Interactive comment on “Faulting patterns determining groundwater flow paths in the Lower Yarmouk Gorge” by Nimrod Inbar et al.

Reviewer #1

Dear reviewer 1,

We thank you for your valuable comments, which very much helped to improve clarity of the manuscript! We hope to reply in the following sufficiently to your remarks.

C1: Major comment: On figure 4, it seems there are no faults leading to the springs of Hamat Gader. Please explain better how water reach those springs? or suggest an alternative strategy to overcome this issue.

A1: This is by all mean an important question. The aim of the current MS is to delineate the main fault block system which controls the different hydrological observations in the area. However, those blocks exhibit extensive inner faults as was clearly described by Bruner and Dekel, 1989. This complexity can be seen also on the geological profile (Fig. 3) where only the main stem of the LYF is shown on the map (Fig. 1). Due to the limited available data, we receive only a coarse picture of the subsurface and hence, our interpretation “provides a **coarse** fault block model..." as mentioned in the abstract - line 30

C2: Minor comments: Line 20: suggest change ‘were previously’ to ‘were so far’ or ‘remain until now’

A2: We follow the suggestion and changed it.

C3: Line 22: reads like the fault was ‘constructed by’ you. . . should be ‘followed a compilations and revisions of. . .’

A3: We follow the suggestion and changed it.

C4: p.3, and Line 110: the Authors have clearly tried to avoid the notion of Israel and Jordan, yet, as observed in the top paragraph this task is not viable. Please add the Israel and Jordan at least to the introduction and map 1.

A4: We included respective information. In map 1, the international borders are included and respective country names are given.

C5: L126: Fig 3 shows map not cross section.

A5: After amending the figures we corrected all figures references.

C6: References: - Suggest to add: Starinsky, A., Kats, A., Levite, D. (1979). Temperature composition-

depth relation in rift Valley hot springs Hamat Gadder, northern Israel. Chem. Geol. 27, 233-244

A6: We follow the suggestion and changed it.

C7: Table 1: - add row for short name as appeared in Figures. - Standard the capitalization on lithology row.

A7: We follow the suggestion and changed it.

C8: Fig 2: - Perhaps add the in-interpreted section as well in the time domain? - On the interpreted sections add units name or numbers (e.g. for Turonian, Jurassic etc)

A8: Adding the un-interpreted GP-3662 section is not possible as the report by Brunner and Dekel (1989) contain only stack (un-interpreted) and migrated (interpreted) sections. The presented section is (as described in the caption) reinterpretation after Bruner and Dekel. Unit names were omitted by mistake in the current version – We follow the suggestion and changed it.

C9: Fig 3 and 4a: - Seems overlapping. Maybe choose on them? Fig. 4: - Split to two figures- one for the map other for the cross section, and give proper titles. - change W-E to SW-NE.

A9: We follow the suggestion and changed it.

C10: I found it strange that the markers are faulted (shifted vertically), yet you state there is no fault.

A10: Based on the available interpreted data in the study area, we are not able to trace a fault along the path of the gorge. Unpublished data by GSI indicate a SW-NE running fault, coming from the Lower Jordan Valley and reaching Hammat Gader indicate, faulting may also have occurred along the gorge. However, according to our interpretation, several faults crosses the gorge but - as far as observable - faults exhibits little to no vertical displacement at the surface.

Interactive comment on "Faulting patterns determining groundwater flow paths in the Lower Yarmouk Gorge" by Nimrod Inbar et al.

Reviewer #2

Dear Dr. Margane,

Particularly due to your long-term expertise in the area, we highly appreciated your kind words and constructive remarks on the manuscript! We hope to meet your points in the following.

C1: on the Syrian side where it should be mentioned that there are no known seismic profiles available (for this it could be referred to BREW et al., 2010 (Tectonic and Geologic Evolution of Syria, GeoArabia, Vol. 6, No. 4); which has e.g. Bussra-1 borehole, also mentioned in Meiler's PhD). It should also be added that on the Jordanian side there are no seismic profiles in this area. The closest oilwell is NH-1.

A1: The aim of the presented study is to delineate the structural guidelines across the Yarmouk Gorge at the area of Hammat Gader – Meizar – Mukheibeh. Therefore, Syrian data are not discussed. Similarly, oil wells and remote seismic lines in Jorden and Israel are not discussed.

C2: By the way, you might also want to refer to geol. structure contour maps for Northern Jordan done by me in the mid 1990s (Margane & Hobler, 1994) and available by your team for the SMART project.

A2: Of course, we only missed that citation. Corrected.

C3: In the abstract and later in the text it should be made clear that the new fault system was not inferred from remote sensing.

A3: In that paper we have not dealt with methods such as remote sensing, gravity, magnetics, etc., and therefore those methods are not discussed.

C4: In fact that's the disturbing part: "your" faults are not even located in the valleys/topo lows. So I am wondering how could they be inferred in areas where there is no geophysics like in NW Jordan?

A4: The faults described in the manuscript were inferred from seismic lines at the Golan Heights and their southward continuation across the gorge was inferred by geological profiles. One of the profiles was constructed as part of the current study, others were published by Sahawneh (2011). A line indicating the northernmost profile by Sahawneh was added to the map.

