Head cut migration and increased gullies incision have also to be considered.

When close to the Dead Sea, Tsunami/seiche hazard have to be considered. The small seiche (defined as a standing wave in an enclosed or partially enclosed body of water) that was triggered by the Nov. 22, 1995 earthquake (Wust et al., 1997) demonstrated that this source of hazard must be considered in relation to coastal installations. Similarly, based on
palaeoseismic evidence, earthquake-triggered waves are also expected in the Dead Sea (Begin et al., 2005a; Begin et al., 2005b).

With Option East 1 the pipe crosses sinkhole areas on a more limited length (Figure 71). At the other hand once the pipeline route as reached the opposite point of Ein Gedi on the East bank of the Dead Sea, the available working areas associated with constructing a pipeline are restricted. The pipeline must be constructed along sharp slopes with locally when cutting the wadis serious slope stability problems.

North of the Dead Sea to Jericho, whatever the alternative no geotechnical problems are expected but there the main active branch of the Dead Sea Fault and numerous secondary active structures have been reported in this region, including active folding, faults, and salt diapirism (e.g., Belitzky, 2002; Lazar et al., 2010; Shamir et al., 2005). The location of the active branches has to be determined in order to design adequate paraseismic devices.

**Transmission to Ein Gedi and Jericho: Conclusions**

The west option with a common part to Ein Gedi is preferred. The sinkhole hazard is an issue.
11 \textbf{BRINE AND SEAWATER TRANSMISSION LINES}

To avoid interaction with Dead Sea works and Arab Potash Cie, it is considered to release the brine after desalination and the sea water more northwards. Two options are possible, one at the west and one at the east similar as the east and west options as for the fresh water pipelines (Figure 72)

The geological considerations are the same as for the fresh water pipeline. Risks of sinkholes but more limited at the East bank, hardly or even not feasible more northward of the place at the latitude of Ein Gedi but on the East bank. A canal should be preferred because in case of failure (sinkhole) the consequences are limited and may be easy repaired.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure72.jpg}
\caption{Discharge works options in the Dead Dea}
\end{figure}
12 BIBLIOGRAPHY – SOURCES OF DATA

   
   Collapse-sinkholes and radar interferometry reveal neotectonics concealed within the Dead Sea basin. 

2. AL-ZOUBI, A.S., HEINRICHS, T., SAUTER, M. & QABBANI, I., 2006
   
   Geological structure of the easter side of the lower Jordan valley / Dead Sea rift: reflection seismic 

3. AMBRASEYS, N.N., DOUGLAS, J., SARMA, S.K. & SMIT, P.M., 2005
   
   Equations for the estimation of strong ground motions from shallow crustal earthquakes using data 
   from Europe and the Middle East: Horizontal peak ground acceleration and Spectral 

   
   Earthquakes in Israel and adjacent areas: Macroseismic observations since 100 B.C.E. Israeli Exploration 

5. AMIT, R., ENZEL, Y., NAOMI, P., HAMIEL, Y. & ZILBERMAN, E., 2009
   
   Late Quaternary Seismicity of the Southern Arava Valley, The Dead Sea Fault. GSI Dead Sea Workshop 
   February 2009.

6. AMIT, R., ZILBERMAN, E., ENZEL, Y., PORAT, N., 2002
   
   Paleoseismic evidence for time dependency of seismic response on a fault system in the southern Arava 

7. AMIT, R., ZILBERMAN, E., PORAT, N., ENZEL, Y., 1999
   
   Relief inversion in the Avrona playa as evidence of large-magnitude historical earthquakes, southern 

8. AMIT, R., HARRISON, J.B.J., ENZEL, Y., 1995
   
   Use of soils and colluvial deposits in analysing tectonic events – the southern Arava valley, 

   
   181-196.

10. ARKIN, Y., AND GILAT, A., 2000
    

11. AVNI, Y., BARTOV, Y., GURFUNKEL, K. & GINAT, H., 2000
    
    Evolution of the Paran drainage basin and its relation to the Plio-Pleistocene history of the Arava rift 
    western margin, Israel. Isr. J. Earth. Sci., v. 49, pp. 215-238
12. **Bartov, Y., 1974**


15. **Begin, Z.B., 2005**


17. **Ben-Avraham, Z., 1985**


18. **Ben-Menahem, A., 1991**

Four thousand years of seismicity along the Dead Sea rift. *Journal of Geophysical Research. v. 96*, 812, p. 20195-20216.

19. **Bienawski, Z.T., 1974**


20. **Bookman (Ken-Tor), R., Enzel, Y., Agnon, A. & Stein, M., 2004**


23. ** Bowman, D., 1995**

Active surface ruptures on the northern Arava fault, the Dead Sea Rift. *Israel J. Earth Sci., v. 44*, p. 51-59.

24. **Closon D. & Abou Karaki N., 2007**

Human-induced geological hazards along the Dead Sea coast.


28. **FREUND, R., GARFUNKEL, Z., ZAK, I., GOLDBERG, M., WEISSBROD, T. & DERIN, B., 1970**  
The shear along the Dead Sea rift. *Philosophical Transactions of the Royal Society of London.* v. 267, p. 107-130.

29. **GARFUNKEL, Z. & BARTOV, Y., 1977**  
The tectonic of the Suez rift. *Israel Geological Survey.* v. 71, pp. 44.

