Report on the Neo-Tectonic Setting and Seismic Sources for the Seismic Hazard Assessment of the Bisri Dam Site.

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Index:

Preamble:

The below is the final report on the assessment of the neo-tectonic setting of the Bisri Dam site and the nearby seismic sources for use in Seismic Hazard assessment of the dam.

Summary of findings:

1- ***Some of the parameters used for characterizing the major faults were reviewed based on modern and latest accepted models of the geology and tectonics of the region. The Length of the Yammouneh Fault considered in previous geological reports equal to the length of the entire transform plate boundary between the Red Sea and Anatolia is revised. In our opinion and given the widely accepted standards and rules in Seismotectonics, this is an exaggeration of the possible rupture length. Adopting a smaller and more realistic value of 200km of length, resulted in a reduction of the MCE for the Yammouneh Fault to 7.9 in compliance with the definitions set by ICOLD 2010 guidelines.***

2- ***We identified the MLT ramp as a new seismic source that can affect the Dam site and characterized its hazard. This is a blind sub-surface thrust ramp that lies below the northern part of the Dam site and is capable of generating MCE of 7.8. Special care should be given when considering the GMPEs of this source because of its special geometry (a thrust).***

3- ***No proof of major active faulting related to the inferred fault below the Dam site was found in the geomorphology or geology of the site. In particular there is no evidence supporting the 3m fault offset under the Dam site.***

4- ***No convincing evidence was found in support of the continuation of the Roum Fault under the sedimentary cover of the Bisri valley.***

5- ***Instead, the gathered data suggest that no active major fault runs under the Marj Bisri valley.***

6- ***Given the important erosion/deposition rates within the valley, the possibility that surface expression of other, less active, deep-seated faults may have been smoothed and covered cannot be totally ruled out. These faults – if they exist – have very limited extent with little to no long-term effects on the Marj-Bisri geology and morphology.***

A- Review of the tectonic structures and seismic sources of the Bisri Dam site:

The Bisri Dam site is located in the Southern Central Mount-Lebanon area, ~15km east of Saida and at midway to the Yammouneh plate boundary located another ~12km east of the Dam-site.

The main tectonic elements in the geology of the area are:

- **The Yammouneh Fault:** is the local segment of the large Arabia/Nubia, dominantly left-lateral, plate boundary in the Eastern Mediterranean area that stretches from the Red Sea south to the East Anatolian Fault in the north. This plate boundary, also known as the Levant Fault System or Dead-Sea Transform is ~1100km long. The Yammouneh Fault is the main local segment of the system and extends in a straight and almost continuous line over ~200km from Huleh basin in the South to Boukaia basin in the north. Because of its N25-30E strike the fault represents a major irregularity (a right bend) in the geometry of the plate boundary. The fault is seismically active and has produced major earthquakes the latest and strongest is M~7.6, 1202 event, with a coseismic slip of 5-6m (Daeron et al 2007). The fault has a slip rate of 4-6mm/yrs (Daeron et al 2004, Gomez et al 2007). Because of the irregularity in the fault geometry within the LFS, the fault ruptures associated with seismic events are not likely to extend far beyond the limits of this segment (Daeron et al 2007). The Yammouneh Fault is at ~12km from the Dam site.