C5: Knowing how imprecise the fault system of Jordan was mapped by NRA in particular in the old days when satellite images where not used (until the 1990s) and when there was a lot of shifting in geological maps also due to the way mapping was conducted (we are speaking about hundreds of meters), I wouldn't dare using these as reference.

A5: We are aware of the critical correctness of the old geological maps, available from NRA. The original maps have been made available as GIS files, which have been corrected by Julia Sahawneh and own work at the UFZ.

C6: 119-21: there is no proof for these faults.

A6: That's correct, we reshaped the sentence.

C7: 123: relies Chapter 4: explain details of seismic data acquisition, e.g. spacing Text/graphics (Figures 2/3/4): text uses DS-3545, graphics use DS-3543; plz correct whichever is wrong.

A7: general description of seismic data collection was added with references to works with detailed description of the various parameters. DS-3545 is correct, typo was corrected.

C8: Chapter 5: Would be good to add mentioned locations, like Hamat Gader spring and Meizar 2 well in Fig. 3

A8: According to the remarks of RC1 we amended figures and new fig. 1 includes all information

C9: 219: why should faults be a constraint for GW modelling?

A9: Faults are often regarded as relative flow barriers with different hydraulic properties from the surrounding rock. Depending on the specific properties of the fault, it may either block or divert GW flow. In both cases it is constraining the model.

C10: Figure 1: you might want to add SF-Siwaqa Fault . Figure 2: plz add in Figure 3 which part of that seismic profile is shown here

A10: all maps were joined into a new Figure (Fig.1), which does not show any more Siwaqa Fault. The figure show the entire length of the seismic lines presented in Fig. 2

C11: Table 1: I have doubts Daisy is a valid reference. Can the described data be accessed by anyone (not being eligible)?

A11: We included the original reference Margane and Hobler, 1994, which is made available via DAISY. Daisy is accessible at http://www.ufz.de/daisy and holds data from several sources.

C12: Figure 3/4: add that the cute green lines are adopted from NRA geological maps MARGANE, A. & HOBLER, M. (1994): Groundwater Resources of Northern Jordan, Vol.3: Structural Features of the Main Hydrogeological Units in Northern Jordan. - Technical Cooperation Project 'Advisory Services to the Water Authority of Jordan', BGR & WAJ, BGR archive no. 118702:1-3, 57 p., 30 app., 38 ann.; Amman.

A12: Yes, please see answer on that comment above. Corrected also in the new Fig. 1.

Interactive comment on “Faulting patterns determining groundwater flow paths in the Lower Yarmouk Gorge” by Nimrod Inbar et al.

Reviewer #3

Dear Reviewer 3,

We thank you a lot for these critical remarks, by which the quality of the paper was much improved! We hope to sufficiently reply to your comments in the following.

C1: The main issue I have is the lack of a proper, comprehensive discussion. Currently, the discussion is mixed in with the results of the study. By separating them into two individual sub-chapters, both will benefit. The Results section needs to be expanded and presented in a more precise and focused way. The discussion must go into more critical issues that are currently lacking such as: - Tectonic implications - Hydrological implications.

A1: This comment, which refers to the structure of the manuscript was seriously considered. We have tried to transform Chapter 5 (Results) into results and discussion chapters as suggested. Those attempts, has further strengthen our initial consideration that the discussions parts of the chapter are in most cases supporting the rational presentation of results. However, the point raised is absolutely clear and therefore we have transformed the "Conclusion" chapter (chapter 6) into "Summary and conclusion". We hope that this new chapter answers most of the points raised in regards to the order and clarity of the presentation. With that said and done another point has to be clarified, it is not the scope of the current research to provide all answers regarding implications. The current manuscript suggests a new structural framework for future hydrological research together with questions that will hopefully lead to additional tectonic study and subsequently a much more advanced understanding of the geotectonic in that complex area.

C2: In a paper titled “Faulting patterns determining groundwater flow paths in the Lower Yarmouk Gorge” – you do not discuss groundwater flow patterns - A discussion of the mechanism that formed these faults - do they fit in with what we know about the stress field in the area?

A2: The aim of the presented research is to provide additional information to the structural framework of the area, which doubtless implies the geohydrological systems, as suggested by Tzoufka et al., 2018. It is correct, groundwater flow pattern is neither investigated nor discussed here.

The structure is described following interpretation of geological and geophysical data/findings and not following a study of kinematics, which may resolve once the questions of faulting mechanism.

That point is substantially important and we hence changed the title of the manuscript accordingly.

C3: It is not enough to say that since they are along the DSF, it fits. Also, statements such as: “The present study shows that although there is no evidence for large vertical displacements, strikeslip faults must cross the LYG forming fault-blocks. Therefore, these faults must be taken into consideration when discussing groundwater hydrology” (lines 118-120) need to be formulated in a more rigorous way. Why “must” strike slip faults cross the LYG?

A3: Thank you for that remark, we changed it to "might be related" and "suggested to consider".

