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Faulting patterns determining groundwater flow paths in the Lower Yarmouk Gorge

Inbar Nimrod[1,2,3], Eliahu Rosenthal[1], Fabien Magri[4,5], Marwan Alraggad[6], Peter Möller[7], Akiva Flexer[1], Joseph Guttman[8], Christian Siebert[9]

[1]The School of Geosciences, Tel Aviv University, Israel
[2]Department of Geophysics and Space Sciences, Eastern R&D, Ariel, Israel
[3]Departmemt of Physics, Ariel University, Ariel, Israel
[4]UFZ Helmholtz Centre for Environmental Research, Dept. Environmental Informatics, Leipzig, Germany
[5] Freie Universität Berlin, Chair of Hydrogeology, Berlin, Germany
[6] Water, Energy and Environment Center, University Of Jordan.
[7] Helmholtzentrum Potsdam, German Research Center for Geosciences, GFZ, Telegrafenberg, Potsdam, Germany
[8]Hydrology department, Mekorot, the National Water Company, Israel
[9]UFZ Helmholtz Centre for Environmental Research, Dept. Catchment Hydrology, Halle, Germany

Correspondence to: Nimrod Inbar (inbar.nimrod@gmail.com)

Abstract. Recent studies investigating groundwater parameters e.g., heads, chemical composition and heat transfer, argued that groundwater flow paths in the Lower Yarmouk Gorge area are controlled by geological features such as faults or dikes (Goretzki et al., 2016; Magri et al., 2016; Roded et al., 2013; Siebert et al., 2014). However, the nature of such features as well as their exact locations were previously unknown. In the present manuscript, we propose a new fault pattern in the Lower Yarmouk Gorge area constructed by compiling and revising geological and geophysical data from the study area including borehole information, geological maps cross-sections and seismic data from southern Golan Heights and northern Ajloun Mountain. The presented pattern is composed of strike-slip and thrust faults, which are associated with the Dead Sea Transform system and with the Kinnarot pull-apart basin. Compressional and tensional structures developed in different places forming a series of fault-blocks probably causing a non-uniform spatial hydraulic connection between them. This study provides a coarse fault block model and improved structural constraints that serve as fundamental input for future hydrogeological modelling.

1 Introduction

The Lower Yarmouk Gorge (LYG) is a prominent geomorphological feature located east of the Dead Sea Transform (DST) between the Sheikh Ali fault to the north (in the central Golan Heights, henceforth called GH) and the Zarka fault to the south, in northwest Jordan (Fig. 1). Structurally, the LYG is located along the southern extremity of the Golan syncline bounded by Mt. Hermon in the north and by the Ajloun dome in the south (Mor, 1986). The hinge line of the Golan syncline is considered to be located along the Sheikh Ali tensional fault zone, a few km north of the LYG (Meiler, 2011; Shulman et al., 2004).

The LYG drains the natural flow of the 6,833 km^2 large surface catchment of the Yarmouk River basin (Fig. 1). Runoff flows into the Jordan River south of the Sea of Galilee. Groundwater flows from additional two directions, from the Ajloun Dome (El-Naser, 1991) and from Mt. Hermon through deep aquiferous formations in the subsurface of the Golan Heights (Gvirtzman et al., 1997).

The Hammat-Gader and Mukheibeh springs and the Mukheibeh and Meizar wells located along the LYG, differ by hydraulic head, chemical composition and temperature. Most studies of the springs emerging on both sides of the gorge carried out between 1970 and 1990's, considered mainly their geochemical and hydrological characteristics and concluded that their outflow is a mixture of shallow, cold and fresh groundwater with a deep water body of higher salinity and temperature (Arad and Bein, 1986; Arad et al., 1986; Baijjali et al., 1997; Eckstein and Simmonsi, 1977; El-Naser, 1991; Mazor et al., 1973; Mazor et al., 1980). However, the mechanism allowing the deep hot brines to ascend remained obscure.

Recent studies attempted to explain the mechanism responsible for the outflow of hot springs and high pressure groundwater identified in wells located along the LYG. Roded et al. (2013) used a conceptual structural model of the Golan syncline for numerical simulations of groundwater flow and heat transfer, introducing an enhanced 5 km wide vertical permeability zone, below the LYG. Based on geochemical considerations, Siebert et al. (2014) suggested that the LYG groundwater are fed by water originating from three replenishment areas : (a) Mt. Hermon, (b) Northern Jordan and (c) the Hauran Plateau in Syria. They also suggested that buried dikes could be possible sources of heat and that weakness zones allow heated brines to ascend and feed the springs and boreholes in the central LYG.