30. **GARFUNKEL, Z., 1981**  

31. **GARFUNKEL, Z., ZAK, I. & FREUND, R., 1981**  

32. **GARFUNKEL, Z., 1988**  

33. **GARFUNKEL, Z., 1997**  

34. **GARFUNKEL, Z. & BEN-AVRAHAM, Z., 1996**  

35. **GARFUNKEL, Z., BEN-AVRAHAM, Z. 2001**  

36. **GEOLOGICAL SURVEY OF ISRAËL, 2002**  
37. **GEOLOGICAL SURVEY OF ISRAEL, 2006**
   

38. **GOTTSCHÄMMER, E., WENZEL, F., WUST-BLOCH, H. & BEN-AVRAHAM, Z., 2002**
   

   

40. **HARZA JRV GROUP, 1998**
   

41. **HATCHER, R.D., ZEIZ, I., REAGAN, R.D. & ABU-AJAMEH, M., 1981**
   
   Sinistral strike-slip motion of the Dead Sea rift: confirmation from new magnetic data. *Geology,* v. 9, p. 458-462.

42. **IDRISS, I.M. & BOULANGER, R.W., 2004**
   
   Semi-empirical procedures for evaluating liquefaction potential during earthquakes. *11th International conference on soil dynamics & Earthquake Engineer.*

43. **JIMENEZ, M.J., 2004**
   

44. **JMWI, PWA & IHS, 1998**
   

45. **JOFFE, S. & GARFUNKEL, Z., 1987**
   

46. **KASHAI, E. & CROKER, P., 1987**
   

47. **KEAREY, P. & VINE, F.J., 1995**
   

   


50. **Le Beon, M., Klinger, Y., Amrat, A., Agnon, A., Dorbath, L., Baer, G., Ruegg, J.C., Charade, O. & Mayyas, O., 2008**

   Slip rate and locking depth from GPS profiles across the southern Dead Sea transform. *Journal of geophysical research*, **v. 113**, n°B11, 2 p.


   Geodetic versus geologic slip rate along the Dead Sea. *Seismological society of America - Annual Meeting, San Fransisco.*

52. **LePichon, X. & Gaulier, J.M., 1988**


   Emplacements mechanism and fracture mechanics of clastic dikes. *GSI Dead Sea Workshop February 2009.*

54. **Malkawi, A.I.H., Numayri, K.S. & Barakat, S., 1999**


56. **Marco, S., 2007**


57. **Marinos, P. & Hoek, E., 2000**


59. **Niemi, T., 2009**

   Paleoseismology and archaeoseismology of sites in Aqaba and Petra, Jordan. *GSI Dead Sea Workshop February 2009.*

60. **Peck, R., Hanson, W. & Thornburn, T., 1957**

61. Picard, L., 1943

62. Quennell, A.M., 1958

63. Quennell, A.M., 1959

A short note on the Seismic Hazard in Israel. PROHITECH Project – WP 3.

Multiscale3D architecture and mechanics of the margins of the Dead Sea pull-apart. Tectonics. v. 22, p. 1004.

66. Salameh E., 2009
Hydrogeological et hydrochemical data of the Quaternary Alluvium Aquifer.

Changes in the dead sea level and their impacts on the surrounding groundwater bodies.

68. Salameh E. & El-Naser H., 2000


Seismicity of the eastern Mediterranean region: Perspective from the Sinai subplate. Tectonophysics., v. 263, pp. 293-305.

71. Saman, J., 1999
The properties of the curative water and its uses for therapeutical treatment in Jordan. Geomedicine Seminar Vienna – Baden.

72. Schmertmann, J.H., 1975
73. Shapira, A., 1979


74. Shapira, A. & Van Eck, T., 1993

Synthetic uniform hazard site specific response spectrum. *Natural Hazard*, v. 8, pp. 201-205.

75. Shtivelman, V., Marco, S., Reshef, M., Agnon, A. & Hamiel, Y., 2005


76. Skempton, A.W., 1986


77. Sneh, A., 1979

Late Pleistocene fan deltas along the Dead Sea Rift. *Journal of Sedimentary Petrology*, v. 49, pp. 541-552.


*Geological Map of Israel to 1:200,000, 4 Sheets*. *Geological Survey of Israel, Jerusalem*.

79. Swiss Agency for Development and Cooperation (SDC), 2009

Technical report No. CS/09/EQ.1 – Part A: Seismological part – Seismic Hazard Mitigation in Jordan

80. Taqieddin, S.A., Abderahman, N.S., and Atallah, M., 2000


81. UNESCO, 2006

Cooperation in Seismic Hazard mapping of the Dead Sea rift region. Reduction of Earthquake losses in the extended Mediterranean region.

82. Weber, M. et al., 2009


84. Wust-Bloch, G.H., 2002


85. Yechiel Yoseph, Meir Abelson, Amos Bein, Onn Crouvi, 2006


Aquifer characteristics derived from the interaction between water levels of a terminal lake (Dead Sea) and an adjacent aquifer. *Water Resources Research*. v. 32(4), p. 893-902

87. Yuval Bartov, Amotz Agnon, Yehouda Enzel and Mordechai Stein, 2006


88. Zak, I. and Freund, R., 1966