- **The Mount-Lebanon Thrust (MLT)** is a thrust system that accommodates shortening associated with the Lebanese Restraining Bend of the Levant Fault System (Tapponnier et al. 2001a, Daeron et al 2004, Elias et al 2007). This shortening perpendicular to the Yammouneh Fault is obvious in the surface geology and structuring of the ranges (Elias et al 2003) and was also demonstrated using geodetic measurements as well (Gomez et al 2007). The main MLT fault is an east-dipping thrust ramp that offsets the seafloor offshore Lebanon and is connected at depth with the Yammouneh Fault. The surface expression of this deep ramp is the Lebanese Flexure, a relatively well localized zone of important westward increase of the structural dips of all geological layers that can be mapped over the entire western Lebanon between the coastal Chouf area, north of the Bisri valley in the south and the extreme north of Lebanon in Akkar where the flexure re-connects with the Yammouneh Fault (Fig1a). This Flexure corresponds also with important increase in elevation of the topography to the east, relatively to the western compartment (Fig1b). It represents the western boundary of the high relief of Mount-Lebanon range and thus can be associated with its build-up. The Mount-Lebanon Thrust ramp is mostly a blind fault onshore, the ramp cuts the surface in the offshore. Evidence of rupture of the Quaternary and recent marine sediments at the tip of the MLT faults were observed during the SHALIMAR marine geophysical campaign (Elias et al. 2007, Carton et al 2009). The location of the offshore ruptures and faults corresponds with the observed uplift of the shoreline as indicated by stairs of uplifted marine terraces (Elias et al 2007). A complex system of offshore thrust faults is also associated with the MLT (Fig1a). The MLT and the Flexure run alongside each other over the entire Lebanese coast between Saida and Tripoli. This 40-45°, east–dipping thrust ramp mostly located in the upper, seismogenic, ~16km of the crust (Fig1b) has a vertical slip-rate ~1.5 mm/yr (Elias et al 2007). Although at depth the ramp merges with the Yammouneh Fault, the transfer of slip between the offshore ramp and the onshore compressive structures such as the Roum and Akkar Faults happens over lateral fault ramps such as the Aabdeh fault in the north and Roum Fault in the south. The junction between this Thrust System offshore and its onshore counterpart in the Roum Fault area is complex and not very well known (see below). The Bisri Dam site is located at a distance south of the MLT ramp in the transfer area between the MLT and the Roum Fault (Fig1a).

A geological cross-section of the area at the south end of the ramp helps constrain the geometry of the ramp at depth (Fig1b). The key elements of the cross-section are the location of the fault on the seafloor and within its sediments as revealed by geophysical data from the offshore, and the position and attitude of the Lebanese Flexure and associated structures onland as well as known stratigraphic constrains of the local geology such as thickness of the geological units. The resulting cross-section gives a first approximate estimation of the depth to the base of the ramp located between 16 and 18km depth. The deeper geometry connecting with the Yammouneh Fault is poorly constrained but is of lesser importance for seismic hazard as it is considered to lie entirely outside the seismogenic layer. The M~7.5, AD 551 earthquake is the best-known event associated with this fault system. It ruptured the entire ramp where possible co-seismic rupture between 2-3 m was also inferred based on measured uplift indicators along the shoreline between Tripoli and Saida (Elias et al 2007). The surface rupture of this event was located in the offshore at the tip of the main ramp and further away on some of the smaller thrusts located in front of it (to the west). Based on the mapped fault trace the expected MLT co-seismic rupture can therefore be at least 40km away from the Dam site.

- **The Roum Fault** is a secondary branch of the Plate Boundary that splays into the Lebanon at Huleh south. It has a N-S strike over most of its 35km length. The fault is considered as mostly left-lateral strike-slip with a compressive component increasing towards the north. All known geological mapping literature concur that the Roum Fault doesn't reach beyond the Awali river (the Dam site) as it merges into the Jezzine Anticline south of the Awali. The Mazraa or Chouf Monocline to the north would correspond to its northern structural equivalent (Dubertret 1955, Nemer & Meghraoui 2006, Elias et al 2006). The generally accepted mapping of the Roum Fault is the one based on the geological mapping of the pioneering work done by Louis Dubertret in the 1960s. More recently, within the discovery of the Mount-Lebanon Thrust system located mostly offshore and responsible for the growth of the range, the Roum Fault was reinterpreted as a lateral ramp of this system (Daeron 2005, Elias 2006). This requires the presence of slip transfer between Roum and the offshore thrusts in southern Lebanon. The structures accommodating this transfer are still poorly known. The slip transfer may be accommodated by diffuse deformation on small scale structures. The mapping of Roum fault as done by Daeron (2005) simply reflects this theoretical model and not a ground based structural mapping of the fault trace in the area. No major and continuous structure accommodating the transfer is known from the geology that could represent an important seismic threat for the Bisri area. The geological fault as mapped by Dubertret should serve best for the seismic design of the Dam site.

The Roum Fault is seismically active. It has produced the two most recent destructive earthquakes onshore Lebanon the M~7, 1837 and the M~5.7, 1956 events. Its horizontal slip rate is ~1mm/yr. The mapped geological fault trace stops ~2km south of the Dam-site. Continuation of the fault further north into the Bisri valley was suggested by previous site investigations conducted within the frame of this project. Our own re-assessment of the geology of the area found no evidence of possible active faulting associated with the faults inferred by these studies (to be detailed later). In particular our results question the validity of the suggested 3m of possible offset under the dam.