Numerical modeling of a 2D section crossing the LYG which inferred the existence of a fault in the gorge revealed in the study area a complex groundwater flow pattern (Magri et al., 2015). This was followed by a 3D model of a hypothetical fault tracing along the LYG and suggested a mechanism of heat- driven convection cells (Magri et al., 2016). Consequently, the anomalous heat flow was studied by a method of inverse problem, suggesting that the thermal constrains of the system requires one of two scenarios, (a) relatively permeable and continuous faults, cutting through the entire geological section, reaching at depth the Triassic beds, or (b) local fractures interconnected by a highly permeable Cretaceous aquifer (Goretzki et al., 2016). However, the above mentioned studies are based on simplified assumptions of fault locations and orientation.

Using available geological and geophysical data (Fig. 2), from the southern Golan and northern Ajloun, a new fault pattern is suggested for the LYG area. This pattern includes a series of strike-slip faults, which seem to be strongly associated with the adjacent Kinnarot pull-apart basin. This fault pattern forms a set of fault-blocks causing non-uniform spatial hydraulic conductivity across the study area. It is suggested that this particular fault pattern should be the controlling factor of groundwater flow and related processes such as solute transport, thermal convection and mixing of different sources.

2 Stratigraphy

The exposed stratigraphy of the Golan Heights reveals mostly Pliocene to Quaternary basalts (Dafny et al., 2003; Heimann et al., 1996; Mor, 1986). In the north, the entire sequence from Quaternary basalts to Jurassic limestone is exposed close to Mt. Hermon (Hirsch, 1996; Picard and Hirsch, 1987). In the central part of the Golan Heights and along its southern margins Eocene to Miocene sediments are exposed in the wadis flowing towards the DST (Michelson, 1979). Middle Cretaceous rocks crop out in the Ajloun Dome, revealing a Campanian formation which does not exist neither west of the DST (Flexer, 1964) nor in the northern part of the GH. This formation is known by the Jordanian nomenclature as the Amman Silicified Limestone (ASL) or - by its hydrological term - the B2 Aquifer (Andrews, 1992; El-Naser, 1991).

By its distinctive lithology of silicified limestone and chert, the Campanian ASL formation is easily identified in outcrops and boreholes. It overlies the Santonian (B1) limestone and is overlain by a thick Maastrichtian (B3) layer of marl. The transition to the underlying Santonian (B1) is somehow difficult to identify because the B1 unit is a thin layer (30-50 m) of limestone without cherts. However, the occurrence of dolomite or of dolomitic limestone, clearly defines the Turonian (A7). Contrarily to the hydrological characteristics of the Senonian aquiclude in central and northern Israel, the ASL (B2) in northern Jordan makes up the upper part of the most essential aquifer in Jordan. The Meizar 1, 2 & 3 boreholes drilled in the southern Golan up to a distance of 6 km north of the LYG, reveals a lithostratigraphic sequence, similar to the Ajloun, confirming that the units continue across the gorge.

South of the Ajloun Dome, the exposed stratigraphy reveals the lithostratigraphic sequence down to Jurassic beds, which are exposed in Wadi Zarka (Fig. 1). The full section down to the Precambrian basement occurs in several deep boreholes drilled in northern Jordan and within the eastern escarpment of the Lower Jordan Valley (Abu-Saad and Andrews, 1993). In the southern GH, borehole Meizar-1 is the northernmost borehole drilled to Turonian, beds providing a complete section of the overlaying lithology.

3 Tectonics

The Kinnarot basin is a link in the chain of pull-apart basins scattered along the Dead Sea Transform (DST) formed by the left lateral movement along the Sinai – Arabian Plate boundary that started during Early to Middle Miocene (Garfunkel, 1981; Gvirtzman and Steinberg, 2012). The transform itself was located on the eastern side of the basin by seismic interpretation showing the compressional structure of the Tel-Qatzir elevated block (Inbar, 2012). To the north, Mt. Hermon manifests a shift in the en-echelon arrangement from left- to right-stepping resulting in a restraining geometry (Weinberger et al., 2009) which causes uplifting of the Lebanon and Anti-Lebanon mountains (Beydoun, 1977) as well as the deepening of the Golan syncline. The LYG, the southern GH and the Northern Ajloun located along the eastern rim of the Kinnarot basin are considered here to be subjected to the regional forces applied by this active plate boundary.