C4: In addition, the discussion should address issues brought up in the Introduction. On lines 56-64

you mention the hypothetical fault trace of Magri et al. (2016), yet you do not refer back to this to show if your results support this trace or not. This is also true for the results of Goretzke et al (2016), which you mention in the introduction – do your results support or disprove their theories?

A4: This remark contributed to the new chapter "summary and conclusion", thank you! We agree with the work of Magri et al. (2015); Goretzki et al. (2016) and Tzoufka et al. (2018) that simulate groundwater flow and heat transfer across a fault crossing the lithological sequence. However, due to the limited available data, we receive only a coarse picture of the subsurface. Based on these available data in the study area, we are not able to trace a fault along the path of the gorge. However, unpublished data by GSI indicate a SW-NE running fault, coming from the Lower Jordan Valley and reaching Hammat Gader indicate, faulting may also occurred along the gorge, which would directly support the cited hydrological modeling studies

C5: The GII provides a comprehensive database of historical-recent seismicity. In such a study, I would also expect you to use seismicity to prove the presence of strike-slip faults or thrusts and help rule out previous suggestions. I think this would strengthen your arguments.

A5: We have scanned that database for all its content (about 100 years). We have not found any event with epicenter located in the study area. We can only conclude that the system has not been active for the last 100 years. As we believe that such statement does not contribute to the presentation it was omitted from the final text.

C6: Technical issues: - While the paper is well written, there are still a few grammatical mistakes. Please check the English again.

A6: We followed the advice and corrected grammatical mistakes.

C7: Every location, borehole, seismic line, etc. mentioned in the text needs to appear on a comprehensive location map, which is referred to in the text (e.g. Meizar 1,2 & 3 (Fig. 1)). This should be the very first figure of the manuscript (and not the third). This holds for every place name mentioned in the introduction and throughout the paper (GH, LYG, Golan syncline, Mt. Hermon, Sheikh Ali fault, Ajloun Dome, Hammat Gader and Mukheibeh springs, Meizar 1,2 & 3)

A7: Following that remark we have changed figure 1 to include also figure 3 and 4a. The new figure 1 has all required information. Thank you very much this step dramatically improved the MS.

C8: Line 19-20: Please do not cite in the Abstract

A8: Agree. Citation was removed from the abstract

C9: Line 31: The more correct term is “Dead Sea fault (DSF)” in keeping with the “San Andreas fault”

A9: The term DST is well known and accepted in the literature. Google scholar gives about 359,000 results for that term, starting with Garfunkel, Zvi. "Internal structure of the Dead Sea leaky transform (rift) in relation to plate kinematics." *Tectonophysics*80.1-4 (1981): 81-108. We prefer to keep this term.

C10: Line 97-98: The DST was already defined above. There is no need to define it again.

A10: Agree. Changed

C11: Lines 99-100: You present the eastern fault entering the Sea of Galilee as the main branch of the DSF. Why do you rule out the western branch (Hurwitz et al., 2002)?

A11: we accept this suggestion and added faults on the western side of the lake to complete the picture. Still, it is important to note that the N-S fault on the western side is not a strike-slip fault but an oblique-slip fault (Inbar, 2012)

C12: Line 134: “dots were connected” – please use a more scientific term. Perhaps “interpolation was carried out between data points”

A12: Thank you, we change it to more scientific terminology.

C13: Lines 140-146: From this paragraph it seems that you use the interpretation of Meiler (2011) for seismic cross section DS-3545. So when you say “reinterpretation” on line 149, what do you mean? It is not clear if you just took Meiler’s interpretation or if you did something of your own. Please clarify.

A13: It is repeatedly mentioned that we used Meiler's PSDM processes line and added our interpretation. The new interpretation adds new faults, which were previously neglected by Shulman (1989 and 2004) as well as by Meiler (2011). Those newly interpreted faults were probably not important for the regional study however they are highly significant when studying the LYG. We have also amended horizon identification, however acceding the scope of the current MS this topic is not discussed.

C14: Line 151-152: I do not understand the logic of the argument. Please rephrase so that it is clearer. Why is a thrust fault the more logical solution?

A14: Rephrased. "Another possible solution for the 2D seismic data is a thrust fault. This solution seem to fit better with the newly presented structural frame."

C15: Line 156: Seismic data is not measured. It is collected.

A15: Thank you, it's corrected.

C16: Line 159: Repetition

A16: Thanks. Deleted

C17: Line 184-187: Please refer to Figure 4

A17: Thanks, done.

C18: Lines 191-193: Repetition

A18: Yes, the entire paragraph is rephrased.

C19: Figures: Figure 1 should be a comprehensive location map that includes all places, boreholes, seismic lines, features, etc. mentioned in the text.

A19: Yes, it has been changed accordingly.

C20: Figure 2: please show non-interpreted seismic line together with the interpretation. Also on 2b – the vertical scale cannot be depth since this is a time section.

A20: yes, that’s correct – we changed it.

C21: Figure 3: this is in fact your location map and should come first. I cannot see the difference between Figure 4a and the bottom of Figure 3. Why do you need both if they are the same except for the location of profile A-A’?

