

**in black reviewer comments**

**in red our response**

**in green changes in the manuscript**

5 **REV#1: (N. Roberts)**

**GREATEST ISSUES:**

i. Overall imbalance of content, with over half of the manuscript comprising background material;

10 **We agree.** We re-organized the manuscript balancing the content between background information and new data. In particular:

1) we rewrote the *Introduction* to better outline the gap of knowledge we want to fill (lack of time constraints to the Seymareh River valley evolution before and after the Seymareh Landslide occurrence, to outline the role of the geomorphic processes both as predisposing factors for MRC processes and as response to this giant gravitational instability)

15 2) we reduced the regional geological and geomorphological settings by 50% into a unique section: **“2 Regional geological and geomorphological framework”**.

ii. Unnecessary details and focus on some topics (numerical modeling, pre-failure creep, seismicity and hazard/risk) that take up large parts of the abstract and/or introduction, but that are not part of the current contribution and are not directly relevant to its conclusions;

20 **We agree.** We eliminated the speculative parts of the manuscript and focused on the topics relevant for our original contribution, both in the Abstract and Introduction.

iii. Incomplete review of previous work on the Seymareh landslide and geology of Kabir Kuh, including misattribution of several findings and interpretations;

25 **We are grateful for evidencing such a weak point and we agree.** We implemented the lacking references regarding the regional geological stratigraphy and the Seymareh Landslide, attributing the information correctly.

iv. Insufficient methodologic descriptions that prevent the new work from being properly evaluated or replicated;

**We agree.** We implemented a complete and accurate description of the OSL technique as well as of the source and scale of the aerial and satellite imagery used.

- v. Confusing organization that includes: a section purported to present new material (section 4) comprising largely a repeat of what was already known; a results section (section 5.2) containing a mix of observations/interpretations and results; and a discussion (section 6) presenting apparently new observations/interpretations.

**We totally agree.** We changed the structure of the manuscript, hopefully making it clearer and more understandable in its sections. We worked a lot on both the Results and Discussion in order to fix these weaknesses. In particular:

- 1) we eliminated the section **“4 Revised stratigraphic column and geological sections of Seymareh river valley”**
- 2) we removed the interpretations from the Results
- 3) we moved the text with new observations from the Discussion into the Results

## MAJOR ISSUES

1. The writing is very wordy and convoluted. Many sentences are unnecessarily long and complex, making them hard to follow. Grammatical and language errors are abundant. The scale of these problems make substantial rewriting necessary, and thus in my view is a major issue. Many examples of such instances are provided in the list of minor issues below, but this is not an exhaustive list.

**1. We agree.**

1. The revised manuscript underwent an official language editing service (see the attached Certificate).
2. The title does not accurately convey the main thrust of the paper. It suggests that the paper provides new understanding of the causes of the landslide, which it does not. This paper is about valley-bottom geomorphic evolution before and after a gigantic landslide.
2. **We agree: the focus of the paper is on the valley-bottom geomorphic evolution before and after a gigantic landslide, while the rest are implications.**
2. The new proposed title is:  
**“New constraints to river valley evolution before and after the emplacement of the largest landslide on the exposed Earth surface: the Seymareh rockslide - debris avalanche (Zagros Mts., Iran)”**.
3. The abstract does not summarize the present study well, and instead mentions all sorts of things that are not part of the authors’ work; although some of these are peripherally related (hazard, seismic triggering, causes of the landslide) they do

not constitute anything new as far as I can tell from the presentation of the rest of the paper. At the same time, the abstract lacks details about some of the major interpretations and results from the body of the paper. It needs to be rewritten and streamlined.

3. We agree: we removed from the text of the abstract the peripherally related arguments, focusing on the main topic of the valley-bottom geomorphic evolution before and after the gigantic landslide and on the methods to reconstruct it.

3. The new proposed abstract is:

“The Seymareh Landslide detached ~10 ka from the northeastern flank of the Kabir-kuh fold (Zagros Mts., Iran), is recognized worldwide as the largest rock slope failure (44 Gm<sup>3</sup>) ever recorded on the exposed Earth surface. Detailed studies have been performed that have described the landslide mechanism and different scenarios have been proposed for explaining the induced changes in landscape. The purpose of this study is to provide still missing time constraints to the evolution of the Seymareh River valley, before and after the emplacement of the Seymareh Landslide, to highlight the role of geomorphic processes both as predisposing factors and as response to the landslide debris emplacement.

We used optically stimulated luminescence (OSL) to date lacustrine and fluvial terrace sediments, whose planometric distribution has been correlated to the detectable knickpoints along the Seymareh River longitudinal profile, allowing the reconstruction of the evolutionary model of the fluvial valley. We infer that the knickpoint migration along the main river and the erosion wave propagated upstream through the whole drainage network caused the stress release and the ultimate failure of the rock mass involved in the landslide. We estimated that the stress release activated a Mass Rock Creep (MRC) process with gravity-driven deformation processes occurring over an elapsed time-to-failure on the order of 10<sup>2</sup> ky. We estimated also that the Seymareh damming lake persisted for ~3500 years before starting to empty ~6.6 ka due to lake overflow. A sedimentation rate of 10 mm y<sup>-1</sup> was estimated for the lacustrine deposits, which increased up to 17 mm y<sup>-1</sup> during the early stage of lake emptying due to the increased sediment yield from the lake tributaries. We calculated an erosion rate of 1.8 cm y<sup>-1</sup> since the beginning of the landslide cut by Seymareh River, which propagated through the drainage system up to the landslide source area.

The evolutionary model of the Seymareh River valley can provide the necessary constraints for future stress-strain numerical modeling of the landslide slope to reproduce the MRC and demonstrate the possible role of seismic forcing in anticipating the time-to-failure for such an end-member case study.”

4. The summary of previous work on the Seymareh landslide is missing many key points and attributes some details to the wrong sources. Other details are not attributed at all. For instance:

A. Page 3, line 6: Some important and very relevant contributions of Roberts (2008) and Roberts and Evans (2013) are not mentioned. Those sources propose a detailed model of how the geologic and tectonic evolution of Kabir Kuh predisposed the slope to such large-scale failure, including formation of structural/kinematic and rheological control. As far as I can see, this

contribution is not recognized in the current paper, despite it being directly related to the authors' claimed contribution of improved understanding of factors predisposing the slope to gigantic failure.

B. Page 3, line 9: It is not sufficiently clear that the age estimate of 9800 radiocarbon years is based on the interpretation of three separate radiocarbon ages. This 9800 a BP age is taken from Roberts and Evans (2013) and must be cited accordingly.

5 The ages provided by other sources - at least those from Griffiths et al. (2001), which were not influence by the 'hard-water effect' – should also be noted so that the reader does not have to refer back to Roberts and Evans (2013).

C. Page 3, line 6: Yamani et al. (2012) provide no new details on emplacement mechanisms of the landslides (at least not from the details in the English language extended abstract of their paper writing in Farsi). If there are some details missing from the Yamani et al.'s English text that they present manuscript refers to, it would be very helpful to provide translated quotes in the supplemental material. Otherwise, mention of new details on landslide emplacement attributed to that source needs to be removed. Yamani et al.'s (2012) main contribution comprises some general details on the evolution of lake drainage.

4. Of course, we did not mean to forget the important and very relevant contributions by Roberts (2008) and Roberts and Evans (2013), which we referred to maybe not enough explicitly. Therefore:

15 4A. We better referred to Roberts (2008) and Roberts and Evans (2013):

4A. **“Roberts (2008) and Roberts and Evans (2013) provided a detailed model of how the geological and tectonic evolution of the Kabir-kuh fold predisposed the slope to such a large-scale failure, including formation of structural/kinematic and rheological control, and inferred a seismic trigger.”**

4B. We clarified that the Seymareh landslide age estimate of 9800 radiocarbon years is based on the interpretation of three separate radiocarbon ages based on other sources:

20

4B. **“Specifically, Roberts and Evans (2013) obtained from a charcoal-rich layer approximately 15 m above the base of the lacustrine sequence with a <sup>14</sup>C age of 8710 years BP. Based on the interpretation of three separate radiocarbon ages provided additionally by Griffiths et al. (2001) an estimated radiocarbon bracket age of the Seymareh event was suggested between 9800–8710 <sup>14</sup>C years BP”**

25 4C. We corrected the text describing the Yamani et al. (2012) main contribution.

4C. **“Yamani et al. (2012) provided some general details on the evolution of the dam lake drainage, describing a sequence of entrenched lacustrine terraces upstream of the landslide dam.”**

5. The paper includes a lot of largely unimportant, or at least overly specific, background details. Many of the details about tectonic features and some of the details about seismicity in section 2 are well beyond what is necessary to provide relevant background to the reader. These extraneous details could appear in the supplement to provide further context for the interested reader, but they take up too much of the main paper. Given that modeling is not part of the present paper, much of the background provided about modeling is irrelevant.

30

5. We agree: we merged the Section 2, Section 3 and the Section 4 removing many of the details about tectonic features and some of the details about seismicity and about the modelling that are included in the supplementary material.

5. The new background section named “2 Regional geological and geomorphological framework”, is as following:

5 “The SL detached from the northeastern flank of the Kabir-kuh fold, the largest and highest anticline in the Pusht-e  
5 Kuh arc, in the northwestern part of Iran (Vergés et al., 2011). The Zagros mountain range is part of the Alpine-  
Himalayan orogenic system that originates from the Late-Cretaceous-Cenozoic convergence between Africa/Arabia-  
Eurasia (Talbot and Alavi, 1996; Stampfli and Borel, 2002; Golonka, 2004; McQuarrie, 2004; Mouthereau et al.,  
2012). The Zagros orogen was traditionally classified by distinctive lithological units and structural styles into four  
10 NW trending tectono-metamorphic and magmatic belts (Fig. 1). These are bounded by defects on a regional scale  
such as the Main Zagros Thrust (MZT), High Zagros Fault (HZF) and Mountain Front Fault (MFF) (Agard et al.,  
2005 and references therein). These tectonic units are from the inner to the outer sectors of the belt are: the Urumieh  
Dokhtar volcanic arch, the Sanandaj-Sirjan Zone, the Imbricate Zone, the Zagros (or Simply) folded belt and the  
continental Mesopotamian Foreland (Fig. 1).

15 Seismicity is distributed in a 200-300 km wide area of the Zagros mountain range (Hatzfeld et al., 2010, Paul et al.,  
2010, Rajabi et al., 2011), with a sharp cut along the Main Zagros Reverse Fault in the NE (e.g., Yamini-Fard et al.,  
2016), with recurrent earthquakes of Mw 5-6 and exceptional earthquakes of higher magnitude, i.e., up to Mw 6-8  
(see supplementary material). The SL occurred in a very densely seismically active area, so that Roberts and Evans  
(2013) hypothesized that seismic forcing may have played a primary role in triggering the landslide.

20 The outcropping formations in the Kabir-kuh anticline date to a time interval ranging from the Late Cretaceous to  
the early Miocene and are characterized by different lithological and rheological properties (Vergés et al., 2011).  
Since the geo-structural setting of the fold flanks represented a crucial predisposing factor for the catastrophic  
massive rock slope failure (Roberts and Evans, 2013), we referred to the most detailed stratigraphic column proposed  
by James and Wynd (1965), Alavi (2004) and to the detailed mapping of the Kabir-kuh fold conducted by the Iran Oil  
Operating Companies (Setudehnia and Perry 1967; Takin et al. 1970; Macleod 1970). Specifically, the investigated  
25 area includes the middle and low reaches of Seymareh River starting approximately 60 km upstream of the SL down  
to the SE termination of the Kabir-kuh fold. In Fig. 2, the geological map of the study area, the stratigraphic column  
and two geological cross-sections related to different structural sectors are reported.

30 It is noteworthy that, in the Kabir-kuh anticline, the Pabdeh Formation is composed of three rheologically  
contrasting members, which crop out in the SL scar area: i) the lower Pabdeh member (150 m thick), which is  
dominated by marls and shales, ii) the Taleh Zang member (50 m thick), consisting of platform limestone, and iii) the  
upper Pabdeh member (150 m thick), composed mainly of calcareous marl. The Asmari Formation creates a  
carapace originally covering the top of the Kabir-kuh fold, while in the synclinal valleys between the Kabir-kuh fold  
and the adjacent folds, the Asmari Formation is overlapped by a Miocene-Pliocene succession (Homke et al., 2004).  
Referring to the Changuleh syncline studied by Homke et al., 2004, the foreland stratigraphy includes the following:

i) the Gachsaran Formation (early Miocene - 12.3 Ma, thickness approximately 400 m), composed of salt, anhydrite, marl and gypsum; ii) the Agha Jari Formation (12.3 Ma – 3 Ma, thickness approximately 1400 m); and iii) the Bakhtiari Formation (3 Ma – early Pleistocene, thickness approximately 900 m). The Agha Jari Formation consists of sandstones and conglomerates, linked to the evolution from deltaic to fluvial transitional environments (Elyasi et al., 2014), and the Bakhtiari formation consists of conglomerates characterized by coarse and mud-supported grains, sandstones, shales and silts and marks the onset of syn-orogenic fluvial environment conditions (Shafiei and Dusseault, 2008).

The reported cross-sections intersect the synclinal valley of the Seymareh River. The dip angle of the northeastern flank of the syncline considerably decreases from NW to SE from 45° (section A-A') to 18-20° (section B-B'). Therefore, along the section A-A' the Cretaceous-Paleogene bedrock (from the Sarvak Formation to the Asmari Formation) offers a greater accommodation volume to the continental and epicontinental formations (Gachsaran Formation and Agha Jari Formation), as the synclinal axis is located at a lower elevation than in the B-B' section.

The Zagros Range globally provides one of the most spectacular examples of landscape evolution in response to active tectonics (Bourne and Twidale, 2011) because its drainage network clearly adapted to the growth of the thrust-fold structures (Ramsey et al., 2008) and to the erodibility of the outcropping formations (Oberlander, 1985). Oberlander (1968) suggested that the drainage network in the NW Zagros was superimposed from structurally conformable younger horizons. In his model, the breaching of hard geological units of the antiformal ridges follows a phase of river cutting and expansion of the fold axial fold basins through the softer overlying units. In the Kabir-kuh fold, the transverse cutting of the Asmari limestone, and the exposure of the underlying more erodible Pabdeh-Gurpi marls, leads to the formation of a low-relief landscape with synformal ridges on which the new through-going drainage system can be developed. In Oberlander's hypothesis, it is the Pabdeh and Gurpi marls that facilitate the creation of a low-relief landscape across the anticline crests and are therefore integral to the story of drainage superimposition.

Tucker and Slingerland (1996) computed a numerical landscape evolution model, calibrated on the Kabir-kuh fold, to understand how the growth and propagation of the folds, the different lithologies and the drainage network can influence the sediment flux from a tectonically active belt towards the foreland basin. The authors calibrated the landscape evolution model with the current topography of the range, obtaining time constraints for landscape evolution modeling. According to the Oberlander model, Fig. 3 shows four main steps that describe the landscape evolution of the Kabir-kuh fold with the timing provided in the model by Tucker and Slingerland (1996).

Step 1 - Approximately 4.3 Ma, in response to the initial stages of fold growth, an orthoclinal drainage develops, parallel to the main structures. The tributaries flowing along the flanks of the folds transport debris, which is deposited in the synclines. In the Kabir-kuh fold the carbonate core is still buried by the Miocene cover units.

Step 2 - Approximately 3.8 Ma, as soon as the deformation front migrates towards the SW, new folds raise with a progressive adjustment of the drainage to these morpho-structures. The previously deposited sediments are remobilized and transported towards the depocenter of the syncline basins and partly outside; the syn-orogenic

deposits are strongly eroded along the crests of the anticlines, thus exposing the underlying formations. This causes a topography characterized by resistant hogbacks that flank the inner cores.

Step 3 - Approximately 2.4 Ma, with the ongoing deformation, the drainage develops in a “trellis” pattern. The river erosion affects the erodible units located stratigraphically between the limestone of the Asmari Formation and the inner core of the fold. At the end of this step the Miocene cover is completely removed from the ridges and the river erosion also affects the marls and evaporites of the syn-orogenic formations in the valleys, exposing the underlying limestone of the Asmari Formation.

Step 4 - Approximately 1.6 Ma, due to the continuous uplift and exhumation of younger, more external folds, the sediment accumulation becomes negligible and the Asmari limestone is strongly eroded giving rise to syncline ridges.

The following Quaternary landscape evolution is then likely driven by the evolution of the drainage network and is also influenced by climatic factors and by the slope-to-channel dynamics.

The model by Tucker and Slingerland (1996) is the unique numerical model existing on the Kabir-kuh fold and this motivates our choice of using it as a reference for the medium-to-long term evolution of the Seymareh River valley.

The Seymareh River valley is arranged parallel to the Kabir-kuh fold and its evolution was inevitably influenced by the exceptional landslide event that temporarily dammed it, causing the formation of the three-lake system which includes the Seymareh, Jaidar and Balmak lakes (Fig. 4). The valley evolution before and after the event is well recorded by Quaternary landforms preserved along the valley. Yamani et al. (2012) focused on the post-failure evolution of the valley describing four levels of terraces upstream of the landslide dams as a sequence of lacustrine terraces. Shoaiei (2014), in addition to evaluating the longevity of the SL dams, identified in the merging of Seymareh

River with a left tributary as the reason for strong river incision at the base of the northeastern flank of the Kabir-kuh fold and as a possible causal factor for the SL collapse.

However, none of the previous studies on the Quaternary evolution of the Seymareh River valley provided absolute dating of

geomorphic markers (mainly fluvial terraces) preserved upstream as well as downstream of the landslide dam or provided robust and quantitative constraints to the pre-failure valley evolution as a possible geomorphological factor for failure occurrence.”

6. If the mechanism and behaviour of large bedrock landslides are to be discussed, some recent reviews pertaining to this topic should be cited (principally Brideau and Roberts [2015], which includes this event as a case study, and Hermanns and Longva [2012]). Those sources provide numerous additional references on progressive failure that should also be considered if the authors can make a suitable case for discussing this topic.

6. In fact, the mechanism and the behavior of large bedrock landslides are not part of the current contribution and are not directly relevant to our conclusions. Purpose of the study is rather to provide still missing time constraints to the evolution of the Seymareh River valley, before and after the emplacement of the Seymareh Landslide, to highlight the role of geomorphic

processes both as predisposing factors and as response to massive rock slope failures. Therefore, we decided not to include the suggested references in the manuscript.

7. Much of the background information lack proper referencing, including tectonic setting (section 2), seismicity (section 2), and geologic setting (section 3). For example, the paragraph starting on page 4, line 27 presents many details that are clearly not part of the current study, but only provides references in two places. Furthermore, this generalization of sources does not allow the reader to sort out what details have come from what sources. The hypothesis cited in the final paragraph of section 2 is based on much more than just the frequency of strong earthquakes in the region, as this submission suggests. Progressive steepening of the slope at a very slow rate relative to the modern recurrence rate of nearby strongly felt earthquakes is a crucial consideration as it makes failure initiation in the absence of seismic loading hard to explain.

7. We agree. First, the background information including tectonic setting, seismicity and geologic setting were strongly reduced and many of the details about tectonic features and seismicity were included in the supplementary material.

7. The new background section “**2 Regional geological and geomorphological framework**”) is attached in the point 5. More specifically, the paragraph regarding the seismicity is reduced to the following:  
“Seismicity is distributed in a 200-300 km wide area of the Zagros mountain range (Hatzfeld et al., 2010, Paul et al., 2010, Rajabi et al., 2011), with a sharp cut along the Main Zagros Reverse Fault in the NE (e.g., Yamini-Fard et al., 2016), with recurrent earthquakes of Mw 5-6 and exceptional earthquakes of higher magnitude, i.e., up to Mw 6-8 (see supplementary material). The SL occurred in a very densely seismically active area and recurrence rate of nearby strongly felt earthquakes considerably higher than the rate of slope steepening led Roberts and Evans (2013) to hypothesize that seismic forcing may have played a primary role in triggering the landslide.”

8. Thickening of the Pabdeh Formation (top of page 6) very well may have in influence on landscape development. However, the position of the nw trending deformation front also strongly inferences the westward change in landscape. This was also recognized by Oberlander in his work but appears to have been overlooked.

8. We strongly reduced the regional geomorphological setting, including it in a unique background section, named “Regional geological and geomorphological framework”, by removing parts not functional to the results presented, included the text this comment is referred to.

8. The paragraph regarding Oberlander’s landscape evolution model is the following:  
“Oberlander (1968) suggested that the drainage network in the NW Zagros was superimposed from structurally conformable younger horizons. In his model, the breaching of hard geological units of the antiformal ridges follows a phase of river cutting and expansion of the fold axial fold basins through the softer overlying units. In the Kabir-kuh fold, the transverse cutting of the Asmari limestone, and the exposure of the underlying more erodible Pabdeh-Gurpi marls, leads to the formation of a low-relief landscape with synformal ridges on which the new through-going drainage system can be developed. In Oberlander’s hypothesis, it is the Pabdeh and Gurpi marls that facilitate the



**creation of a low-relief landscape across the anticline crests and are therefore integral to the story of drainage superimposition.”**

9. In contrast to what the authors claim, I see no evidence that this work revised the the stratigraphy of the study area to any  
5 substantial degree. The stratigraphy of the part of this Zagros fold-thrust belt is extensively reported in previous work (much  
of which has not been referenced here). The stratigraphy described here matches very closely (in sequence order,  
composition, and thickness) with the stratigraphy already reported in the literature. For instance, I see very little difference  
between the sequence in Fig. 5 of the present manuscript and the stratigraphy summarized from review of existing literature  
by Roberts and Evans (2013, their Fig. 5). Several important references on the sequence are missing and should be included.  
10 For the overall region this includes James and Whynd (1965) and Alavi (2004). Detailed mapping of Kabir Kub conducted  
by Iran Oil Operating Companies (Setudehnia and Perry, 1967; Takin et al., 1970; Macleod, 1970) already covers much of  
what the authors would have covered in their 'new' mapping presented in section 4 and in Fig. 5. The authors need to first  
clearly describe what has already been documented (in a section on geologic background). Only after that should they try to  
justify how their 'new' stratigraphy differs. From what I can tell, they contribute only some additional detail on the Pabdeh  
15 Formation, although at least some of this is similar to that reported in the Iran Oil Operating Companies maps. A much more  
convincing argument will need to be made if any new contribution to the area's stratigraphy/geology is to be claimed. The  
details presented in section 4 nearly all belong in the background material. This further highlights an issue with the paper's  
layout and balance: the new contribution of the 15-page manuscript doesn't start until page 9, meaning that over half of the  
paper is background information.

20 9. This was effectively a mistake, induced by the detailed field work we performed. Such a field-work included also a deep  
check of the local stratigraphic column, which in turn did not provide any significant new data with respect to the literature.  
We re-organized the text by removing Section 4 and integrating the text within the unique background section named  
“Regional geological and geomorphological framework”.

9. **“The outcropping formations in the Kabir-kuh anticline date to a time interval ranging from the Late Cretaceous  
25 to the early Miocene and are characterized by different lithological and rheological properties (Vergés et al., 2011).  
Since the geo-structural setting of the fold flanks represented a crucial predisposing factor for the catastrophic  
massive rock slope failure (Roberts and Evans, 2013), we referred to the most detailed stratigraphic column proposed  
by James and Wynd (1965), Alavi (2004) and to the detailed mapping of the Kabir-kuh fold conducted by the Iran Oil  
Operating Companies (Setudehnia and Perry 1967; Takin et al. 1970; Macleod 1970). Specifically, the investigated  
30 area includes the middle and low reaches of Seymareh River starting approximately 60 km upstream of the SL down  
to the SE termination of the Kabir-kuh fold. In Fig. 2, the geological map of the study area, the stratigraphic column  
and two geological cross-sections related to different structural sectors are reported.**

**It is noteworthy that, in the Kabir-kuh anticline, the Pabdeh Formation is composed of three rheologically  
contrasting members, which crop out in the SL scar area: i) the lower Pabdeh member (150 m thick), which is**

dominated by marls and shales, ii) the Taleh Zang member (50 m thick), consisting of platform limestone, and iii) the upper Pabdeh member (150 m thick), composed mainly of calcareous marl. The Asmari Formation creates a carapace originally covering the top of the Kabir-kuh fold, while in the synclinal valleys between the Kabir-kuh fold and the adjacent folds, the Asmari Formation is overlapped by a Miocene-Pliocene succession (Homke et al., 2004).  
5 Referring to the Changuleh syncline studied by Homke et al., 2004, the foreland stratigraphy includes the following:  
i) the Gachsaran Formation (early Miocene - 12.3 Ma, thickness approximately 400 m), composed of salt, anhydrite, marl and gypsum; ii) the Agha Jari Formation (12.3 Ma – 3 Ma., thickness approximately 1400 m); and iii) the Bakhtiari Formation (3 Ma – early Pleistocene, thickness approximately 900 m). The Agha Jari Formation consists of sandstones and conglomerates, linked to the evolution from deltaic to fluvial transitional environments (Elyasi et al.,  
10 2014), and the Bakhtiari formation consists of conglomerates characterized by coarse and mud-supported grains, sandstones, shales and silts and marks the onset of syn-orogenic fluvial environment conditions (Shafiei and Dusseault, 2008).”

10. The Gachsaran formation has a high gypsum content, which dominates its geomechanic and geomorphic behaviour. The  
15 description provided here (Page 8, line 17) instead suggests that it comprises only more typical clastics. Given this manuscript’s focus on valley-bottom evolution, this unit needs to be accurately characterized.

10. This was a typo (Gachsaran instead of Agha Jari) that we corrected.

10. “The Agha Jari Formation consists of sandstones and conglomerates, linked to the evolution from deltaic to fluvial transitional environments (Elyasi et al., 2014)”

20

11. The details, or even relevance, of anticline flank dips (second paragraph of section 4) are unclear. Dips along the three sections probably need to be considered more carefully. Due the nature of the anticline, structural variation is to be expected. Dips will of course decrease to the southeast toward the nose of the anticline. What is possibly more interesting is how much steeper dips are to the northwest beyond the mapping presented here. Furthermore, this is a complex box fold with a hinge  
25 near the upper part of the Seymareh detachment zone. Downslope variation flank dips will reflect this structure. Due to the complexity of the fold, stratigraphic position will also affect dip. For example, Roberts and Evans (2013) noted steepening (see their Fig. 9H for example) of the Eman Hassan member in the upper, central part of the landslide scar. In contrast, the adjacent upper surface of the Asmari Formation on either side of the landslide is much less steep. Variations between other units are noted also in mapping by Iran Oil Operating Companies (summarized in part in Fig. 4B of Roberts and Evans).  
30 Such variation has important implications for dip-slope failure of the flank. In light of these points, it would thus be very helpful (and far more informative) if the authors provided a detailed map of their structural measurements and clarify how these may build upon those provided by past studies of the landslide and by mapping by Iran Oil Operating Companies and by Roberts and Evans (2013). Conversely, if these measurements are based only DEM profiles, that needs to be clearly stated. In any case, how well profiles through the eroded core of the anticline represent the Asmari limestone

limbs beneath the valley floor needs to be evaluated given stratigraphic variation in dips relating to the complex nature of the flood. Finally, profile C-C' is oblique to the true dip of the anticline flank and appears to thus under represent dip of the Asmari surface (based on Fig. 5, it appears that the apparent dip, not the true dip, is being represented).

5 11. Since we do not provide in this work any new data on the geological structural setting of the fold flank, we moved to the new background section "Regional geological and geomorphological framework" the geological map and sections and just recall in the Discussion the arguments already provided by Roberts and Evans (2013). In this perspective, the profile C-C' was eliminated, since not necessary.

10 11. "The reported cross-sections intersect the synclinal valley of the Seymareh River. The dip angle of the northeastern flank of the syncline considerably decreases from NW to SE from 45° (section A-A') to 18-20° (section B-B'). Therefore, along the section A-A' the Cretaceous-Paleogene bedrock (from the Sarvak Formation to the Asmari Formation) offers a greater accommodation volume to the continental and epicontinental formations (Gachsaran Formation and Agha Jari Formation), as the synclinal axis is located at a lower elevation than in the B-B' section."

15 12. Is this the reconstruction of the Asmari carapace (Page 8, line 29) immediately pre-failure or a reconstruction of the anticline prior to unroofing? Please clarify. In the latter case, 2100 m a.s.l. is a substantial underestimate and the structure of the box fold suggests that the Asmari carapace extended much higher.

12. In the light of the response above (Point 11) this point is no longer discussed.

12. See the changes in the manuscript attached at point 11.

20

13. The authors' point about the position of the Seymareh River (Page 8 line 31) does not become clearly relevant later one in the paper. Depending on its significance for the current study, which remains unclear, the authors will need to clarify whether this river position is related to migration of the channel within the Lake Seymareh lacustrine deposits (i.e. following valley damming and sediment in-filling of the Lake Seymareh basin) or is the result of some older physiographic control.

25 The river has obviously migrated to the northwest in the last several hundred years as a Sasanian-era bridge over the old river position at Pul-i-Shikari is nowhere near the modern river (see observation and discussion by Harrison and Falcon, 1938).

30 13. This point is no longer discussed since we removed the entire Section 4. Nonetheless, we recognized in the field relict landforms that testify for the presence of an abandoned valley (that we attributed to a paleo-Seymareh river), which is important in our Evolutionary model of the landscape. The northwestward migration of the river in the last several hundred years, is not related to the long-term evolution of the valley that we discuss, but seems attributable to 'physiological' local variations of the river path, which could fall in the normal variability, of a meandering path in a short time-scale.

13. See the changes in the manuscript attached at point 11.

14. I cannot understand what the final five lines of section 4 mean. I assumed the kinematic release suggested here is that of the Seymareh landslide. What is the 'connectivity' supposed to be? How are the flatirons envisioned to control sliding? Note that several previous studies suggest fluvial undercutting of the slope as the source of kinematic freedom at the slope toe. However, breakout across the upper units is also necessary for the failure to have occurred as the failure surface cuts stratigraphically upward in the downslope direction (Roberts and Evans, 2013); this feature is an important part of the kinematic release.

14. This point is no longer discussed since this part was removed with Section 4.

14. See the changes in the manuscript attached at point 11.

15. The methods section lacks sufficient detail. What are the source and scale of the air photos used? Were they interpreted quantitatively or only qualitatively? What specific imagery was used from Google Earth (there is of course a very wide range of imagery types and qualities available in that software)? What as the source of the map used? What inputs specifically were used the creating the DEM (current wording is unclear)? No methods are provided for the new geologic investigation that the authors claim to have conducted. OSL can be a finicky technique. Many critical aspects of the sampling are not considered, particularly those necessary to rule out partial bleaching during sample collection and transport: was the slope cleared off first? was an opaque sample vessel used? how far was it inserted into the slope? OSL sampling methodologies vary quite a bit, so unless the approach exactly follows that of a pervious study, simply citing in past source here is insufficient.

15. We agree: we implemented the lacking information.

15. Attached the new "3 Methods" section:

"The geomorphological study of the area was carried out first through the analysis and interpretation of remote sensing data, such as aerial photos (National Cartographic Center of Iran, aerial photo, scale:1:20000, acquired on 24 August 1955), Google Earth satellite optical images (2018 Landsat Imagery) and vector topographic maps (National Cartographic Center of Iran, topographic map of Kuhdasht, scale: 1:25,000), which led to the first detection of possible geomorphic markers within the Seymareh River valley. Vector topographic data also allowed the construction of a 10 m Digital Elevation Model (DEM) for terrain analyses and led to the projection of the possible geomorphic markers along the river longitudinal profile (Wilson and Gallant; 2001; Burbank and Anderson, 2012). The DEM was obtained by the ArcGIS 10® software package, starting from vector topographic data (contour lines, hydrography and point elevation) and using the ANUDEM interpolation algorithm (Hutchinson et al., 2011 and references therein). To automatically extract the hydrographic network from the DEM and then to project the geomorphic markers along the longitudinal river profiles, some of the ArcGIS® 10 tools of the Hydrology toolbox were used (Flow Direction, Flow Accumulation, Reclassify, Stream Order and Stream to Feature), setting the flow accumulation threshold according to that proposed for the fluvial domain ( $10^{-1}$  km<sup>2</sup>) by Montgomery and Foufoula-Georgiu (1993). The longitudinal profile was therefore transformed into a route along which the elevation of the top

surfaces of geomorphic markers identified in the area were projected through the Linear Referencing Tools (Create Route and Locate Features along Route).

A geological and geomorphological field survey was then carried out with the aims of mapping the most significant active and relict landforms for the Quaternary evolution of the Seymareh River valley and of sampling the corresponding deposits in order to date them with the OSL method (optically stimulated luminescence; Murray and Olley, 2002; Wintle and Murray, 2006 and references therein).