Along the eastern side of the DST, strike-slip faults are known to branch out and penetrate inland, northeastward and eastward, across its rims (Fig. 1; Andrews 1992; Shulman 2004). Though the LYG is a prominent morphological feature east of the DST, its structure was never explored by continuous land geophysics (e.g. seismic, electric, etc.) due to its function as international border. Consequently, attempting to bridge the gap in data resulted only in theoretical and qualitative models.

Considering the extreme thickness difference between Jurassic sections in Mt. Hermon and in the Ajloun (2,000 m and 400 m, respectively) and by comparing seismic lines from southern GH and from the Coastal Plain of Israel, Shulman et al. (2004) suggested the existence of a major fault tracing along the LYG. However, based on interpolation between the results of interpretation of seismic data in the southern GH and deep borehole data in Jordan, it was suggested that the thickness of the Jurassic rocksequence increases gradually from the south northwards and therefore a major fault in the gorge area should not be inferred (Meiler, 2011). The present study shows that although there is no evidence for large vertical displacements, strike-slip faults must cross the LYG forming fault-blocks. Therefore, these faults must be taken into consideration when discussing groundwater hydrology.

4 Data and methods

The current study relays on reviewing, compiling and evaluating available geological and geophysical data from southern Golan and northern Ajloun. Seismic data (Bruner and Dekel, 1989; Meiler, 2011; Shulman et al., 2004) was reinterpreted thus considerably improving the structural information on the southern Golan Heights (Fig. 2) and facilitating the creation of a new geological section, which was drawn along the LYG using borehole lithological data (Table 1; Fig. 3). Faults from surface mapping (Michelson, 1972) and reinterpreted seismic lines and geological profiles (Sahawneh, 2011) were considered in order to generate an aerial view of faults and of fault-block patterns in the study area based on the tectonic concept of pull-apart basin rims. Such models predict evolution of different types of faults at the margins of the main basin mainly according to its maturity, size and symmetry (obliqueness) (Rahe et al., 1998; Smit et al., 2010; Smit et al., 2008; Sugan et al., 2014; Wu et al., 2009). Finally, the previously mapped faults were plotted together with those identified during the present study on satellite images (Source: Google Earth). Following the hypothesis that normal or reverse faults detected on the surface or at shallow depths may indicate deep-seated strike-slip faults, the dots were connected resulting in a newly suggested faults pattern. It is important to note that the fault lines drawn on aerial view maps are a representation of an actual near surface fault zones which converges to a single deep root as illustrated by seismic interpretation and geological cross-section.

5 Results

5.1 Reinterpretation of seismic data

The ENE-WSW trending and 17 km long seismic line DS-3545 (Fig. 2a) runs parallel to the LYG, about 6 km north of it. Reinterpretation of the pre-stack depth migration (PSDM) conducted by Meiler (2011), show an additional flower-structure fault at its SW part indicating a set of strike slip faults crossing that line. Although little to no horizontal displacement is visible on that seismic section, folds between the flower structure faults branches clearly indicate lateral displacement. Moreover, the deep roots of the traced strike-slip faults suggest that it is related to a significant regional tectonics. Its proximity to the DST combined with its effect on shallow lithology may advocate its connection to the DST tectonics.

Seismic line GP-3662 (Fig. 2b) trends NE-SW and is 4.5 km long. Its SW end is located near Meizar 2. The time migrated line described by Bruner and Dekel (1989) was reevaluated considering the results from the reinterpretation of seismic line DS-3545. The compressional feature clearly visible on the seismic line was previously interpreted by Bruner and Dekel (1989) as flower structure i.e. strike-slip motion was assumed along the fault. As this fault is located within the lateral movement zone generated by two main strike-slip faults, a thrust fault seems to be a better solution for the seismic data.