A21: We changed it entirely.

A list of all relevant changes made in the manuscript

All changes were introduced following reviewer remarks.

The list below contains the major changes made to the MS:

1. **Title:** The message was softened. "determining" was replaced with "potentially influencing".
2. **Abstract:** Citations has been removed.
3. **Chapter 4:** Text was extended to include additional information regarding the seismic data.
4. **Chapter 5:** Title changed from "results" to "results and discussion" and the text was edited to better explain the issues raised in the review.
5. **Chapter 6:** This chapter was completely rewritten
6. **Figures:** All figures were amended and their order has been changed
    a. **Figure 1:** New figure 1 is a combination of figures 1, 3 and 4a of the older version.
    b. **Figure 2:** Horizons markers were added stratigraphic identification
    c. **Figure 3:** The older version figure 4b. Suggested fault (dashed line) was added question marks. Fault Identification was added.
7. **Table:** A code (abbreviation) column was added.

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

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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 geological features such as faults or dikes ~~-~~(Roded et al., 2013; Siebert et al., 2014; Magri et al., 2016; Goretzki et al., 2016). However, the nature of such features as well as their exact locations were ~~previously~~ so far unknown. In the present manuscript, we propose a new fault pattern in the Lower Yarmouk Gorge area by ~~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 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 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~~.~~ ~~Runoff~~ flows into the Jordan River south of the Sea of Galilee. Additionally, the LYG is receiving g~~G~~roundwater 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) 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 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 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~~high-pressure groundwater identified in wells located along the LYG. Roded et al. (2013) used a conceptual structural model of the Golan syncline ~~for~~ to numerically simulate~~ions~~ regional ~~of~~ groundwater flow and heat transfer,~~,~~ introducing below the LYG ~~an~~ a ~~enhanced~~ 5 km wide zone of enhanced vertical permeability~~ zone, below the LYG.~~ . Based on geochemical ~~considerations~~evidences, Siebert et al. (2014) suggested that the groundwaters in 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, 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 ~~They also suggested that buried dikes could be possible sources of heat and that weakness zones allow heated brines to ascend~~ and feed the Hammat Gader springs and some boreholes in the central LYG.

Numerical modeling of a 2D section crossing the LYG ~~which~~ inferred the existence of a fault in the gorge and revealed ~~in the study area~~ 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 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 groundwater migration across the plane is impeded. However, the above-~~-~~mentioned studies are based on simplified assumptions of fault locations and orientation.

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2 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 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 ~~(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~~ displacements at the surface, seismic and borehole data indicate strike-slip faults ~~must~~ cross~~ing~~ing the LYG forming fault-blocks. Therefore, ~~these~~ such faults ~~must~~should 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. Most of the seismic data were~~was~~ collected at the Golan Heights during the 1980's ~~as part of hydrocarbon exploration by the Israel National Oil Company~~ (Shulman and May, 1989), published later as~~.~~ t~~T~~ime migrated data ~~and interpretation~~analyses ~~was published at 2004~~ (Shulman et al., 2004) and ~~. This data was~~ 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 (~~was used~~ i.e. Meiler neglected ~~and the interpretation of faults was amended. T~~the westernmost fault ~~which was ignored at~~ in the regional context, which might ~~found to~~ be relevant at a local scale. ~~In 1989, a~~Additionally, seismic data ~~was collected at the~~from southern Golan (Mevo Hamma; Fig. 1) ~~area as part of a hydrological investigation of~~ (Shulman et al., 2004; Bruner and Dekel, 1989; Meiler, 2011) ~~was~~ were reinterpreted ~~thus~~ to considerably improving the structural information ~~on the southern Golan Heights~~in the vicinity of the Lower Yarmouk Gorge ~~(Fig. 2)~~. Based on these data, in combination with ~~and~~ lithological data from boreholes (Table 1), ~~facilitating the creation of~~ a new geological cross section ~~, which~~ was ~~drawn~~ constructed along the LYG, running SW-NE (Fig. 3). ~~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) (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 ~~plotted~~ traced 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 and Discussion

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 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 ~~seems~~ is the more compatible ~~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 (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 ~~measured~~ 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). ~~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 Meizar 2 and 3 wells and the Mukheibeh wells ~~field~~ (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 ~~in the study area~~along major parts of the gorge. Based on lithological interpretation of ~~these well~~well logs (IHS, (Margane and Hobler, 1994))~~s~~ 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 ~~As~~ Campanian B2 horizon ~~beds~~is disclosed in all wells of the study area. Hence, borehole data about its elevation and thickness ~~represent the upper part of the B2-A7 aquifer system, most water wells in the area penetrated at least partly this strata providing~~ provide good coverage ~~of data~~ in the study area and are ~~. 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, base of B2 ~~the top Campanian horizon~~ displays large elevation changes over small distances, e.g. ~~. One such case is~~ in borehole Mu~~kheibeh~~-6 located between Mu~~kheibeh~~-JRV1 and Mu~~kheibeh~~-8 (Fig. 4a), at distances of 1.2 km and 0.6 respectively. Although the ~~top Campanian (~~B2~~)~~ horizon ~~occurs~~ appears at similar elevations in boreholes Mu~~kheibeh~~-JRV1 ~~(-~~(-408 m msl.) and Mu~~kheibeh~~-8 (~~-~~-403 m msl.), it was encountered ~~at a considerably deeper level~~ in well Mu~~kheiba~~-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 ~~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.~~ The~~i~~se differences ~~is the~~ result from ~~of~~ faulting.