OSL sampling is a very delicate and quite complex technique. In fact, it is absolutely necessary to prevent the sample from being exposed to light because the luminescence signal could be reduced or even reset. In choosing the most suitable site to sample, of course, levels were identified with original sedimentary structures, avoiding bioturbations and post-depositional alterations. Once the site for sampling was identified, it was important to carefully clean off the slope and prepare, according to the state of thickening, consistency or cementation of the material, the equipment necessary for taking the sample, without it being exposed to light. Furthermore, to minimize the effects of cosmic radiation and to thereby avoid the risk of rejuvenated ages, the samples were taken at least one meter below the topographic surface (or below eventual erosional surfaces identified within the deposits). All of the samples, mainly characterized by fine-grained loose sediments (size <2 mm) were taken directly by using a hammer to insert a metal tube into the ground, which must be isolated from light and humidity immediately after collection. To maximize the uniformity of the natural radioactivity of the burial period, the sampled material was surrounded by at least 30 cm of homogeneous sediment. From the same level where it was sampled, an additional 500 - 800 g of sediment was extracted to evaluate natural radioactivity (if the annual dose rate measurement is not performed in situ), for the mineralogical and granulometric analyses, as well as to determine the moisture content.

The OSL dating was performed by the LABER OSL Laboratory, in Waterville, Ohio (U.S.). Quartz was extracted for equivalent dose ( $D_e$ ) measurements. In the OSL laboratory, the sample was treated first with 10% HCl and 30%  $H_2O_2$  to remove organic materials and carbonates, respectively. After grain-size separation, the fraction of 90-125  $\mu m$  size is relatively abundant, so this fraction was chosen for  $D_e$  determination. The grains were treated with HF acid (40%) for approximately 40 minutes to remove the alpha-dosed surface, followed by 10% HCl acid to remove fluoride precipitates. Luminescence measurements were performed using an automated Risø TL/OSL-20 reader. Stimulation was carried out by a blue LED ( $\lambda=470\pm 20$  nm) stimulation source for 40 s at 130°C. Irradiation was carried out using a  $^{90}Sr/^{90}Y$  beta source built into the reader. The OSL signal was detected by a 9235QA photomultiplier tube through a U-340 filter with 7.5 mm thickness. For  $D_e$  determination, the SAR protocol was adopted. The preheating temperature was chosen to be 260°C for 10 s and the cut-heat was 220°C for 10 s. The final  $D_e$  is the average of the  $D_e$ s of all aliquots, and the final  $D_e$  error is the standard error of the  $D_e$  distribution. For each sample, at least 12 aliquots were measured for  $D_e$  determination. The  $D_e$  was measured using SAR on quartz, and the aliquots that passed criteria checks were used for final  $D_e$  calculation.

Recycling ratios were between 0.90-1.1, and recuperation was relatively small. The cosmic ray dose rate was estimated for each sample as a function of depth, altitude and geomagnetic latitude. The concentration of U, Th and K was measured by neutral activation analysis (NAA). The elemental concentrations were then converted into the annual dose rate, taking into account the water content (lab measured) effect. The final OSL age is then:  $De/Dose-rate$ .”

16. the results section (section 5.2) is rather hard to follow and contains a mix of observations, interpretations and results. furthermore, several observations/interpretations (conveyed in Figs. 14 and 15) are skipped over here and are referenced only in the discussion. The formatting of this section needs work. I see no benefit to using lists here (or anywhere in the paper); all text should be in paragraph format. Several parts of the lists are not even full sentences. Issues with in the content include a lack of clarity over how the authors believe the dated sequences to relate to each other. For example, the wording at the start of the section (Page 10, line 9) seems to suggest that the lacustrine terrace pre-dates the landslide, but I cannot imagine how this is possible. Such as suggestion also conflicts with the post-landslide age reported for samples SEY4 and SEY5.

16. We agree: we reduced and formatted a new more concise results section without interpretations.

16. Attached the new “4 Results” section:

“The best geomorphic markers preserved in the study area are represented by a lacustrine terrace and two suites of fluvial terraces. The suites are distributed both upstream and downstream of the landslide debris, marking the evolutionary stages of the valley, respectively, after and before the landslide emplacement. Fluvial and lacustrine terrace deposits mainly consist of gravel, sand, silt and clay, and conglomerates outcropping immediately upstream and downstream of the landslide pertain to inactive alluvial fans connected to a relict position of the valley floor, likely of a paleo-Seymareh river.

In the middle reach of the Seymareh River valley, the upstream geomorphic markers include: inactive, terraced conglomeratic alluvial fans (Cg<sub>m</sub>), a terraced lacustrine deposit and a suite of four orders of fill terraces (named from Qt1<sub>m</sub> to Qt4<sub>m</sub>). The geometry of the terraced conglomerates (section A-A' in Fig. 2) can be associated with alluvial fans generated on the flanks of a former synclinal valley by streams likely forming the tributaries of a paleo-Seymareh river whose path was to the SW of the present one. The fill terraces are entrenched in the terraced lacustrine deposit of Seymareh Lake upstream of the landslide, in the area where Harrison and Falcon (1938), Roberts and Evans (2013) and Shoaiei (2014) hypothesized the natural damming lake could be extended (Figs. 5 and 6). Prograding lacustrine fan deltas formed by tributaries of Seymareh Lake have been recognized, which likely formed during the emptying phase of the lake. In this sector, we successfully dated 4 samples (SEY4, SEY5, SEY6, and SEY8; Table 1 and supplementary material); in particular the lacustrine deposit at two different stratigraphic levels, 560 and 590 m a.s.l., which provided OSL ages of  $10.4 \pm 0.90$  ka (sample SEY8) and  $7.37 \pm 0.73$  ka (sample SEY4), respectively. The OSL age of  $17.9 \pm 1.50$  ka (SEY6) obtained for an alluvial deposit at the base of the lacustrine deposits is coherent with the age of emplacement of the SL, as already inferred by Roberts and Evans (2013).

A suite of 2 strath terraces and a flood plain shaped onto the landslide debris along the Seymareh River gorge have been identified (Figs. 7a and 7b), which are important markers of the evolution of the natural dam because they formed after its cut likely due to an overflow of the damming lake. Here, we successfully dated one sample taken on a strath terrace (SEY9; Table 1 and supplementary material), which provided an age of  $6.59 \pm 0.49$  ka as time constrain  
5 for the initial stage of lake emptying.

In the lower reach of the Seymareh River valley, the downstream geomorphic markers include: inactive, terraced conglomeratic alluvial fans (Cg\_1) and a suite of four orders of fill terraces (named from Qt1\_1 to Qt4\_1) downstream of the SL (Figs. 7c and 8). Here, we successfully dated three samples from the fill terraces deposits (SEY3, SEY10, SEY11; Table 1 and supplementary material). The ages obtained provide useful time constraints to the main  
10 depositional events during the pre-failure valley evolution. Minimum ages of  $373 \pm 34$  ka and  $312 \pm 45$  ka have been obtained for samples SEY3 and SEY10, respectively, since these samples were saturated due to their low concentration of quartz grains, and SEY11 was dated at  $60 \pm 5$  ka.

The above-described geomorphic markers of the Seymareh River valley have been mapped and reported in morpho-stratigraphic profiles. The most significant landforms for the valley slope evolution are presented with a detail for the  
15 post-failure fluvial and lacustrine terrace suites upstream of the landslide dam (Fig. 6) and the pre-failure fluvial terrace suite downstream of the landslide dam (Fig. 8), respectively.

Figures 9 and 10 report the longitudinal profile of Seymareh River, along which, in addition to the geomorphic markers, were projected also: the benchmarks of the basal contact of the Quaternary deposits on the bedrock, the projection of points corresponding to the top of the SL debris, the upstream and downstream limits of the landslide, the location of the OSL sampling, and the projection of the outcrop of the Bakhtiari Formation (Fig. 9), which is  
20 rarely preserved and marks the initial alluvial infill of the Seymareh River valley. Figure 9 shows the height distribution of the pre-failure geomorphic markers. The benchmarks along Seymareh River indicate a mostly bedrock channel, and the longitudinal profile is characterized by two knickpoints located upstream of the SL and downstream of the lowest suite of alluvial terraces, as indicated by the black arrows. The geomorphic markers  
25 downstream and upstream do not belong to the same suite of terraces, as their projections along Seymareh River do not have any topographic correlation to each other (Fig. 9 and 10). The tops of all the fluvial terraces downstream of the SL are located lower in height than the most important knickpoint located immediately upstream and sculpted in the bedrock. Figure 10 shows the height distribution of the post-failure geomorphic markers. The markers are represented by: i) the horizontal lacustrine terrace formed by the incision of the deposits pertaining to the Seymareh  
30 Lake, formed as a consequence of the landslide damming; ii) the two levels of the strath terraces and a flood plain formed on the landslide debris during the initial stages of dam cutting and emptying of the lake; and iii) the four fill terrace levels formed after the emptying of the Seymareh Lake.

The geomorphological field survey, supported by a remote survey based on optical satellite and aerial images, also allowed us to demonstrate the evidence of gravity-induced features of the downslope dipping strata, along the scar of the SL (Fig. 11).

5 Clear evidence of MRC driving towards stress concentration and failure has been recognized in gravity-induced folding within the thin-layered Pabdeh Formation just below the sliding surface of the SL (i.e., that cannot be ascribed to parasitic structural folding). Furthermore, impressive buckling of the downslope dipping strata, which crop on the sliding surface of the SL, have been interpreted as a release of concentrated stresses due to the post-failure rebound caused by the collapsed rock mass.”

10 17. The discussion lacks any details about reliability of osl ages presented here. There are many possible error sources in this technique, but it is unclear if these were considered.

17. The error sources of OSL ages are discussed in depth in the new Method Section (see point 15) and the degree of error of the ages is reported in the table as a column (see Table 1). Talking about the argument also in the Discussion Section could be quite redundant.

15

18. The discussion suggests that the current study provides some new insight on the geologic succession and its role in mass rock creek (MRC). I see no such contribution in the paper. The authors seem to claim in the abstract and introduction that their study somehow addresses pre-failure creep, but this topic is not investigated in any detail. Pre-failure creep is hardly mentioned, and even then, is based only on a couple of field observations. The suggestion that features noted in the Pabdeh Formation (Page 13, line 2) indicate pre-failure creep is not sufficiently supported. It is also possible that these features are not a result of progressive failure of the slope. The plastic deformation shown in Fig. 14B could well be the result of pre-failure creep, but not enough detail is provided to evaluate this. Rock mass strength reduction and associated deformation is also to be expected as a result of fold formation (see Roberts and Evans, 2013 and references therein). The brittle deformation shown in Fig. 14C could well be the results of sliding during catastrophic failure, so I see no reason to use it to argue for pre-failure.

25

18. Although we agree that the current study does not provide any new insight on the geologic succession, we disagree on the remaining content of this comment: it is important to note that based on the known stratigraphy, a rheological contrast in terms of stiffness and viscosity can be hypothesized between Asmari Formation, the Upper Pabdeh and the Taleh Zang members. Evidence of ductile deformations within the Pabdeh layers, which cannot be ascribed to parasitic structural folding (since they can be only observed just below the SL sliding surface), and buckling landforms that demonstrate relevant rebound effects (which are related to an intense stress release after the SL collapse) can be regarded as a proxy for MRC affecting the SL slope before failure due to gravity-induced deformations. Much of the literature ignores that this process is the basis of the triggering of this landslide, while in our opinion this is a fundamental point. In order to better explain this

30



point, not only we described the above cited field evidence in the Results, but we also added a specific sub-section in the Discussion which is **“5.4 Implications of the evolutionary model for future back-analysis of the SL”**.

18. “According to the multi-modeling approach proposed by Martino et al. (2017), Quaternary landscape evolution modeling of slope-to-valley floor systems plays a key role as a tool for chronological constraints to the creep evolution of entire slopes (Bozzano et al., 2016; Della Seta et al., 2017).

5 The geomorphic processes developed before the failure of the SL likely acted as predisposing factors for MRC processes in the rock mass successively collapsed. Kinematic freedom, both at the top and on the fold flank was created by the incising network of streams that dissect the Asmari Formation carbonate caprock following the major joint set in the Asmari Formation already described in Roberts and Evans (2013; and references therein). In particular, the headward erosion of streams towards the anticline’s structural high described by Oberlander (1968), caused the expansion of the fold axial basins through the softer units, determining the upslope kinematic freedom. In the timing proposed by Tucker and Slingerland (1996) the latter was reached at approximately 1.6 ka. Stress release at the slope base was definitely produced by the Middle-Late Pleistocene upstream migration of the knickpoint along the Seymareh River longitudinal profile. Unfortunately, since the emplacement of the landslide swept away the uppermost outcrops of the alluvial terraces formed in response to the upstream knickpoint migration, the rate of knickpoint migration cannot be inferred. Nonetheless, an elapsed time-to-failure on the order of  $10^2$  ky, since the kinematic freedom at the slope base was reached, can be reasonably estimated by the age of the oldest terrace in the lower reach of the river minus the age of the landslide occurrence.

15 It is noteworthy that the stratigraphy of the source rock mass, also described in detail by Roberts and Evans (2013), accounts for different rheological behaviors, which could have induced differential strain rates within the slope leading to failure according to a MRC process. More particularly, the time-dependent visco-plastic behavior, more typical of clayey and marly deposits, which have lower viscosity values, can justify time-dependent (creep) strains which could have generated high stress concentration within the higher viscosity level over time (i.e., mostly characterized by elasto-plastic rheology), inducing their cracking and leading to failure. In fact, a stiffness contrast exists between the upper member of the Pabdeh Formation and the overlying Asmari Formation. The attitude of the strata is moderately dipping downslope ( $15^\circ$ - $20^\circ$ ), and a reduced lateral confining effect is due to continental and epicontinental deposits ascribable to the Gachsaran and Agha Jari Formations. Moreover, the low dip angle of the strata reduces the vertical thickness of the Asmari Formation caprock, which was completely eroded by Seymareh River during its engraving, thus allowing the sliding mechanism of the Pabdeh and Asmari layered formations.

20 Therefore, the results of this work have implications for a future back-analysis through stress-strain numerical modeling of the SL because they can be used to constrain the elapsed time since MRC initiation and ultimate failure conditions. Such a perspective is to be regarded as a key challenge for dimensioning such an end member event in regard to both time and space distribution as well as for evaluating the possible role of impulsive triggering actions (i.e., strong to very strong earthquakes) in anticipating the time-to-failure of the slope.”

19. The authors also bring up numerical modeling in the abstract, introduction and discussion, despite it not factoring into the study. Perhaps they mean to indicate that their results could be used to guide/inform numerical modeling, but their wording is unclear. Given that numerical modeling is not addressed in the study, the background on modeling in the introduction is too extensive and Figure 14 seems irrelevant.

19. We agree that the numerical modeling was not performed in this work. Nonetheless, the evolutionary model of the river valley here proposed provide useful constrains for future stress-strain numerical modelling of the landslide slope to reproduce the MRC and the possible role of seismic forcing in anticipating the time-to-failure of the gravity-driven deforming processes for such an end-member case study of rock slope failure. We better explained these implications in the text in a specific section which is **“5.4 Implications of the evolutionary model for future back-analysis of the SL”**.

19. See the changes reported at point 18.

20. From what I can tell, the authors provide no clear new evidence regarding predisposure of the slope to failure. They start to suggest two interesting aspects, but do not adequately address them. The first aspect is that of pre-failure creep (noted above). The second, which is more closely tied to their investigation, is the possibility of knickpoint migration along Seymareh River, which is inadequately communicated. The extensive evaluation geologic and geomorphic controls on the failure by previous studies (particularly Roberts and Evans, 2013) is hardly addressed, although authors of the present study claim that this is one of their main focuses.

20. We totally agree: we discussed more in depth these points about the pre-failure valley evolution in the Discussion, both in **“5.1 Constraints to pre-failure valley evolution”** and in **“5.4 Implications of the evolutionary model for future back-analysis of the SL”**

20. Attached the “Constraints to pre-failure valley evolution” section:

**“The longitudinal profile of the Seymareh River and the geomorphic markers preserved mainly downstream of the landslide dam provided new constraints on the pre-failure valley evolution. The major knickpoint located immediately upstream of the SL is the most interesting to be analyzed in relation with the landslide event. Its shape in the longitudinal profile clearly let us identify it as a “slope-break knickpoint” (Kirby and Whipple, 2012; Boulton et al., 2014), thus developed as a knickpoint retreating in response to a persistent perturbation to the fluvial system (Tucker and Whipple, 2002), as frequently observed in tectonically active regions. The location of this knickpoint upstream of the SL and the outcrop of the basal contact of the landslide at the bottom of the Seymareh River gorge (Fig. 7a) suggests that this shape of the longitudinal profile was already developed before the failure, meaning that the erosion wave which generated the knickpoint affected the SL slope foot before the failure occurrence.**

**The poorly preserved, well-cemented alluvial fan conglomeratic deposits outcropping upstream of the landslide lie on the Miocene Agha Jari Formation, at a higher elevation than the outcrops of the Bakhtiari Formation. Their remnants are aligned in correspondence with the axis of a relict synclinal valley, likely corresponding to a very early**

stage (Pliocene?) of the Seymareh valley evolution. On the other hand, the conglomerate deposits outcropping downstream of the landslide (Cg\_1) are closer in height to the major knickpoint, thus suggesting that they were in equilibrium with a local base level corresponding to the early propagation of the major knickpoint. Furthermore, they must be younger than the Bakhtiari Formation, which is preserved at higher elevation.

- 5 The alluvial terraces preserved downstream of the SL likely mark the valley evolutionary stages during the major knickpoint retreat (Demoulin et al., 2017). Along the longitudinal river profile, the uppermost outcrops of each level of this terrace suite were swept away by the landslide, which unfortunately prevents estimation of the rates of knickpoint retreat. Nonetheless, according to what was observed by Bridgland et al. (2017) about river terrace development in the NE Mediterranean region, the sedimentation phases should correspond to cold periods. In particular, Bridgland et al. (2012) observed, in the valleys of the Tigris and Ceyhan in Turkey, the Kebir in Syria and the trans-border rivers Orontes and Euphrates, a regular terrace formation in synchrony with 100 ka climatic cycles that can be correlated with MIS 12, 10, 8, 6 and 4-2. Therefore, the minimum ages obtained for the SEY3 and SEY10 samples could be reasonably extended to 478 ka (MIS 12) and 374 ka (MIS 10), respectively, and the OSL age of the SEY11 fits well with the Last Glacial Period.”
- 10
- 15 See also the changes reported at point 18 for “5.4 Implications of the evolutionary model for future back-analysis of the SL” section.

21. Why are landslide kinematics described in the discussion (top of page 13) when they are not part of the new work presented here and when the detailed examination of this topics by previous workers is not mentioned in the background sections? For instance, the geomechanical strength contrast between the Asmari and Pabdeh formations is mentioned in the current paper but has not been characterized. It is, however, approximated in Roberts and Evans (2013). What evidence is there for kinematic freedom provided by gullies along the flank of Kabir Kuh (Page 13, line 13)? The lateral margins of the main landslide are nearly vertical features following a major joint set in the Asmari Formation (characterized in Roberts and Evans, 2013 and references therein, but not mentioned here). There is no evidence I can see for these being related to fluvial processes. Roberts and Evans (2013) propose that these features are instead inherited from the tectonic history of the Zagros’ simply folded zone.
- 20
- 25

21. In the new structure of the manuscript we better explain the role of the drainage network in the onset of the kinematic freedom of the rock mass in the subsection “5.4 Implications of the evolutionary model for future back-analysis of the SL”.

- 30 21. See the changes reports at point 18.

22. What is the basis for the suggestion that failure was preceded by an ‘elapsing time’ on the order of 100 ka (Page 13, line 17)? It’s not even clear what this period is meant to represent. Is this a period of pre-failure creep? The period between the knickpoint passing the toe and the slope failure? This is very hard to follow.

22. See the above response (point 21).

22. See the changes reports at point 18.

23. The conclusion has several issues. It seems to include material – some kind of modeling related to the Seymareh River valley – that is not only not part of the present study, but as far as I can tell is not included in any other published research. I do not see how this fits in, other than also being mentioned in the abstract and introduction. The list summarizing landscape evolution of this part of the Seymareh River valley seems very similar to the list presented on the previous page in the discussion and is thus quite redundant. The conclusion ends with a sentence about seismic triggering, which is hardly mentioned in the paper other than stating that previous workers have suggested it (and even then fails to adequately explain what has been done before). I don't see how the new work done here will contribute to evaluation of a seismic trigger. This text seems to be irrelevant to the conclusions of the paper.

23. We agree: we removed the list presented in previous section and focused on the main topic resulted from the study.

23. Attached the revised conclusion section:

“ In a multi-modeling approach to the study of MRC processes affecting slopes at a large space-time scale, the performed geomorphic analysis allowed us to constrain the evolution of the Seymareh River valley in the northwestern Zagros Mts., before and after the failure of the largest landslide ever recorded on the exposed Earth surface. The identification and OSL dating of different suites of lacustrine, alluvial and strath terraces constrained in time the major pre- and post-failure evolutionary steps of the river valley system.

The oldest geomorphic markers in the Seymareh River valley are represented by relict conglomerates preserved upstream of the landslide, which demonstrate the early (Pliocene?) position of a paleo-Seymareh river flowing into a synclinal valley close to the northeastern flank of the Kabir-kuh fold.

Drainage evolution associated with the growth of the Kabir-kuh fold was characterized by the deep incision of the stream network, which allowed the kinematic release of the rock mass involved in the Seymareh giant landslide. Such a stream incision was accompanied by the retreat of a major “slope-break knickpoint” along the Seymareh longitudinal profile, time-constrained by the age of a suite of river fill terraces. According to the age of pre-failure terraces, in the middle-late Pleistocene the erosion wave reached the portion of the Kabir-kuh fold that ~10 ka was affected by the SL. According to the timing of the landscape evolution model proposed by Tucker and Slingerland (1996), the upper slope underwent kinematic release about 1.6 ka. Therefore, the collapse was prepared by MRC processes acting over a time window of  $10^2$  ky;

The geomorphic response to the landslide dam consisted in the formation of three lakes, among which Seymareh Lake persisted for ~3500 years before its emptying phase started ~6.6 ka due to lake overflow. A sedimentation rate of  $10 \text{ mm y}^{-1}$  was estimated for the lacustrine deposits, which increased up to  $17 \text{ mm y}^{-1}$  during the early stage of lake emptying due to the increased sediment yield from the lake tributaries. Since ~4.5 ka, a suite of four alluvial terraces

upstream of the landslide demonstrates the alternating erosion/deposition phases of the re-established Seymareh River.

An incision rate of  $1.8 \text{ cm y}^{-1}$  was estimated since the beginning of the landslide cut by Seymareh River, and such a strong erosion started propagating up to the landslide source area where badlands developed, eroding the marly

5 Pabdeh-Gurpi Formation.

The results obtained here provide new constraints to the valley evolution in view of future stress-strain numerical modeling of the MRC process that involved the SL slope before its generalized collapse. Such a modeling could also be considered to discuss the possible role of impulsive triggering (earthquakes) in anticipating the time-to-failure due to the gravity-driven deformational processes.”

10

24. The figures are too numerous. Several can be combined (particularly the photos) and others seem to have limited relevance. Fig. 2 is probably more appropriate in the supplement given the lack of relevance of seismicity to the current study. Figs. 1 and 3 could probably be combined, especially if some of the extraneous detail in Fig. 1 is removed. Figures 13 and 14 are irrelevant to the main focus of the paper. Fig. 13 does not add anything to the paper. Figure 14 relates to the suggestion of prefailure creep of the slope, which contrary to what the authors state in the introduction of the paper, is not a major component of the present study. Figure 15 seems to be an afterthought, although it has far more relevance to the paper’s focus on valley-bottom geomorphology than either of the preceding figures.

15

24. We agree: Fig. 2 was included in the supplementary material. Fig. 1 and Fig. 3 cannot be combined because they refer to very different space-time scales. Fig. 13 was included in the new Fig. 2, as a field evidence of the already known outcropping stratigraphy. While Fig. 14 (new Fig. 11) was moved to the Results section. Also Fig. 15 was moved to the Results section, being included it in the new Fig.5. Finally, Fig. 9 was integrated the Fig. 8 (new Fig. 7).

20

25

30

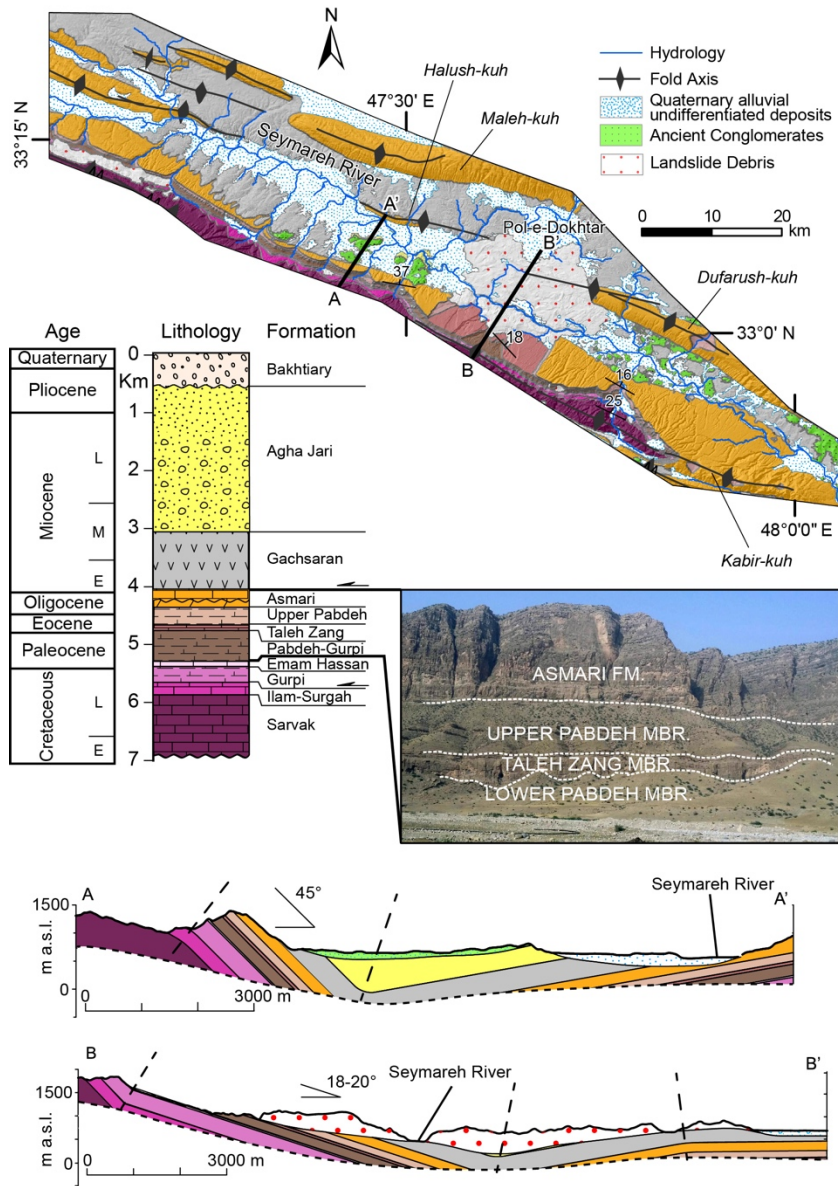


Figure 2: Geological Map, stratigraphic column and cross sections of the study area.

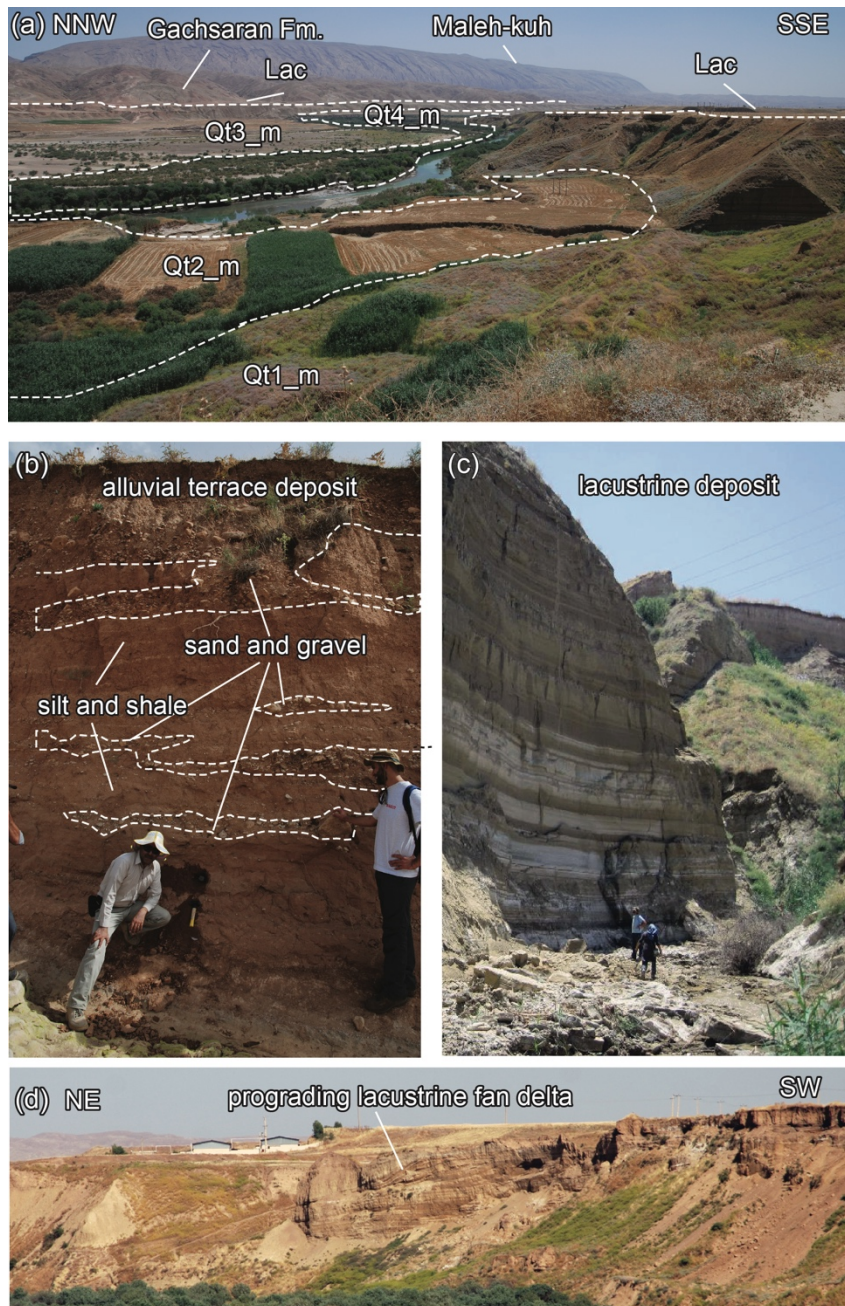


Figure 5: Geomorphic markers upstream of the SL, represented by a suite of four orders of alluvial terraces entrenched in the lacustrine deposits (Lac) of Seymareh Lake upstream of the landslide, in the areas where Harrison and Falcon (1938), Roberts and Evans (2013) and Shoaee (2014) hypothesized the natural damming lake could be extended. a) Overall view of the suite of terraces; b) example of fluvial terrace deposit; c) example of lacustrine deposit; d) evidence of a prograding lacustrine fan delta formed by one of the right tributaries of Seymareh Lake during its early emptying phase.