Surface and shallow geological data in the southern GH and northern Ajloun indicate possible surface and shallow fault patterns (El-Naser, 1991; Michelson, 1979; Sahawneh, 2011). All this data suggests the existence in the study area of short faults of limited vertical displacement. However, deep seismic data measured in the southern GH (Meiler, 2011; Shulman et al., 2004) revealed that normal faults with minor to no vertical displacement at the surface and shallow subsurface, may indicate deep strike-slip faults (Fig. 2a). Shallow penetrating seismic data at Mevo-Hamma (Bruner and Dekel, 1989) reveal a compressional thrust fault in close proximity to the LYG (Fig. 2b).

5.2 Geological section along the LYG

Borehole information from the Mukheibeh well-field, located opposite to Meizar 2 and 3 wells and close to area of the Hammat Gader springs (Fig. 4a) provide a unique opportunity to explore the complex faulting pattern in the study area. Based on lithological interpretation of these wells that are drilled along the LYG, a geological cross-section was constructed and validated by the lithological description of all other well-sections in the area (Fig. 4b). As Campanian beds represent the upper part of the B2-A7 aquifer system, most water wells in the area penetrated at least partly this strata providing good coverage of data in the study area. Hence, the thickness of Campanian beds and the elevation of the top Campanian (B2) horizon (as found in the wells of the study area) are the key to the current work (Table 1).

In the study area, the top Campanian horizon displays large elevation changes over small distances. One such case is in borehole Mukheibeh-6 located between Mukheibeh-JRV1 and Mukheibeh-8 (Fig. 4a), at distances of 1.2 km and 0.6 respectively. Although the top Campanian (B2) horizon occurs at similar elevations in boreholes Mukheibeh-JRV1 (-408 m msl.) and Mukheibeh-8 (-403 m msl.), it was encountered at a considerably deeper level in well Mukheiba-6 (-480 m msl.). This difference is the result of faulting. Between boreholes Mukheibeh-7A, Mukheibeh-4 and Mukheibeh-2, the indication of faulting is even more prominent. Between these wells the displacement of reference horizon B2 is of 110 to 130 m over a distance of 40 m respectively.

Considering thicknesses only in places in which the Campanian beds were fully penetrated (Table 1), the average thickness of the chert-bearing Campanian B2 layer is 189 m. In all other wells, thicknesses are assumed to vary within the standard deviation (i.e. 189 ± 14 m), except for Mukheibeh-8, where the Senonian exceeds 290 m. Though the Senonian sequence in the region is well known for its thickness variations (Rosenthal, 1972; Rosenthal et al., 2000a; Rosenthal et al., 2000b), such variations over short distances are exceptional and require a different explanation. It is therefore suggested that the unit is either strongly tilted or thickness was "doubled" in the drilling due to crossing a thrust fault.

In the study area the thickness of Turonian beds (A7) is fairly uniform and ranges between 300 to 350 m. However, in borehole Mukheibeh-JRV1, a section of about 700 m consisting of two repeating sequences of marly limestone and dolomitic limestone, is regarded to be a Turonian unit "doubled" by thrust faulting.

5.3 Tracking fault paths

Previously mapped faults (manifested either as surface lineaments or revealed on geological cross-sections and seismic lines) were plotted together with those identified during the present study on satellite images (Source: Google Earth). Following the hypothesis that normal or reverse faults detected on the surface or at shallow depths may indicate deep-seated strike-slip faults, the dots were connected and the newly suggested faults were drawn (Fig. 3).

The geological cross-sections in the western Ajloun area (Sahawneh, 2011) show the Lower Yarmouk Fault (LYF) branching out from the DST and continuing to northeast. The fault crosses the LYG west of the Hammat Gader – Meizar – Mukheibeh area (Fig. 4a). It occurs that north of the gorge, the fault turns further eastwards following the outcropping fault-lineaments mapped by Michelson (1979). Another possibility is a northward continuation of the fault joining with the Nov Fault Zone (NFZ) (Shulman et al., 2004).

Another SE-NW strike-slip fault was drawn according to previous interpretation and current reinterpretation of seismic data. Although parts of this fault were previously mapped as normal faults, our revised interpretation suggests that it is most likely to be a strike-slip fault (Mevo-Hama Fault, MHF). In between these two newly mapped strike-slip faults (MHF and LYF) there is a thrust fault which is clearly stands out in two seismic lines, GP-3661 and GP-3662. The compressional expression of this thrust fault, strengthens the hypothesis on the connection with the left-lateral strike-slip of the DST system.