- Other smaller faults are also present in the vicinity of the dam-site but are of much less significance for the seismic hazard of the dam area. In particular it is worthy to note the existence of a set of E-W to NW-SE faults that appear to offset the Lower and Middle Cretaceous and die out in the upper (Paleozoic) layers. These faults are associated with growth evidence in the Mesozoic times and are considered to be inactive at present. This type of faults is very dominant in the geology of the Chouf area in particular and western Lebanon in general (Dubertret 1955, Elias 2006, Hajj-Chehadeh & Elias 2014).

B- The seismic design criteria of the corresponding faults:

The instrumental seismicity of Lebanon and the area is poorly constrained. Large uncertainties reside in the available earthquake catalogues and no reliable information can be extracted for statistically analyzing the frequency-magnitude relationships for earthquakes in the area. However the historical record of around 2 millennia covers the entire seismic cycle span of most of these faults as shown by paleoseismic studies. Therefore, the maximum observed magnitudes are the best possible approximations of the

Mmax values. Systematically a value of 0.3 units of magnitude can be added to account for uncertainties and variability of earthquake events. Scaling laws as in Wells and Coppersmith (1994) can be used as guidelines or for sanity check in estimating plausible maximum earthquake magnitudes on the different faults.

From the above we can set the following seismic criteria for the area:

	Maximum Observed (Mw)	MCE	Type of faults
Yammouneh Fault	7.6	7.9	Strike-slip
Roum Fault	7.0	7.3	Strike-slip
MLT ramp	7.5	7.8	Thrust

As for the Operating Basis Earthquake, the best estimation for a magnitude with a return period of 144 yrs is exactly the latest strongest observed in this area, given the quality of instrumental data available compared with the long recurrence intervals of earthquakes on the present faults. Therefore the OBE should be the M= 5.7+0.3 event of 1956 on the Roum Fault.

C- Investigating the extension of the Roum Fault under the Bisri Dam site:

- Previous studies:

Correlation of logs from wells drilled inside the Marj Bisri revealed differences in the age of the underlying substratum that suggest the presence of faulting in the bedrock under the mid valley floor under the Dam site. The inferred mapped fault trace strikes NE-SW and then bends to the right in a more E-W direction. Interpretation of the geology shown on all the sections (A-A, B-B, C-C, D-D and E-E in DAHNT/NOVEC 2013) suggests that the fault accommodates vertical slip with eastern/southern block moving up. The geological reports suggest this to be the continuation of Roum Fault in the area.

In the Section 3 (Seismotectonics and Seismic Criteria) of Appendix-A of the Feasibility Report, Paragraph 3.4.3 refers to field investigations done

Moreover, previous geological reports from field surveys in 1983 mention "possible evidence of fault movement" uncovered in two test pits, TP-17 and TP-21, located towards the center of the valley[1]. They report the presence of abnormal dips in clay seams interpreted as possible evidence of fault movement. During field investigations undertaken in 1994 two trenches T1 and T2 were excavated on the northern side of the valley at the edge of the alluvial infill on the highest of the riverbed terraces[2]. In Trench T2 oriented NE-SW and located closest to the talus of the northern flank of the valley, a 20-30cm vertical offset of the infill layers were uncovered and interpreted as evidence of fault ruptures. The suspected fault was assumed to be a subsidiary of Roum and this overall setting was considered as an evidence for the presence of an active Roum fault under the Dam site. These conclusions raise serious questions: What justifies the choice of the two trenching sites, especially that they are located away from the location of the TP-17 and TP-21 where the possible evidence of fault movement was first observed? How is this suggested fault connected with Roum fault? What is the structural relationship between these two hypothetical faults?

Very little information about this particular aspect of the original fieldwork in 1983 and 1994 was available to us. Given the location of the trenches T1 and T2 at the base of the talus of the northern valley flank, the observed offsets are most probably due to slope failure or slope erosion and deposition processes, and does not necessitate the presence of a tectonic fault underneath. Moreover that no lateral extension of this assumed fault was presented on any of the geological documents from previous surveys reveals the difficulty to have an active fault in that area.

-Work method:

We conducted a geological study of the Marj Bisri area in order to constrain the presence of the Roum Fault or any other fault that cut through the site and to characterize its activity.