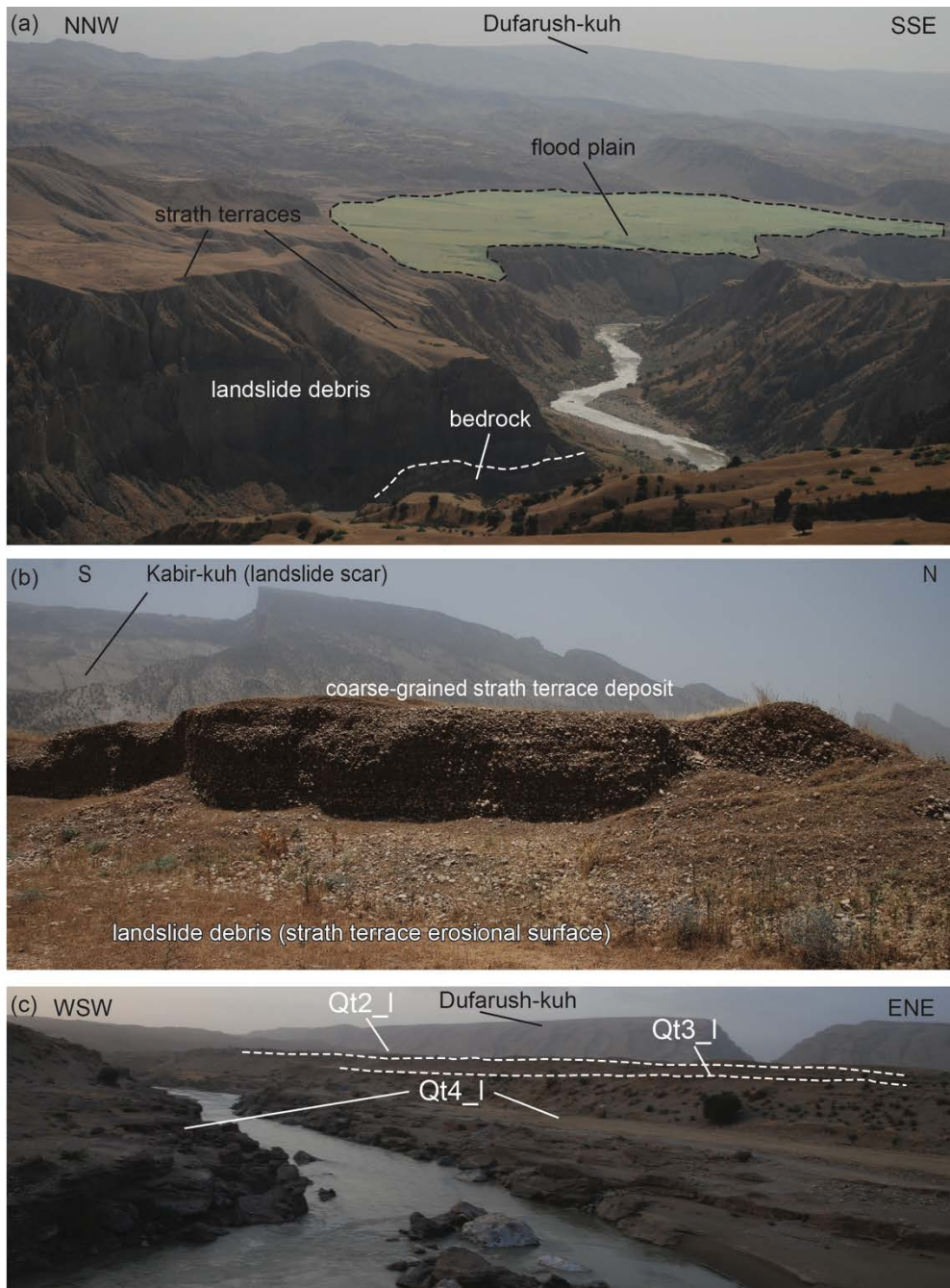


Figure 7: Geomorphic markers upstream of the SL. a) A strath terrace and a flood plain developed over the landslide debris, which are important markers of the evolution of the natural dam since they testify to the moment of the overcoming of the damming lake and the overflowing of the river onto the landslide debris, respectively; b) detail of the strath terrace deposit sampled for OSL dating; c) The suite of fluvial terraces downstream of the SL; the Qt1 level is poorly preserved and not visible in this photo.



The list below provides references for several works that the authors should consult and that are missing from the current paper:

- Alavi, 2004. Regional stratigraphy of the Zagros fold–thrust belt of Iran and its proforeland evolution. *American Journal of Science*, 304, 1–20. Brideau and Roberts, 2015. Mass movements in bedrock, in: *Landslides Hazards, Risks and Disasters*, [Davies and Shroder, eds.]. Academic Press, Amsterdam, Netherlands, 43–90.
- 5 Griffiths et al. 2001. Environmental change in southwestern Iran: the Holocene ostracod fauna of Lake Mirabad. *Holocene*, 11, 757–764. Hermanns and Longva, 2012. Rapid rock-slope failures, in: *Landslides: Types, Mechanisms and Modeling* [Clague and Stead, eds.]. Cambridge Univ. Press, Cambridge, UK, 59–70.
- James and Wynd, 1965. Stratigraphic nomenclature of Iranian Oil Consortium Agreement Area. *AAPG Bulletin*, 49, 2182–
- 10 2245.
- Macleod, 1970. Kabir Kuh, 1:100000 Geological Map. Iran Oil Operating Companies, Geological Exploration Division, Tehran.
- Setudehnia and Perry, 1967. Dal Parri. 1:100000 Geological Map. Iran Oil Operating Companies, Geological Exploration Division, Tehran.
- 15 Takin, M., Akbari, Y. & Macleod, J.H. 1970. Pul-E Dukhtar. 1:100000 Geological Map. Iran Oil Operating Companies, Geological Exploration Division, Tehran.

We added these reference in the manuscript

20

## MINOR ISSUES

1. Page 1, line 10: The anticline is variously referred to as ‘the Kabir-kuh fold’, ‘the Kabir-kuh Fold’, ‘Kabir-kuh fold’, and ‘the Kabir-kuh’. Kabir-kuh is a proper physiographic feature whereas the fold feature is not officially recognized as a name.
- 25 Thus, the only proper version of the naming used here are ‘Kabir-kuh’ and ‘the Kabir-kuh fold’.

1. Right.

1. Changed.

2. Page 1, line 15: Proper capitalization and use of ‘the’ are: ‘the Seymareh River valley’ and ‘Seymareh River’. This needs
- 30 to be corrected throughout the manuscript.

2. Right.

2. Changed.

3. Page 2, line 28: What is meant by 'different evolutionary stages'?

3. Right.

3. Removed when re-writing.

5

4. Page 2, line 28: 'allows to construct' is improper language.

4. Right.

4. Changed.

10 5. Page 2, line 28: What are 'interesting valley sections'?

5. Right.

5. Removed when re-writing.

15 6. Page 2, line 33: The location description is incomplete. The Seymareh River valley straddles the border between Lorestan and Ilam provinces, respectively to the east and west of the river. The landslide initiated in what is now Ilam province, but most of the debris lies in Lorestan.

6. Right.

6. Removed when re-writing.

20 7. Page 2, line 34: What is meant by 'evolutionary scenarios'?

7. Right.

7. Removed when re-writing.

25 8. 9. Page 3, line 1: I am not familiar with the region 'External Zagros Mountains'. Is this the simply-folded zone/belt?

8.9. Right.

8.9. Changed.

30 10. Page 3, line 13: 'Seimareh' should be 'Seymareh'. Although various spellings have been used over the years, 'Seymareh' seems to be the currently recognized version. In any case, spelling should be consistent throughout the manuscript. This corps up in a few other places.

10. Right.

10. Changed.

11. Page 3, line 15: It is far more informative to state here what the study achieved, rather than what it intended to achieve. Also 'aims at better understanding' is improper English.

11. Right.

11. Changed.

5

12. Page 3, line 16: Here, in the abstract and again later on risk (or risk mitigation) is thrown in. However, this topic is not explored. Practically, the only mitigation would be complete evacuation (either temporality based on some kind of warning system or permanently) of an area that could experience landslide of this magnitude and stabilization or localized avoidance are impossible. Furthermore, the very low probability of a landslide of this magnitude means that its risk is potentially rather low.

12. Right.

12. Removed when re-writing.

10

13. Page 3, line 25: What is 'e.g.' used? Also, this is hardly the more relevant source for this statement given that several studies have investigated the landslide.

13. Right.

13. Removed when re-writing.

15

14. Page 3, line 27: Units should be m a.s.l. as this is an elevation.

14. Right.

14. Changed.

20

15. Page 4, line 1: 'The Zagros' is not the proper way to refer to the range. This statement also requires references to back it up.

11. Right.

11. Changed.

25

16. Page 4, line 15: 'landslide' not 'Landslide'.

11. Right.

11. Changed. When we refer to the Seymareh Landslide, we use SL, as in Shoaiei (2014).

30

17. Page 4, line 15: Given that this is a new paragraph, reference back to the previous content (using 'latter') is confusing.

17. Right.

17. Changed.

18. Page 4, line 22: Parentheses missing around publication year.

18. Right.

18. Changed.

5

19. Page 4, line 22: What is meant by the ‘onset of the [sic] deformation’? Is this supposed to be propagation of the deformation front?

19. Right.

19. Removed when re-writing.

10

20. Page 5, line 13: I’ve never come across ‘Delful Zagros’ as a term. Are the authors certain that this is a properly recognized physiographic region?

20. Right.

20. Changed.

15

21. Page 5, line 14: Missing year of source.

21. Right.

21. Changed.

20

22. Page 5, line 21: The mobile and competent units have not yet been introduced, and are part of the geology not the geomorphology (as the section title would suggest). These have not yet been introduced. The geology should be briefly summarized before the geomorphology, especially given the apparent influence of the former on the latter. A few of the units are mentioned in the following lines, but the geology is of course much more complex than that.

22. Right.

25

22. Changed, including in the new “**2 Regional Geological and Geomorphological Framework**” the description of the stratigraphy.

23. Page 5, line 22: This fold is in Ilam province, not Lorestan. The boarder between them in this area follows Seymareh River.

30

23. Right.

23. Changed.

24. Page 6, line 28: Should be ‘the Asmari Formation’. Spell formation out throughout the text of the paper; do not abbreviate to ‘Fm.’ (as on line 31).

24. Right.

24. Changed.

25. Page 6, line 5: This is general physiographic background that should appear much earlier on in the paper.

5 25. We completely re-wrote the Regional Geological and Geomorphological Framework, deleting the unnecessary text.

26. Page 6, line 6: Identify the lakes here and how they were formed (i.e. which rivers were blocked). Lake Balmak is not named until the discussion and is hard to place in the figures. It would also be helpful to very briefly note that much of the previous literature calls this lake Chah Javal.

10 26. Right.

26. Changed.

27. Page 6, line 9: Regarding ‘. . .formed in response to a sequence of landslide’, clarify whether this is multiple separate landslides or all related to the Seymareh landslide.

15 27. Right.

27. Changed.

28. Page 6, line 9: Consider simplifying to ‘the landslide dams’ so that the reader does not mistake your meaning to be multiple landslide dams of Seymareh Lake (instead of multiple lakes dammed by the Seymareh landslide).

20 28. Right.

28. Changed.

29. Page 7, line 12: Combining ‘none’ and ‘neither’ forms a double-negative. Also, ‘study’ should be ‘studies’.

29. Right.

25 29. Changed.

30. Page 7, line 13: Specify ‘fluvial’ geomorphic markers (and remove ‘the’).

30. Right.

30. Changed.

30

31. Page 7, line 17: ‘landslide’ not ‘Landslide’.

31. Right.

31. Changed. When we refer to the Seymareh Landslide, we use SL, as in Shoaiei (2014).

32. Page 7, line 18: Presumably 'refer to' means 'date to'?

32. Right.

32. Changed.

5 33. Page 7, line 19: Geologic ages should be late/early, not upper/lower. The latter pertain the stratigraphy, not ages.

33. Right.

33. Changed.

34. Page 7, line 19: The ages should be 'Late Cretaceous' (an officially recognized age) and 'early Miocene' (not an  
10 officially recognised age).

34. Right.

34. Changed.

35. Page 8, line 21: Unless I've missed a break, the paragraph ending on this line is massive and needs to be broken up.

15 35. Right.

35. Changed.

36. Page 8, line 29: Do not abbreviate 'Formation'.

36. Right.

20 36. Changed.

37. Page 8, line 34: The river name should be 'paleo-Seymareh river' as this is not an officially recognized name.

37. Right.

37. Changed.

25

38. Page 9, line 12: 'literature' is insufficient. What were the sources?

38. Right.

30 **38. "The geomorphological study of the area was carried out first through the analysis and interpretation of remote sensing data, such as aerial photos (National Cartographic Center of Iran, aerial photo, scale:1:20000, acquired on 24 August 1955), Google Earth satellite optical images (2018 Landsat Imagery) and vector topographic maps (National Cartographic Center of Iran, topographic map of Kuhdasht, scale: 1:25,000), which led to the first detection of possible geomorphic markers within the Seymareh River valley. Vector topographic data also allowed the construction of a 10 m Digital Elevation Model (DEM) for terrain analyses and led to the projection of the possible geomorphic markers along the river longitudinal profile (Wilson and Gallant; 2001; Burbank and Anderson, 2012).**

The DEM was obtained by the ArcGIS 10® software package, starting from vector topographic data (contour lines, hydrography and point elevation) and using the ANUDEM interpolation algorithm (Hutchinson et al., 2011 and references therein).”

5 39. Page 9, line 18: Unclear what is meant by the ‘data where [sic] acquired’.

39. Right.

39. Changed.

40. Page 9, line 20: Write ‘minutes’ out in full.

10 40. Right.

40. Changed.

41. Page 10, line 4: Which components of the Hydrology toolbox were used?

41. Right.

15 41. “To automatically extract the hydrographic network from the DEM and then to project the geomorphic markers along the longitudinal river profiles, some of the ArcGIS® 10 tools of the Hydrology toolbox were used (Flow Direction, Flow Accumulation, Reclassify, Stream Order and Stream to Feature), setting the flow accumulation threshold according to that proposed for the fluvial domain ( $10^{-1}$  km<sup>2</sup>) by Montgomery and Foufoula-Georgiu (1993). The longitudinal profile was therefore transformed into a route along which the elevation of the top surfaces of  
20 geomorphic markers identified in the area were projected through the Linear Referencing Tools (Create Route and Locate Features along Route).”

42. Page 10, line 17: Should be ‘the Seymareh River gorge’.

42. Right.

25 42. Changed.

43. Page 11, line 10: Why is this knickpoint ‘. . .the most interesting...’? The authors seem to be implying that this may related to instability within the flank of Kabir Kuh, but the reader can only guess.

43. Right.

30 43. Changed.

44. Page 13, line 20: Lake Balmak is mentioned here for the first time. Why?

44. Right.

44. Changed.

45. Page 13, line 24: What about the drainage was progressive? The actual drainage is now well characterized here.

44. Right.

44. Changed.

5

46. Page 13, line 28: This duration for the lake needs to be compared with estimates provided in other sources.

46. We agree with concept of comparing the results with other sources. In this regard, we compare the result for the persistence of the Seymareh lake of about 5 ky with the estimate of 935 years supposed on the same lake by Shoaiei (2014).

46. “As indicated by the age of the Qt1\_m terrace (of  $4.49 \pm 0.48$  ka), the Seymareh Lake likely persisted up to ~5 ka, much longer than the 935 years estimated by Shoaiei (2014)”.

10

47. Page 13, line 30: This is the only place this figure is cited. The figure does not alone indicate what the authors suggest. Has some further work been done on this stratigraphic section that I missed?

47. Right.

15 47. Changed.

48. Page 14, line 3: What is meant by ‘time scan’?

48. Right.

48. Changed.

20

49. Page 14, line 5: I again see no benefit to a list instead of writing out the description in proper paragraph format.

49. Right.

49. Changed.

25 50. Text in some figures, particularly the labels (and markers) for sample locations in Figs. 7 and 10, is too small and thus hardly legible.

50. Right.

50. Changed.

30



## REV#2: (D. Petley)

### FUNDAMENTAL ISSUES:

5 1. The manuscript is very poorly organised. It is hard to understand what is new, what is a reinterpretation, and what is background information. I found the paper difficult to read and to follow, and at the end I am not sure I really managed to work out what was new.

1. We absolutely agree.

1. We re-organized the manuscript balancing the content between background information and new data. In particular:

10 a) we rewrote the introduction to better focus the gap of knowledge we want to fill (lack of time constraints to the Seymareh River valley evolution before and after the Seymareh Landslide occurrence, to outline the role of the geomorphic processes both as predisposing factors for MRC processes and as response to this giant gravitational instability;

b) we moved any new observation to the Results and any interpretation to the Discussion, which was organized in 4 subsections to improve the readability.

15 (SEE ALSO THE RESPONSES to REV#1)

2. There is a huge amount of background information. Much of this seems to be irrelevant or tangential. In some cases, it misrepresents the literature (e.g to say "which is mainly focused on predictive models" in page 2 is not correct. The authors really need to work out what is needed and what is not.

2. We agree.

20 2. We reduced the part concerning the background information by 50% into a unique section: “**2 Regional geological and geomorphological framework**”., focusing on what of the literature is needed for the present study. We also moved the paragraph relative to Seismicity and to the general Tectonics of the area to the supplementary material. Furthermore, the section on the “Revised stratigraphic column and geological sections of the Seymareh river valley” was removed.

(SEE ALSO THE RESPONSES to REV#1)

25 3. Very little of the paper is really about predisposing factors. This seems to be focused on knickpoint migration, but it is it clear as to whether this is really a factor in such a large landslide.

3. We agree.

30 3. We refocused the topic of the paper highlighting the real new insights on this exceptional case of study: new time constraints to the Seymareh River valley evolution before and after the emplacement of the Seymareh landslide, to outline the role of the geomorphic processes both as predisposing factors for MRC processes and as response to this giant gravitational instability. We then discussed the “**Implications of the evolutionary model for future back-analysis of the SL**” in a subsection of the Discussion. Accordingly, we changed also the Title of the manuscript into “**New constraints to**

river valley evolution before and after the emplacement of the largest landslide on the exposed Earth surface: the Seymareh rockslide - debris avalanche (Zagros Mts., Iran)".

Attached the new "5.4 Implications of the evolutionary model for future back-analysis of the SL" subsection:

5 "According to the multi-modeling approach proposed by Martino et al. (2017), Quaternary landscape evolution modeling of slope-to-valley floor systems plays a key role as a tool for chronological constraints to the creep evolution of entire slopes (Bozzano et al., 2016; Della Seta et al., 2017).

The geomorphic processes developed before the failure of the SL likely acted as predisposing factors for MRC processes in the rock mass successively collapsed. Kinematic freedom, both at the top and on the fold flank was created by the incising network of streams that dissect the Asmari Formation carbonate caprock following the major joint set in the Asmari Formation already described in Roberts and Evans (2013; and references therein). In particular, the headward erosion of streams towards the anticline's structural high described by Oberlander (1968), caused the expansion of the fold axial basins through the softer units, determining the upslope kinematic freedom. In the timing proposed by Tucker and Slingerland (1996) the latter was reached at approximately 1.6 ka. Stress release at the slope base was definitely produced by the Middle-Late Pleistocene upstream migration of the knickpoint along the Seymareh River longitudinal profile. Unfortunately, since the emplacement of the landslide swept away the uppermost outcrops of the alluvial terraces formed in response to the upstream knickpoint migration, the rate of knickpoint migration cannot be inferred. Nonetheless, an elapsed time-to-failure on the order of  $10^2$  ky, since the kinematic freedom at the slope base was reached, can be reasonably estimated by the age of the oldest terrace in the lower reach of the river minus the age of the landslide occurrence.

20 It is noteworthy that the stratigraphy of the source rock mass, also described in detail by Roberts and Evans (2013), accounts for different rheological behaviors, which could have induced differential strain rates within the slope leading to failure according to a MRC process. More particularly, the time-dependent visco-plastic behavior, more typical of clayey and marly deposits, which have lower viscosity values, can justify time-dependent (creep) strains which could have generated high stress concentration within the higher viscosity level over time (i.e., mostly characterized by elasto-plastic rheology), inducing their cracking and leading to failure. In fact, a stiffness contrast exists between the upper member of the Pabdeh Formation and the overlying Asmari Formation. The attitude of the strata is moderately dipping downslope ( $15^\circ$ - $20^\circ$ ), and a reduced lateral confining effect is due to continental and epicontinental deposits ascribable to the Gachsaran and Agha Jari Formations. Moreover, the low dip angle of the strata reduces the vertical thickness of the Asmari Formation caprock, which was completely eroded by Seymareh River during its engraving, thus allowing the sliding mechanism of the Pabdeh and Asmari layered formations.

30 Therefore, the results of this work have implications for a future back-analysis through stress-strain numerical modeling of the SL because they can be used to constrain the elapsed time since MRC initiation and ultimate failure conditions. Such a perspective is to be regarded as a key challenge for dimensioning such an end member event in

regard to both time and space distribution as well as for evaluating the possible role of impulsive triggering actions (i.e., strong to very strong earthquakes) in anticipating the time-to-failure of the slope.”

4. The sections on the post-event landscape evolution is interesting, and probably represents the best part of the paper. But it needs to be organised in a more systematic manner that allows the reader to follow the argument. At the moment it feels somewhat chaotic and disorganised, and extremely difficult to follow. The substantive part of this section (5.2) is brief and hard to follow. There are results elsewhere though, which is confusing.

4. We agree.

4. We re-organized the results, formatting a new more concise results section without interpretations. Then we re-organized the Discussion in 4 subsections to improve the readability.

Attached the new “4 Results” section:

“The best geomorphic markers preserved in the study area are represented by a lacustrine terrace and two suites of fluvial terraces. The suites are distributed both upstream and downstream of the landslide debris, marking the evolutionary stages of the valley, respectively, after and before the landslide emplacement. Fluvial and lacustrine terrace deposits mainly consist of gravel, sand, silt and clay, and conglomerates outcropping immediately upstream and downstream of the landslide pertain to inactive alluvial fans connected to a relict position of the valley floor, likely of a paleo-Seymareh river.

In the middle reach of the Seymareh River valley, the upstream geomorphic markers include: inactive, terraced conglomeratic alluvial fans (Cg\_m), a terraced lacustrine deposit and a suite of four orders of fill terraces (named from Qt1\_m to Qt4\_m). The geometry of the terraced conglomerates (section A-A' in Fig. 2) can be associated with alluvial fans generated on the flanks of a former synclinal valley by streams likely forming the tributaries of a paleo-Seymareh river whose path was to the SW of the present one. The fill terraces are entrenched in the terraced lacustrine deposit of Seymareh Lake upstream of the landslide, in the area where Harrison and Falcon (1938), Roberts and Evans (2013) and Shoaiei (2014) hypothesized the natural damming lake could be extended (Figs. 5 and 6). Prograding lacustrine fan deltas formed by tributaries of Seymareh Lake have been recognized, which likely formed during the emptying phase of the lake. In this sector, we successfully dated 4 samples (SEY4, SEY5, SEY6, and SEY8; Table 1 and supplementary material); in particular the lacustrine deposit at two different stratigraphic levels, 560 and 590 m a.s.l., which provided OSL ages of  $10.4\pm 0.90$  ka (sample SEY8) and  $7.37\pm 0.73$  ka (sample SEY4), respectively. The OSL age of  $17.9\pm 1.50$  ka (SEY6) obtained for an alluvial deposit at the base of the lacustrine deposits is coherent with the age of emplacement of the SL, as already inferred by Roberts and Evans (2013).

A suite of 2 strath terraces and a flood plain shaped onto the landslide debris along the Seymareh River gorge have been identified (Figs. 7a and 7b), which are important markers of the evolution of the natural dam because they formed after its cut likely due to an overflow of the damming lake. Here, we successfully dated one sample taken on a

strath terrace (SEY9; Table 1 and supplementary material), which provided an age of  $6.59 \pm 0.49$  ka as time constrain for the initial stage of lake emptying.

In the lower reach of the Seymareh River valley, the downstream geomorphic markers include: inactive, terraced conglomeratic alluvial fans (Cg\_1) and a suite of four orders of fill terraces (named from Qt1\_1 to Qt4\_1) downstream of the SL (Figs. 7c and 8). Here, we successfully dated three samples from the fill terraces deposits (SEY3, SEY10, SEY11; Table 1 and supplementary material). The ages obtained provide useful time constraints to the main depositional events during the pre-failure valley evolution. Minimum ages of  $373 \pm 34$  ka and  $312 \pm 45$  ka have been obtained for samples SEY3 and SEY10, respectively, since these samples were saturated due to their low concentration of quartz grains, and SEY11 was dated at  $60 \pm 5$  ka.

The above-described geomorphic markers of the Seymareh River valley have been mapped and reported in morpho-stratigraphic profiles. The most significant landforms for the valley slope evolution are presented with a detail for the post-failure fluvial and lacustrine terrace suites upstream of the landslide dam (Fig. 6) and the pre-failure fluvial terrace suite downstream of the landslide dam (Fig. 8), respectively.

Figures 9 and 10 report the longitudinal profile of Seymareh River, along which, in addition to the geomorphic markers, were projected also: the benchmarks of the basal contact of the Quaternary deposits on the bedrock, the projection of points corresponding to the top of the SL debris, the upstream and downstream limits of the landslide, the location of the OSL sampling, and the projection of the outcrop of the Bakhtiari Formation (Fig. 9), which is rarely preserved and marks the initial alluvial infill of the Seymareh River valley. Figure 9 shows the height distribution of the pre-failure geomorphic markers. The benchmarks along Seymareh River indicate a mostly bedrock channel, and the longitudinal profile is characterized by two knickpoints located upstream of the SL and downstream of the lowest suite of alluvial terraces, as indicated by the black arrows. The geomorphic markers downstream and upstream do not belong to the same suite of terraces, as their projections along Seymareh River do not have any topographic correlation to each other (Fig. 9 and 10). The tops of all the fluvial terraces downstream of the SL are located lower in height than the most important knickpoint located immediately upstream and sculpted in the bedrock. Figure 10 shows the height distribution of the post-failure geomorphic markers. The markers are represented by: i) the horizontal lacustrine terrace formed by the incision of the deposits pertaining to the Seymareh Lake, formed as a consequence of the landslide damming; ii) the two levels of the strath terraces and a flood plain formed on the landslide debris during the initial stages of dam cutting and emptying of the lake; and iii) the four fill terrace levels formed after the emptying of the Seymareh Lake.

The geomorphological field survey, supported by a remote survey based on optical satellite and aerial images, also allowed us to demonstrate the evidence of gravity-induced features of the downslope dipping strata, along the scar of the SL (Fig. 11).

Clear evidence of MRC driving towards stress concentration and failure has been recognized in gravity-induced folding within the thin-layered Pabdeh Formation just below the sliding surface of the SL (i.e., that cannot be

ascribed to parasitic structural folding). Furthermore, impressive buckling of the downslope dipping strata, which crop on the sliding surface of the SL, have been interpreted as a release of concentrated stresses due to the post-failure rebound caused by the collapsed rock mass.”

- 5 5. I am not sure why so much detail is needed on the large-scale geomorphic evolution of the area. This would be better dealt with through references.

5. We agree

5. We reduced the text on the geomorphic evolution into a unique section: “**2 Regional geological and geomorphological framework**”., focusing on what of the literature is needed for the present study.

- 10 Attached the paragraph regarding the large-scale geomorphic evolution of the area:

“The Zagros Range globally provides one of the most spectacular examples of landscape evolution in response to active tectonics (Bourne and Twidale, 2011) because its drainage network clearly adapted to the growth of the thrust-fold structures (Ramsey et al., 2008) and to the erodibility of the outcropping formations (Oberlander, 1985). Oberlander (1968) suggested that the drainage network in the NW Zagros was superimposed from structurally conformable younger horizons. In his model, the breaching of hard geological units of the antiformal ridges follows a phase of river cutting and expansion of the fold axial fold basins through the softer overlying units. In the Kabir-kuh fold, the transverse cutting of the Asmari limestone, and the exposure of the underlying more erodible Pabdeh-Gurpi marls, leads to the formation of a low-relief landscape with synformal ridges on which the new through-going drainage system can be developed. In Oberlander’s hypothesis, it is the Pabdeh and Gurpi marls that facilitate the creation of a low-relief landscape across the anticline crests and are therefore integral to the story of drainage superimposition.

- 20 Tucker and Slingerland (1996) computed a numerical landscape evolution model, calibrated on the Kabir-kuh fold, to understand how the growth and propagation of the folds, the different lithologies and the drainage network can influence the sediment flux from a tectonically active belt towards the foreland basin. The authors calibrated the landscape evolution model with the current topography of the range, obtaining time constraints for landscape evolution modeling. According to the Oberlander model, Fig. 3 shows four main steps that describe the landscape evolution of the Kabir-kuh fold with the timing provided in the model by Tucker and Slingerland (1996).

- 25 Step 1 - Approximately 4.3 Ma, in response to the initial stages of fold growth, an orthoclinal drainage develops, parallel to the main structures. The tributaries flowing along the flanks of the folds transport debris, which is deposited in the synclines. In the Kabir-kuh fold the carbonate core is still buried by the Miocene cover units.

- 30 Step 2 - Approximately 3.8 Ma, as soon as the deformation front migrates towards the SW, new folds raise with a progressive adjustment of the drainage to these morpho-structures. The previously deposited sediments are remobilized and transported towards the depocenter of the syncline basins and partly outside; the syn-orogenic

deposits are strongly eroded along the crests of the anticlines, thus exposing the underlying formations. This causes a topography characterized by resistant hogbacks that flank the inner cores.

5 Step 3 - Approximately 2.4 Ma, with the ongoing deformation, the drainage develops in a “trellis” pattern. The river erosion affects the erodible units located stratigraphically between the limestone of the Asmari Formation and the inner core of the fold. At the end of this step the Miocene cover is completely removed from the ridges and the river erosion also affects the marls and evaporites of the syn-orogenic formations in the valleys, exposing the underlying limestone of the Asmari Formation.

10 Step 4 - Approximately 1.6 Ma, due to the continuous uplift and exhumation of younger, more external folds, the sediment accumulation becomes negligible and the Asmari limestone is strongly eroded giving rise to syncline ridges. The following Quaternary landscape evolution is then likely driven by the evolution of the drainage network and is also influenced by climatic factors and by the slope-to-channel dynamics.

The model by Tucker and Slingerland (1996) is the unique numerical model existing on the Kabir-kuh fold and this motivates our choice of using it as a reference for the medium-to-long term evolution of the Seymareh River valley. The Seymareh River valley is arranged parallel to the Kabir-kuh fold and its evolution was inevitably influenced by the exceptional landslide event that temporarily dammed it, causing the formation of the three-lake system which includes the Seymareh, Jaidar and Balmak lakes (Fig. 4). The valley evolution before and after the event is well recorded by Quaternary landforms preserved along the valley. Yamani et al. (2012) focused on the post-failure evolution of the valley describing four levels of terraces upstream of the landslide dams as a sequence of lacustrine terraces. Shoaiei (2014), in addition to evaluating the longevity of the SL dams, identified in the merging of Seymareh River with a left tributary as the reason for strong river incision at the base of the northeastern flank of the Kabir-kuh fold and as a possible causal factor for the SL collapse.

20 However, none of the previous studies on the Quaternary evolution of the Seymareh River valley provided absolute dating of geomorphic markers (mainly fluvial terraces) preserved upstream as well as downstream of the landslide dam or provided robust and quantitative constraints to the pre-failure valley evolution as a possible geomorphological factor for failure occurrence.”

6. The discussion is also hard to follow, needing a restructure.

6. We agree.

30 6. We re-organized the discussion section, formatting a new one as follows:

#### - 5.1 Constraints to pre-failure valley evolution:

“The longitudinal profile of the Seymareh River and the geomorphic markers preserved mainly downstream of the landslide dam provided new constraints on the pre-failure valley evolution. The major knickpoint located

immediately upstream of the SL is the most interesting to be analyzed in relation with the landslide event. Its shape in the longitudinal profile clearly let us identify it as a “slope-break knickpoint” (Kirby and Whipple, 2012; Boulton et al., 2014), thus developed as a knickpoint retreating in response to a persistent perturbation to the fluvial system (Tucker and Whipple, 2002), as frequently observed in tectonically active regions. The location of this knickpoint upstream of the SL and the outcrop of the basal contact of the landslide at the bottom of the Seymareh River gorge (Fig. 7a) suggests that this shape of the longitudinal profile was already developed before the failure, meaning that the erosion wave which generated the knickpoint affected the SL slope foot before the failure occurrence.

The poorly preserved, well-cemented alluvial fan conglomeratic deposits outcropping upstream of the landslide lie on the Miocene Agha Jari Formation, at a higher elevation than the outcrops of the Bakhtiari Formation. Their remnants are aligned in correspondence with the axis of a relict synclinal valley, likely corresponding to a very early stage (Pliocene?) of the Seymareh valley evolution. On the other hand, the conglomerate deposits outcropping downstream of the landslide (Cg\_1) are closer in height to the major knickpoint, thus suggesting that they were in equilibrium with a local base level corresponding to the early propagation of the major knickpoint. Furthermore, they must be younger than the Bakhtiari Formation, which is preserved at higher elevation.

The alluvial terraces preserved downstream of the SL likely mark the valley evolutionary stages during the major knickpoint retreat (Demoulin et al., 2017). Along the longitudinal river profile, the uppermost outcrops of each level of this terrace suite were swept away by the landslide, which unfortunately prevents estimation of the rates of knickpoint retreat. Nonetheless, according to what was observed by Bridgland et al. (2017) about river terrace development in the NE Mediterranean region, the sedimentation phases should correspond to cold periods. In particular, Bridgland et al. (2012) observed, in the valleys of the Tigris and Ceyhan in Turkey, the Kebir in Syria and the trans-border rivers Orontes and Euphrates, a regular terrace formation in synchrony with 100 ka climatic cycles that can be correlated with MIS 12, 10, 8, 6 and 4-2. Therefore, the minimum ages obtained for the SEY3 and SEY10 samples could be reasonably extended to 478 ka (MIS 12) and 374 ka (MIS 10), respectively, and the OSL age of the SEY11 fits well with the Last Glacial Period.”

#### - 5.2 Constraints to post-failure valley evolution:

“The geomorphic markers preserved upstream of the landslide dam provided new constraints on the geomorphic response of the Seymareh valley to the 44 Gm<sup>3</sup> natural dam. Such a response was first the formation of three lakes (Seymareh, Jaidar and Balmak; Fig. 4) whose persistence and evolution is well recorded by the deposits outcropping in the valley. In this regard, the estimation of a sedimentation rate of 10 mm y<sup>-1</sup> in the Seymareh Lake was obtained using the OSL ages of 10.4±0.90 ka and 7.37±0.73 ka for the lacustrine deposit sampled at 560 and 590 m a.s.l., respectively.