Considering ~~thicknesses only in~~ places in which ~~the Campanian~~ B2 beds were fully penetrated (Table 1) only, the average thickness of the chert-bearing ~~Campanian~~ B2 layer is 189± 14 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~~ 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~~kheibeh~~-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. ~~4~~3).

5.3 Tracking fault paths

~~By searching all available data resources (e.g. geological cross-sections, seismic lines) Ppreviously mapped fault tracess (manifested either as surface lineaments or revealed on geological cross-sections and seismic lines) were graphically merged with plotted together with those identified in the present study during the present study onfrom 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 connecteddata points were connected and the newly suggested faults were drawn (Fig. 3).~~

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~~The~~ geological cross-sections in the western Ajloun area (Sahawneh, 2011) were considered the southern extension of ~~show~~ 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. ~~4a~~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 ~~mapped~~ 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.

6 Summary and Conclusions

~~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.~~

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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References

Abu-Saad, L., and Andrews, I. J.: A database of stratigraphic information from deep boreholes in Jordan Subsurface Geology Bulletin. 6, edited by: NRA, A., Natural Resources Authority (NRA), Amman, 182 pp., 1993.

Andrews, I. J.: Cretaceous and Paleogene lithostratigraphy in the subsurface of Jordan, Subsurface Geology Bulletin. 5, edited by: NRA, A., Natural Resources Authority (NRA), 60 pp., 1992.

Arad, A., and Bein, A.: Saline versus fresh water contribution to the thermal waters of the northern Jordan Rift Valley, Israel, J. Hydrol., 83, 49 - 66, 1986.

Arad, A., Kafri, U., Halicz, L., and Brenner, I.: Genetic identification of the saline origins of groundwaters in Israel by means of minor elements, Chemical Geology, 54, 251-270, https://doi.org/10.1016/0009-2541(86)90140-3, 1986.

Baijjali, W., Clark, I. D., and Fritz, P.: The artesian thermal groundwaters of northern Jordan: insights into their recharge history and age, Journal of Hydrology, 192, 355-382, https://doi.org/10.1016/S0022-1694(96)03082-X, 1997.

Beydoun, Z.: Petroleum prospects of Lebanon: reevaluation, AAPG Bulletin, 61, 43-64, 1977.

Bruner, I., and Dekel, I.: High resolution seismic reflection survey in the southern Golan Heights The Institute for Petroleum Research and GeophysicsRep. 120/1939/88, 1989.

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Corti, G., and Dooley, T. P.: Lithospheric-scale centrifuge models of pull-apart basins, Tectonophysics, 664, 154-163, https://doi.org/10.1016/j.tecto.2015.09.004, 2015.

Dafny, E., Gvirtzman, H., Burg, A., and Fleischer, L.: The hydrogeology of the Golan basalt aquifer, Israel, Israel Journal of Earth Sciences, 52, 139-153, 2003.

Eckstein, Y., and Simmonsi, G.: Measurement and interpretation of terrestrial heat flow in Israel, Geothermics, 6, 117-142, https://doi.org/10.1016/0375-6505(77)90023-2, 1977.

El-Naser, H.: Groundwater resources of deep aquifer system in NW-Jordan: hydrogeological and hydrogeochemical quasi 3-dimensional modelling, Uni. Würzburg, Würzburg, 144 pp., 1991.

Flexer, A.: The paleogeography of the Senonian and Maestrichtian in northern Israel, Ph.D., Hebrew University, Jerusalem, 157 pp., 1964.

Garfunkel, Z.: Internal structure of the Dead Sea leaky transform (rift) in relation to plate kinematics, Tectonophysics, 80, 81-108, 1981.

Goretzki, N., Inbar, N., Kühn, M., Möller, P., Rosenthal, E., Schneider, M., Siebert, C., Raggad, M., and Magri, F.: Inverse Problem to Constrain Hydraulic and Thermal Parameters Inducing Anomalous Heat Flow in the Lower Yarmouk Gorge, Energy Procedia, 97, 419-426, http://dx.doi.org/10.1016/j.egypro.2016.10.038, 2016.

Gvirtzman, Z., and Steinberg, J.: Inland jump of the Arabian northwest plate boundary from the Levant continental margin to the Dead Sea Transform, Tectonics, 31, n/a-n/a, 10.1029/2011TC002994, 2012.

Heimann, A., Steinitz, G., Mor, D., and Shaliv, G.: The Cover Basalt Formation, its age and its regional and tectonic setting: implication from K-Ar and Ar40/Ar39 geochronology, Isr. J. Earth Sci., 45, 55-72, 1996.