[1] Bisri Dam Feasibility Report, Appendix-A, Section 3 - Seismotectonics and Seismic Criteria, Paragraph 3.4.3.

[2] Figure A4-4-Geologic Section and Boring Location Plan, *in* Appendix-A of the Feasibility Report

The study included review of available geological documents related to the area, and inspection of topographic maps, satellite images and other remote sensing products. In particular the analysis of aerial photos numbers 223, 224 and 225 of the region taken in 1962, revealed to be very useful because of the good exposures of the geological outcrops and morphology at a time before the development of heavy vegetation cover. The desk study was also combined with field visits to the area in May 2014.

-The Roum Fault zone within the accepted structural model of South Lebanon:

The Roum Fault was first considered a branch of the active Dead Sea plate boundary in Lebanon. Its North-South strike was considered by some authors to be the only active branch of the plate boundary (Girdler 1990) extending northward under Beirut area, and continuing offshore over the seafloor towards Cyprus (Butler & Spencer 1998).

Recent tectonic research shows that the Yammouneh Fault is the main active segment of the Arabia/Sinai plate boundary in Lebanon accommodating most of the strike-slip plate motion (Daeron et al 2004). Geophysical data acquired offshore Lebanon show undeniably that the Roum Fault does not cut the sea floor. Geodetic and paleoseismic investigations in Lebanon and on the Roum Fault in particular show that the latter is accommodating a minor component of strike-slip as well as a compressive component.

The Roum Fault with an oblique reverse/left-lateral component of slip is the main topographic boundary in the region of south Lebanon separating the high relief area of south Barouk and Mt-Lebanon range to the east, from the relatively flat, low lying and mostly tabular Nabatiyeh plateau to the west (Fig 1).

The fault trace is clearly mapped in a ~N-S direction in its southern segment between Marjeyoun and Jbaa where it has mostly a strike-slip character. North of Jbaa the fault changes direction into a N10-16E and has a less clear geological surface trace where it becomes dominantly compressive and merges with the broad and asymmetric Jezzine anticline. The steep western limb of the anticline seems to be cut by the fault. Secondary folding probably related to frontal splays associated with the Roum fault are also observed to the west. However the intensity of the folding and compression seems to decrease northward and the steep structural dips of the Upper-Jurassic to Lower-Cretaceous units forming the western limb of the Jezzine anticline between Sniye and Aazour decrease to the north near Bisri. The structural elevations also decrease northward: the top of the Upper-Jurassic (J7) layers located at a maximum of 900 masl west of Homsiyeh in the center of the anticline, is around 750 masl southeast of Taaid and decreases fast near Bisri. The periclinal closure of the Jezzine anticline starts at Bisri and is clearly observed in the structure of the northern flank of Ouadi Bisri between Bsaba and Jabal Baiqoun. The structural units of the anticline can be traced astride the valley continuously with no sign for interruption or offset. The hinge line of the Jezzine anticline extending around 9km in a ~N13E direction plunges steeply to the north.

Structural investigations in the Chouf area – north of Bisri Valley – found no continuation of the Roum Fault beyond the Bisri Valley. A smaller equivalent of a deep-seated thrust ramp under the Mazraa Flexure between Gharife and Beit-Eddine, may be the equivalent of the Roum fault under the Jezzine anticline but at a smaller scale and with no trace of surface faulting. Moreover no active fault from the area east or north of Marj Bisri can be a possible candidate for a possible continuation of the fault inferred to exist within the Marj.

The geology of the Chouf region in general and the Jezzine Bisri area in particular reveals the existence of an important number of small, mostly E-W to ESE-WNW striking, normal faults offsetting the Mesozoic geology. Where these faults are well developed they appear to end within the Upper Cretaceous layers. Offsets along these faults can be significant reaching sometimes around 300m of apparent vertical offset (Dubertret 1955, Hajj Chehadeh & Elias 2014). Structural studies (Dubertret 1955, Elias 2006, Homberg 2010) suggest that these are old Mesozoic normal faults inherited from the earliest phases of extension of the western Arabian continental margin. No evidence of recent tectonic activity can be associated with them. An extensive array of similar faults was mapped in the area in the previous geological studies done within the frame of the Bisri Dam Project[3]. Faulting of this type is suitably oriented to be responsible for the observed changes in the lithology of the substratum under the Dam site. In fact the inferred fault has a similar ~E-W trend as these old Mesozoic faults. Moreover not only the inferred fault trace is based on discrete observations done in wells with no direct continuity of observations, but it also results in a very unusual fault trace with almost a 90 degrees bend making its existence very doubtful given the structural difficulty to explain the occurrence of such a fault trace.