The strath terrace sculpted on the landslide deposit and dated at 6.59±0.49 ka constrains the cut of the natural dam due to overflow which caused the lake to empty. The lake overflow was likely caused by the gradual filling of the

reservoir with lacustrine deposits, which progressively reduced the dam infiltration section. Nevertheless, the possible role of groundwater seepage within the pervious natural dam in balancing the Seymareh River discharge and delaying the dam overflow remains a questionable topic to be approached and solved in future studies. Despite their interpretation as progressively younger lacustrine deposits by Yamani et al. (2012), the four terrace levels entrenched in the terraced lacustrine deposit show a longitudinal downstream gradient, which, along with their sedimentological characters, identify them as fill terraces. Furthermore, the OSL age obtained for the lacustrine deposit at the base of the Qt2\_m terrace (sample SEY8) is  $10.4 \pm 0.90$  ka, demonstrating that the suite of alluvial terraces is entrenched into the same (and unique) lacustrine deposit. The OSL age of  $4.49 \pm 0.48$  ka obtained for the Qt1\_m terrace (sample SEY5) provides time constraints to the emptying phase of Seymareh Lake. Such time constraints are fine-tuned by the age of the strath terrace formed on the landslide debris, which corroborate the initial stage of lake emptying at  $6.59 \pm 0.49$  ka (SEY9). As indicated by the age of the Qt1\_m terrace (of  $4.49 \pm 0.48$  ka), the Seymareh Lake likely persisted up to  $\sim 5$  ka, much longer than the 935 years estimated by Shoaiei (2014). Since the top of the lacustrine deposit lies at 630 m a.s.l., an increased sedimentation rate of  $\sim 17$  mm  $y^{-1}$  can be inferred for the late stage of the lake evolution, which is in agreement with an increased sediment yield from tributaries during the early stages of lake emptying (Fig. 5d).

The overflow, at  $6.59 \pm 0.49$  ka allows us to calculate the erosion rate affecting the landslide deposit after the overflow. The ratio between the thickness of the eroded sediment ( $\sim 120$  m) and the time elapsed since the beginning of the process ( $\sim 6.59$  ky) allows estimation of an erosion rate of  $1.8$  cm  $y^{-1}$  for Seymareh River along the gorge. The cut of the landslide dam induced a new change in the fluvial base level, bringing the slope-to-valley floor system into disequilibrium. For this reason, a dense drainage system was set on the scar area, which, due to the high erodibility and low permeability of the less competent Pabdeh-Gurpi Formation immediately below the sliding surface on the Kabir-kuh ridge NE slope, has generated the badlands mapped in Fig. 6.”

### - 5.3 Evolutionary model of the Seymareh River valley:

“The landscape evolution of the Seymareh River valley before and after the failure occurrence can be summarized in the following six phases:

1. Setting of a paleo-Seymareh river into a synclinal valley, likely developed in the Pliocene, to the west of the present position of the Seymareh River and deposition of fan deposits (Cg\_m) (Fig. 12a).
2. Development of the valley with local base level correlated to the Seymareh longitudinal profile segment upstream of the major knickpoint along the Seymareh River and coeval to the deposition of the Bakhtiari Formation (late Pliocene-early Pleistocene) (Fig. 12b).
3. Emplacement of the downstream fan deposits corresponding to the Cg\_I conglomerates (early Pleistocene) and generation of the four orders of Middle-Late Pleistocene alluvial terraces (Qt1\_I-Qt4\_I) preserved downstream of the



landslide and formed during the progressive migration of the major knickpoint, which is presently located upstream of the landslide (Fig. 12c).

4. SL event (~10 ka), according to the <sup>14</sup>C ages by Roberts and Evans (2013) and to the OSL ages provided in this work for the lacustrine deposits (Lac) (Fig. 12d).

5 5. Formation and permanence of the Seymareh Lake (~10-6.6 ka), according to the <sup>14</sup>C estimated ages by Roberts and Evans (2013) and to the OSL ages provided in this study for the lacustrine deposits (Lac) (Fig. 12e). The progressive infilling of the lake reservoir progressively reduced the infiltration section on the upstream side of the landslide dam. The presence of a minor emissary on the downstream side of the landslide debris cannot be excluded.

10 6. Overflow of the lake and cut of the natural dam with formation of the first strath terrace (6.59±0.49 ka), followed by a second strath terrace and a flood plain during the emptying of the lake, which upstream is associated with the sedimentation of a fluvio-lacustrine sequence at the top of the lacustrine sediments (Fig. 12f).

7. Complete emptying of the lake and generation of the suite of fill terraces entrenched in the deposits of Seymareh Lake (4.5 ka. - Present) (Fig. 12g).”

15 - 5.4 Implications of the evolutionary model for future back-analysis of the SL (see the text attached at point 3).

7. I am not sure that the review of previous studies of this landslide really present them in a correct manner. I think the abstract needs rewriting - it does not present the contents of the paper well.

20 7. We agree.

7. The summary of previous work on the Seymareh landslide was corrected as following:

25 “Different interpretations have been proposed so far by the scientific community to explain the generation of such an exceptional event and different scenarios have been hypothesized for explaining the induced changes in landscape. Harrison and Falcon (1937, 1938) provided much of the present knowledge on the rock avalanche, including the geology and structure of the source area, the general geomorphology and the basic geometry of the landslide. Oberlander (1965) included a short appendix on the landslide in his study of Zagros streams and discussed its origin in relation to the activity of Seymareh River. Later, in the 1960s, Watson and Wright (1969) characterized the geomorphology and stratigraphy of the debris, discussed the origin of the initial rockslide, and examined the debris avalanche emplacement mechanisms. Roberts (2008) and Roberts and Evans (2013) provided a detailed model of how  
30 the geological and tectonic evolution of the Kabir-kuh fold predisposed the slope to such a large-scale failure, including formation of structural/kinematic and rheological control, and inferred a seismic trigger. Specifically, Roberts and Evans (2013) obtained from a charcoal-rich layer approximately 15 m above the base of the lacustrine sequence with a <sup>14</sup>C age of 8710 years BP. Based on the interpretation of three separate radiocarbon ages provided additionally by Griffiths et al. (2001) an estimated radiocarbon bracket age of the Seymareh event was suggested

between 9800–8710 <sup>14</sup>C years BP. Yamani et al. (2012) provided some general details on the evolution of the dam lake drainage, describing a sequence of entrenched lacustrine terraces upstream of the landslide dam. Finally, Shoaei (2014) reviewed the possible mechanisms of failure and interpreted the post-failure geomorphic features through analyzing the processes responsible for the formation and erosion of the landslide dams of the Seymareh, Jaidar and Balmak (called also Chah Javal) lakes by using available annual sedimentation data and field measurements of the deposits in these lakes.”

The abstract was rewritten as following:

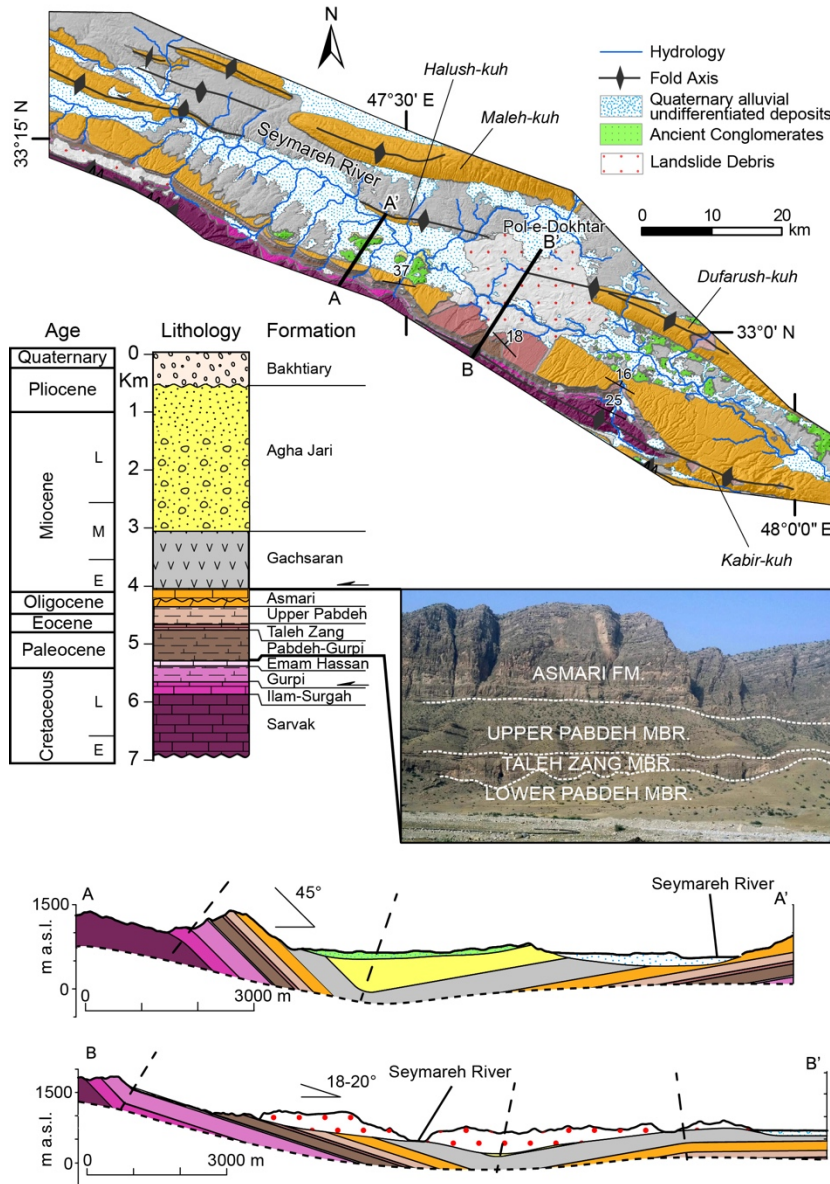
“The Seymareh Landslide detached ~10 ka from the northeastern flank of the Kabir-kuh fold (Zagros Mts., Iran), is recognized worldwide as the largest rock slope failure (44 Gm<sup>3</sup>) ever recorded on the exposed Earth surface. Detailed studies have been performed that have described the landslide mechanism and different scenarios have been proposed for explaining the induced changes in landscape. The purpose of this study is to provide still missing time constraints to the evolution of the Seymareh River valley, before and after the emplacement of the Seymareh Landslide, to highlight the role of geomorphic processes both as predisposing factors and as response to the landslide debris emplacement.

We used optically stimulated luminescence (OSL) to date lacustrine and fluvial terrace sediments, whose planometric distribution has been correlated to the detectable knickpoints along the Seymareh River longitudinal profile, allowing the reconstruction of the evolutionary model of the fluvial valley. We infer that the knickpoint migration along the main river and the erosion wave propagated upstream through the whole drainage network caused the stress release and the ultimate failure of the rock mass involved in the landslide. We estimated that the stress release activated a Mass Rock Creep (MRC) process with gravity-driven deformation processes occurring over an elapsed time-to-failure on the order of 10<sup>2</sup> ky. We estimated also that the Seymareh damming lake persisted for ~3500 years before starting to empty ~6.6 ka due to lake overflow. A sedimentation rate of 10 mm y<sup>-1</sup> was estimated for the lacustrine deposits, which increased up to 17 mm y<sup>-1</sup> during the early stage of lake emptying due to the increased sediment yield from the lake tributaries. We calculated an erosion rate of 1.8 cm y<sup>-1</sup> since the beginning of the landslide cut by Seymareh River, which propagated through the drainage system up to the landslide source area. The evolutionary model of the Seymareh River valley can provide the necessary constraints for future stress-strain numerical modeling of the landslide slope to reproduce the MRC and demonstrate the possible role of seismic forcing in anticipating the time-to-failure for such an end-member case study.”

8. I also recommend that the authors think carefully about the figures. Fig 5 for example does not seem to really present the information being presented, figure 16 is impossible to understand, Figure 11 needs annotation, Fig 7 is too complex to understand in its current form.

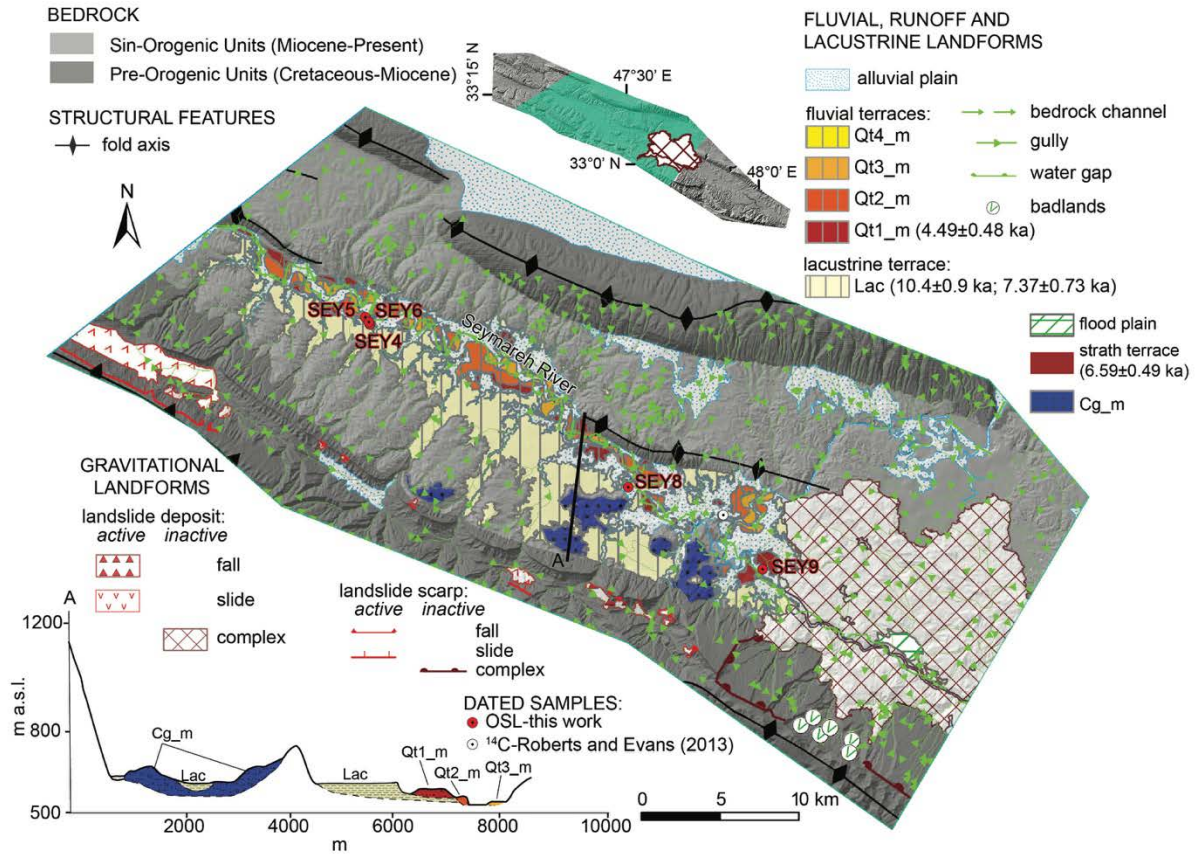
8. We agree.

8. We revised Fig. 5 (new Fig. 2), removing the section C-C' and including the photo of the outcropping stratigraphy of Fig. 13. Fig. 16 (new Fig. 12) was implemented information for a better interpretation. Fig. 7 (new Fig. 6) was improved increasing the text size. We do not understand what kind of annotation is needed in Fig. 11.



5

**Figure 2: Geological Map, stratigraphic column and cross sections of the study area.**



5 **Figure 6: Map of the lacustrine and alluvial terrace suite and of the most significant landforms for the valley slope evolution upstream of the SL.**

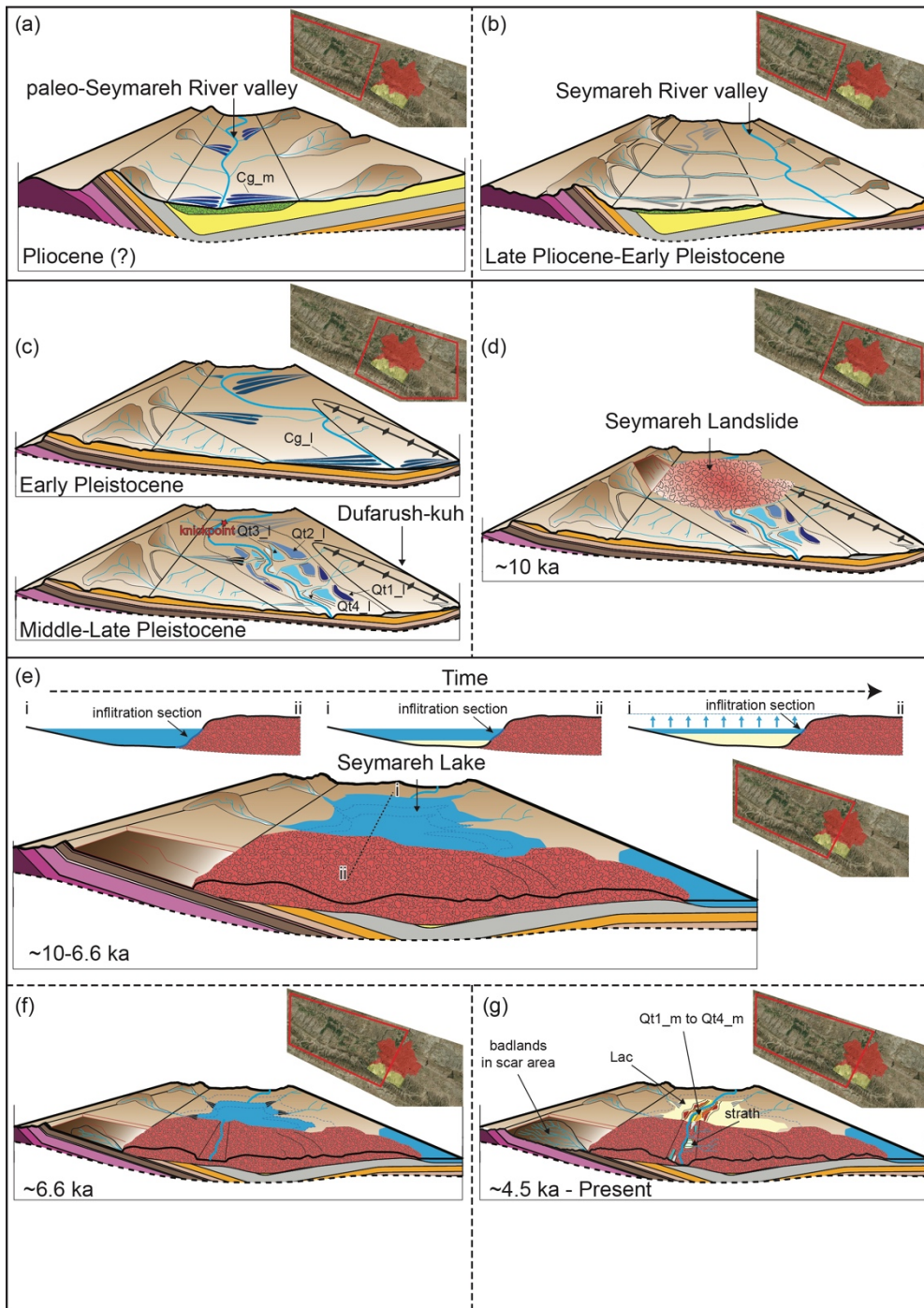


Figure 12: Evolutionary model of the Seymareh River valley. See text for explanation. Traces and legend of geological cross-sections are reported in Fig. 2.



# EDITORIAL CERTIFICATE

This document certifies that the manuscript listed below was edited for proper English language, grammar, punctuation, spelling, and overall style by one or more of the highly qualified native English speaking editors at American Journal Experts.

## Manuscript title:

New constraints to river valley evolution before and after the emplacement of the largest landslide on emerged Earth surface: the Seymareh rock slide - debris avalanche (Zagros Mts., Iran)

## Authors:

Michele Delchiaro, Marta Della Seta, Salvatore Martino, Maryam Dehbozorgi, Reza Nozaem

## Date Issued:

April 24, 2019

## Certificate Verification Key:

A83A-E037-B9A8-6291-476D



This certificate may be verified at [www.aje.com/certificate](http://www.aje.com/certificate). This document certifies that the manuscript listed above was edited for proper English language, grammar, punctuation, spelling, and overall style by one or more of the highly qualified native English speaking editors at American Journal Experts. Neither the research content nor the authors' intentions were altered in any way during the editing process. Documents receiving this certification should be English-ready for publication; however, the author has the ability to accept or reject our suggestions and changes. To verify the final AJE edited version, please visit our verification page. If you have any questions or concerns about this edited document, please contact American Journal Experts at [support@aje.com](mailto:support@aje.com).

# New ~~insights on~~ constraints to river valley evolution before and after the ~~predisposing factors and geomorphic response to~~ emplacement of the largest landslide on ~~emerged~~ the exposed Earth surface: the Seymareh ~~rock slide~~ rockslide - debris avalanche (Zagros Mts., Iran)

5 Michele Delchiaro<sup>1</sup>, Marta Della Seta<sup>1</sup>, Salvatore Martino<sup>1</sup>, Maryam Dehbozorgi<sup>2</sup>, Reza Nozaem<sup>3</sup>

<sup>1</sup>Department of Earth Sciences, Sapienza University of Rome, Rome, Italy

<sup>2</sup>Department of Earth Science, Kharazmi University, Tehran, Iran

<sup>3</sup>School of Geology, College of Science, University of Tehran, Iran

10 *Correspondence to:* Michele Delchiaro ([michele.delchiaro@uniroma1.it](mailto:michele.delchiaro@uniroma1.it))

**Abstract.** The Seymareh ~~landslide~~ Landslide, detached ~10 ka from the ~~north-eastern~~ northeastern flank of the Kabir-kuh fold (Zagros Mts., Iran), is ~~worldwide~~ worldwide as the largest ~~massive~~ rock slope failure (44 Gm<sup>3</sup>) ever recorded on the ~~emerged~~ exposed Earth surface. ~~Understanding the hazard conditions and the risk associated to this out-of-scale event would provide important pin points for risk mitigation strategies in case of extreme landslide scenarios. Controversial theories~~ Detailed   
15 studies have been ~~proposed so far by the scientific community to explain the generation of such an exceptional event~~ performed   
that have described the landslide mechanism and different scenarios have been proposed for explaining the induced changes   
~~of~~ in landscape. ~~This~~ The purpose of this study ~~provides new~~ is to provide still missing time constraints to the evolution of the   
Seymareh ~~river~~ River valley, before and after the emplacement of the Seymareh ~~landslide occurrence~~ Landslide, to ~~correctly~~   
~~identify~~ highlight the role of geomorphic processes both as predisposing factors, ~~to suggest possible triggers and deduce the~~   
20 geomorphic and as response to the ~~slope failure~~ landslide debris emplacement.

We ~~performed detailed geological and geomorphological surveys and mapping of the Seymareh valley and dated with~~ used   
optically stimulated luminescence (OSL) ~~two suites of fluvial terraces (one older and one younger than the Seymareh landslide)~~   
~~as well as a~~ to date lacustrine and fluvial terrace ~~(formed after the temporary landslide damming), as useful geomorphic markers~~   
~~of the valley evolution. River profile metrics showed the evidence of a transient landscape and the~~ sediments, whose plano-   
25 altimetric distribution ~~of the geomorphic markers~~ has been correlated to the detectable knickpoints along the Seymareh   
~~river~~ River longitudinal profile. ~~We thus provide time constraints to the main~~, allowing the reconstruction of the evolutionary   
~~stages of~~ model of the fluvial valley. We infer that the knickpoint migration along the main river and the erosion wave   
propagated upstream through the whole drainage network caused the stress release and the ~~valley before and after the~~   
~~emplacement of the landslide, to be used as inputs for future stress strain time dependent numerical modelling in the~~   
30 ~~perspective of calibrating the~~ ultimate failure of the rock mass ~~viscosity and verifying the possible earthquake trigger~~ involved   
in the landslide. We estimated that the stress release activated a Mass Rock Creep (MRC) process with gravity-driven   
deformation processes occurring over an elapsed time-to-failure on the order of 10<sup>2</sup> ky. We estimated also that the Seymareh

damming lake persisted for ~3500 years before starting to empty ~6.6 ka due to lake overflow. A sedimentation rate of 10 mm y<sup>-1</sup> was estimated for the lacustrine deposits, which increased up to 17 mm y<sup>-1</sup> during the early stage of lake emptying due to the increased sediment yield from the lake tributaries. We calculated an erosion rate of 1.8 cm y<sup>-1</sup> since the beginning of the landslide cut by Seymareh River, which propagated through the drainage system up to the landslide source area.

- 5 The evolutionary model of the Seymareh River valley can provide the necessary constraints for future stress-strain numerical modeling of the landslide ~~as an ultimate scenario of ongoing mass rock creep processes,~~ slope to reproduce the MRC and demonstrate the possible role of seismic forcing in anticipating the time-to-failure for such an end-member case study.

10

## 1 Introduction

Tectonically active landscapes are very dynamic systems, ~~where in which~~ threshold conditions on hillslopes are often reached, ~~with.~~ Therefore, there are considerable implications for natural hazards related to seismicity and to the geomorphic coupling between hillslopes and rivers, with both fluvial control on hillslopes and landslide ~~effects on~~ affecting the fluvial network. In response to rock uplift, relief and hillslope angles increase linearly in time due to erosional processes in landscapes affected by low to moderate tectonic forcing (Montgomery and Brandon, 2002; Binnie et al., 2007; Larsen and Montgomery, 2012). Nonetheless, such a linear increase in relief and hillslope angles is limited by the reaching ~~of the~~ threshold slope conditions associated ~~to~~ with the hillslope material strength (Schmidt and Montgomery, 1995), until the latter is exceeded by gravitational stress giving rise to bedrock landslides. This leads to a nonlinear increase ~~of in~~ erosion rates in landscapes affected by long-  
15 lasting or high-rate tectonic forcing, where the increase in the rate of channel incision is accommodated by an increased frequency of slope failure rather than by slope steepening. These slope failures may represent the ultimate conditions of mass rock creep (MRC; Chigira, 1992) processes contributing to the development of gravity-driven deformations due to time-dependent rheology. This kind of deformations can evolve into generalized failure and slope collapse when the increased strain rate leads to an accelerating deformation. The strain limit conditions are reached when the stationary creep stage evolves into  
20 the accelerating creep stage. Failure is typically associated with mass strength reduction as an effect of rock mass damage occurring over time during the ongoing gravity-driven deformations (Eberhardt et al., 2004; Stead et al., 2006). The ultimate collapse for MRC leads to rock avalanches originating from the instantaneous fragmentation of rock masses (Hungr et al., 2001).

~~A vast literature exists on earthquake induced landslides in tectonically active regions, which is mainly focused on predictive models, based on empirical co-relations derived from databases collected worldwide (Keefer, 1996; Rodriguez et al., 1999; Li et al. 2004; Owen et al. 2008; Delgado et al., 2011; Hovius et al., 2011; Parker et al., 2011; Jibson and Harp, 2012; Malamud et al., 2014; Martino et al., 2014; Mare et al., 2017), for depicting the expected distribution of the effects. On the other hand,~~

30



~~few~~ This work is focused on the evolution of the Seymareh River valley before and after the valley was dammed by the landslide worldwide recognized as the largest subaerial rock landslide ever observed, the Seymareh rockslide – debris avalanche that occurred in the northwestern Zagros Mts. (Iran). Different interpretations have been proposed so far by the scientific community to explain the generation of such an exceptional event and different scenarios have been hypothesized for explaining the induced changes in landscape. Harrison and Falcon (1937, 1938) provided much of the present knowledge on the rock avalanche, including the geology and structure of the source area, the general geomorphology and the basic geometry of the landslide. Oberlander (1965) included a short appendix on the landslide in his study of Zagros streams and discussed its origin in relation to the activity of Seymareh River. Later, in the 1960s, Watson and Wright (1969) characterized the geomorphology and stratigraphy of the debris, discussed the origin of the initial rockslide, and examined the debris avalanche emplacement mechanisms. Roberts (2008) and Roberts and Evans (2013) provided a detailed model of how the geological and tectonic evolution of the Kabir-kuh fold predisposed the slope to such a large-scale failure, including formation of structural/kinematic and rheological control, and inferred a seismic trigger. Specifically, Roberts and Evans (2013) obtained from a charcoal-rich layer approximately 15 m above the base of the lacustrine sequence with a  $^{14}\text{C}$  age of 8710 years BP. Based on the interpretation of three separate radiocarbon ages provided additionally by Griffiths et al. (2001) an estimated radiocarbon bracket age of the Seymareh event was suggested between 9800–8710  $^{14}\text{C}$  years BP. Yamani et al. (2012) provided some general details on the evolution of the dam lake drainage, describing a sequence of entrenched lacustrine terraces upstream of the landslide dam. Finally, Shoaie (2014) reviewed the possible mechanisms of failure and interpreted the post-failure geomorphic features through analyzing the processes responsible for the formation and erosion of the landslide dams of the Seymareh, Jaidar and Balmak (called also Chah Javal) lakes by using available annual sedimentation data and field measurements of the deposits in these lakes.

Despite the number of scenarios proposed so far, quantitative constraints on the river valley evolution before and after the emplacement of this giant landslide are still missing, which could help in quantitatively modeling the trigger scenario of this end-member case study of massive rock slope failures. In this regard, recently, some works (Bozzano et al., 2012, 2016; Della Seta et al., 2017; Martino et al., 2017) have focused on the role of landscape evolution rates on the development of ~~gravitational slope deformations driven by time dependent rheology, known as Mass Rock Creep (MRC; Chigira, 1992). This kind of deformations can evolve into massive failure due to generalized slope collapse when the increased strain rate leads to progressive failure associated to strength reduction (Eberhardt et al., 2004; Stead et al., 2006).~~ MRC processes. Among these, Bozzano et al. (2016) demonstrated that ~~These collapses lead to rock avalanches originating from the instantaneous fragmentation of rock masses (Hungr et al., 2001) which reach the limit strain conditions when the stationary creep stage evolves in the accelerating creep one. Massive rock slope failures have been widely documented in tectonically active regions and in most cases only speculatively interpreted as earthquake induced landslides. However, the deformations reached within a rock mass result from a combination of stress conditions and strain rates, both depending on the shape and dimensions of slopes as well as on the time available for creep evolution. In this perspective, as demonstrated by Bozzano et al. (2016),~~ erosion rates play a key role in the development of MRC processes within the rock masses and, consequently, in their possible

evolution into massive rock slope failures, even without invoking transient external forcing (e.g., earthquakes). Furthermore, evidence of giant rock slides due to MRC that caused valley river damming have been recently documented by Zhao et al. (2019) in the Sichuan; these rockslides are related to the effects of river knickpoint propagation and inner gorge formation and serve as a further confirmation of the combined role played by the fluvial dynamics and the geological structural setting.

5 To infer a more suitable evaluation of the elapsing time for failure in creep evolving slopes, a multi-modelling approach was recently proposed (Martino et al., 2017), in which Quaternary ~~This work is aimed at filling the knowledge gap in landscape evolution modelling of slope to valley floor systems plays a key role as a tool for chronological constraints to the creep evolution of entire slopes (Bozzano et al., 2016; Della Seta et al., 2017).~~ On one hand, such a modelling can highlight the presence of gravity induced instability affecting slopes in different evolutionary stages; on the other hand, it allows to reconstruct the timing of the variation of interesting valley sections, thus providing important chronological constraints for the engineering geological and numerical stress-strain modelling of slopes, through the plano-altimetric analysis and the dating of geomorphic markers, to be correlated to the anomalies in river longitudinal profiles.

This methodological approach is here applied for the first time to define the evolution associated with the emplacement of the Seymareh river valley (Lorestan, Iran), before and after this was dammed by the landslide internationally recognized as the largest subaerial rock landslide ever observed. Different evolutionary scenarios were proposed for the Seymareh landslide detached from the anti-form Kabir kuh fold of the External Zagros Mountains. ~~Harrison and Falcon (1937, 1938) provided much of the present knowledge on the rock avalanche, including the geology and structure of the source area, the general geomorphology and the basic geometry of the landslide. Oberlander (1965) included a short appendix on the landslide in his study of the Zagros streams and discussed its origin in relation to the activity of the Seymareh River. Later in the 1960s, Watson and Wright (1969) characterized the geomorphology and stratigraphy of the debris, discussed the origin of the initial rock slide, and examined the debris avalanche emplacement mechanisms. Roberts (2008) and Roberts and Evans (2013) provided new insight into the role of geological factors in defining the original rock slide mass, the detachment mechanisms of the initial rock slide, and the geomechanical behaviour of the rock units involved. Moreover, these papers reported a radiocarbon age that dated back the occurrence of the rock avalanche at 9800 <sup>±</sup>4C years BP. Yamani et al. (2012) provided a new interpretation of the Seymareh landslide emplacement mechanism, in which a sequence of landslide events would be testified by a sequence of entrenched lacustrine terraces upstream of the landslide dam. Finally, Shoaie (2014) reviewed the possible mechanisms of failure and interpreted the post failure geomorphic features, analyzing the processes responsible for the formation and erosion of the landslide dams of the Seimareh and Jaidar lakes, by using available annual sedimentation data and field measurements of the deposits in these lakes.~~

30 This study aims at better understanding the predisposing factors, the geometry, the effects and the hazard conditions associated to the Seymareh landslide, which can be considered as exemplary for providing important pin-points to risk mitigation management strategies in case of extreme landslide events. In particular, a revision of the stratigraphic column and some significant geological cross-sections have been performed along the Kabir kuh Fold, to provide new insights on the geo-structural predisposing factors of the landslide. Furthermore, a detailed mapping, plano-altimetric analysis and dating of

the Landslide (hereafter referred to as SL). Detailed geomorphological mapping, correlation and dating of certain geomorphic markers (Burbank and Anderson, 2012), represented by fluvial and lacustrine terraces pre- and post-failure event, have been performed upstream and downstream of the landslide dam, in order to better constrain provide new time constraints to the geomorphological Seymareh River valley evolution and to outline the role of the geomorphic processes both as predisposing factors for MRC processes and the geomorphic as response to the landslide emplacement. this giant gravitational instability.

