Faulting patterns in the Lower Yarmouk Gorge - potentially influence groundwater flow paths

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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
20   geological features such as faults or dikes. However, the nature of such features as well as their exact locations were so far unknown. In the present manuscript, we propose a new fault pattern in the Lower Yarmouk Gorge area 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,
25   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.

30   **Introduction**

The Lower Yarmouk Gorge (LYG) is a prominent geomorphological feature located in the triangle between Israel, Syria and Jordan, 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
35   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) and flows into the Jordan River south of the Sea of Galilee. Additionally, the LYG is receiving

40   groundwater flows from the Ajloun Dome (El-Naser, 1991), from Mt. Hermon through deep aquiferous formations in the subsurface of the Golan Heights (Gvirtzman et al., 1997) and from the Hauran Plateau (Siebert et al., 2014), situated NE-wards.

The Hammat-Gader and Mukheibeh springs and the Mukheibeh and Meizar wells located along the LYG, differ by hydraulic head, chemical composition and temperature (Siebert et al., 2014). Most studies of

45   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 and pathways, allowing the deep hot

50   brines to ascend remained obscure. Deep-reaching faults below the area of the LYG would be promising structural features, controlling such hydrogeological systems.

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 to numerically simulate regional groundwater flow and heat

55   transfer, introducing below the LYG a 5 km wide zone of enhanced vertical permeability. Based on geochemical evidences, Siebert et al. (2014) suggested that the groundwaters in the LYG are fed by water originating from: (a) Mt. Hermon, (b) Northern Jordan and (c) the Hauran Plateau in Syria, and do not mix, which suggests the existence of a zone of hydraulic anisotropy along the LYG. Along that weakness zone, brines likely heated by buried dikes may ascend and feed the Hammat Gader springs and some

60   boreholes in the central LYG.

Numerical modeling of a 2D section crossing the LYG inferred the existence of a fault in the gorge and revealed a complex groundwater flow pattern in the study area (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

65   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). Tzoufka et al. (2018) could substantiate the existence of a zone of hydraulic anisotropy along the LYG, possessing high hydraulic conductivity along its course, while S⇔N oriented

70   groundwater migration across the plane is impeded. However, the above-mentioned studies are based on simplified assumptions of fault locations and orientation.

Stratigraphy

The exposed stratigraphy of the Golan Heights reveals mostly Pliocene to Quaternary basalts (Mor, 1986; Heimann et al., 1996; Dafny et al., 2003). In the north, the entire sequence from Quaternary basalts to

75   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.

Tectonics

The Kinnarot basin is a link in the chain of pull-apart basins scattered along the 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 rock-sequence 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 at the surface, seismic and borehole data indicate strike-slip faults crossing the LYG forming fault-blocks. Therefore, such faults should be taken into consideration when discussing groundwater hydrology.

Data and methods

The current study relays on reviewing, compiling and evaluating available geological and geophysical data from southern Golan and northern Ajloun. Most of the seismic data were collected at the Golan Heights during the 1980's (Shulman and May, 1989), published later as time migrated data analyses (Shulman et al., 2004) and reprocessed by Meiler (2011) using PSDM (Pre-Stack Depth Migration) to analyse regional aspects. In the current study, we aimed to refine Meiler's faulting interpretation of PSDM line DS-3545 (Figs. 1; 2) to shift the precision for a less broad perspective (i.e. Meiler neglected the westernmost fault in the regional context, which might be relevant at a local scale. Additionally, seismic data from southern Golan (Mevo Hamma; Fig. 1) (Shulman et al., 2004; Bruner and Dekel, 1989; Meiler, 2011) were reinterpreted to considerably improving the structural information in the vicinity of the Lower Yarmouk Gorge. Based on these data, in combination with lithological data from boreholes (Table 1), a new geological cross section was constructed along the LYG, running SW-NE (Fig. 3). Faults from surface mapping (Michelson, 1972) ,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) (Wu et al., 2009; Rahe et al., 1998; Sugan et al., 2014; Smit et al., 2008; Smit et al., 2010). Finally, the previously mapped faults were traced together with those identified during the present study. 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.

Results and Discussion

1.1   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 re-evaluated 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 is the more compatible solution for the seismic data.