6 Conclusions

A new fault pattern has been delineated across the Lower Yarmouk Gorge composed of strike-slip and thrust faults, which are associated with the regional Dead Sea Transform system and with the local Kinnarot pull-apart basin. These compressional and tensional structures have been developed to form a series of fault-blocks, causing a non-uniform spatial hydraulic connection between them.

Previous hydrological studies (Arad and Bein, 1986; Arad et al., 1986; Baijjali et al., 1997; Eckstein and Simmonsi, 1977; El-Naser, 1991; Goretzki et al., 2016; Magri et al., 2016; Mazor et al., 1973; Mazor et al., 1980; Roded et al., 2013; Siebert et al., 2014) suggested different mechanisms for the flow of groundwater from different sources to the LYG. It is suggested that the new pattern of fault-blocks creates the structural medium determining groundwater flow paths in the Lower Yarmouk Gorge. It will serve as constrain for future hydrological modeling in this area.

Further analysis of the newly presented faults should be conducted to better determine their exact relation the adjacent pull-apart basin tectonics. Such study will improve our understanding of faulting mechanism at pull-apart basins rims.

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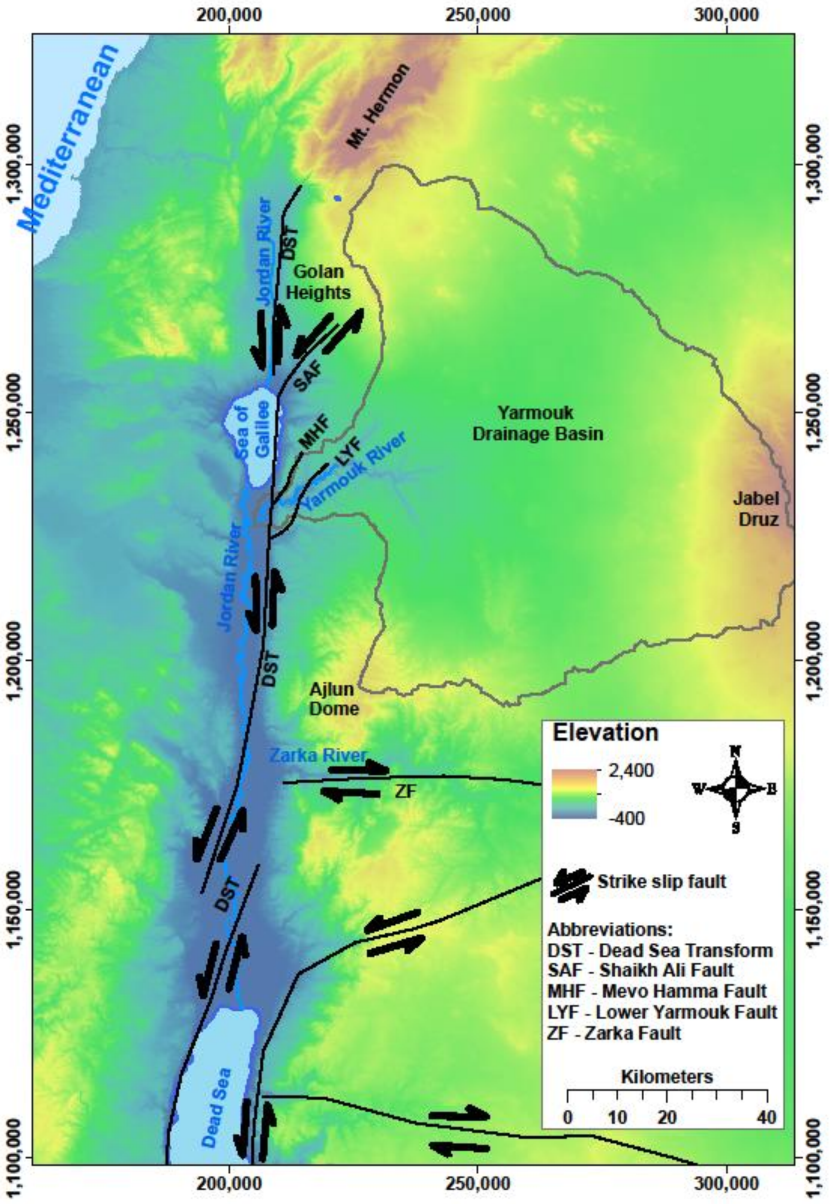

Figure 1: Regional location map on top of digital elevation model, presenting the faults at the eastern rim of the Dead Sea Transform. Current study proposed faults are at the area of the LYG east of Kinnarot pull-apart basin (marked: MHF and LYF).