## 2 Regional geological and geomorphological framework

The Seymareh landslide detached from the north-eastern flank of the Kabir-kuh fold, the longest anticlinal of the Zagros fold-thrust belt, in the south-western part of Iran (e.g., Sepchr and Cosgrove, 2004). The Zagros chain stretches out from the Tauern Mountains in south-eastern Turkey to south-western Iran, ending near the Strait of Hormuz. It reaches a maximum height of 4548 m in the province of Khuzestan, in the north-western part of Iran, and extends for 2000 km from the Anatolian fault in eastern Turkey (45 ° E, 36 ° E) to the subduction zone of Makran in the south of Iran (26 ° N, 58 ° E) (Mouthereau et al., 2012). The SL detached from the northeastern flank of the Kabir-kuh fold, the largest and highest anticline in the Pusht-e Kuh arc, in the northwestern part of Iran (Vergés et al., 2011). The Zagros mountain range is part of the Alpine-Himalayan orogenic system that originates from the Late-Cretaceous-Cenozoic convergence between Africa/Arabia-Eurasia (Talbot and Alavi, 1996; Stampfli and Borel, 2002; Golonka, 2004; McQuarrie, 2004); Mouthereau et al., 2012). The Zagros were orogen was traditionally classified by distinctive lithological units and structural styles into four NW trending tectono-metamorphic and magmatic belts (Fig. 1). These are bounded by defects on a regional scale such as the Main Zagros Thrust (MZT), High Zagros Fault (HZF) and Mountain Front Fault (MFF) (Agard et al., 2005 and references therein). These tectonic units are from the inside inner to the outside outer sectors of the belt are: the Urumieh Dokhtar volcanic arch, the Sanandaj-Sirjan Zone, the Imbricate Zone, the Zagros (or Simply) folded belt and the continental Mesopotamian Foreland (Fig. 1). Agard et al. (2005) consider the Main Zagros Thrust (MZT) that separates the Sanandaj-Sirjan area from the Imbricate Zone as the Zagros suture (Fig. 1). The Sanandaj-Sirjan zone represents the accretionary prism of the Arabian margin of the Zagros orogen in which metamorphosed Paleozoic to Mesozoic sedimentary rocks mainly crop out (Mohajjel and Fergusson, 2000 and references therein). Also, calc-alkaline Jurassic to Early Eocene intrusions occur in the tectonic domain. The southwestward boundary between the Sanandaj-Sirjan zone and the Imbricate zone is defined by the Main Zagros Thrust (MZT). Imbricated tectonic sheets involving radiolarite ophiolite complexes, Mesozoic and Cenozoic sedimentary and volcanic rocks compose the Imbricate Zone, or High Zagros, which is defined as the innermost deformed part of the Arabian plate. The southwestward boundary between the Imbricate zone and the Simply Folded Belt is defined by the High Zagros Fault (e.g., Agard et al., 2005). The Seymareh Landslide occurred in the latter tectonic domain, included between the High Zagros Fault (HZF) to the northeast and the Mountain Front Fault (MFF) to the southwest. The Simply Folded Belt involve in spectacular folds the 12–14 km thick sedimentary rocks of the Arabian margin succession covering the continental basement (e.g., McQuarrie, 2004 and references

therein). The irregular geometry of the MFF that bounds the Simply Folded Belt southwestward from the Mesopotamian foreland basin, describes salients and reentrants (McQuarrie, 2004; Sepehr and Cosgrove, 2004): respectively, from northwest to southeast, the Pusht-e Kuh Arc (Lorestan), the Dezful Embayment, the Izeh Zone and the Fars Arc (Fig. 1). A representative balanced cross section of the Dezful embayment (Blanc et al., 2003) indicates ~49 km of shortening across the Simple Folded Zone. Homke et al., 2004 provide the dates of 8.1 and 7.2 Ma for the onset of the deformation in the front of the Push-e-Kush Arc (related to the base of the growth strata observed in the NE flank of the Changuleh syncline) that lasted until 2.5 Ma, around the Pliocene-Pleistocene boundary. A long-term shortening rate of ~10 mm y<sup>-1</sup> was derived for the deformation in the Simple Folded Zone, which is the same as the present-day one derived by GPS measurements (Tatar et al. 2002).

Seismicity is distributed in a 200-300 km wide area of the Zagros mountain range (Hatzfeld et al., 2010, Paul et al., 2010, Rajabi et al., 2011), with a sharp cut along the Main Zagros Reverse Fault in NE. Looking at the depth and magnitude of recent earthquakes (Fig. 2), the seismogenic faults can generate the NE (e.g., Yamini-Fard et al., 2016), with recurrent earthquakes of Mw 5-6 and exceptional earthquakes of higher magnitude, i.e., up to Mw 6-8. These seismogenic faults follow the general trend of the Zagros, having NW-SE direction in the northwestern portion of the chain, while in the southeastern part they assume an E-W trend; they are characterized by high angle planes (40-50°) reaching depths between 4 and 19 km (Hatzfeld et al., 2010; Paul et al., (see supplementary material). The SL 2010, Rajabi et al., 2011). The earthquakes, which originate at a variable depth of 12-19 km, are probably located in the crystalline basement or at the interface with the Cambrian-Pliocene cover, whose thickness reaches about 12 km. The shallowest earthquakes, located at 4-8 km of depth, are located inside the sedimentary cover and, in general, these events do not produce surface ruptures, probably due to the presence of marly and evaporitic levels that accommodate the deformation (Hatzfeld et al., 2010; Leturmy and Robin, 2010; Navabpour et al., 2010; Paul et al., 2010; Saura et al., 2011).

The Seymareh landslide occurred in a very densely seismic/seismically active area, so that and recurrence rate of nearby strongly felt earthquakes considerably higher than the rate of slope steepening led Roberts and Evans (2013) hypothesized to hypothesize that seismic forcing may have played a primary role in triggering the landslide.

### 3 Geomorphological background

The outcropping formations in the Kabir-kuh anticline date to a time interval ranging from the Late Cretaceous to the early Miocene and are characterized by different lithological and rheological properties (Vergés et al., 2011). Since the geo-structural setting of the fold flanks represented a crucial predisposing factor for the catastrophic massive rock slope failure (Roberts and Evans, 2013), we referred to the most detailed stratigraphic column proposed by James and Wynd (1965), Alavi (2004) and to the detailed mapping of the Kabir-kuh fold conducted by the Iran Oil Operating Companies (Setudehnia and Perry 1967; Takin et al. 1970; Macleod 1970). Specifically, the investigated area includes the middle and low reaches of Seymareh River starting approximately 60 km upstream of the SL down to the SE termination of the Kabir-kuh fold. In Fig. 2, the geological map of the study area, the stratigraphic column and two geological cross-sections related to different structural sectors are reported.

It is noteworthy that, in the Kabir-kuh anticline, the Pabdeh Formation is composed of three rheologically contrasting members, which crop out in the SL scar area: i) the lower Pabdeh member (150 m thick), which is dominated by marls and shales, ii) the Taleh Zang member (50 m thick), consisting of platform limestone, and iii) the upper Pabdeh member (150 m thick), composed mainly of calcareous marl. The Asmari Formation creates a carapace originally covering the top of the Kabir-kuh fold, while in the synclinal valleys between the Kabir-kuh fold and the adjacent folds, the Asmari Formation is overlapped by a Miocene-Pliocene succession (Homke et al., 2004). Referring to the Changuleh syncline studied by Homke et al. (2004), the foreland stratigraphy includes the following: i) the Gachsaran Formation (early Miocene - 12.3 Ma, thickness approximately 400 m), composed of salt, anhydrite, marl and gypsum; ii) the Agha Jari Formation (12.3 Ma – 3 Ma., thickness approximately 1400 m); and iii) the Bakhtiari Formation (3 Ma – early Pleistocene, thickness approximately 900 m). The Agha Jari Formation consists of sandstones and conglomerates, linked to the evolution from deltaic to fluvial transitional environments (Elyasi et al., 2014), and the Bakhtiari formation consists of conglomerates characterized by coarse and mud-supported grains, sandstones, shales and silts and marks the onset of syn-orogenic fluvial environment conditions (Shafiei and Dusseault, 2008). The reported cross-sections intersect the synclinal valley of the Seymareh River. The dip angle of the northeastern flank of the syncline considerably decreases from NW to SE from 45° (section A-A') to 18-20° (section B-B'). Therefore, along the section A-A' the Cretaceous-Paleogene bedrock (from the Sarvak Formation to the Asmari Formation) offers a greater accommodation volume to the continental and epicontinental formations (Gachsaran Formation and Agha Jari Formation), as the synclinal axis is located at a lower elevation than in the B-B' section.

The Zagros Range globally provides one of the most spectacular examples of landscape evolution in response to active tectonics (Borne Bourne and Twidale, 2011), since because its drainage network clearly adapted to the growth of the thrust-fold structures, also in relation with (Ramsey et al., 2008) and to the erodibility of the outcropping formations (Oberlander, 1985).

~~Several landscape evolution models have been carried out to explain the drainage history of the Zagros in association with tectonic deformation of the area. One of the most famous models was suggested by Oberlander (1968, 1985), who interpreted the transverse rivers cutting the structural highs NE of Dezful as a consequence of the regional stratigraphy. His observations focused on the 'tangs' of the Dezful Zagros. The tangs are steep, narrow gorges cut by rivers transverse to the fold length, often through the highest structural and topographic part of the anticline crests. Oberlander suggested that the morphology of the gorges varied from V-shaped valleys in the older northern parts of the mountain belt, to slot like canyons in the Simple Folded Belt, the present-day focus of deformation. He believed that the pattern was repeated too often to be by chance, and that previous explanation for transverse drainage formation (e.g. that the rivers are antecedent to the structure) did not account for the close proximity of the tangs to the anticline structural highs. Oberlander (1968) suggested that the drainage network in the NW Zagros was instead superimposed from structurally conformable younger horizons. In his model, the breaching of hard geological units of the antiformal ridges follows a phase of river cutting and expansion of the fold axial fold basins through the softer overlying units. This is cyclical, according to the alternating "mobile" and "competent" units in the Zagros fold stratigraphy. In the Kabir-kuh fold of the simply folded belt of Lorestan, the transverse cutting of the Asmari limestone,~~

and the exposure of the underlying ~~easily~~more erodible Pabdeh-Gurpi marls, ~~results in~~leads to the formation of a low-relief landscape with synformal ridges on which the new through-going drainage system can be developed. ~~These new drainage systems are then superimposed on the Mesozoic Bangestan limestone as it is exhumed by continued fold growth.~~ In Oberlander's hypothesis, it is the Pabdeh and Gurpi marls that facilitate the creation of a low-relief landscape across the anticline crests and are therefore integral to the story of drainage superimposition. ~~However, the deep-marine Pabdeh marls, which are sandwiched between the Asmari and Bangestan limestones, grade southeastward into the dolomitic, sabkha-type Jahrum limestone (Sepehr and Cosgrove, 2004; Sherkati et al., 2005). As such, a significant thickness of soft, easily erodible sediment is not present in Fars province, where the development of a low-relief landscape on which to generate new through-going drainage systems evolves in response to folding in hard and resistant lithologies. Lateral variations in stratigraphy are thus shown to exert a major control on the patterns of drainage, and hence sedimentation, at a regional scale. It is likely that, moving westwards through the Zagros, the gradually increasing thickness of the soft Pabdeh marls can be the cause for a gradual transition towards the type of landscape described by Oberlander (1968, 1985) in Dezful.~~ Ramsey et al. (2008) proposed an alternative model that considers the response of drainage network to active folding. They suggested that the rivers are diverted around the tips of laterally growing anticlines until the merger of individual fold segments becomes important in forcing drainage evolution. Fold segmentation, lateral growth and linkage has profound importance on the development of through-going drainage and sedimentation patterns in the Fars province of the Zagros. In the absence of independent constraints on the timing of landscape evolution, Ramsey et al. (2008) described the fan-shaped tributary patterns on fold flanks and other geomorphological features (such as wind gaps and water gaps, deflection of rivers parallel to anticline axes and trapping of rivers between fold tips) as indicators of drainage evolution in the present day landscape. In the less uplifted areas of the chain, the initial stages of cross-river evolution are still ongoing, and this makes it possible to formulate ergodic models for landscape evolution, also in relation to the fundamental role that stratigraphy plays in the development of transverse drainage in uplifting chains. Tucker and Slingerland (1996) computed a numerical landscape evolution model, calibrated on the Kabir-kuh fold, to understand how the growth and propagation of the folds, the different lithologies and the drainage network can influence the sediment flux from a tectonically active belt towards the foreland basin. The authors calibrated the landscape evolution model with the current topography of the range, obtaining time constraints for landscape evolution modeling. According to the Oberlander model, Fig. 3 shows four main steps ~~to~~that describe the landscape evolution of the Kabir-kuh fold with the timing provided in the model by Tucker and Slingerland (1996).

Step 1 - ~~About~~Approximately 4.3 Ma, in response to the initial stages of fold growth, an orthoclinal drainage develops, parallel to the main structures. The tributaries flowing along the flanks of the folds transport debris, which is deposited in the synclines. In the Kabir-kuh fold the carbonate core is still buried by the Miocene cover units.

Step 2 - ~~About~~Approximately 3.8 Ma, as soon as the deformation front migrates towards the SW, new folds raise with a progressive adjustment of the drainage to these morpho-structures. The previously deposited sediments are remobilized and transported towards the depocenter of the syncline basins and partly outside; the syn-orogenic deposits are strongly eroded

along the crests of the anticlines, thus exposing the underlying formations. This causes a topography characterized by resistant hogbacks that ~~border~~flank the inner cores.

Step 3 - ~~About~~Approximately 2.4 Ma, with the ongoing ~~of~~ deformation, the drainage develops in a “trellis” pattern. The river erosion affects the erodible units located stratigraphically between the limestone of the Asmari ~~formation~~Formation and the inner core of the fold. At the end of this step the Miocene cover is completely removed from the ridges and the river erosion also affects the marls and evaporites of the syn-orogenic formations in the valleys, exposing the underlying limestone of the Asmari ~~Fm~~Formation.

Step 4 - ~~About~~Approximately 1.6 Ma, due to the continuous uplift and exhumation of younger, more external folds, the sediment accumulation becomes negligible and the Asmari limestone is strongly eroded giving rise to syncline ridges. The following Quaternary landscape evolution is then likely driven by the evolution of the drainage network, and is also influenced by climatic factors, and by the slope-to-channel dynamics.

The model by Tucker and Slingerland (1996) is the unique numerical model existing on the Kabir-kuh fold and this motivates our choice of using it as a reference for the medium-to-long term evolution of the Seymareh ~~river~~River valley. The Seymareh ~~river~~River valley is arranged parallel to the Kabir-kuh fold and its evolution was inevitably influenced by the exceptional landslide event that temporarily dammed it, causing the formation of the three-lake system which includes the Seymareh, Jaidar and Balmak lakes (Fig. 4). The valley evolution before and after the event is well recorded by Quaternary landforms preserved along the valley. Yamani et al. (2012) focused on the post-failure evolution of the valley and interpreteddescribing four levels of terraces upstream of the landslide ~~dam~~dams as a sequence of lacustrine terraces ~~formed in response to a sequence of landslide events~~. Shoaie (2014), in addition to evaluating the longevity of the ~~Seymareh landslide~~SL dams, identified in the merging of Seymareh River with a left tributary as the reason for strong river incision at the base of the ~~north-eastern~~northeastern flank of the Kabir-kuh fold and as a possible causal factor for the ~~Seymareh landslide~~SL collapse. However, none of the previous ~~study~~studies on the Quaternary evolution of the Seymareh ~~river~~River valley ~~neither~~ provided absolute dating of ~~the~~ geomorphic markers (mainly fluvial terraces) preserved upstream but also as well as downstream of the landslide dam, ~~nor or~~ provided robust and quantitative constraints to the pre-failure valley evolution as a possible geomorphological factor for failure occurrence.

#### ~~4 Revised stratigraphic column and geological sections of Seymareh river valley~~

~~The Seymareh Landslide detached from the north-eastern flank of the anti-form Kabir-kuh fold into the Simply folded Zagros in the Lorestan region. The outcropping formations in the anticline area refer to a time interval ranging from the Upper Cretaceous to the Lower Miocene and are characterized by different lithological and rheological properties (Vergés et al., 2011). In this regard, Tucker and Slingerland (1996) referred to a 300 m thick resistant unit, corresponding to the Oligocene Asmari Limestone over a 1000 m thick weak unit corresponding to Campanian to Eocene flysch (Pabdeh-Gurpi Fm.), while,~~

Roberts and Evans (2013) referred to an involved section including: 225 m of limestone of the Asmari Fm., 525 m of marls of the Pabdeh Fm. and the upper part (50 m), mainly marls, of the Gurpi Fm. Since the geo-structural setting of the fold flanks could have been a crucial predisposing factor for the catastrophic massive rock slope failure, we revised the stratigraphic column and performed some geological sections of the Seymareh valley. Specifically, the investigated area includes the middle and low reaches of Seymareh River starting ~60 km upstream of the Seymareh landslide down to the SE termination of the Kabir kuh fold. In Fig. 5 the geological map of the Seymareh river valley is reported. At the base of the stratigraphic column there is the Sarvak Fm. (Cretaceous, thickness > 750 m) consisting of a thick carbonate unit that represents one of the largest reservoirs for hydrocarbons in Iran (Elyasi et al., 2014). At the top of the Sarvak Fm. there is the Ilam-Surgah Fm. (Upper Cretaceous, thickness about 250 m), consisting of limestone of transgressive regressive foredeep facies deposited in the pro-foreland basin (Elyasi et al., 2014). The Ilam-Surgah Fm. is limited at the top by Gurpi Fm. (Upper Cretaceous, thickness about 400 m) consisting of a marly limestone, marl and hemipelagic shales of deep marine facies associated to the progressive migration towards S of the pro-foreland areas, which are in unconformity with the Sarvak and in onlap with the Ilam-Surgah (Elyasi and Goshtasbi, 2015). Within the Gurpi Fm. it is possible to recognize a considerably more calcareous horizon called Emam Hassan Member (25 m thick). Above the Gurpi Fm. there is the Pabdeh Fm. (Upper Paleocene—Lower Oligocene, thickness about 350 m) consisting of hemipelagic pelagic calcareous shales (Elyasi and Goshtasbi, 2015). Specifically, a detailed study on this formation was performed on the stratigraphy outcropping along the north-eastern flank of the Kabir kuh fold, thus allowing the discrimination of several lithostratigraphic based members. The Pabdeh Fm. is composed of three members: 1) the lower Pabdeh member (150 m thick), which is dominated by marls and shales, 2) the Taleh Zang member (50 m thick), consisting of platform limestone, and 3) the upper Pabdeh member (150 m thick), composed mainly of calcareous marl. The succession is completed by the Asmari Fm. (Oligocene—Miocene, thickness about 200 m), which creates a carbonatic carapace originally covering the top of the Kabir kuh fold. The Asmari Fm. consists of alternating fossiliferous, massive, thinly stratified gray brown limestone, microcrystalline limestone, dolomitic limestone, and marly limestone (Khoshboresh, 2013). In the synclinal valleys between the Kabir kuh fold and the adjacent ones, the Asmari Fm. is overlapped by a Miocene-Pliocene succession (Homke et al., 2004). Referring to the Changuleh syncline studied by Homke et al., 2004, the latter foreland stratigraphy include: i) the Gachsaran Fm. (Late Lower Miocene—12.3 Ma, thickness about 400 m), composed of salt, anhydrite, marl and gypsum; ii) the Agha Jari Fm. (12.3 Ma—3 Ma., thickness about 1400 m); and iii) the Bakhtiari Fm. (3 Ma—Early Pleistocene, thickness about 900 m). More in particular, the Gachsaran Fm. consists of sandstones and conglomerates, linked to the evolution from deltaic to fluvial transitional environments (Elyasi et al., 2014) while the Bakhtiari formation consists of conglomerates characterized by coarse and mud-supported grains, sandstones, shales and silts and marks the onset of syn-orogenic fluvial environment conditions (Shafiei and Dusseault, 2008). Figure 5 shows also the revised stratigraphic column and three geological cross sections related to different structural sectors are reported. All the reported cross sections intersect the synclinal valley of the Seymareh River. Specifically, the dip angle of the syncline north-eastern flank considerably decreases from NW to SE from 45° (section A-A') to 18–20° (section B-B'), down to 5–15° (section C-C'). As a consequence, along the section A-A' the Cretaceous-Palaeocenic bedrock (from the Sarvak Fm. to the



Asmari Fm.) offers a greater accommodation volume to the continental and epicontinental formations (Gachsaran Fm. and Agha Jari Fm.), since the synclinal axis is located at a lower elevation than in B-B' and C-C' sections. For this reason, in this sector of the valley it is possible to observe extensive outcrops of the Agha Jari Fm.

From the topographic point of view, the section crossing the Seymareh landslide (B-B') shows about 1600 m of relief between the highest elevation of the carbonatic caprock outcrop of the reconstructed Asmari Fm. (about 2100 m a.s.l.) and the river bed elevation (449 m a.s.l.), which is considerably higher if compared to section A-A' (820 m) and C-C' (1180 m).

Moreover, along section A-A', the Seymareh river bed does not coincide with the syncline axis, as it is located northeastwards. In this regard, along this sector of the valley, terraced conglomerate deposits crop out extensively. Their geometry (section A-A' in Fig. 5) can be associated with alluvial fans generated on the flanks of a former synclinal valley, by streams likely being

the tributaries of a Paleo-Seymareh River whose path was to the SW of the present one. The absence of a kinematic release at the base of the hillslope and of a connectivity between the slope and valley floor evolutions imply that this sector is characterized by sliding phenomena mostly controlled by the structural arrangement of the flatiron slopes of the north-eastern flank of the Kabir kuh. The slope to valley floor interaction is evident in the B-B' and C-C' sections, where the river incised the carbonate caprock (Asmari Fm., section B-B') and, led to the formation of a canyon about 200 m deep in the Asmari Fm., although the latter is not yet completely released (section C-C').

## 5 Evolutionary analysis of the Seymareh valley

### 5.1 Methods

#### 3 Methods

The geomorphological study of the area was carried out ~~firstly~~first through the analysis and interpretation of remote sensing data ~~(, such as aerial photos and (National Cartographic Center of Iran, aerial photo, scale:1:20000, acquired on 24 August 1955), Google Earth satellite optical images)– (2018 Landsat Imagery) and~~ vector topographic maps (scale National Cartographic Center of Iran, topographic map of Kuhdasht, scale: 1:25,000), which led to the first detection of possible geomorphic markers within the Seymareh ~~river~~River valley, ~~to~~. Vector topographic data also allowed the construction of a ~~40m~~10 m Digital Elevation Model (DEM) for terrain analyses, and led to the projection of the possible geomorphic markers along the river longitudinal profile, (Wilson and Gallant; 2001; Burbank and Anderson, 2012). The DEM was obtained by ~~ArcGIS~~the ArcGIS 10@ software package, starting from vector topographic data ~~derived from literature~~(contour lines, hydrography and point elevation) and using the ANUDEM interpolation algorithm (Hutchinson et al., 2011 and references therein). ~~A~~To automatically extract the hydrographic network from the DEM and then to project the geomorphic markers along the longitudinal river profiles, some of the ArcGIS® 10 tools of the Hydrology toolbox were used (Flow Direction, Flow Accumulation, Reclassify, Stream Order and Stream to Feature), setting the flow accumulation threshold according to that proposed for the fluvial domain ( $10^{-1}$  km<sup>2</sup>) by Montgomery and Foufoula-Georgiu (1993). The longitudinal profile was

therefore transformed into a route along which the elevation of the top surfaces of geomorphic markers identified in the area were projected through the Linear Referencing Tools (Create Route and Locate Features along Route).

A geological and geomorphological field survey was then carried out with the aim of mapping the most significant active and relict landforms for the Quaternary evolution of the Seymareh River valley and of sampling the corresponding

5 lacustrine and fluvial deposits in order to date them with the OSL method (Optically Stimulated Luminescence; Murray and Olley, 2002; Wintle and Murray, 2006 and references therein). For each

OSL sampling is a very delicate and quite complex technique. In fact, it is absolutely necessary to prevent the sample from being exposed to light because the luminescence signal could be reduced or even reset. In choosing the most suitable site, we

10 sampled to sample, of course, levels were identified with original sedimentary structures, avoiding bioturbations and post-depositional alterations. Once the site for sampling was identified, it was important to carefully clean off the slope and prepare,

according to the state of thickening, consistency or cementation of the material, the equipment necessary for taking the sample, without it being exposed to light. Furthermore, to minimize the effects of cosmic radiation and to thereby avoid the risk of

rejuvenated ages, the samples were taken at a depth >1 m least one meter below the top depositional topographic surface (or the below eventual erosional surfaces recognized identified within the deposit to avoid the risk of rejuvenated ages. deposits).

15 All of the samples, mainly characterized by fine-grained loose sediments (size <2 mm) were taken directly by using a hammer to insert a metal tube into the ground, which must be isolated from light and humidity immediately after collection. To

maximize the uniformity of the natural radioactivity of the burial period, the sampled material was surrounded by at least 30 cm of homogeneous sediment. From the same level where it was sampled, an additional 500 - 800 g of sediment was extracted

20 to evaluate natural radioactivity (if the annual dose rate measurement is not performed in situ), for the mineralogical and granulometric analyses, as well as to determine the moisture content.

The OSL data where acquired at dating was performed by the LABER OSL Laboratory, in Waterville, Ohio (U.S.). Quartz was extracted for equivalent dose (De) measurements. In the OSL laboratory, the sample was treated firstly first with 10% HCl

and 30% H<sub>2</sub>O<sub>2</sub> to remove organic materials and carbonates, respectively. After grain-size separation, the fraction of 90-125 μm size is relatively abundant, so this fraction was chosen for De determination. The grains were treated with HF acid (40%)

25 for about approximately 40 min minutes to remove the alpha-dosed surface, followed by 10% HCl acid to remove fluoride precipitates. Luminescence measurements were performed using an automated Risø TL/OSL-20 reader. Stimulation was

carried out by a blue LED (λ=470±20 nm) stimulation source for 40 s at 130°C. Irradiation was carried out using a 90Sr/90Y beta source built into the reader. The OSL signal was detected by a 9235QA photomultiplier tube through a U-340 filter with

7.5 mm thickness. For De determination, the SAR protocol was adopted. The preheat preheating temperature was chosen to be

30 260°C for 10 s and the cut-heat is was 220°C for 10 s. The final De is the average of the Des of all aliquots, and the error of the final De error is the standard error of the De distribution. For each sample, at least 12 aliquots were measured for De

determination. The De was measured using SAR on quartz, and the aliquots that passed criteria checks were used for final De calculation.

Recycling ratios were between 0.90-1.1. ~~Recuperation is, and recuperation was~~ relatively small. The cosmic ray dose rate was estimated for each sample as a function of depth, altitude and geomagnetic latitude. The concentration of U, Th and K was measured by neutral activation analysis (NAA). The elemental concentrations were then converted into the annual dose rate, taking into account ~~of~~ the water content (lab measured) effect. The final OSL age is then: De/Dose-rate.

5 ~~In order to automatically extract the hydrographic network from DEM and then to project the geomorphic markers along the longitudinal river profiles, some of the ArcGIS 10 tools of the Hydrology toolbox were used, setting the flow accumulation threshold according to that proposed for the fluvial domain ( $10^+ \text{ km}^2$ ) by Montgomery and Foufoula-Georgiu (1993). The longitudinal profile was therefore transformed into a route along which the elevation of the top surfaces of geomorphic markers identified in the area were projected through the Linear Referencing Tools.~~

10 5.2

#### 4 Results

The best geomorphic markers preserved in the study area are represented by a lacustrine terrace and two suites of fluvial terraces, ~~which mark to~~. The suites are distributed both upstream and downstream of the landslide debris, marking the evolutionary stages of the valley, respectively, after and before and after the landslide emplacement. These markers are

15 ~~reported in the following list~~ Fluvial and lacustrine terrace deposits mainly consist of gravel, sand, silt and clay, and conglomerates outcropping immediately upstream and downstream of the landslide pertain to inactive alluvial fans connected to a relict position of the valley floor, likely of a paleo-Seymareh river.

~~In the middle reach of the Seymareh river~~ River valley, conglomerates (Cg\_m) pertaining to the upstream geomorphic markers include: inactive, terraced conglomeratic alluvial fans (Cg\_m), a terraced lacustrine deposit and a suite of four orders of fill terraces (named from Qt1\_m to Qt4\_m). The latter The geometry of the terraced conglomerates (section A-A' in Fig. 2) can be associated with alluvial fans generated on the flanks of a former synclinal valley by streams likely forming the tributaries of a paleo-Seymareh river whose path was to the SW of the present one. The fill terraces are entrenched in the terraced lacustrine deposit of Seymareh Lake upstream of the landslide, in the area where Harrison and Falcon (1938), Roberts and Evans (2013) and Shoaiei (2014) hypothesized the natural damming lake could be extended (Figs. 5 and 6). Prograding lacustrine fan deltas

25 formed by tributaries of Seymareh Lake have been recognized, which likely formed during the emptying phase of the lake. In this sector, we successfully dated 4 samples (SEY4, SEY5, SEY6, and SEY8; Table 1 and supplementary material): in particular the lacustrine deposit at two different stratigraphic levels, 560 and 590 m a.s.l., which provided OSL ages of 10.4±0.90 ka (sample SEY8) and 7.37±0.73 ka (sample SEY4), respectively. 6 and 7). Here we dated successfully 4 samples (SEY4, SEY5, SEY6, SEY8; Table 1 and supplementary material The OSL age of 17.9±1.50 ka (SEY6) obtained for an alluvial deposit at the base of the lacustrine deposits is coherent with the age of emplacement of the SL, as already inferred by Roberts and Evans (2013).

30 ~~A suite of 2 strath terraces and a flood plain shaped onto the landslide debris along the Seymareh river~~ River gorge have been identified (Figs. 87a and 40)7b), which are important markers of the evolution of the natural dam because they formed after

its cut likely due to an overflow of the damming lake. Here, we ~~dated~~ successfully dated one sample taken on a strath terrace (SEY9; Table 1 and supplementary material), which provided an age of 6.59±0.49 ka as time constrain for the initial stage of lake emptying.

5 ~~In the lower reach of the Seymareh river~~River valley, ~~conglomerates (Cg\_1) pertaining to the downstream geomorphic markers include:~~ inactive, terraced conglomeratic alluvial fans (Cg\_1) and a suite of four orders of fill terraces (named from Qt1\_1 to Qt4\_1) downstream of the Seymareh landslideSL (Figs. 97c and 108). Here, we ~~dated~~ successfully dated three samples from the fill terraces deposits (SEY3, SEY10, SEY11; Table 1 and supplementary material).

10 Fluvial ~~The ages obtained provide useful time constraints to the main depositional events during the pre-failure valley evolution. Minimum ages of 373±34 ka and lacustrine terrace deposits mainly consist of gravel, sand, silt~~312±45 ka have been obtained for samples SEY3 and clay, while conglomerates outcropping immediately upstream and downstream of the landslide ~~pertain to inactive alluvial fans connected to a relict position of the valley floor, likely of a Paleo-Seymareh River. The strath terraces and flood plain developed onto the landslide debris are important markers of the evolution of the natural dam~~SEY10, respectively, since they formed after its cut likely due to an overflow of the damming lake ~~these samples were saturated due to their low concentration of quartz grains, and SEY11 was dated at 60±5 ka.~~

15 The above-described geomorphic markers of the Seymareh ~~river~~River valley have been mapped and reported in morpho-stratigraphic profiles. The ~~landforms~~ most significant landforms for the valley ~~slopes~~slope evolution are ~~here~~ presented with a detail for the post-failure fluvial and lacustrine terrace suites upstream of the landslide dam (Fig. 76) and the pre-failure fluvial terrace suite downstream of the landslide dam (Fig. 108), respectively.