[3] FigA2-1 Geological Map of Reservoir Area, in Bisri Dam feasibility report

-The alluvial infill:

The northern pericline of the Jezzine anticline is breached by the deep incision of the Bisri river. This incision is mostly the resultant of the waters from the Barouk-river as they reach the friable and weak lower Cretaceous sandstone layers downstream from Ouadi Bater. After flowing in an E-W direction over this Chouf Sandstone formation, the river leaves the Jezzine anticline through a breach in the steep western limb west of Bisri village. Downstream the Awali-river has a much narrower valley incised in the monotonous Mid-Cretaceous Cenomanian limestone layers. A number of slope failures – some of them of very large size – has contributed to the damming of the river flow at many times and places. In particular a clear large landslide east of Anane resulted in the flooding of the upstream Bisri valley and the accumulation of alluvials and lacustrine material in the deep valley. The geological and geotechnical studies in the Marj Bisri area presented in the Geological report of the Bisri Dam project suggest the existence of a maximum 135.16m of Quaternary deposits in the valley (DAHNT/NOVEC 2013 p14). This value also roughly corresponds to the difference in elevation between the mean altitude in Marj Bisri (~400m) and the altitude of the deep riverbed immediately downstream from the Anane landslide (~270m) suggesting there is no place for vertical offset of the deep substratum forming the floor of the valley under the Marj, which rules out the possibility of any activity on this inferred fault at least since the incision of the deep substratum and the filling of the valley.

- The geomorphology of Marj Bisri:

Three sets of river terraces were nested in the floodplain of the area since the river breached the damming landslide volume (Fig4). These terraces can be followed over much of the Bisri Valley floodplain but they are the most clear in the western half of Marj Bisri. The elevation of these terraces increases gradually from west to east along the river profile, as expected. However when the same terrace is considered over a segment of the river profile on both sides of the valley, they are always found to be at similar elevation[4]. Although different type of alluvials have been identified within the fill of the Marj, the surface of the terraces has leveled all of them independently of their type[5] which indicates that the terraced morphology of the Marj results from a principal morphogenetic process and not a secondary result of the depositional processes.

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[4] Figure A4-2, Geological section Axis A, from the Bisri Dam Feasibility Report.
[5] Section B-B, DAHNT/NOVEC 2013.

The water of the Bisri River is flowing within the limits of the lowest present terrace or active floodplain. It resulted in many small oxbow lakes and meander scars typical of meandering rivers. Comparison between present situation and aerial photos of the area taken in 1962, shows some important shifts in riverbed position suggesting important lateral erosion of the Bisri river within its lower, active floodplain.

Ouadi Houarit is a smaller branch of the Bisri Valley that opens south of Bisri village in N-S direction. It is caught between Taaid from the east and Arid Qdoum from the west. The valley is filled and covered by the same alluvials as Marj, where nested river terraces have developed. A large upper terrace – the Houarit terrace – is located over most of the surface of this valley, at around 415m asl. The Ouadi Houarit and Ouadi er Rejme are two seasonal streams that incise their streams inside this surface before converging with the Bisri-river.

The exact age of these alluvials and the terraces is not known. They are estimated to be Quaternary in age. In fact given the abundance of landslide scars on the valley flanks, and in particular on the southern flank were the nature and the important northward dip of the rocks is more prone to sliding, the filling of the valley may have happened in different stages as a result of many landslides. Part of this may have happened relatively recently as suggested by the presence of a buried archeological site of a Roman temple in the upper Marj Bisri (Aliquot 2009). However the steep incision of the river near El-Kherbe, exactly where it passes over the slid volume of Anane suggests that this landslide was the latest to dam the valley and to result in the flooding of the upper stream. When did this happen is unknown. Given the important thickness of the sediments the filling should have happened at least during the late Pleistocene.