Surface and shallow geological data in the southern GH and northern Ajloun indicate possible surface and shallow fault patterns (Sahawneh, 2011; El-Naser, 1991; Michelson, 1979). All this data suggests the existence in the study area of short faults of limited vertical displacement. However, deep seismic data were collected in the southern GH (Shulman et al., 2004; Meiler, 2011) revealed that normal faults with minor to no vertical displacement at the surface and shallow subsurface, may indicate deep strike-slip faults (Fig. 2a).

1.2   Geological section along the LYG

Borehole information from Meizar 2 and 3 wells and the Mukheibeh wells (henceforth abbreviated as Mu), drilled along the LYG and partly located opposite to Meizar 2 and 3 wells and close to the area of the Hammat Gader springs (Figs. 1; 4a) provide a unique opportunity to explore the complex faulting pattern along major parts of the gorge. Based on lithological interpretation of well logs (IHS, (Margane and Hobler, 1994)) 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). At least the uppermost part of the B2-A7 aquifer, the Campanian B2 horizon is disclosed in all wells of the study area. Hence, borehole data about its elevation and thickness provide good coverage in the study area and are the key to the current work (Table 1).

In the study area, base of B2 displays large elevation changes over small distances, e.g. in borehole Mu-6 located between Mu-JRV1 and Mu-8 (Fig. 4a), at distances of 1.2 km and 0.6 respectively. Although the B2 horizon appears at similar elevations in boreholes Mu-JRV1 (-408 m msl.) and Mu-8 (-403 m msl.), it was encountered in well Mu-6 considerably deeper (-480 m msl.). Even more distinct, between boreholes Mu-7A, Mu-4 and Mu-2, the elevation of base B2 is varying over a horizontal distance of 40 m to an extend of 130 m. These differences result from faulting.

Considering places in which B2 beds were fully penetrated (Table 1) only, the average thickness of the chert-bearing B2 layer is 189± 14 m. Mu-8 well manifests an exceptionally thick Senonian sequence exceeding 290 m. Though the Senonian sequence in the region is well known for its thickness variations (Rosenthal et al., 2000a; Rosenthal et al., 2000b; Rosenthal, 1972), 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 Mu-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 (Fig. 3).

1.3 Tracking fault paths

Following the seismic interpretation, it is suggested that faults detected on the surface or at shallow depths in the study area are likely to indicate deep-seated strike-slip faults. Based on that hypothesis, faults shown on geological cross-sections in the western Ajloun area (Sahawneh, 2011) were considered the southern extension of the Lower Yarmouk Fault (LYF). At the southernmost end, the fault is branching out from the DST and continuing to northeast. The fault crosses the LYG west of the Hammat Gader – Meizar – Mukheibeh area (Fig. 1). 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 suggested 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.

Summary and Conclusions

A comprehensive reinterpretation and compilation of available geological and geophysical data across the LYG at a local scale is presented. Former seismic analysis of the deep structure in the Golan Heights (Meiler, 2011; Shulman et al., 2004; Shulman and May, 1989) used deep borehole data from Jordan and Syria to study regional scale structures. However, in these studies, all rock units between the Turonian and Pliocene basalts were presented as one undivided unit and some of the faults at the southernmost DS-3545 line were neglected. The shallow seismic survey conducted at Mevo Hamma area (Bruner and Dekel, 1989) has been originally interpreted simultaneously with preliminary results of Shulman and May (1989) and with no access to data from northern Ajloun. Since then, the Mevo Hamma data has not been used by any other study, done in the area.

As the Mukeiba well field has been further developed in later years more data of Upper Cretaceous is made available alongside with the hydrological observation. The rejuvenation of hydrological studies of the LYG started with conceptual models (Roded et al., 2013; Siebert et al., 2014), which speculated about potential reasons for local hydraulic anisotropies in order to explain the complex hydrological system manifested by groundwater pressure, temperature and chemical variations. This was followed by a series of numerical 2D models (Goretzki et al., 2016; Magri et al., 2015; Tzoufka et al., 2018), which used a combination of previous works to construct their structural model. The results achieved by those studies simulate groundwater flow, and heat transfer over a fault in the geological sequence of the area. However, an expansion of the 2D model into semi-3D (Magri et al., 2016) emphasized the problem of numerically simulating groundwater dynamic processes using a speculated structural model and the need for a unified structural solution in the LYG area.