20 Figures 119 and 1210 report the longitudinal profile of Seymareh River, along which ~~were projected besides, in addition to the~~ geomorphic markers:

- a) ~~were projected also:~~ the benchmarks of the basal contact of the Quaternary deposits on the bedrock;
- b) ~~the projection of points corresponding to the top of the~~ Seymareh landslideSL debris;
- c) ~~the upstream and downstream limits of the landslide;~~
- d) ~~the location of the OSL sampling;~~
- 25 e) ~~and~~ the projection of the outcrop of the Bakhtiari Fm.Formation (Fig. 139), which is rarely preserved and marks the initial alluvial infill of the Seymareh River valley.

30 Figure 119 shows the height distribution of the pre-failure geomorphic markers. The benchmarks along the Seymareh River indicate a mostly bedrock channel, and the longitudinal profile is characterized by two knickpoints ~~respectively~~ located upstream of the Seymareh landslideSL and downstream of the lowest suite of alluvial terraces, as indicated by the black arrows. ~~The major knickpoint is~~ The geomorphic markers downstream and upstream do not belong to the same suite of terraces, as their projections along Seymareh River do not have any topographic correlation to each other (Fig. 9 and 10). The tops of all the fluvial terraces downstream of the SL are located lower in height than the most important knickpoint located immediately upstream and sculpted in the bedrock. Figure 10 shows the height distribution of the post-failure geomorphic markers. The markers are represented by: i) the horizontal lacustrine terrace formed by the incision of the deposits pertaining

to the Seymareh Lake, formed as a consequence of the landslide damming; ii) the two levels of the strath terraces and a flood plain formed on the landslide debris during the initial stages of dam cutting and emptying of the lake; and iii) the four fill terrace levels formed after the emptying of the Seymareh Lake.

The geomorphological field survey, supported by a remote survey based on optical satellite and aerial images, also allowed us to demonstrate the evidence of gravity-induced features of the downslope dipping strata, along the scar of the SL (Fig. 11). Clear evidence of MRC driving towards stress concentration and failure has been recognized in gravity-induced folding within the thin-layered Pabdeh Formation just below the sliding surface of the SL (i.e., that cannot be ascribed to parasitic structural folding). Furthermore, impressive buckling of the downslope dipping strata, which crop on the sliding surface of the SL, have been interpreted as a release of concentrated stresses due to the post-failure rebound caused by the collapsed rock mass.

## 5 Discussion

### 5.1 Constraints to pre-failure valley evolution

The longitudinal profile of the Seymareh River and the geomorphic markers preserved mainly downstream of the landslide and dam provided new constraints on the pre-failure valley evolution. The major knickpoint located immediately upstream of the SL is the most interesting to be analyzed in relation with respect to the landslide event. Its shape in the longitudinal profile clearly let us identify it as a “slope-break knickpoint” (Kirby and Whipple, 2012; Boulton et al., 2014), thus developed as a knickpoint migrating retreating in response to a persistent perturbation to the fluvial system (Tucker and Whipple, 2002), as frequently observed in tectonically active regions. Figures 11 and 12 show that the preserved geomorphic markers do not belong to the same suite of terraces, as their projections along the Seymareh River do not have each other any topographic correlation. The top of all the fluvial terraces downstream of the Seymareh landslide is located lower in height than the most important knickpoint located immediately upstream and sculpted in the bedrock. The location of this knickpoint upstream of the Seymareh landslide SL and the outcrop of the basal contact of the landslide at the bottom of the Seymareh River gorge (Fig. 8a) testify 7a) suggests that this shape of the longitudinal profile was already developed before the failure, that means meaning that the erosion wave which generated the knickpoint affected the Seymareh landslide SL slope foot before the failure occurrence of failure.

The poorly preserved, well-cemented alluvial fan conglomeratic deposits outcropping upstream of the landslide lie on the Miocene Agha Jari Fm., Formation, at a higher elevation higher than than the outcrops of the Bakhtiari Fm. Formation. Their remnants are aligned in correspondence of with the axis of a relict synclinal valley, likely corresponding to a very early stage (Pliocene?) of the Seymareh valley evolution.

On the other hand, the conglomerate deposits outcropping downstream of the landslide (Cg\_1) are closer in height to the major knickpoint, thus suggesting that they were in equilibrium with a local base level corresponding to the early propagation of the major knickpoint. Furthermore, they must be younger than the Bakhtiari Fm., Formation, which is preserved at higher elevation.

The alluvial terraces ~~located~~preserved downstream of the ~~Seymareh landslide~~SL likely mark the valley evolutionary stages during the major knickpoint retreat (Demoulin et al., 2017). ~~Unfortunately, along~~Along the longitudinal river profile, the uppermost outcrops of each level of this terrace suite were swept away by the landslide. ~~Nonetheless, the deposits, which unfortunately prevents estimation of the three youngest levels downstream~~rates of the landslide were suitable for OSL dating (samples SEY3, SEY10 and SEY11, respectively) and provided useful time constraints to the main depositional events during the knickpoint retreat. ~~Minimum ages of 373±34 ka and 312±45 ka have been obtained for samples SEY3 and SEY10 respectively since this samples were saturated due to their very little quartz grains), while SEY11 was dated at 60±5 ka. According~~Nonetheless, according to what was observed by Bridgland et al. (2017) about river terrace development in the NE Mediterranean region, the sedimentation phases should correspond to cold periods. In particular, Bridgland et al. (2012) observed, in the valleys of the Tigris and Ceyhan in Turkey, the Kebir in Syria and the trans-border rivers Orontes and Euphrates, a regular terrace formation in synchrony with 100 ka climatic cycles ~~to~~that can be correlated with MIS 12, 10, 8, 6 and 4-2. Therefore, the minimum ages obtained for the SEY3 and SEY10 samples could be reasonably extended to 478 ka (MIS 12) and 374 ka (MIS 10), respectively, ~~while~~and the OSL age of the SEY11 fits well with the Last Glacial Period.

~~Figure 12 shows the height distribution of the post failure geomorphic markers. They are represented by: i) a horizontal lacustrine terrace formed by the incision of the deposits pertaining to the Seymareh lake, formed as a consequence of the landslide damming; ii) two levels of strath terraces and a flood plain formed on the landslide debris during the initial stages of dam cutting and emptying of the lake; iii) four levels of fill terraces formed after the emptying of the Seymareh lake. We sampled and dated the lacustrine deposit at two different stratigraphic levels, at 560 and 590 m a.s.l., which provided OSL ages of 10.4±0.90 ka (sample SEY8) and 7.37±0.73 ka (sample SEY4), respectively. The OSL age of 17.9±1.50 ka (SEY6) obtained for an alluvial deposit at the base of the lacustrine deposits is in coherent with the age of emplacement of the Seymareh landslide, as already inferred by Roberts and Evans (2013).~~

~~Despite their interpretation as progressively younger lacustrine deposits by Yamani et al. (2012), the four levels of terraces entrenched in the lacustrine deposit show a longitudinal downstream gradient, which, along with their sedimentological characters, identify them as fill terraces. Furthermore, the OSL age obtained for the lacustrine deposit at the base of the Qt2\_m terrace (sample SEY8) is 10.4±0.90 ka, testifying that the suite of alluvial terraces is all entrenched into the same (and unique) lacustrine deposit. The OSL age of 4.49±0.48 ka obtained for the Qt1\_m terrace (sample SEY5) provides time~~

## 5.2 Constraints to post-failure valley evolution

~~The geomorphic markers preserved upstream of the landslide dam provided new constraints to the emptying phase of the Seymareh lake. Such time constraints are fine tuned by the age of the strath terrace formed on the landslide debris, which testify to the initial stage of lake emptying at 6.59±0.49 ka (SEY9).~~

## 6 Discussion

The here obtained results provide significant time constraints for the evolutionary model of the Seymareh valley before and after the natural damming caused by the Seymareh landslide. This giant event was already dated to  $\sim 9.8$  ka by Roberts and Evans (2013). This study provides new insights about the predisposing factors and the on the geomorphic response of the valley system to such a catastrophic phenomenon. A first consideration derives from the geological succession outcropping on the north-eastern slope of the Kabir kuh, since the layering of formations (Fig. 13), which could be associated to different rheological behaviors, could induce differential strain rates within the slope which can justify the strain evolution toward failure according to a MRC process. More in particular, the time dependent visco-plastic behavior, more typical of clayey and marly deposits, which have lower viscosity values, justifies time dependent (creep) strains which generate high stress concentration within the higher viscosity level over time (i.e. mostly characterized by elasto-plastic rheology), inducing their cracking and leading to failure mechanisms. Clear evidences of these rheological effects have been recognized in gravity-induced folding within the thin layered Pabdeh Fm. as well as in impressive buckling of its downslope dipping strata which crop out just along the sliding surface of the Seymareh landslide (Figs. 14b and 14c). As for the kinematic constraints, the geological setting and the attitude of layers in addition with the slope dip represent strong predisposing factors for a rock mass sliding mechanism. In fact, along the NE flank of the Kabir-kuh fold, the outcropping succession is characterized by a stiffness contrast between the upper member of the Pabdeh Fm. and the overlying Asmari Fm. The attitude of strata is likely moderately dipping downslope ( $15^\circ$ – $20^\circ$ ), and a reduced lateral confining effect is due to continental and epi-continental deposits ascribable to Gachsaran and Agha Jari Fms. Moreover, the lower dip angle reduced the vertical thickness of the carbonate Asmari Fm. caprock which was completely eroded by the Seymareh River during its engraving, thus causing the kinematic release at the slope toe. Moreover, the topographic relief of 1600 m between the highest outcropping point of the carbonate formation and the lowest point of the sector where the landslide occurred is significant for the potential energy of the slope mass in deformation and much higher than in the adjacent sectors of the Kabir-kuh ridge. Finally, a relevant kinematic freedom degree was created by the engraved network of gullies that dissect the Asmari Fm. carbonate caprock. The stress release at the bottom of the slope was likely produced by the Middle Late Pleistocene upstream migration of the knickpoint along the Seymareh river longitudinal profile. Unfortunately, since the emplacement of the landslide swept away the uppermost outcrops of the alluvial terraces formed in response to the knickpoint upstream migration, the rate of knickpoint migration cannot be inferred. Nonetheless, an elapsing time to failure in the order of  $10^2$  ky can be reasonably attributed to the slope to valley floor system before the generalized failure occurrence.

The geomorphic response of the Seymareh valley to the  $44 \text{ Gm}^3$  natural dam. Such a response was first the formation of three lakes (Seymareh, Jaidar and Balmak; Fig. 4) whose persistence and evolution is well recorded by the deposits outcropping in the valley. In this regard, the estimation of a sedimentation rate of  $10 \text{ mm y}^{-1}$  in the Seymareh Lake was obtained using the OSL ages of  $10.4 \pm 0.90$  ka and  $7.37 \pm 0.73$  ka for the lacustrine deposit sampled at 560 and 590 m a.s.l., respectively. 4) whose persistence and evolution is well recorded by the deposits outcropping in the valley. In this regard, the estimation of a

sedimentation rate of  $10 \text{ mm y}^{-1}$  in the Seymareh Lake was obtained using the OSL ages of  $10.4 \pm 0.90 \text{ ka}$  and  $7.37 \pm 0.73 \text{ ka}$  for the lacustrine deposit sampled at 560 and 590 m a.s.l., respectively. Furthermore, the

The strath terrace sculpted on the landslide deposit and dated at  $6.59 \pm 0.49 \text{ ka}$  constrains the cut of the natural dam due to overflow which caused the progressive lake emptying to empty. The lake overflow was likely caused by the progressive gradual filling of the reservoir with lacustrine deposits, which reduced progressively reduced the dam infiltration section. Nevertheless, the possible role of groundwater seepage within the pervious natural dam in balancing the Seymareh river/River discharge and delaying the dam overflow remains a questionable topic to be approached and solved in future studies. Despite their interpretation as progressively younger lacustrine deposits by Yamani et al. As it results (2012), the four terrace levels entrenched in the terraced lacustrine deposit show a longitudinal downstream gradient, which, along with their sedimentological characters, identify them as fill terraces. Furthermore, the OSL age obtained for the lacustrine deposit at the base of the Qt2 m terrace (sample SEY8) is  $10.4 \pm 0.90 \text{ ka}$ , demonstrating that the suite of alluvial terraces is entrenched into the same (and unique) lacustrine deposit. The OSL age of  $4.49 \pm 0.48 \text{ ka}$  obtained for the Qt1 m terrace (sample SEY5) provides time constraints to the emptying phase of Seymareh Lake. Such time constraints are fine-tuned by the age of the strath terrace formed on the landslide debris, which corroborate the initial stage of lake emptying at  $6.59 \pm 0.49 \text{ ka}$  (SEY9). As indicated by the age of the Qt1\_m terrace (of  $4.49 \pm 0.48 \text{ ka}$ ), the Seymareh lake/Lake likely persisted likely up to  $\sim 5 \text{ ka}$ , much longer than the 935 years estimated by Shoaie (2014). Since the top of the lacustrine deposit lies at 630 m a.s.l., an increased sedimentation rate of  $\sim 17 \text{ mm y}^{-1}$  can be inferred for the late stage of the lake evolution, which is in agreement with an increased sediment yield from tributaries during the early stages of lake emptying (Fig. 15). 5d).

The overflow, at  $6.59 \pm 0.49 \text{ ka}$  allows us to calculate the erosion rate affecting the landslide deposit after the overflow. The ratio between the thickness of the eroded sediment ( $\sim 120 \text{ m}$ ) and the time elapsed since the beginning of the process ( $\sim 6.59 \text{ ky}$ ) allows to estimate estimation of an erosion rate of  $1.8 \text{ cm y}^{-1}$  for the Seymareh River along the gorge. The cut of the landslide dam induced a new change in the fluvial base level, bringing the slope-to-valley floor system into disequilibrium. The cut of the landslide dam induced a new change in the fluvial base level, bringing the slope to valley floor system into disequilibrium. For this reason, a dense drainage system was set on the scar area, which, thanks due to the high erodibility and low permeability of the less competent Pabdeh-Gurpi Fm. Formation immediately below the sliding surface on the Kabir-kuh ridge NE slope, has generated the badlands mapped in Fig. 7-6.

### 5.3 Evolutionary model of the Seymareh River valley

The time scan of landscape evolution in of the Seymareh river/River valley before and after the failure occurrence can be summarized in the following listed six phases:

1. Setting of a Paleopaleo-Seymareh River/river into a synclinal valley, likely developed in the Pliocene, to the west of the present position of the Seymareh River and deposition of fan deposits (Cg\_m) (Fig. 16a|2a).



2. Development of the valley with local base level correlated to the Seymareh longitudinal profile segment upstream of the major knickpoint along the Seymareh River and coeval to the deposition of the Bakhtiari Fm. (~~Late~~Formation (late Pliocene-~~Early~~early Pleistocene) (Fig. ~~16b~~12b).

3. Emplacement of the downstream fan deposits corresponding to the Cg\_1 conglomerates (~~Early~~early Pleistocene) and generation of the four orders of Middle-Late Pleistocene alluvial terraces (Qt1\_1-Qt4\_1) preserved downstream of the landslide and formed during the progressive migration of the major knickpoint, which is presently located upstream of the landslide (Fig. ~~16e~~12c).

4. ~~Seymareh landslide~~SL event (~10 ka), according to the <sup>14</sup>C ages by Roberts and Evans (2013) and to the OSL ages provided in this work for the lacustrine deposits (Lac) (Fig. ~~16d~~12d).

5. Formation and permanence of the Seymareh Lake (~10-6.6 ka), according to the <sup>14</sup>C ~~estimated~~ ages by Roberts and Evans, ~~(2013)~~ and to the OSL ages provided in this study for the lacustrine deposits (Lac) (Fig. ~~16e~~12e). The progressive infilling of the lake reservoir ~~reduced~~ progressively ~~reduced~~ the infiltration section on the upstream side of the landslide dam. ~~It cannot be excluded the~~The presence of a minor emissary on the downstream side of the landslide debris ~~cannot be excluded~~.

6. Overflow of the lake and cut of the natural dam with formation of ~~at~~the first strath terrace (6.59±0.49 ka), followed by a second strath terrace and a flood plain during the emptying of the lake, which upstream is associated ~~to~~with the sedimentation of a fluvio-lacustrine sequence at the top of the lacustrine sediments (Fig. ~~12f~~).

7. Complete emptying of the lake and generation of the suite of fill terraces entrenched in the deposits of Seymareh Lake (4.5 ka. - Present) (Fig. 12g).

#### **5.4 Implications of the evolutionary model for future back-analysis of the SL**

According to the multi-modeling approach proposed by Martino et al. (2017), Quaternary landscape evolution modeling of slope-to-valley floor systems plays a key role as a tool for chronological constraints to the creep evolution of entire slopes (Bozzano et al., 2016; Della Seta et al., ~~16f~~).

~~7. Complete emptying of the lake and generation of the suite of fill terraces entrenched in the deposits of Seymareh Lake (4.5 ka. - Present) (Fig. ~~16g~~).~~

~~7~~2017).

The geomorphic processes developed before the failure of the SL likely acted as predisposing factors for MRC processes in the rock mass successively collapsed. Kinematic freedom, both at the top and on the fold flank was created by the incising network of streams that dissect the Asmari Formation carbonate caprock following the major joint set in the Asmari Formation already described in Roberts and Evans (2013; and references therein). In particular, the headward erosion of streams towards the anticline's structural high described by Oberlander (1968), caused the expansion of the fold axial basins through the softer units, determining the upslope kinematic freedom. In the timing proposed by Tucker and Slingerland (1996) the latter was reached at approximately 1.6 ka. Stress release at the slope base was definitely produced by the Middle-Late Pleistocene

upstream migration of the knickpoint along the Seymareh River longitudinal profile. Unfortunately, since the emplacement of the landslide swept away the uppermost outcrops of the alluvial terraces formed in response to the upstream knickpoint migration, the rate of knickpoint migration cannot be inferred. Nonetheless, an elapsed time-to-failure on the order of  $10^2$  ky, since the kinematic freedom at the slope base was reached, can be reasonably estimated by the age of the oldest terrace in the lower reach of the river minus the age of the landslide occurrence.

It is noteworthy that the stratigraphy of the source rock mass, also described in detail by Roberts and Evans (2013), accounts for different rheological behaviors, which could have induced differential strain rates within the slope leading to failure according to a MRC process. More particularly, the time-dependent visco-plastic behavior, more typical of clayey and marly deposits, which have lower viscosity values, can justify time-dependent (creep) strains which could have generated high stress concentration within the higher viscosity level over time (i.e., mostly characterized by elasto-plastic rheology), inducing their cracking and leading to failure. In fact, a stiffness contrast exists between the upper member of the Pabdeh Formation and the overlying Asmari Formation. The attitude of the strata is moderately dipping downslope ( $15^\circ$ - $20^\circ$ ), and a reduced lateral confining effect is due to continental and epicontinental deposits ascribable to the Gachsaran and Agha Jari Formations. Moreover, the low dip angle of the strata reduces the vertical thickness of the Asmari Formation caprock, which was completely eroded by Seymareh River during its engraving, thus allowing the sliding mechanism of the Pabdeh and Asmari layered formations.

Therefore, the results of this work have implications for a future back-analysis through stress-strain numerical modeling of the SL because they can be used to constrain the elapsed time since MRC initiation and ultimate failure conditions. Such a perspective is to be regarded as a key challenge for dimensioning such an end member event in regard to both time and space distribution as well as for evaluating the possible role of impulsive triggering actions (i.e., strong to very strong earthquakes) in anticipating the time-to-failure of the slope.

## 6 Conclusion

In a multi-modelling modeling approach to the study of MRC processes affecting slopes at a large space-time scale (Martino et al., 2017), the analysis of performed geomorphic markers analysis allowed us to constrain the landscape evolution of the Seymareh river valley in north-western the northwestern Zagros Mts., before and after the failure of the largest landslide ever recorded on emerged the exposed Earth surface, provided a time scan of the main stages of valley evolution. The revised geological setting as well as the identification and OSL dating of different suites of lacustrine, alluvial and strath terraces, highlighted the predisposing factors that led to the gravitational instability and the geomorphic effects on the valley system. OSL ages obtained for eight samples, along with the  $^{14}\text{C}$  age provided by Roberts and Evans (2013), allowed us to provide significant constrained in time constrain to the valley evolution, which can be summarized in the following six points: the major pre- and post-failure evolutionary steps of the river valley system.

1- The oldest ~~preserved~~ geomorphic markers in the Seymareh ~~river~~ River valley are represented by relict conglomerates preserved upstream of the landslide, which ~~testify to~~ demonstrate the early (Pliocene?) position of a ~~Paleo~~ paleo-Seymareh ~~River~~ river flowing into a synclinal valley close to the ~~north-eastern~~ northeastern flank of the Kabir-kuh fold.

2- ~~The drainage re-organization~~ Drainage evolution associated ~~to~~ with the growth of the ~~north-western Zagros folds~~ is testified ~~by~~ Kabir-kuh fold was characterized by the deep incision of the stream network, which allowed the kinematic release of the rock mass involved in the Seymareh giant landslide. Such a stream incision was accompanied by the retreat of a major “slope-break knickpoint” along the Seymareh longitudinal profile, ~~whose retreat during the Middle-Late Pleistocene is marked by the development~~ time-constrained by the age of a suite of ~~four alluvial terraces. Such a knickpoint retreat~~ river fill terraces. According to the age of pre-failure terraces, in the middle-late Pleistocene the erosion wave reached the portion of the Kabir-kuh fold that ~10 ka was affected by the Seymareh landslide. The SL. According to the timing of the landscape evolution model proposed by Tucker and Slingerland (1996), the upper slope underwent kinematic release about 1.6 ka. Therefore, the collapse was ~~therefore~~ prepared by MRC processes acting over a time window ~~in the order~~ of  $10^2$  ky;

3- ~~Among the predisposing factors, the above mentioned erosional wave was accompanied by the deep incision of the gully network developed on the slope, which, along with the Seymareh river erosion, released kinematically the rock mass. The geological structural setting of the fold sector affected by the landslide, with respect to the adjacent ones, represents a further predisposing factor.~~

4- The geomorphic response to the landslide dam consisted in the formation of three lakes, among which ~~the~~ Seymareh lake Lake persisted for ~3500 years before ~~the beginning of the~~ its emptying phase started ~6.6 ka due to lake overflow. A sedimentation rate of  $10 \text{ mm y}^{-1}$  was estimated for the lacustrine deposits, which increased up to  $17 \text{ mm y}^{-1}$  during the early stage of lake emptying due to the increased sediment yield from the lake tributaries. ~~Since ~4.5 ka, a suite of four alluvial terraces upstream of the landslide demonstrates the alternating erosion/deposition phases of the re-established Seymareh River.~~

5- ~~Since ~4.5 ka a suite of four alluvial terraces upstream of the landslide testify to the alternating erosion/deposition phases of the re-established Seymareh River.~~

6- An incision rate of  $1.8 \text{ cm y}^{-1}$  was estimated since the beginning of the landslide cut by ~~the~~ Seymareh River, and such a strong erosion started propagating up to the landslide source area where badlands ~~catchments~~ developed, eroding ~~a volume of ~0.1 km<sup>2</sup> in~~ the marly Pabdeh-Gurpi Fm. ~~Such an evidence provided new insights on the geometry of the sliding surface, which likely did not involve the Pabdeh-Gurpi Fm., as inferred by Roberts and Evans (2013).~~ Formation.

The ~~here~~ results obtained ~~results~~ here provide ~~main~~ new constraints to the ~~slope to valley floor~~ evolution ~~that can be very useful for~~ in view of future stress-strain numerical modeling of ~~time-dependent stress-strain evolution of the Seymareh landslide~~ MRC process that involved the SL slope: ~~before its generalized collapse.~~ Such a ~~numerical~~ modeling could ~~be the focus of future researches with the aim of calibrating the rock mass viscosity and verifying~~ also be considered to discuss the possible earthquake trigger of the Seymareh landslide as an ultimate scenario of an ongoing mass rock creep process which reasonably was affecting the slope since  $10^2$  ka role of impulsive triggering (earthquakes) in anticipating the time-to-failure due to the gravity-driven deformational processes.

## Acknowledgments

This work has been possible thanks to the International Agreement between Sapienza University of Rome and Kharazmi University of Tehran and to the associated mobility funds by Sapienza (Grant no. AI2615R3W4). We are particularly grateful to Mohammad Moumeni Taromsari for his efforts and fruitful scientific contributions to the field work.

## 5 References

- Alavi, M.: Regional stratigraphy of the Zagros fold-thrust belt of Iran and its proforeland evolution. Am. J. Sci., 304(1), 1-20, doi: 10.2475/ajs.304.1.1, 2004.
- Agard, P., Omrani, J., Jolivet, L. and Mouthereau, F.: Convergence history across Zagros (Iran): Constraints from collisional and earlier deformation, *Int. J. Earth Sci.*, 94(3), 401–419, doi:10.1007/s00531-005-0481-4, 2005.
- 10 Binnie, S. A., Phillips, W. M., Summerfield, M. A. and Fifield, L. K.: Tectonic uplift, threshold hillslopes, and denudation rates in a developing mountain range, *Geology*, 35(8), 743–746, doi:10.1130/G23641A.1, 2007.
- ~~Blanc, E. J. P., Allen, M. B., Inger, S. and Hassani, H.: Structural styles in the {Zagros} {Simple} {Folded} {Zone}, {Iran}, *J. Geol. Soc. London*, 160Bisbal, 401–412 [online] Available from: [Blanc\\_et\\_al\\_2003.pdf, 2003.](#)~~
- Boulton, S. J., Stokes, M. and Mather, A. E.: Transient fluvial incision as an indicator of active faulting and Plio-Quaternary uplift of the Moroccan high Atlas, *Tectonophysics*, 633(1), 16–33, doi:10.1016/j.tecto.2014.06.032, 2014.
- Bourne, J. A. and Twidale, C. R.: Neglected and cryptostrucutural effects in drainage development, *Cadernos do Laboratorio Xeolóxico de Laxe*, Vol. 36, pp. 41 - 60, 2011.
- Bozzano, F., Martino, S., Montagna, A. and Prestininzi, A.: Back analysis of a rock landslide to infer rheological parameters, *Eng. Geol.*, 131–132, 45–56, doi:10.1016/j.enggeo.2012.02.003, 2012.
- 20 Bozzano, F., Della Seta, M. and Martino, S.: Time-dependent evolution of rock slopes by a multi-modelling approach, *Geomorphology*, 263, 113–131, doi:10.1016/j.geomorph.2016.03.031, 2016.
- Bridgland, D. R., Westaway, R., Romieh, M. A., Candy, I., Daoud, M., Demir, T., Galiatsatos, N., Schreve, D. C., Seyrek, A., Shaw, A. D., White, T. S. and Whittaker, J.: The River Orontes in Syria and Turkey: Downstream variation of fluvial archives in different crustal blocks, *Geomorphology*, 165–166, 25–49, doi:10.1016/j.geomorph.2012.01.011, 2012.
- 25 Bridgland, D. R., Demir, T., Seyrek, A., Daoud, M., Abou Romieh, M. and Westaway, R.: River terrace development in the NE Mediterranean region (Syria and Turkey): Patterns in relation to crustal type, *Quat. Sci. Rev.*, 166, 307–323, doi:10.1016/j.quascirev.2016.12.015, 2017.
- Burbank, D. W. and Anderson R. S.: *Tectonic Geomorphology*. John Wiley and Sons, Second Edition, Ltd., Chichester, West Sussex, UK, 2012.
- 30 Casciello, E., Verges, J., Saura, E., Casini, G., Fernandez, N., Blanc, E., Homke, S. and Hunt, D. W.: Fold patterns and multilayer rheology of the Lurestan Province, Zagros Simply Folded Belt (Iran), *J. Geol. Soc. London.*, 166(5), 947–959, doi:10.1144/0016-76492008-138, 2009.

- Chigira, M.: Long-term gravitational deformation of rocks by mass rock creep, *Eng. Geol.*, 32(3), 157–184, doi:10.1016/0013-7952(92)90043-X, 1992.
- ~~Delgado, J., Garrido, J., López-Casado, C., Martino, S. and Peláez, J. A.: On far field occurrence of seismically induced landslides, *Eng. Geol.*, 123(3), 204–213, doi:10.1016/j.enggeo.2011.08.002, 2011.~~
- 5 ~~Della Seta, M., Del Monte, M., Fredi, P. and Lupia Palmieri, E.: Space-time variability of denudation rates at the catchment and hillslope scales on the Tyrrhenian side of Central Italy, *Geomorphology*, 107(3–4), 161–177, doi:10.1016/j.geomorph.2008.12.004, 2009.~~
- Della Seta, M., Esposito, C., Marmoni, G. M., Martino, S., Scarascia Mugnozza, G. and Troiani, F.: Morpho-structural evolution of the valley-slope systems and related implications on slope-scale gravitational processes: New results from the Mt. Genzana case history (Central Apennines, Italy), *Geomorphology*, 289, 60–77, doi:10.1016/j.geomorph.2016.07.003, 2017.
- 10 Demoulin, A., Mather, A. and Whittaker, A.: Fluvial archives, a valuable record of vertical crustal deformation, *Quat. Sci. Rev.*, 166, 10–37, doi:10.1016/j.quascirev.2016.11.011, 2017.
- Eberhardt, E., Stead, D. and Coggan, J. S.: Numerical analysis of initiation and progressive failure in natural rock slopes—the 1991 Randa rockslide, *Int. J. Rock Mech. Min. Sci.*, 41(1), 69–87, doi:10.1016/S1365-1609(03)00076-5, 2004.
- 15 ~~Elyasi, A. and Goshtasbi, K.: Using different rock failure criteria in wellbore stability analysis, *Geomech. Energy Environ.*, 2, 15–21, doi:10.1016/j.gete.2015.04.001, 2015.~~
- ~~Elyasi, A., Goshtasbi, K., Saeidi, O. and Torabi, S.-R.: Stress determination and geomechanical stability analysis of an oil well of Iran, *Sadhana, Acad. Proc. Eng. Sci.*, 39(1), 207–220, doi:10.1007/s12046-013-0224-3, 2014.~~
- Golonka, J.: Plate tectonic evolution of the southern margin of Eurasia in the Mesozoic and Cenozoic, *Tectonophysics*, 381(1–20 4), 235–273, doi:10.1016/j.tecto.2002.06.004, 2004.
- Griffiths, H. I., Schwalb, A. and Stevens, L. R.: Environmental change in southwestern Iran: the Holocene ostracod fauna of Lake Mirabad, *Holocene*, 11(6), 757-764, doi:10.1191/09596830195771, 2001.
- Harrison, J. V., and Falcon, N. L.: The Saidmarreh landslip, south-west Iran, *Geogr. J.*, 89, 42-47, 1937.
- Harrison, J. V., and Falcon, N. L.: An ancient landslip at Saidmarreh in southwestern Iran, *J. Geol.*, 46, 296-309, 1938.
- 25 Hatzfeld, D., Authemayou, C., ~~van~~ Van der Beek, P., Bellier, O., Lavé, J., Oveisi, B., Tatar, M., Tavakoli, F., Walpersdorf, A. and Yamini-Fard, F.: The kinematics of the Zagros Mountains (Iran), *Geol. Soc. London, Spec. Publ.*, 330(1), 19–42, doi:10.1144/SP330.3, 2010.
- Homke, S., Vergés, J., Garcés, M., Emami, H. and Karpuz, R.: Magnetostratigraphy of Miocene-Pliocene Zagros foreland deposits in the front of the Push-e Kush Arc (Lurestan Province, Iran), *Earth Planet. Sci. Lett.*, 225(3–4), 397–410, 30 doi:10.1016/j.epsl.2004.07.002, 2004.
- ~~Hovius, N., Meunier, P., Lin, C. W., Chen, H., Chen, Y. G., Dadson, S., Horng, M. J. and Lines, M.: Prolonged seismically induced erosion and the mass balance of a large earthquake, *Earth Planet. Sci. Lett.*, 304(3–4), 347–355, doi:10.1016/j.epsl.2011.02.005, 2011.~~

- Hungr, O., Evans, S. G., and Hutchinson, J. N.: A Review of the Classification of Landslides of the Flow Type, *Environ. Eng. Geosci.*, 7(3), 221-238, doi:10.2113/gsegeosci.7.3.221, 2001.
- Hutchinson, M., Xu, T. and Stein, J.: Recent Progress in the ANUDEM Elevation Gridding Procedure, *Geomorphometry*, 19–22, doi:10.1002/osp4.29, 2011.
- 5 ~~Jibson, R. W. and Harp, E. L.: Extraordinary distance limits of landslides triggered by the 2011 Mineral, Virginia, earthquake, *Bull. Seismol. Soc. Am.*, 102(6), 2368–2377, doi:10.1785/0120120055, 2012.~~
- ~~Keefer, D. K.: The importance of earthquake induced landslides to long term slope erosion and slope failure hazards in seismically active regions, *Geomorphology*, 10(1–4), 265–284, doi:10.1016/0169-555X(94)90021-3, 1994.~~
- ~~Khoshboresh, A. R.: A Study on Deformation of Tunnels Excavated in Fractured Rocks, Université Laval, First Edition, 10 Quebec, Canada, 139, 2013.~~
- James, G. A. and Wynd, J. G.: Stratigraphic nomenclature of Iranian oil consortium agreement area. *AApG Bulletin*, 49(12), 2182-2245, 1965.
- Kirby, E. and Whipple, K. X.: Expression of active tectonics in erosional landscapes, *J. Struct. Geol.*, 44, 54–75, doi:10.1016/j.jsg.2012.07.009, 2012.
- 15 Larsen, I. J. and Montgomery, D. R.: Landslide erosion coupled to tectonics and river incision, *Nat. Geosci.*, 5(7), 468–473, doi:10.1038/ngeo1479, 2012.
- ~~Leturmy, P. and Robin, C.: Tectonic and stratigraphic evolution of Zagros and Makran during the Mesozoic-Cenozoic: introduction, *Geol. Soc. London, Spec. Publ.*, 330(1), 1–4, doi:10.1144/SP330.1, 2010.~~
- ~~Li, G., West, A.J., Densmore, A.L., Jin, Z., Parker, R.N., and Hilton, R.G.: Seismic mountain building: Landslides associated with the 2008 Wenchuan earthquake in the context of a generalized model for earthquake volume balance, *Geochem. Geophys. Geosyst.*, 15 (4), 833–844, doi:10.1002/2013GC005067, 2014.~~
- 20 ~~Malamud, B. D., Turcotte, D. L., Guzzetti, F. and Reichenbach, P.: Landslide inventories and their statistical properties, *Earth Surf. Process. Landforms*, 29(6), 687–711, doi:10.1002/esp.1064, 2004.~~
- ~~Mare, O., Niels, H. and Patrick, M.: Seismologically consistent prediction of earthquake induced landsliding: Towards near-real time prediction of total landslide volume, total landslide area and regional area affected by earthquake induced landsliding, *Abstr. EGU2017 14215 Present. 2017 EGU Gen. Assem.*, 19, 14215, 2017.~~
- 25 ~~Martino, S., Prestininzi, A. and Romeo, R. W.: Earthquake induced ground failures in Italy from a reviewed database, *Nat. Hazards Earth Syst. Sci.*, 14(4), 799–814, doi:10.5194/nhess-14-799-2014, 2014.~~
- Macleod, J. H.: Kabir Kuh, 1:100000 Geological Map. Iran Oil Operating Companies, Geological Exploration Division, 30 Tehran, 1970.
- Martino, S., Della Seta, M. and Esposito, C.: Back-analysis of rock landslides to infer rheological parameters, in: *Rock Mechanics and Engineering, Volume 3: Analysis, Modeling and Design*, First Edition, Xia-Ting Feng Editor, London, UK, 237-269, 2017.