Marj Bisri and Ouadi Houarit should have been simultaneously filled by alluvials during the same flooding process. But unlike the Marj, the erosion and incision power of the two small streams that cut through the Ouadi didn't affect much its geomorphology. The two streams are well entrenched in the Houarit surface and do not meander. The elevation and extent of the upper terraces are therefore well preserved and could be used as reliable indicators of any subsequent deformation in this area.

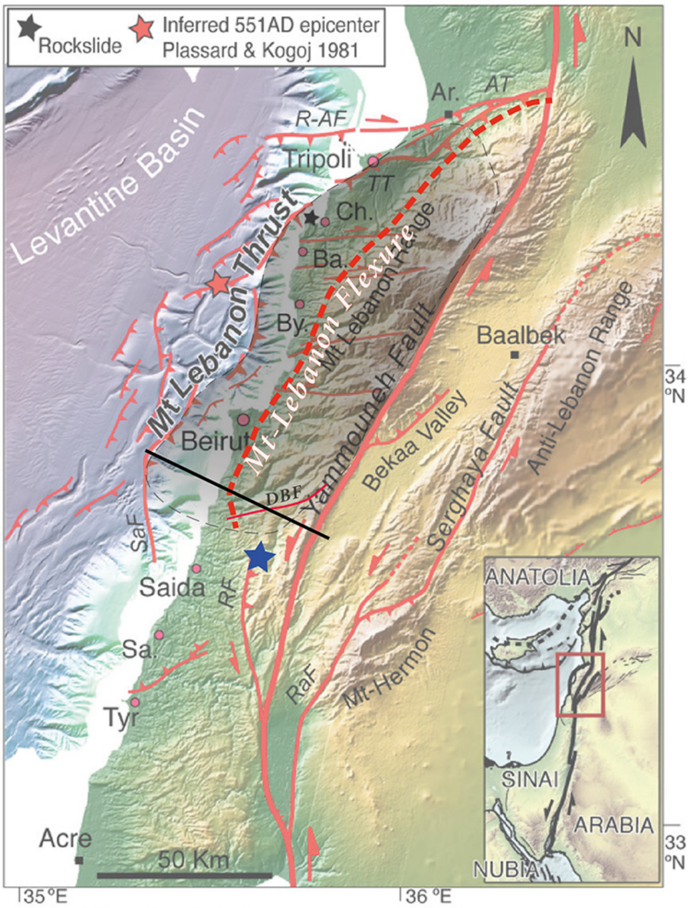
As mapped in previous geological reports for the Dam project, Roum Fault enters the Bisri Valley from Aazour in the south, in the Ouadi Houarit area. According to the geological surveys presented in the previous reports of the Bisri Dam project, the fault continues in the infill of the valley, cuts through the subsurface of the entire Ouadi Houarit and Ouadi er Rejme in a NE-SW direction and continues west of the Bisri village into the wide Marj Bisri plain (Fig 4).

Mapping of the terraces in the Houarit area reveals no deformation effect that can be attributed to the Roum Fault inferred to be present in the infill of its subsurface. The risers of these terrace as well as the channels of the streams are continuous and show no deflection or offset in any horizontal or vertical direction. In particular, the completely abandoned upper Houarit terrace is perfectly flat and connects easily at the same elevation with the other upper terraces of the Marj with no vertical offset suggestive of a fault scarp associated with the deeply seated Roum Fault inferred from previous geological surveys to have a vertical, south block up, slip. The well-incised Ouadi er Rejme channel lies above the inferred Roum Fault trace, but shows no horizontal deflection or offset of its walls, neither does any of the channels incised in the abandoned terraces nor any of the risers (Fig 6). The absence of vertical or horizontal offset in these old and preserved geomorphic features rules out the possibility of the existence of any active fault in the subsurface infill or bedrock of this area. In fact such an active fault if present should have resulted throughout the successive surface seismic ruptures in the formation of fault scarps.

The same observations can also be extended to the wider Marj Bisri. Even though the erosion and deposition rates in this valley are important, the abandoned surface and edges of at least the upper terrace do not show any vertical or horizontal offset. The terraces stand at almost the same elevation on the opposite sides of the valley, and their lateral extension is evident with no interruption astride the mapped fault (Fig 4, 5). This proves that the fault mapped in the substratum had little to no effect on the surface geomorphic features and thus, if present, this fault can be safely considered seismically inactive.