Hirsch, F.: Geology of the southeastern slopes of Mount Hermon, Current Research, Geological Survey of Israel, 10, 22-27, 1996.

Inbar, N.: The evaporitic subsurface body of Kinnarot Basin - Stratigraphy, Structure, Geohydrology, Tel Aviv University, Tel Aviv, 131 pp., 2012.

Magri, F., Inbar, N., Siebert, C., Rosenthal, E., Guttman, J., and Möller, P.: Transient simulations of large-scale hydrogeological processes causing temperature and salinity anomalies in the Tiberias Basin, Journal of Hydrology, 520, 342-355, http://dx.doi.org/10.1016/j.jhydrol.2014.11.055, 2015.

Magri, F., Möller, S., Inbar, N., Möller, P., Raggad, M., Rödiger, T., Rosenthal, E., and Siebert, C.: 2D and 3D coexisting modes of thermal convection in fractured hydrothermal systems - Implications for transboundary flow in the Lower Yarmouk Gorge, Marine and Petroleum Geology, 78, 750-758, http://dx.doi.org/10.1016/j.marpetgeo.2016.10.002, 2016.

Margane, A., and Hobler, M.: Groundwater Resources of Northern Jordan, Vol.3: Structural Features of the Main Hydrogeological Units in Northern Jordan. - Technical Cooperation Project ’Advisory Services to the Water Authority of Jordan’, BGR & WAJ, BGR archive no. 118702:1-3, 57 p., 30 app., 38 ann., Amman, 1994.

Mazor, E., Kaufman, A., and Carmi, I.: Hammat Gader (Israel): Geochemistry of a mixed thermal spring complex, Journal of Hydrology, 18, 289-303, https://doi.org/10.1016/0022-1694(73)90053-X, 1973.

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Mazor, E., Levitte, D., Truesdell, A. H., Healy, J., and Nissenbaum, A.: Mixing models and ionic geothermometers applied to warm (up to 60°C) springs: Jordan Rift Valley, Israel, Journal of Hydrology, 45, 1-19, 10.1016/0022-1694(80)90002-5, 1980.

Meiler, M.: The Deep Geological Structure of the Golan Heights and the Evolution of the Adjacent Dead Sea Fault System, Tel Aviv university, Tel Aviv, 2011.

Michelson, H.: The hydrogeology of the southern Golan Heights, Tahal, Tel AvivHR/72/037, 89, 1972.

Michelson, H.: The Geology and Paleogeography of the Golan Heights, PhD, Tel Aviv University, Tel Aviv, 163 pp., 1979.

Mor, D.: The volcanism of the Golan Heights, Geol. Surv. Isr JerusalemGSI/5/86, 159, 1986.

Picard, L., and Hirsch, F.: The Jurassic stratigraphy in Israel and the adjacent countries, 1987,

Rahe, B., Ferrill, D. A., and Morris, A. P.: Physical analog modeling of pull-apart basin evolution, Tectonophysics, 285, 21-40, https://doi.org/10.1016/S0040-1951(97)00193-5, 1998.

Roded, R., Shalev, E., and Katoshevski, D.: Basal heat-flow and hydrothermal regime at the Golan–Ajloun hydrological basins, Journal of Hydrology, 476, 200-211, http://dx.doi.org/10.1016/j.jhydrol.2012.10.035, 2013.

Rosenthal, E.: Hydrogeology and Hydrogeochemistry of the Bet Shean and Harod Valleys, Geological Survey of IsraelRep. H/2/1972, 1972.

Rosenthal, E., Weinberger, G., Almogi-Labin, A., and Flexer, A.: Late Cretaceous-Early Tertiary Development of Depositional Basins in Samaria as a Reflection of Eastern Mediterranean Tectonic Evolution, AAPG Bulletin, 84, 997-1014, 10.1306/A9673B94-1738-11D7-8645000102C1865D, 2000a.

Rosenthal, E., Weinberger, G., Almogi-Labin, A., and Flexer, A.: Late Cretaceous – Early Tertiary paleostructures in Samaria, Israel, GSI Current Research Jubilee Volume, 12, 159-167, 2000b.

Sagy, A., and Hamiel, Y.: Three-dimensional structure and evolution of an asymmetric pull-apart basin, International Journal of Earth Sciences, 106, 1619-1630, 10.1007/s00531-016-1374-4, 2017.

Sahawneh, J.: Structural Control of Hydrology, Hydrogeology and Hydrochemistry along the Eastern Escarpment of the Jordan Rift Valley, JORDAN, PhD, Karlsruher Institut für Technologie (KIT), 284 pp., 2011.

Shulman, H., and May, P. R.: Seismic survey in the Golan Heights and its results, Isr. Geol. Soc. An. Meet. p. 155-156, Ramot 1989.

Shulman, H., Reshef, M., and Ben-Avraham, Z.: The structure of the Golan Heights and its tectonic linkage to the Dead Sea Transform and the Palmyrides folding Isr. J. Earth Sci., 53, 225-237, 2004.