- McQuarrie, N.: Crustal scale geometry of the Zagros fold-thrust belt, Iran, *J. Struct. Geol.*, 26(3), 519–535, doi:10.1016/j.jsg.2003.08.009, 2004.
- ~~Mohajjel, M., and Fergusson, C. L.: Dextral transpression in Late Cretaceous continental collision, Sanandaj-Sirjan zone, western Iran, *J. Struct. Geol.*, 22(8), 1125–1139, doi:10.1016/S0191-8141(00)00023-7, 2000.~~
- 5 Montgomery, D. R., and Brandon, M. T.: Topographic controls on erosion rates in tectonically active mountain ranges, *Earth. Planet. Sc. Lett.*, 201(3-4), 481-489, doi:10.1016/S0012-821X(02)00725-2, 2002.
- Montgomery D. R. and Foufoula-Georgiou E.: Channel Network Source Representation Using Digital Elevation Models, *Water. Resour. Res.*, Vol. 29, No. 12, pp. 3925-3934, doi:10.1029/93WR02463, 1993.
- Mouthereau, F., Lacombe, O. and Vergés, J.: Building the Zagros collisional orogen: Timing, strain distribution and the  
10 dynamics of Arabia/Eurasia plate convergence, *Tectonophysics*, 532–535, 27–60, doi:10.1016/j.tecto.2012.01.022, 2012.
- Murray, A. S., and Olley, J. M.: Precision and accuracy in the optically stimulated luminescence dating of sedimentary quartz: a status review, *Geochronometria*, 21(1), 1-16, 2002.
- ~~Navabpour, P., Angelier, J., and Barrier, E.: Mesozoic extensional brittle tectonics of the Arabian passive margin, inverted in the Zagros collision (Iran, interior Fars), *Geol. Soc. London, Spec. Publ.*, 330(1), 65–96, doi:10.1144/SP330.5, 2010.~~
- 15 Oberlander, T. M.: The Zagros streams: a new interpretation of transversedrainage in an orogenic zone, Syracuse Geographical Series, Syracuse University Press, New York, 1965.
- Oberlander, T. M.: The origin of the Zagros defiles. *The Cambridge History of Iran*, 1: The Land of Iran, Fisher W.B (Ed.), Cambridge University Press, Cambridge, UK, 195-211, 1968.
- Oberlander, T. M.: Origin of drainage transverse to structures in orogens. In: *Tectonic Geomorphology*, Proceedings of the  
20 15th Binghamton Geomorphology Symposium 1984. Morisawa, M. and Hack, J. T. (eds.), Allen & Unwin, Boston, MA, 155–182, 1985.
- ~~Owen, L. A., Kamp, U., Khattak, G. A., Harp, E. L., Keefer, D. K. and Bauer, M. A.: Landslides triggered by the 8 October 2005 Kashmir earthquake, *Geomorphology*, 94(1–2), 1–9, doi:10.1016/j.geomorph.2007.04.007, 2008.~~
- ~~Parker, R.N., Densmore, A.L., Rosser, N.J., De Michele, M., Li, Y., Huang, R., Whadecoat, S., and Petley, D.N.: Mass wasting triggered by the 2008 Wenchuan earthquake is greater than orogenic growth, *Nat. Geosci.*, 4 (7), 449–452, doi:10.1038/ngeo1154, 2011.~~
- 25 Paul, A., Hatzfeld, D., Kaviani, A., Tatar, M. and Péquegnat, C.: Seismic imaging of the lithospheric structure of the Zagros mountain belt (Iran), *Geol. Soc. London, Spec. Publ.*, 330(1), 5–18, doi:10.1144/SP330.2, 2010.
- Ramsey, L. A., Walker, R. T., and Jackson, J.: Fold evolution and drainage development in the Zagros mountains of Fars  
30 province, SE Iran, *Basin. Res.*, 20(1), 23-48, doi:10.1111/j.1365-2117.2007.00342.x, 2008.
- Rajabi, A. M., Mahdaviifar, M. R., Khamchian, M. and ~~del~~Del Gaudio, V.: A new empirical estimator of coseismic landslide displacement for Zagros Mountain region (Iran), *Nat. Hazards*, 59(2), 1189–1203, doi:10.1007/s11069-011-9829-1, 2011.
- Roberts, N. J.: Structural and geologic controls on gigantic (1 Gm<sup>3</sup>) landslides in carbonate sequences : case studies from the Zagros Mountains, Iran and Rocky Mountains, Canada, Master's thesis, University of Waterloo, Canada, 2008.

- Roberts, N. J. and Evans, S. G.: The gigantic Seymareh (Saidmarreh) rock avalanche, Zagros Fold–Thrust Belt, Iran, *J. Geol. Soc. London.*, 170(4), 685–700, doi:10.1144/jgs2012-090, 2013.
- ~~Rodriguez, C. E., Bommer, J. J. and Chandler, R. J. (1999). Earthquake induced landslides: 1980–1997, *Soil. Dyn. Earthq. Eng.*, 18, 325–346, doi:10.1016/S0267-7261(99)00012-3, 1999.~~
- 5 ~~Saura, E., Verges, J., Homke, S., Blanc, E., Serra-Kiel, J., Bernaola, G., Casciello, E., Fernandez, N., Romaine, I., Casini, G., Embry, J. C., Sharp, I. R. and Hunt, D. W.: Basin architecture and growth folding of the NW Zagros early foreland basin during the Late Cretaceous and early Tertiary, *J. Geol. Soc. London.*, 168(1), 235–250, doi:10.1111/j.1601-5037.2004.00096.x, 2011.~~
- Schmidt, K. M. and Montgomery, D. R.: Limits to Relief, *Science*, Vol. 270, 617–621, doi:10.1126/science.270.5236.617, 10 1995.
- ~~Sepehr, M. and Cosgrove, J. W.: Structural framework of the Zagros Fold Thrust Belt, Iran, *Mar. Pet. Geol.*, 21(7), 829–843, doi:10.1016/j.marpetgeo.2003.07.006, 2004.~~
- Setudehnia, A. and Perry, J. T. O.'B.: Dal Parri. 1:100000 Geological Map. Iran Oil Operating Companies, Geological Exploration Division, Tehran, 1967.
- 15 Shafiei, A. and Dusseault, M. B.: Geomechanical Properties of a Conglomerate from Iran Geomechanical Properties of a Conglomerate from Iran, In The 42nd US Rock Mechanics Symposium (USRMS), American Rock Mechanics Association, doi:10.13140/RG.2.1.1722.7684, 2008.
- ~~Sherkati, S., Molinaro, M., de Lamotte, D. F., and Letouzey, J.: Detachment folding in the Central and Eastern Zagros fold-belt (Iran): salt mobility, multiple detachments and late basement control, *J. Struct. Geol.*, 27(9), 1680–1696, 20 doi:10.1016/j.jsg.2005.05.010, 2005.~~
- Shoaei, Z.: Mechanism of the giant Seimareh Landslide, Iran, and the longevity of its landslide dams, *Environ. Earth Sci.*, 72(7), 2411–2422, doi:10.1007/s12665-014-3150-8, 2014.
- Stampfli, G. M., and Borel, G. D.: A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons, *Earth. Planet. Sc. Lett.*, 196(1), 17–33, doi:10.1016/S0012-25 821X(01)00588-X, 2002.
- Stead, D., Eberhardt, E. and Coggan, J. S.: Developments in the characterization of complex rock slope deformation and failure using numerical modelling techniques, *Eng. Geol.*, 83(1–3), 217–235, doi:10.1016/j.enggeo.2005.06.033, 2006.
- Takin, M., Akbari, Y. and Macleod, J.H.: Pul-E Dukhtar. 1:100000 Geological Map. Iran Oil Operating Companies, Geological Exploration Division, Tehran, 1970.
- 30 Talbot, C. J. and Alavi, M.: The past of a future syntaxis across the Zagros, *Geol. Soc. London, Spec. Publ.*, 100(1), 89–109, doi:10.1144/GSL.SP.1996.100.01.08, 1996.
- ~~Tatar, M., Hatzfeld, D., Martinod, J., Walpersdorf, A., Ghafori Ashtiany, M. and Chéry, J.: The present day deformation of the central Zagros from GPS measurements, *Geophys. Res. Lett.*, 29(19), 33–1–33–4, doi:10.1029/2002GL015427, 2002.~~



- Tucker, G. E. and Slingerland, R.: Predicting sediment flux from fold and thrust belts, *Basin Res.*, 8(3), 329–349, doi:10.1046/j.1365-2117.1996.00238.x, 1996.
- Tucker, G. E. and Whipple, K. X.: Topographic outcomes predicted by stream erosion models: Sensitivity analysis and intermodel comparison, *J. Geophys. Res. Solid Earth*, 107(B9), 1-16, doi:10.1029/2001JB000162, 2002.
- 5 Vergés, J., Goodarzi, M., Emami, H., Karpuz, R., Efstathiou, J. and Gillespie, P.: Multiple detachment folding in Pusht-e Kuh arc, Zagros: Role of mechanical stratigraphy, *Thrust fault-related Fold*, *AAPG Mem.*, 69–94, doi:10.1306/13251333M942899, 2011.
- Watson R. A. and Wright H. E.: The Saidmarreh landslide, Iran, Schumm, S. A. and Bradley, W. C. (eds), *United States Contributions to Quaternary Research*, Geological Society of America, Special Papers, 123, pp. 115–139, 1969.
- 10 Wilson, J. P., and Gallant, J. C.: *Terrain analysis: principles and applications*, John Wiley and Sons, New York, USA, 2000.
- Wintle, A. G., and Murray, A. S.: A review of quartz optically stimulated luminescence characteristics and their relevance in single-aliquot regeneration dating protocols, *Radiat. Meas.*, 41(4), 369-391, doi:10.1016/j.radmeas.2005.11.001, 2006.
- Yamani, M., Goorabi, A. and Azimirad, S.: Large Seymareh Landslide and Lake Terraces Sequence, *Physical Geography Research, Quarterly*, Volume 44, Issue 4, pp. 43- 60, 2012.
- 15 [Yamini-Fard, F., Hatzfeld, D., Tatar, M., and Mokhtari, M.: Microearthquake seismicity at the intersection between the Kazerun fault and the Main Recent Fault \(Zagros, Iran\), \*Geophys. J. Int.\*, 166\(1\), 186-196, doi:10.1111/j.1365-246X.2006.02891.x, 2006.](#)
- [Zhao, S., Chigira, M., Wu, X.: Gigantic rockslides induced by fluvial incision in the Diexi area along the eastern margin of the Tibetan Plateau, \*Geomorphology\*, <https://doi.org/10.1016/j.geomorph.2019.04.008>, 2019.](#)

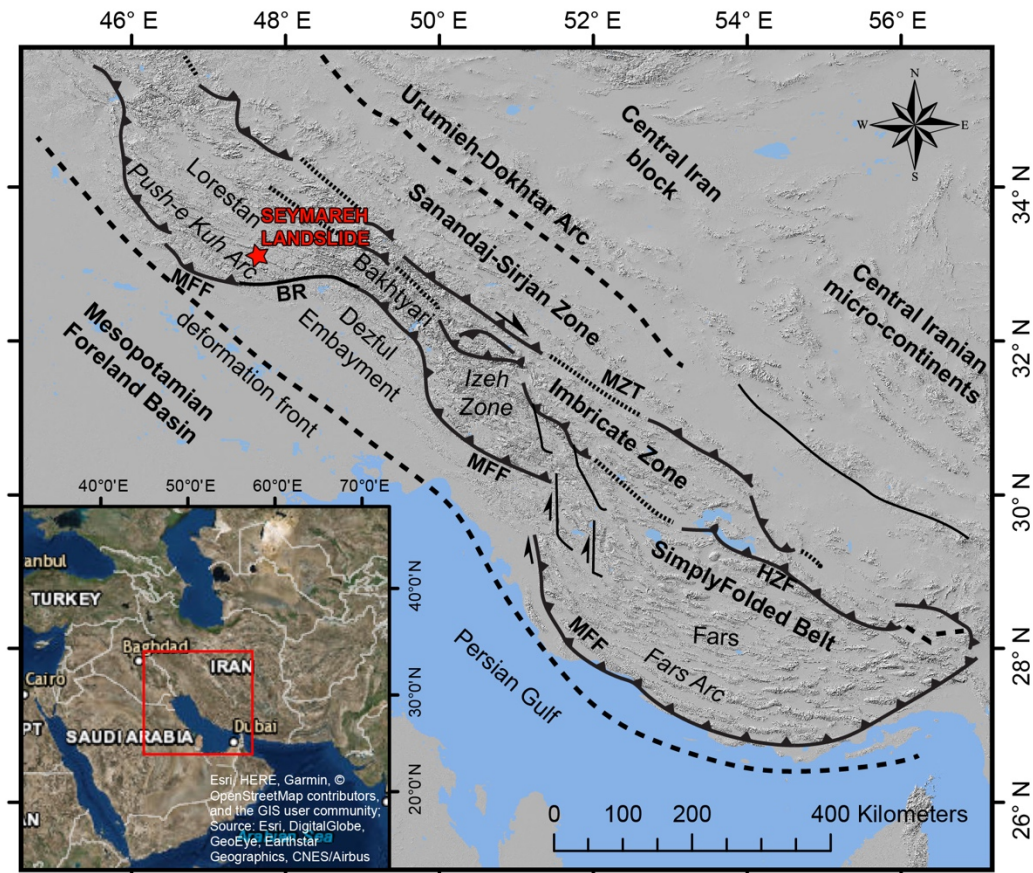
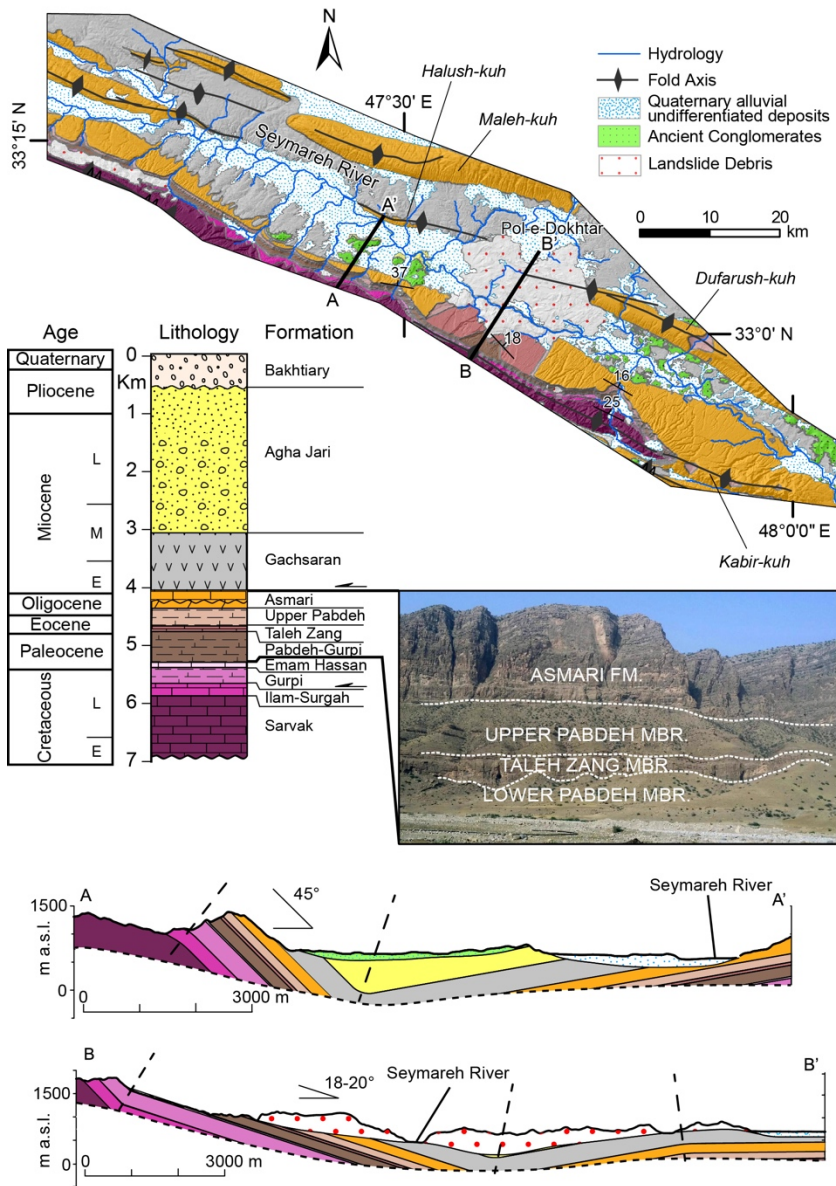
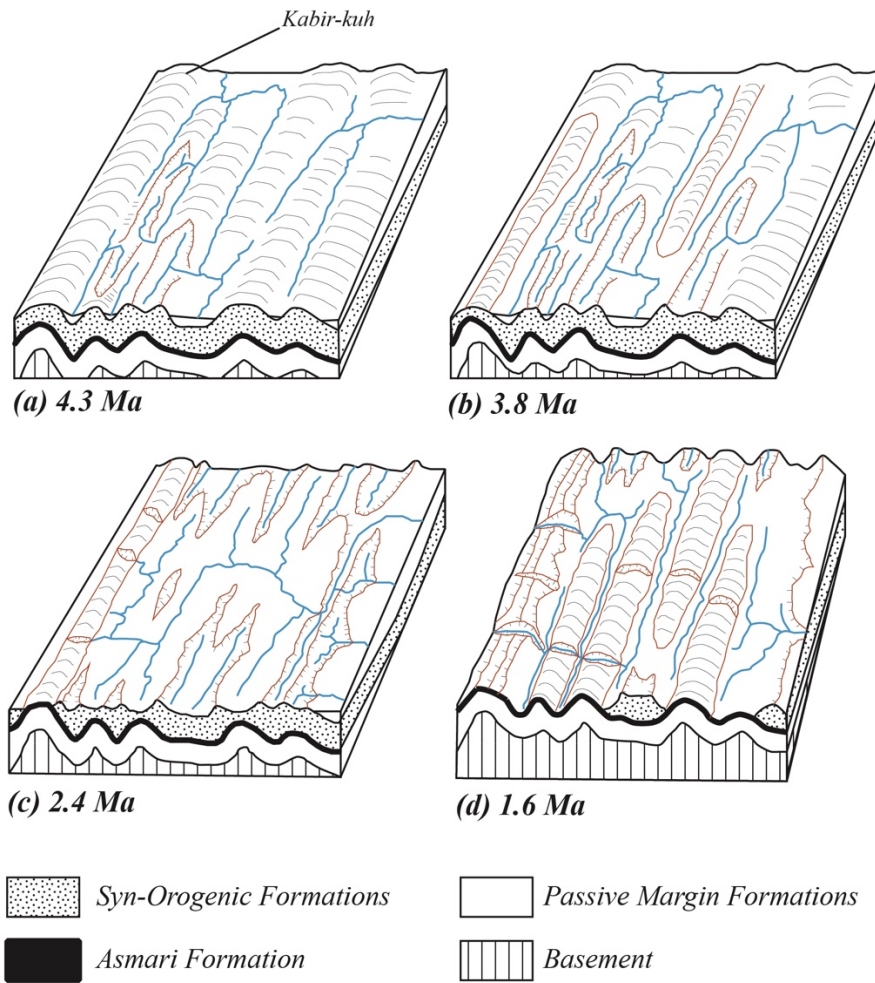


Figure 1: Simplified structural map of the Zagros mountain range with location of the **Seymareh landslide**. MZT, Main Zagros Thrust; HZF, High Zagros Fault; MFF, Mountain Front Fault; BR, Bala Rud fault zone (modified from Casciello et al., 2009).



**Figure 2: Geological Map, stratigraphic column and cross sections of the study area.**



**Figure 3: Evolution of the drainage network in the Zagros chain sector of the Kabir-kuh fold, according to the Oberlander's model and with the timing provided in the landscape evolution model by Tucker and Slingerland (1996). See the text for explanation of the four steps. (modified from Oberlander, 1985).**

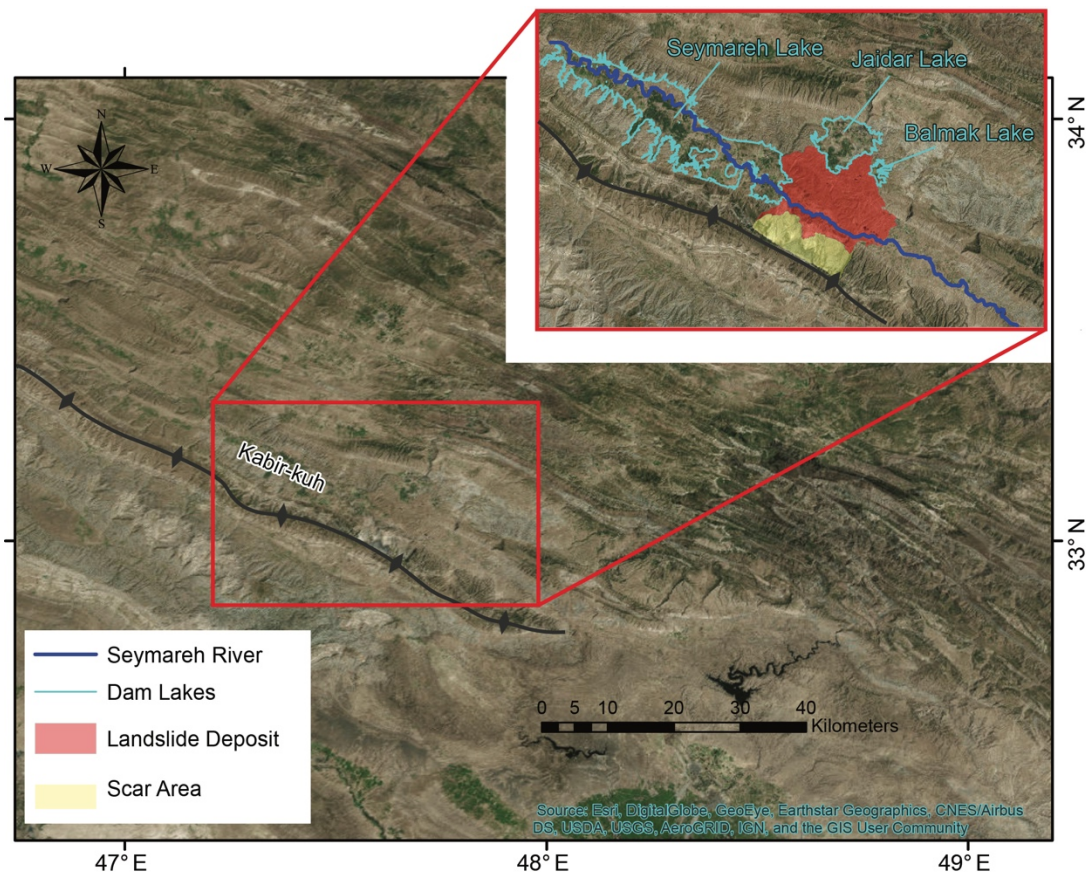
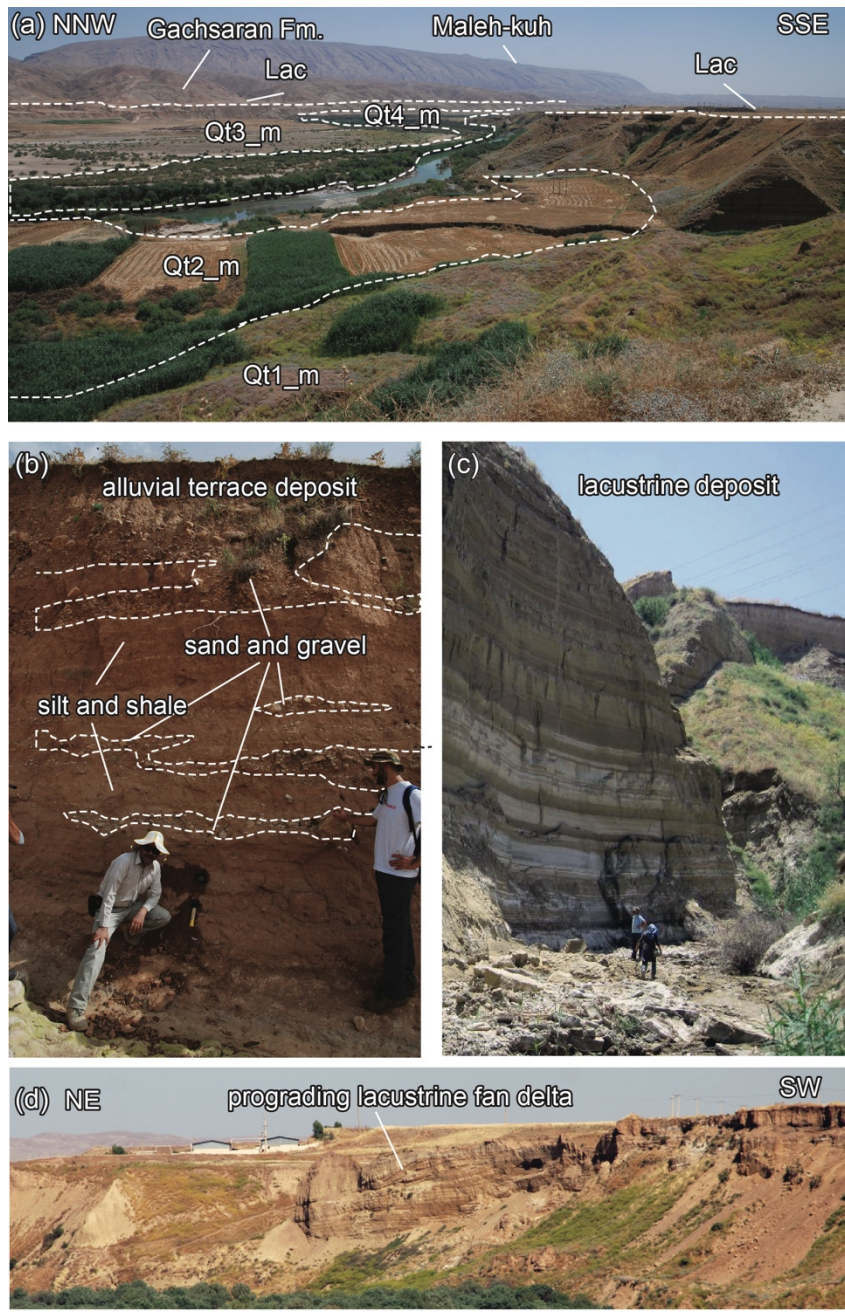


Figure 4: Overview and focus (in the red box) of the **Seymareh rock-avalanche<sup>SL</sup>**, Zagros Fold–thrust Belt, NW Iran. (modified from Google Earth®).



**Figure 5: Geomorphic markers upstream of the SL, represented by a suite of four orders of alluvial terraces entrenched in the lacustrine deposits (Lac) of Seymareh Lake upstream of the landslide, in the areas where Harrison and Falcon (1938), Roberts and Evans (2013) and Shoaee (2014) hypothesized the natural damming lake could be extended. a) Overall view of the suite of terraces; b) example of fluvial terrace deposit; c) example of lacustrine deposit; d) evidence of a prograding lacustrine fan delta formed by one of the right tributaries of Seymareh Lake during its early emptying phase.**

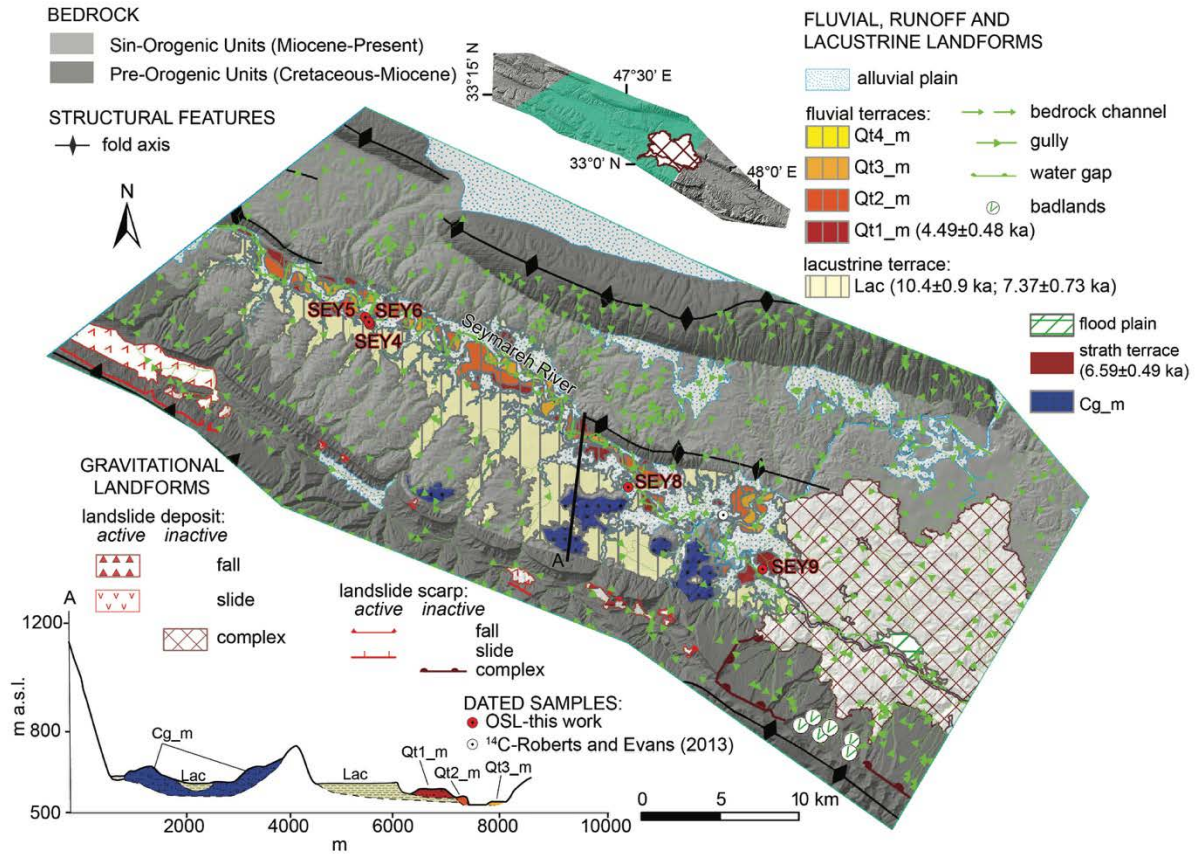


Figure 76: Map of the Seymarch Lake alluvial and lacustrine and alluvial terrace suite and of the most significant landforms for the valley slopes evolution upstream of the SL.