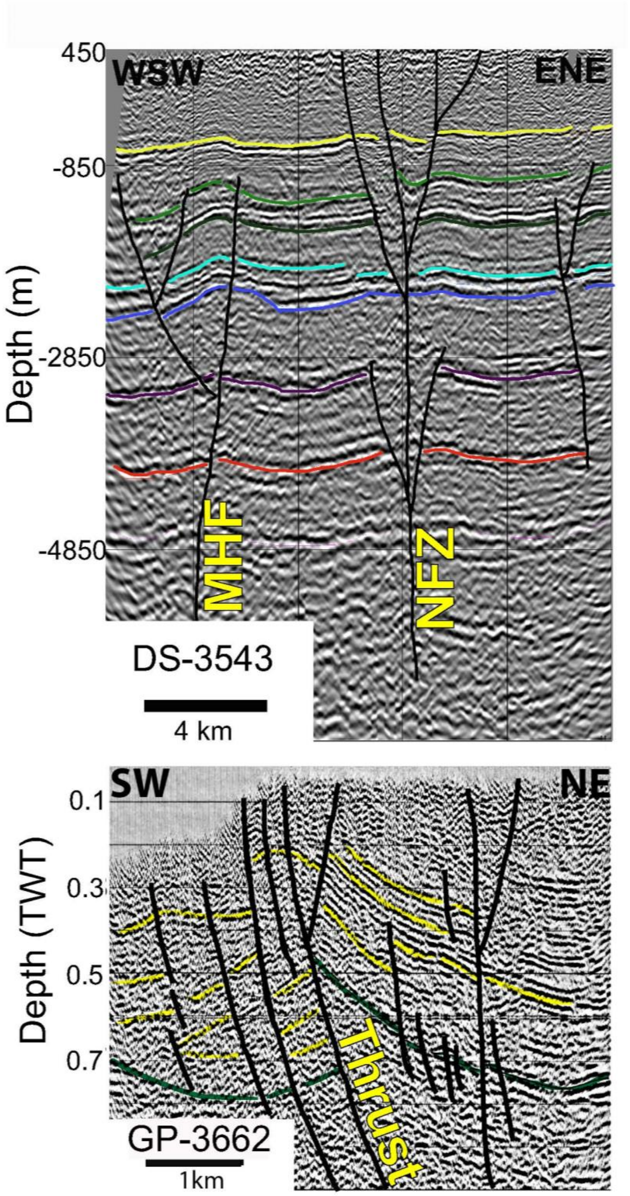

Figure 2: Seismic lines at Southern Golan. (a. top) seismic line DS-3545 showing flower structure reinterpreted after Meiler (2011). Vertical scale in meters. (b. bottom) seismic line GP-3662 showing the thrust fault reinterpreted after (Bruner and Dekel (1989)). Vertical scale in two ways time.

Table 1: Campanian chert bearing formation (B2) - thickness and elevation in wells adjacent to the LYG.

Well name	Lithology	Thickness (m)	Top (m MSL)	Underlying lithology
Mukheibeh 2*	Chert, limestone	128 +	-470	Not penetrated
Mukheibeh 3*	Chert, limestone	75 +	-338	Not penetrated
Mukheibeh 4*	Chert, limestone	174	-450	Limestone, dolomitic limestone
Mukheibeh 5*	Chert, limestone	203	-748	limestone
Mukheibeh 6*	Chert, limestone	90 +	-480	Not penetrated
Mukheibeh 7*	Chert, limestone	160 +	-455	Not penetrated
Mukheibeh 8*	Chert, limestone	290 +	-403	Not penetrated
Mukheibeh JRV1*	Chert, limestone	166	-408	limestone
Meizar 1 **	Chert, chalk, limestone, marl	195	-649	Limestone, chalky limestone
Meizar 2 **	Chert, chalk, limestone, marl	210	-424	Limestone, chalky limestone
Wadi Al Arab 4*	Limestone + Chert	182		limestone
Wadi Al Arab 1*	Limestone + Chert	193		limestone
Wadi Al Arab 2*	Limestone + Chert	180		limestone
Wadi Al Arab 5*	Limestone + Chert	148 +		limestone
Douqara 1*	Chert, marl, marly limestone, bitumineous shale at the top	196		Dolomitic limestone