Siebert, C., Möller, P., Geyer, S., Kraushaar, S., Dulski, P., Guttman, J., Subah, A., and Rödiger, T.: Thermal waters in the Lower Yarmouk Gorge and their relation to surrounding aquifers, Chemie der Erde - Geochemistry, 74, 425-441, http://dx.doi.org/10.1016/j.chemer.2014.04.002, 2014.

Smit, J., Brun, J. P., Fort, X., Cloetingh, S., and Ben-Avraham, Z.: Salt tectonics in pull-apart basins with application to the Dead Sea Basin, Tectonophysics, 449, 1-16, 2008.

Smit, J., Brun, J. P., Cloetingh, S., and Ben-Avraham, Z.: The rift-like structure and asymmetry of the Dead Sea Fault, Earth and Planetary Science Letters, 290, 74-82, 2010.

Sugan, M., Wu, J., and McClay, K.: 3D analogue modelling of transtensional pull-apart basins: comparison with the Cinarcik basin, Sea of Marmara, Turkey, Bollettino di Geofisica Teorica ed Applicata, 55, 2014.

Weinberger, R., Gross, M. R., and Sneh, A.: Evolving deformation along a transform plate boundary: Example from the Dead Sea Fault in northern Israel, Tectonics, 28, 10.1029/2008TC002316, 2009.

Wu, J. E., McClay, K., Whitehouse, P., and Dooley, T.: 4D analogue modelling of transtensional pull-apart basins, Marine and Petroleum Geology, 26, 1608-1623, https://doi.org/10.1016/j.marpetgeo.2008.06.007, 2009.

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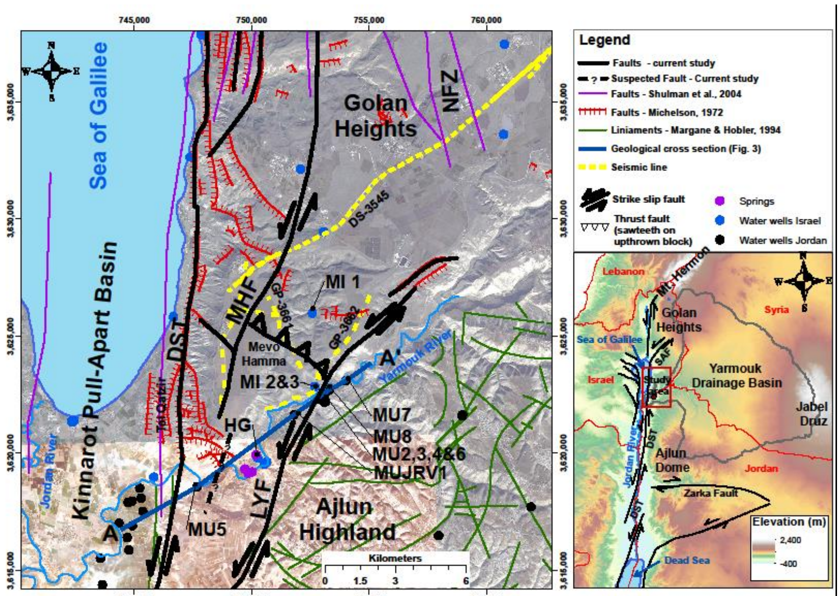

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Figure 1: Regional location map on top of digital elevation model, presenting the faults at the eastern rim of the Dead Sea Transform.~~-~~ Current study proposed faults are at the area of the Lower Yarmouk Gorge, east of Kinnarot pull-apart basin, the major Jordan Dead Sea Rift Transform Fault (DST), Sheikh Ali Fault (SAF), Nov Fault Zone (NFZ), ~~(marked:~~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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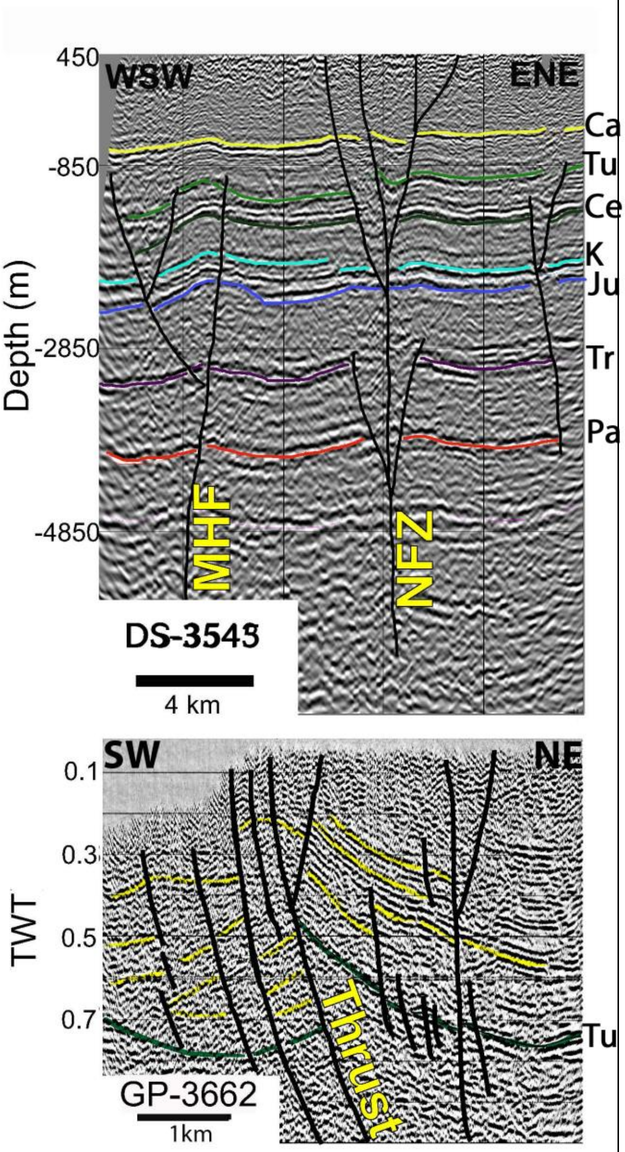