While tectonic models of pull apart basins have been developed for different scales and various places around the world (e.g. (Corti and Dooley, 2015; Sagy and Hamiel, 2017; Sugan et al., 2014) including models for the Dead Sea basin itself (Smit et al., 2008; 2010) they mostly address the shape of basin boundary and internal processes. The unique situation at the eastern rim of the Kinnarot pull-apart basin includes the collision of Golan Heights at the Hermon Mountain. To the best of our knowledge, such scenario was not yet modeled. Hence, the suggested fault system does not entirely comply with the findings of previous research on the surrounding tectonics of pull-apart basins performed in other tectonic settings.

The main motivation for the work presented here was to assist hydrological research at the LYG. Using available geological and geophysical data (Fig. 1), from the southern Golan and northern Ajloun, a new fault pattern has been delineated across the Lower Yarmouk Gorge. It includes a series composed of strike-slip and thrust faults, which may be associated with the regional Dead Sea Transform system and with the local Kinnarot pull-apart basin. It seems that these compressional and tensional structures have been developed to form a series of fault-blocks, causing a non-uniform spatial hydraulic connection between them. The question of their origin and whether they are related to the evolution of the Kinnarot pull-apart basin still remains unanswered.

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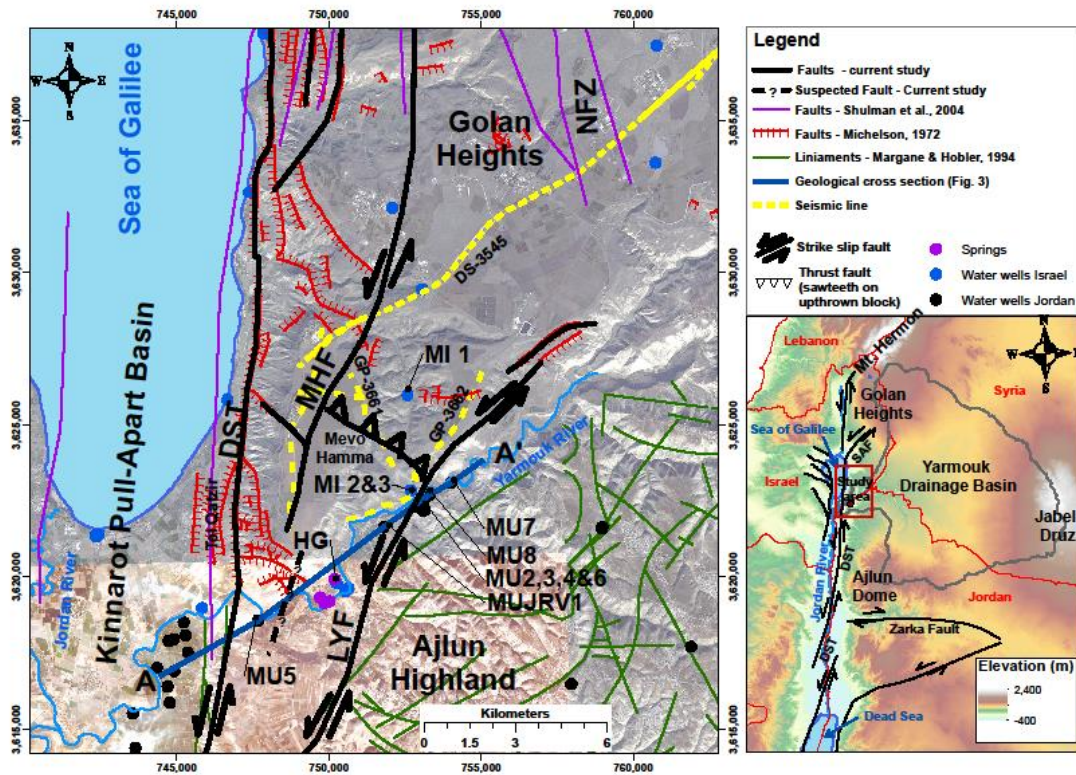
Figure 1: Regional location map on top of digital elevation model, presenting the faults at the eastern rim of the Dead Sea Transform. Current study proposed faults are at the area of the Lower Yarmouk Gorge, east of Kinnarot pull-apart basin, the major Jordan Dead Sea Rift Transform Fault (DST), Sheikh Ali Fault (SAF), Nov Fault Zone (NFZ), Mevo Hamma Fault (MHF) and Lower Yarmouk Fault (LYF). Wells belonging to Meizar (MI) and Mukheibeh (MU) are indicated as well as the location of the Hammat Gader (HG) springs. The location of seismic lines (DS-3543 and GP-3662; Fig. 2) and of a geotectonic cross-section along the LYG (A-A'; Fig. 3) is indicated.