* Source of information: DAISY, 2017 ** Source of information: well log
\+ Partial thickness, not fully penetrated unit

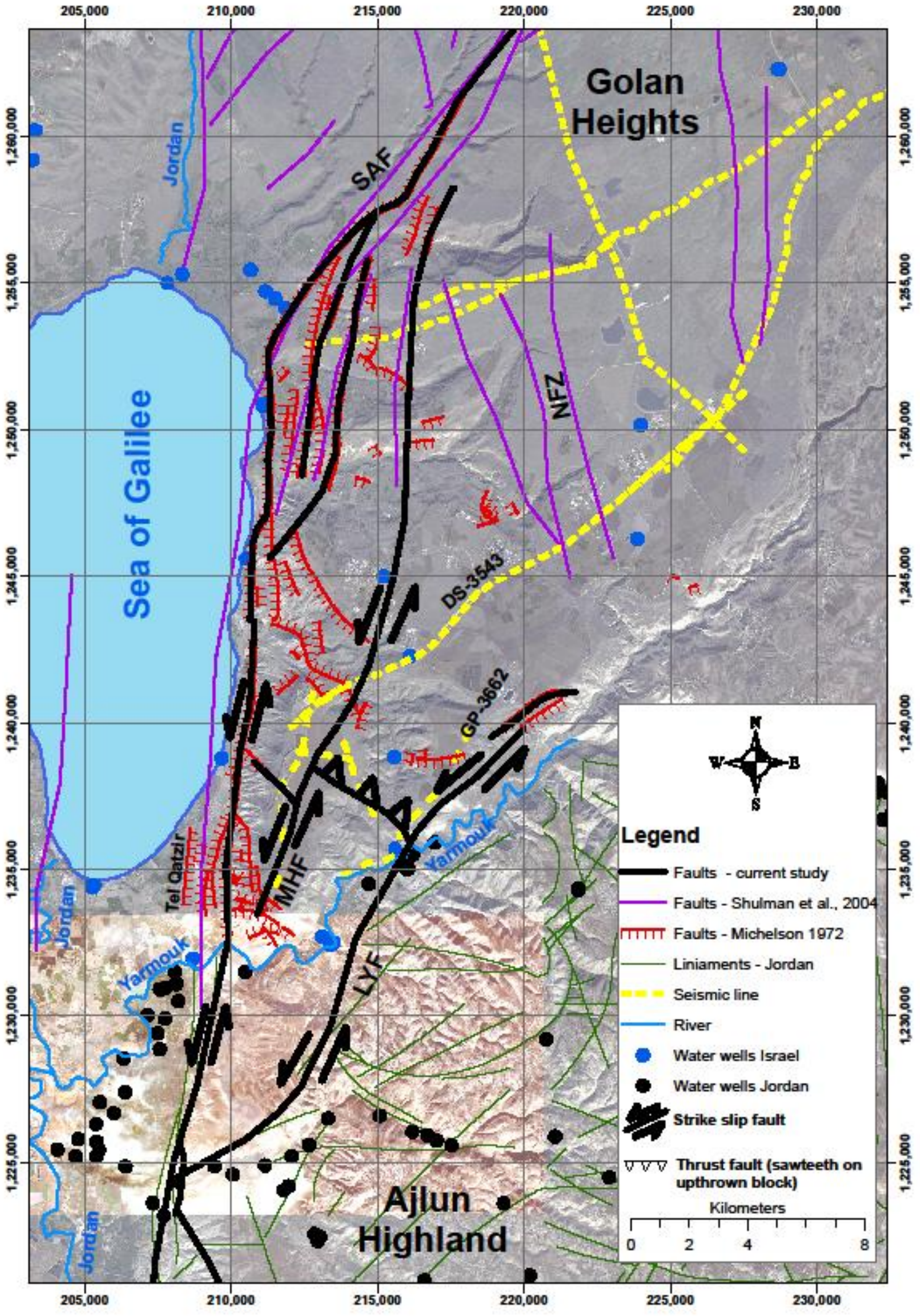

Figure 3: Faults at the Lower Yarmouk Gorge area. Newly interpreted faults are marked with black lines. SAF – Shaikh Ali Fault. NFZ – Nov Fault Zone. MHF – Mevo Hamma Fault. LYF – Lower Yarmouk Fault