Figure 2: Seismic lines at Southern Golan. (a. top) seismic line DS-3545 showing flower structure reinterpreted after Meiler (2011). Vertical scale in meters. (b. bottom) seismic line GP-3662 showing the thrust fault reinterpreted after (Bruner and Dekel (1989)). Vertical scale in two ways time.

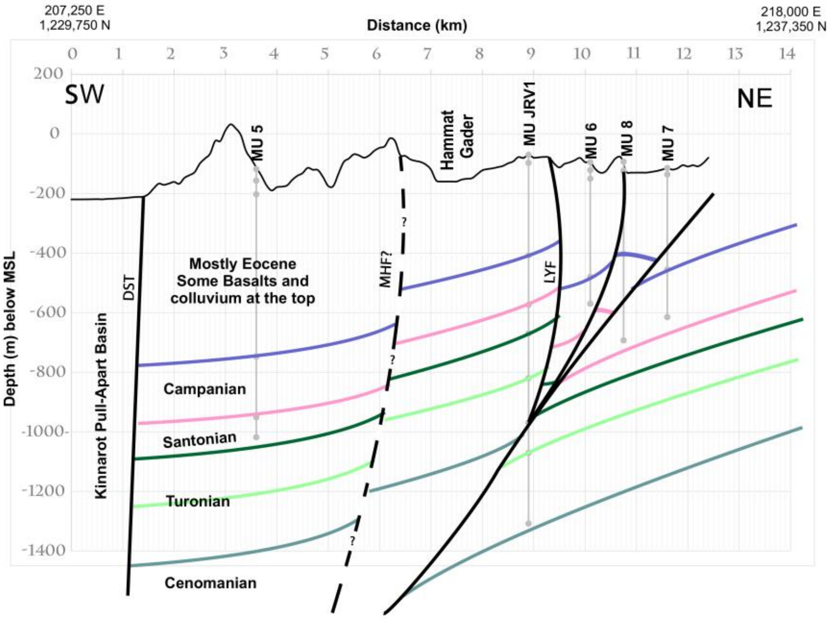

Figure 3: Geotectonic cross-section along the Lower Yarmouk Gorge, showing the interpretation of seismic line data and borehole information, which result in the given faults and depth position of geological formations.

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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~~chert, limestone	128 +	-470	~~Not ~~not penetrated
Mukheibeh 3*	MU3	~~Chert~~chert, limestone	75 +	-338	n~~N~~ot penetrated
Mukheibeh 4*	MU4	~~Chert~~chert, limestone	174	-450	~~Limestone~~limestone, dolomitic limestone
Mukheibeh 5*	MU5	~~Chert~~chert, limestone	203	-748	limestone
Mukheibeh 6*	MU6	~~Chert~~chert, limestone	90 +	-480	~~Not ~~not penetrated
Mukheibeh 7*	MU7	~~Chert~~chert, limestone	160 +	-455	~~Not ~~not penetrated
Mukheibeh 8*	MU8	~~Chert~~chert, limestone	290 +	-403	~~Not ~~not penetrated
Mukheibeh JRV1*	MU JRV1	~~Chert~~chert, limestone	166	-408	limestone
Meizar 1 **	MI1	~~Chert~~chert, chalk, limestone, marl	195	-649	~~Limestone~~limestone, chalky limestone
Meizar 2 **	MI2	~~Chert~~chert, chalk, limestone, marl	210	-424	~~Limestone~~limestone, chalky limestone
Wadi Al Arab 4*	WA4	~~Limestone~~ limestone + ~~Chert~~chert	182		limestone
Wadi Al Arab 1*	WA1	limestone + chert~~Limestone + Chert~~	193		limestone
Wadi Al Arab 2*	WA2	limestone + chert~~Limestone + Chert~~	180		limestone
Wadi Al Arab 5*	WA5	limestone + chert~~Limestone + Chert~~	148 +		limestone
Douqara 1*	D1	~~Chert~~chert, marl, marly limestone, bitumineous shale at the top	196		~~Dolomitic ~~dolomitic limestone

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

+ Partial thickness, not fully penetrated unit

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~~**Figure 3:**~~

~~**Figure 4:** 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.~~