Conclusion,

Different geological evidence and observations of various nature (structural, seismotectonic and geomorphic) from the area are hard to reconcile with the assumption that an active fault runs in the subsurface of the Marj Bisri. In particular *the Roum Fault does not appear to* *continue in the Marj.* There is no evidence for 3m of fault offset associated with any known fault under the dam site. Some minor and small faults with very low tectonic deformation rate, accommodating syn- or post depositional deformation in the thick sedimentary infill or stress within the Jezzine antlicline or at the tip of the Roum Fault, may exist in the subsurface of the Marj. Their surface expression leveled by the much more active geomorphic surface processes. If so these faults are very likely of small extent and should not represent a serious tectonic hazard to the region.



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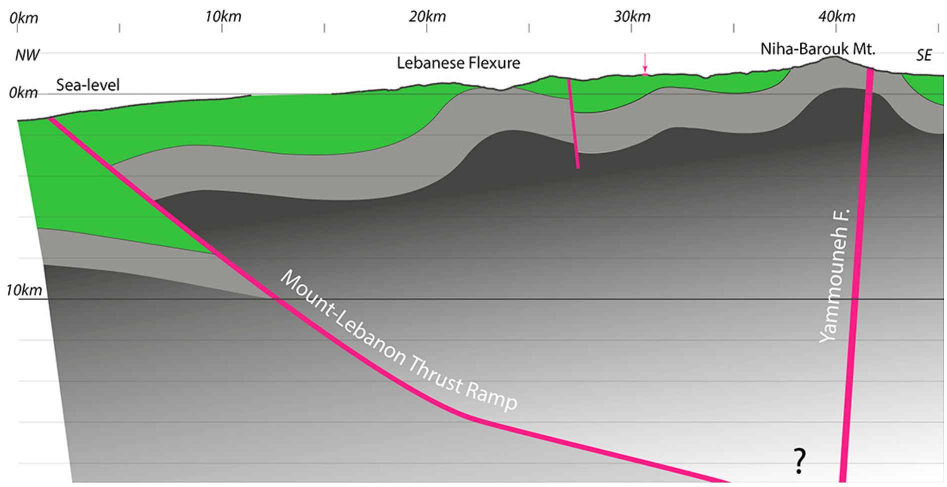

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Figure 1 a- Modified from Elias et al 2007, The Bisri Dam site (blue star) within the tectonic map of Lebanon. Red lines are for active faults. Dashed red line is for the Mt-Lebanon Flexure mapped on the surface geology. Gray shadow represents the ramp surface of the MLT in the sub-surface. (R.F. = Roum Fault; DBF= Damour Beiteddine Fault) b- Interpretatitve NW-SE cross-section of Mt-Lebanon showing the deep structure of the range as estimated from surface geology. Depth of the faults are constrained from surface geology and stratigraphy only. (For location see black line on the map above)

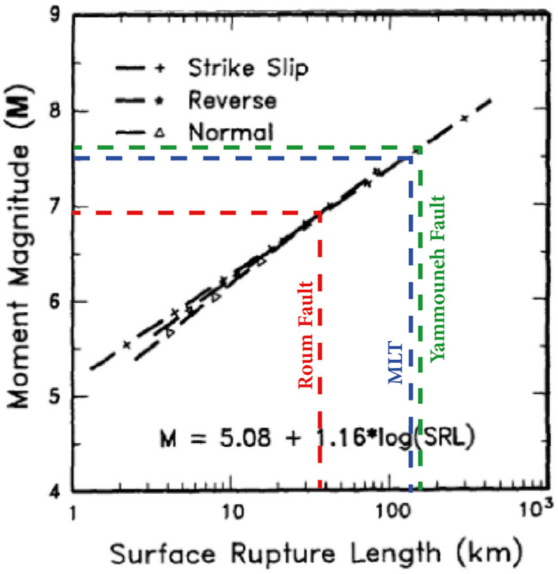

Figure 2 - Estimated moment magnitudes for the three major faults in the area using regression relationship of Surface Rupture Length on Magnitude for different types of faulting (strike-slip, reverse and normal) (Wells and Coppersmith 1994).

Figure 3 Interpreted aerial photo of Marj Bisri area. Only the upper abandoned terrace is mapped. (Photo number 225, mission 1962, scale 1:25000).