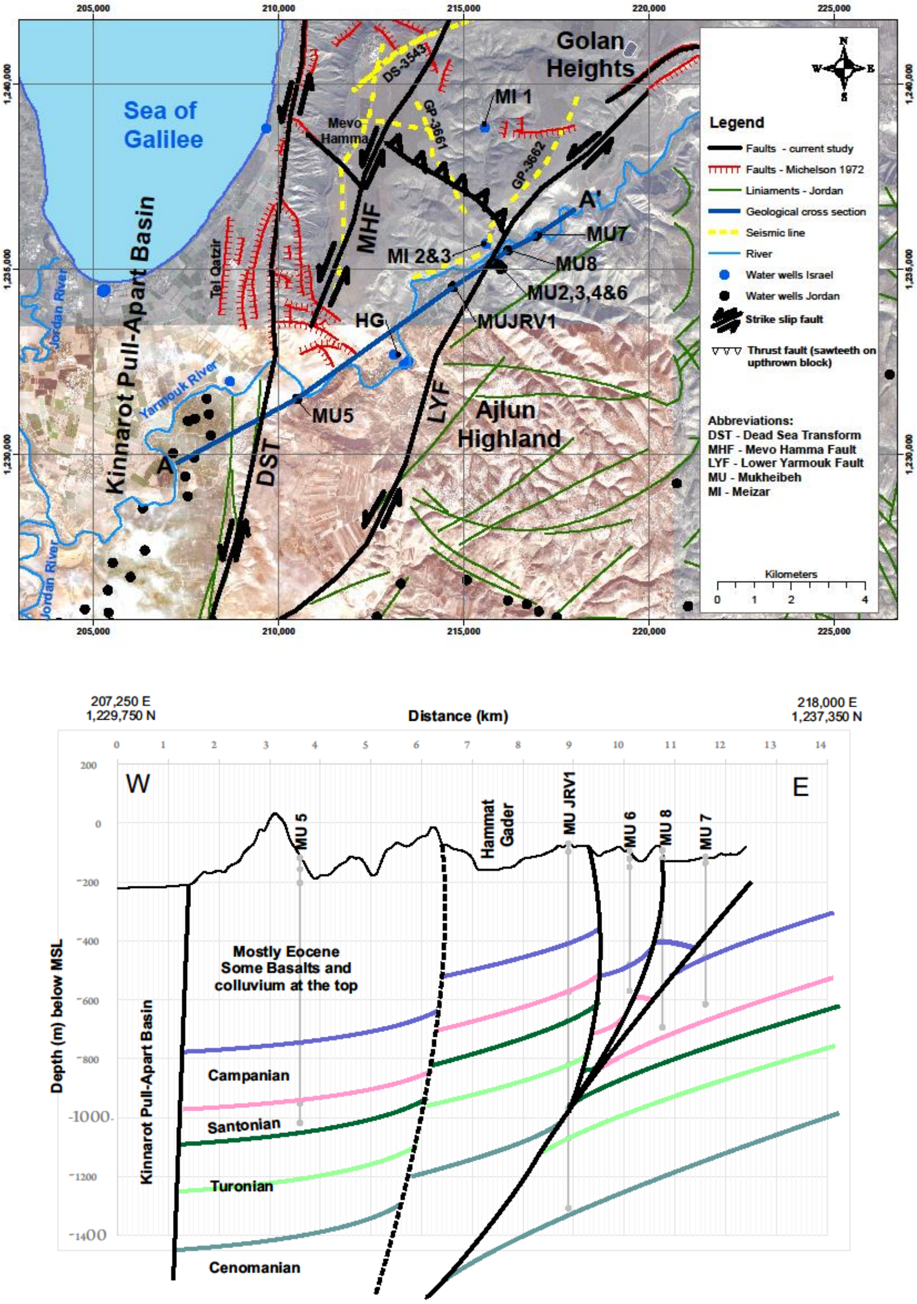

Figure 4: (a. top) A zoom in location map of the Lower Yarmouk Gorge (LYG). (b. bottom) Geological profile along the Yarmouk. In map view (a), the LYG fault line represents the main branch of the flower structure fault located between Mukheibeh JRV1 and Mukheibeh 6 (b). No further evidence was found for the fault suggested west of Hammat Gader (dashed line, b), hence it has not been drawn in map view.