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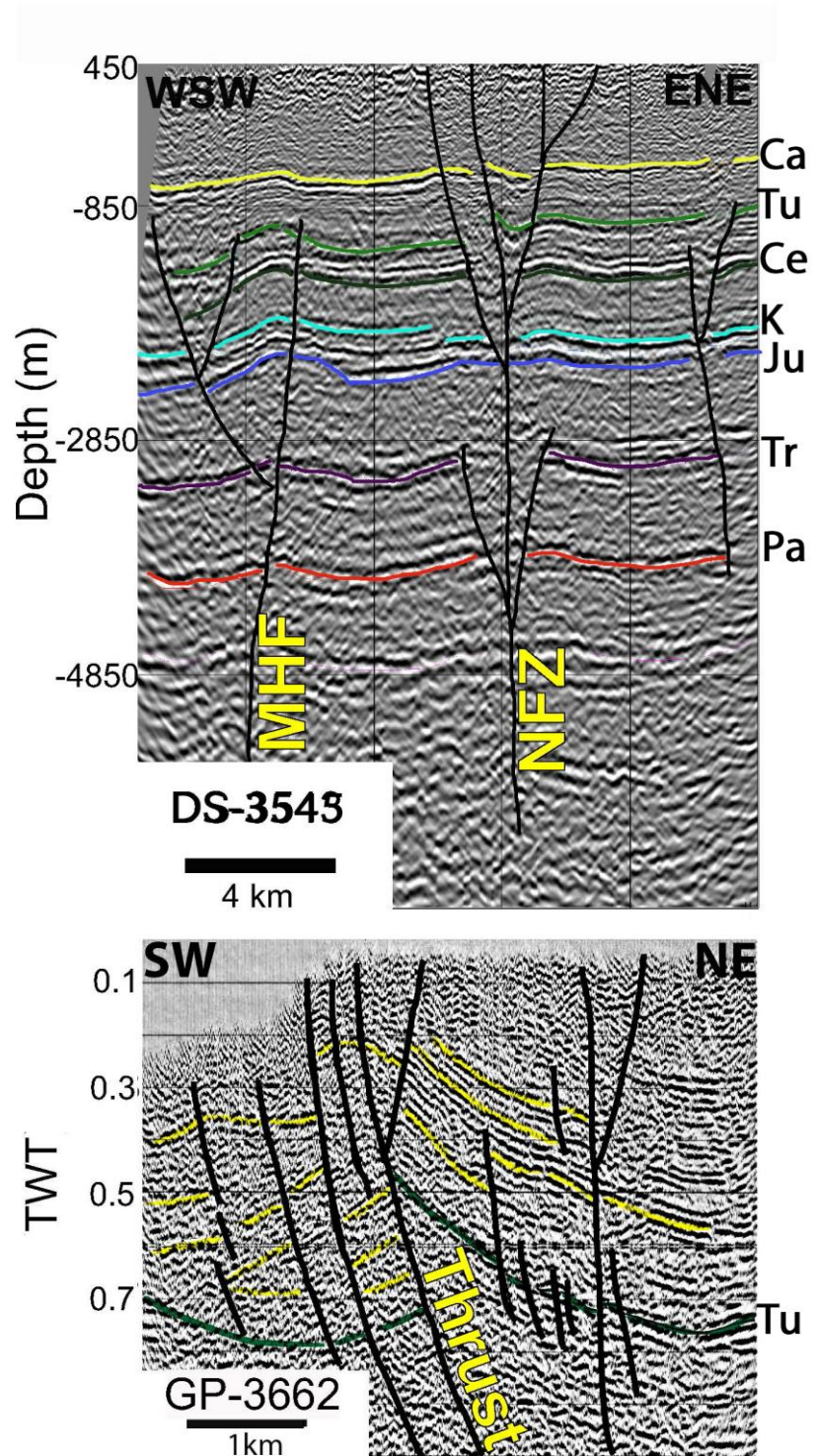
Figure 2: Seismic lines at Southern Golan. (a. top) seismic line DS-3545 showing flower structure reinterpreted after Meiler (2011). Vertical scale in meters. (b. bottom) seismic line GP-3662 showing the thrust fault reinterpreted after (Bruner and Dekel (1989)). Vertical scale in two ways time.
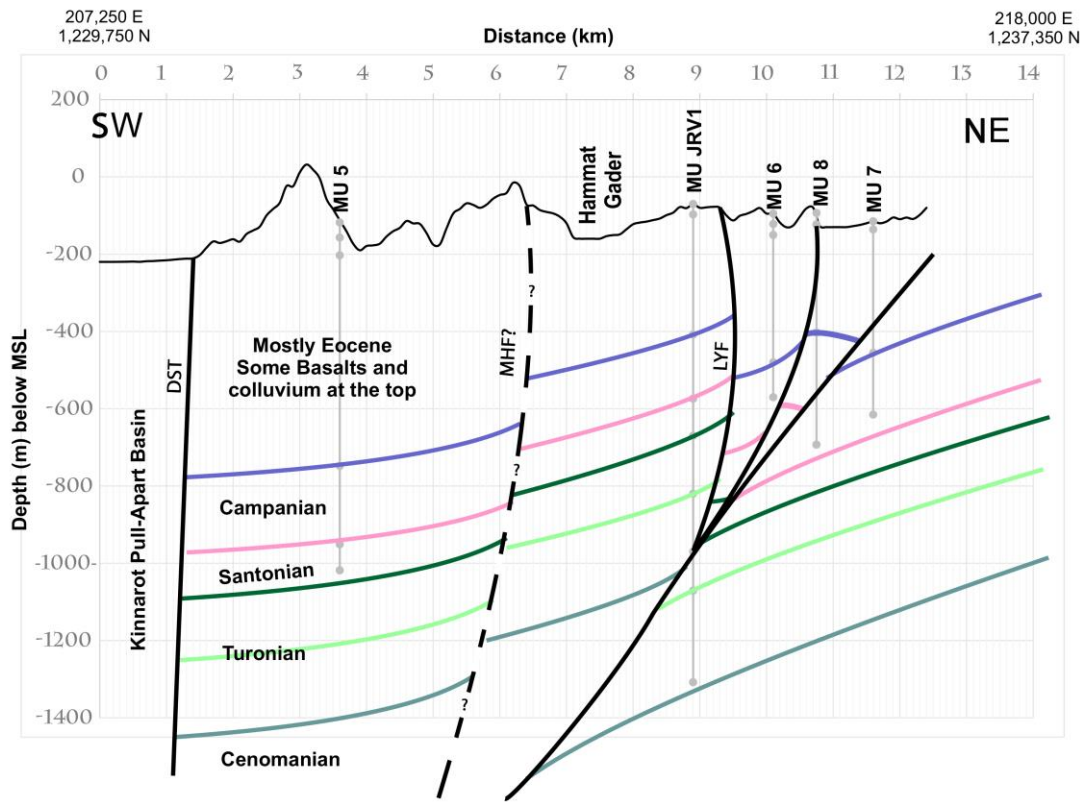
Figure 3: Geotectonic cross-section along the Lower Yarmouk Gorge, showing the interpretation of seismic line data and borehole information, which result in the given faults and depth position of geological formations.