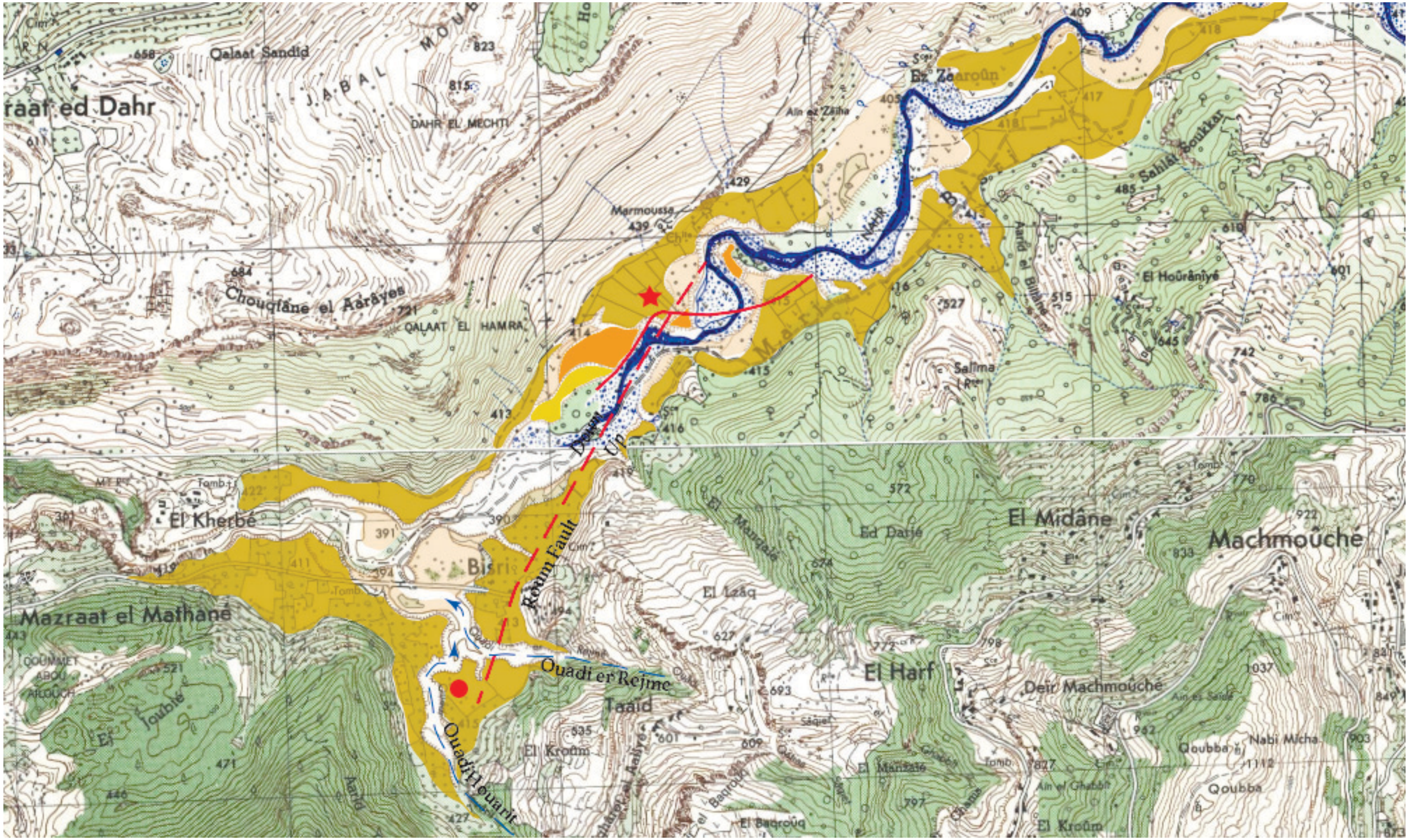

Figure 4 Topographic map of Marj Bisri. Four different levels of abandoned river terraces are mapped with different colours. Red lines are for the inferred Roum Fault mapping from previous geological studies of the Dam project.

Figure 5 Upper abandoned terrace from the northern river bank, located by red star on Fig4. Red line is for inferred Roum Fault from previous studies.

Figure 6 Picture of the Houarit surface showing the absence of any vertical offset of the surface. For location reffer to red circle on Fig4.

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