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

Well name	Code	drilled lithology	Thickness (m)	Top (m MSL)	Underlying lithology
Mukheibeh 2*	MU2	chert, limestone	128 +	-470	not penetrated
Mukheibeh 3*	MU3	chert, limestone	75 +	-338	not penetrated
Mukheibeh 4*	MU4	chert, limestone	174	-450	limestone, dolomitic limestone
Mukheibeh 5*	MU5	chert, limestone	203	-748	limestone
Mukheibeh 6*	MU6	chert, limestone	90 +	-480	not penetrated
Mukheibeh 7*	MU7	chert, limestone	160 +	-455	not penetrated
Mukheibeh 8*	MU8	chert, limestone	290 +	-403	not penetrated
Mukheibeh JRV1*	MU JRV1	chert, limestone	166	-408	limestone
Meizar 1 **	MI1	chert, chalk, limestone, marl	195	-649	limestone, chalky limestone
Meizar 2 **	MI2	chert, chalk, limestone, marl	210	-424	limestone, chalky limestone
Wadi Al Arab 4*	WA4	limestone + chert	182		limestone
Wadi Al Arab 1*	WA1	limestone + chert	193		limestone
Wadi Al Arab 2*	WA2	limestone + chert	180		limestone
Wadi Al Arab 5*	WA5	limestone + chert	148 +		limestone
Douqara 1*	D1	chert, marl, marly limestone, bitumineous shale at the top	196		dolomitic limestone

- *Source of information: Margane and Hobler (1994) available via DAISY, 2017;
- ** Source of information: well log

380   + Partial thickness, not fully penetrated unit