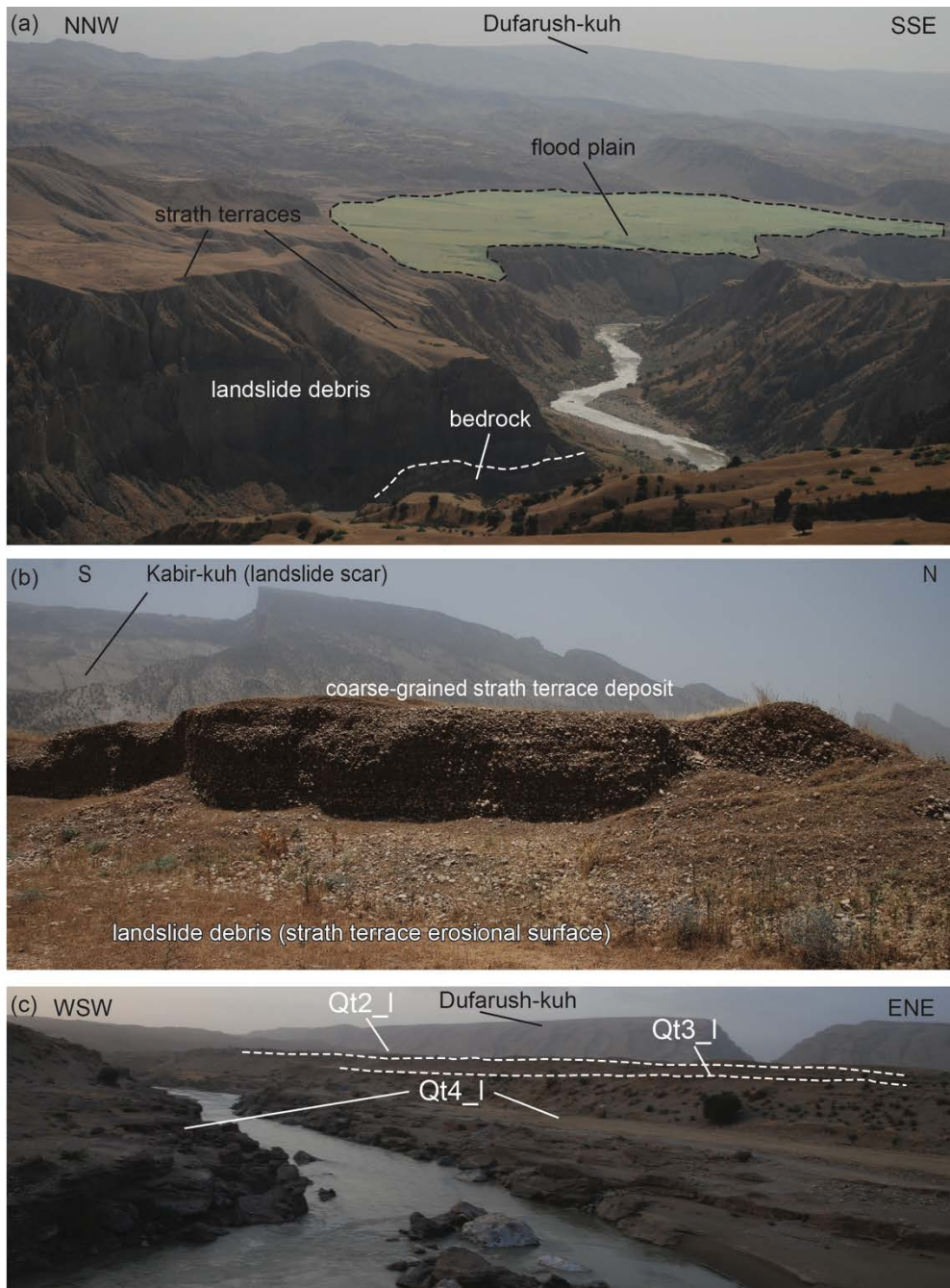
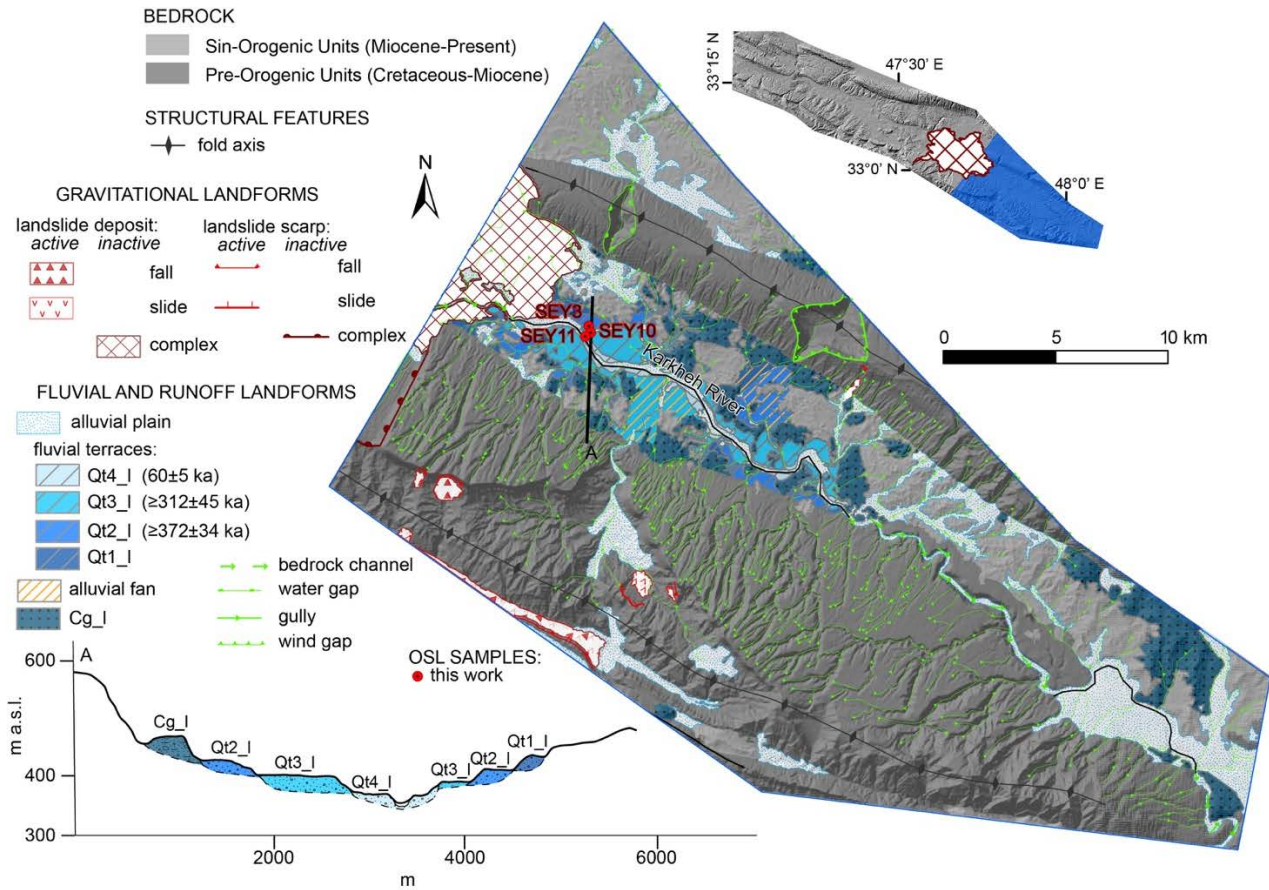


Figure 8:7: Geomorphic markers upstream of the SL. a) ~~Strath terraces~~ A strath terrace and a flood plain developed over the landslide debris, which are important markers of the evolution of the natural dam. ~~In fact, since~~ they testify to the moment of the overcoming of the damming lake and the overflowing of the river onto the landslide debris, respectively. ~~Both the landforms are~~ delimited by steep scarps caused by the fast engraving due to the Seymareh River that cut the entire landslide thickness and the



**underlying bedrock; b) detail of the strath terrace deposit sampled for OSL dating; c) The suite of fluvial terraces downstream of the SL; the Qt1 level is poorly preserved and not visible in this photo.**



5

**Figure 8:** Map of the alluvial terrace suite **downstream of the landslide** and of the most significant landforms for the valley slopes evolution **downstream of the SL**.

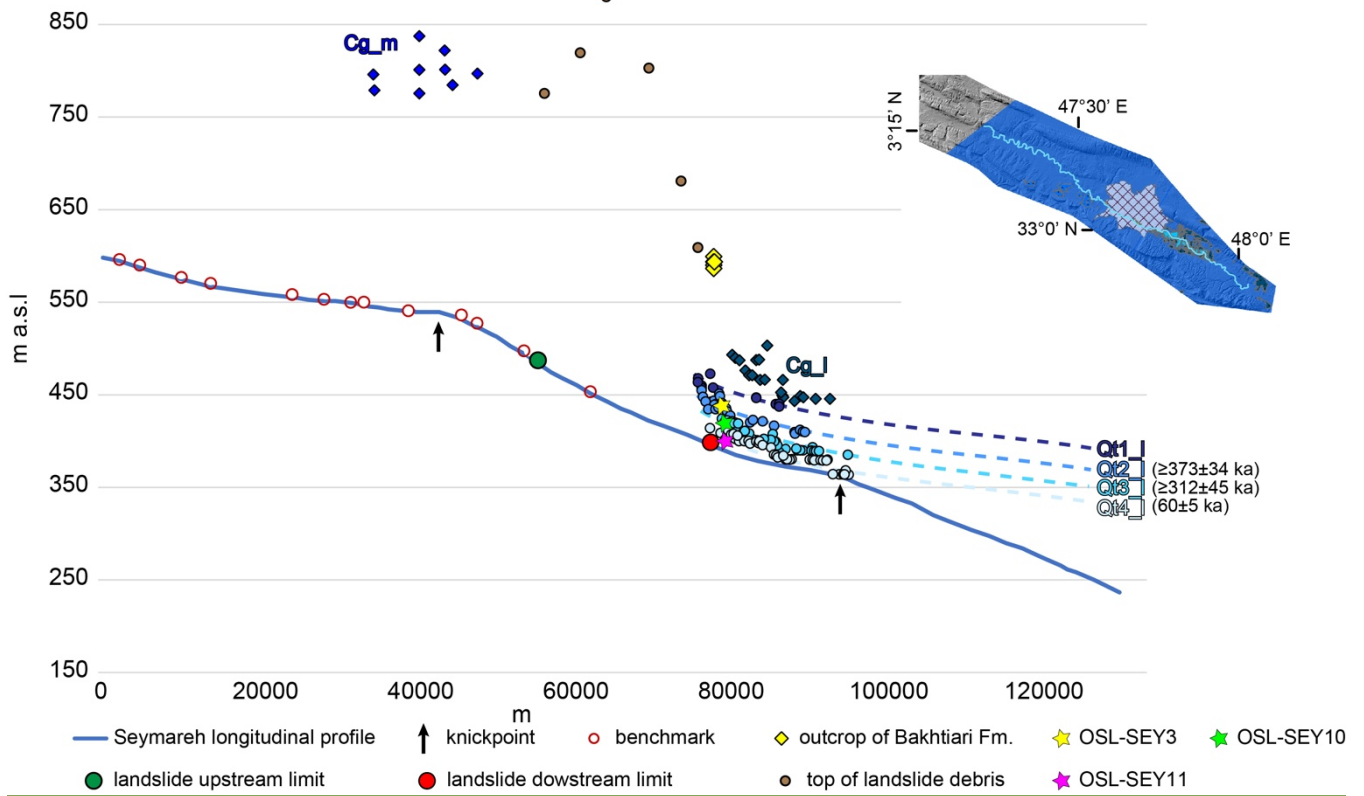


Figure 119: Projection of the pre-failure geomorphic markers (upstream and downstream conglomerates; downstream fluvial terrace suite) along the longitudinal profile of the Seymareh River and the age constraints resulting from the. The obtained OSL dating ages are indicated.

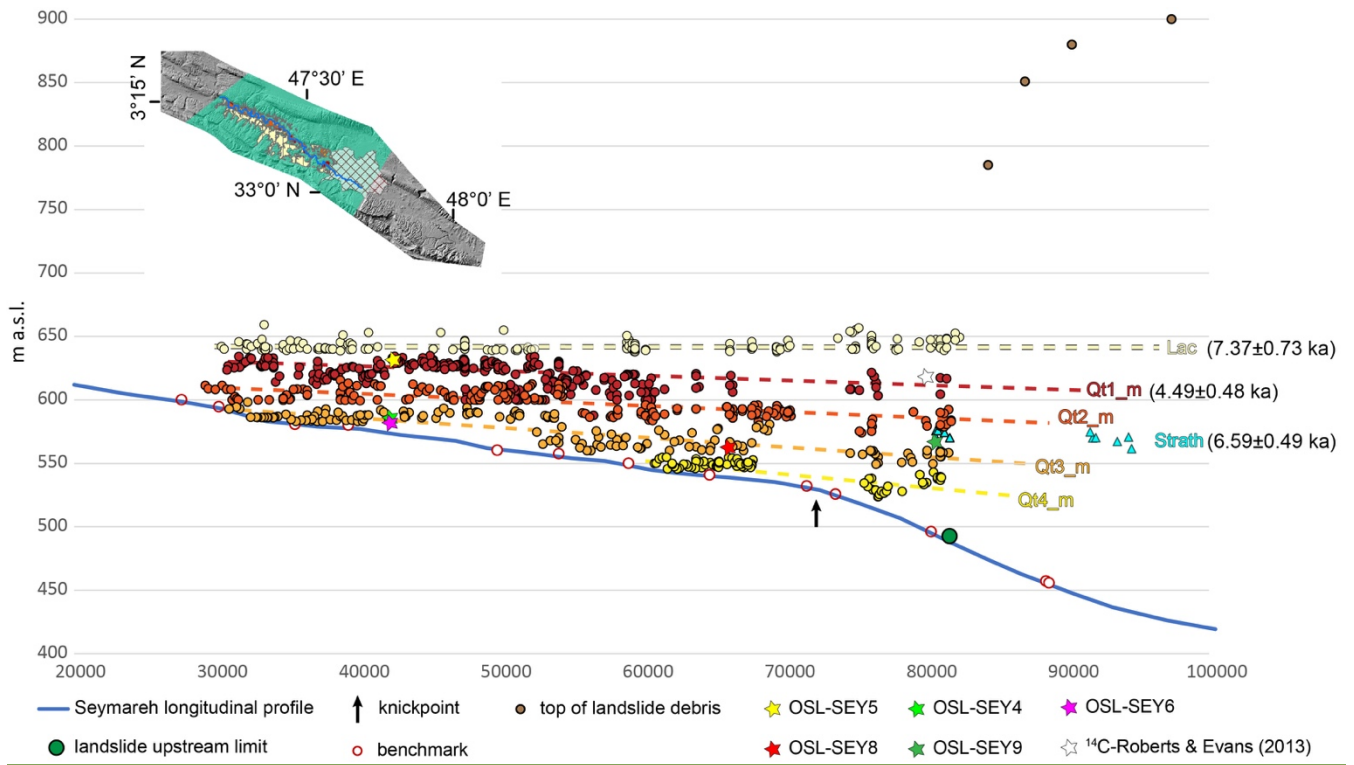
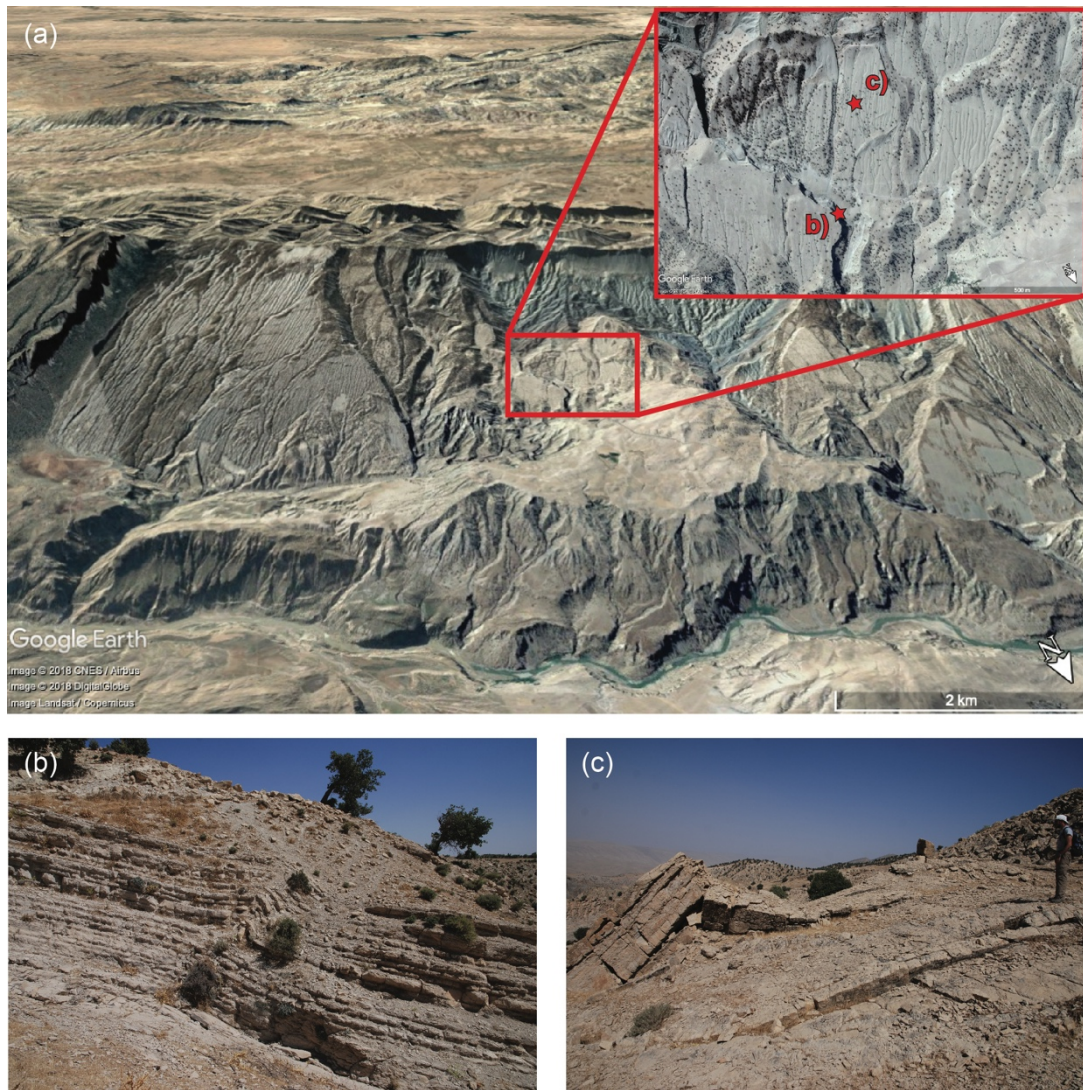


Figure 1210: Projection along the longitudinal profile of the Seymarch River of the post-failure geomorphic markers (fluvial terraces and lacustrine deposits relative to the Seymarch Lake suite) and the age constraints resulting from the. The obtained OSL dating ages are indicated.



**Figure 11: Scar area of the SL. a) front view of the scar area with the location of sites where evidence of buckling has been recognized; b) ductile buckling deformation of the Upper Pabdeh Member deformations within the layers of the Upper Pabdeh Member which cannot be referred to parasitic structural folding due to their localisation just below the SL sliding surface and to their reduced persistency (both lateral and vertical) within the rock mass; c) brittle buckling deformation of the Taleh Zang Member along the scar area.**

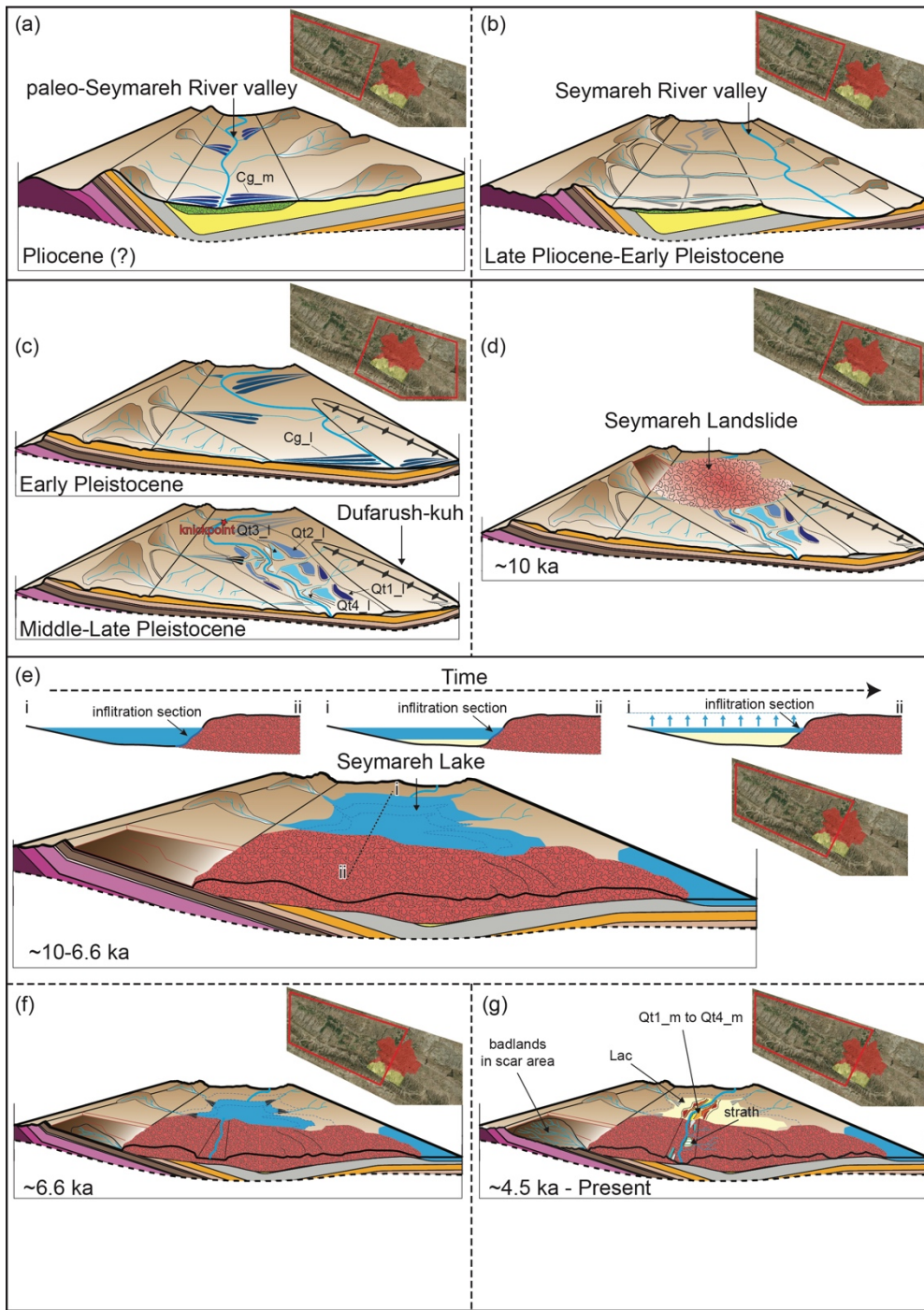


Figure 12: Evolutionary model of the Seymareh ~~river~~River valley. See text for explanation. Traces and legend of geological cross-sections are reported in Fig. 52.

**Table 1: OSL ages obtained for the geomorphic markers recognized in the Seymareh ~~river~~River valley. Detailed information and photos of sampling sites are available in the supplementary material.**

SAMPLE	DESCRITPION	COORDINATES	ELEVATION (m a.s.l.)	OSL AGE (ka)	ERROR (ka)
SEY4	lacustrine deposit	33° 13.197'N 47° 18.382'E	590	7.37	±0.73
SEY5	alluvial terrace deposit (Qt1_m)	33° 13.437'N 47° 18.219'E	607	4.49	±0.48
SEY6	alluvial deposit beneath the lacustrine deposit	33° 13.291'N 47° 18.358'E	580	17.9	±1.50
SEY8	lacustrine deposit at the base of Qt2_m	33° 7.402'N 47° 28.795'E	560	10.4	±0.90
SEY9	deposit of a strath terrace on landslide debris	33° 4.462'N 47° 34.197'E	570	6.59	±0.49
SEY3	alluvial terrace deposit (Qt2_l)	32° 59.591'N 47° 46.144'E	485	≥373*	±34
SEY10	alluvial terrace deposit (Qt3_l)	32° 59.335'N 47° 46.071'E	436	≥312*	±45
SEY11	alluvial terrace deposit (Qt4_l)	32° 59.265'N 47° 45.869'E	400	60	±5

5

# ~~New insights on the predisposing factors and geomorphic response to the largest landslide on emerged Earth surface: the Seymareh rock slide—debris avalanche (Zagros Mts., Iran)~~

Michele Delchiaro<sup>1</sup>, Marta Della Seta<sup>1</sup>, Salvatore Martino<sup>1</sup>, Maryam Dehbozorgi<sup>2</sup>, Reza Nozaem<sup>3</sup>

<sup>1</sup>Department of Earth Sciences, Sapienza University of Rome, Rome, Italy

<sup>2</sup>Department of Earth Science, Kharazmi University, Tehran, Iran

<sup>3</sup>School of Geology, College of Science, University of Tehran, Iran

*Correspondence to:* Michele Delchiaro ([michele.delchiaro@uniroma1.it](mailto:michele.delchiaro@uniroma1.it))

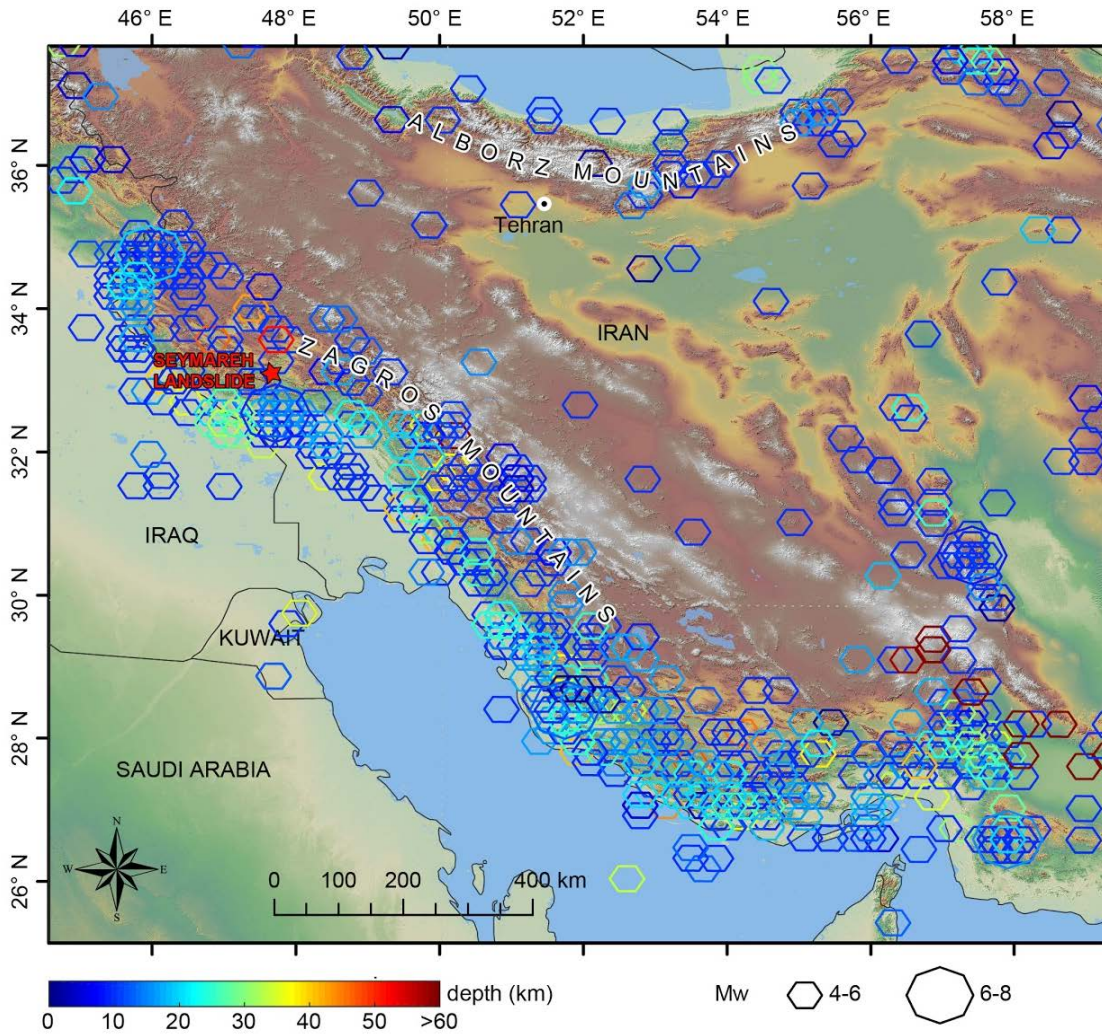
## ~~Supplementary material—S1. The Zagros Fold-Thrust Belt, Tectonics and Seismicity~~

The Seymareh Landslide occurred in the latter tectonic domain, included between the High Zagros Fault (HZF) to the northeast and the Mountain Front Fault (MFF) to the southwest. The Simply Folded Belt involve in spectacular folds the 12–14 km thick sedimentary rocks of the Arabian margin succession covering the continental basement (e.g., McQuarrie, 2004 and references therein). The irregular geometry of the MFF that bounds the Simply Folded Belt southwestward from the Mesopotamian foreland basin, describes salients and reentrants (McQuarrie, 2004; Sepehr and Cosgrove, 2004): respectively, from northwest to southeast, the Pusht-e Kuh Arc (Lorestan), the Dezful Embayment, the Izeh Zone and the Fars Arc. A representative balanced cross-section of the Dezful embayment (Blanc et al., 2003) indicates ~49 km of shortening across the Simple Folded Zone. Homke et al., 2004 provide the dates of 8.1 and 7.2 Ma for the onset of the deformation in the front of the Push-e Kush Arc (related to the base of the growth strata observed in the NE flank of the Changuleh syncline) that lasted until 2.5 Ma, around the Pliocene–Pleistocene boundary. A long-term shortening rate of ~10 mm y<sup>-1</sup> was derived for the deformation in the Simple Folded Zone, which is the same as the present-day one derived by GPS measurements (Tatar et al. 2002).

Seismicity is distributed in a 200-300 km wide area of the Zagros mountain range (Hatzfeld et al., 2010, Paul et al., 2010, Rajabi et al., 2011), with a sharp cut along the Main Zagros Reverse Fault in NE (e.g. Yamini-Fard et al., 2016). Looking at the depth and magnitude of recent earthquakes (Fig. S1), the seismogenic faults can generate recurrent earthquakes of Mw 5-6 and exceptional earthquakes of higher magnitude, i.e. up to Mw 6-8. These seismogenic faults follow the general trend of the Zagros, having NW-SE direction in the northwestern portion of the chain, while in the southeastern part they assume an E-W trend; they are characterized by high-angle planes (40-50°) reaching depths between 4 and 19 km (Hatzfeld et al., 2010;

Paul et al., 2010, Rajabi et al., 2011). The earthquakes, which originate at a variable depth of 12-19 km, are probably located in the crystalline basement or at the interface with the Cambrian-Pliocene cover, whose thickness reaches about 12 km. The shallowest earthquakes, located at 4-8 km of depth, are located inside the sedimentary cover and, in general, these events do not produce surface ruptures, probably due to the presence of marly and evaporitic levels that accommodate the deformation (Hatzfeld et al., 2010; Leturmy and Robin, 2010; Navabpour et al., 2010; Paul et al., 2010; Saura et al., 2011).

5



**Figure. S1: Magnitude and depth of the recent earthquakes recorded in the Zagros Mountains (source: IRIS Earthquake Browser, [https://www.iris.edu/hq/inclass/software-web-app/iris\\_earthquake\\_browser](https://www.iris.edu/hq/inclass/software-web-app/iris_earthquake_browser)).**



**S2. OSL sample details**

5

10

15

20

Sample No. **SEY3**

25 Sample Location (lat. and long required, country, state, county optional)

**LAT: 32° 59.591'N; LONG: 47° 46.144'E – WESTERN IRAN**

Sample depositional environment (e.g. eolian-medium sand, alluvial fan):

**SANDY-GRAVELLY ALLUVIAL DEPOSIT. WE SAMPLED A SANDY LAYER**

Stratigraphic and/or geomorphic context, sketch below (or attach photo):

30 **TERRACED ALLUVIAL DEPOSIT (LEVEL 2 OF 4 – same terrace sequence of SEY10 and SEY11)**



Estimate of burial moisture content:

**The one expected for an alluvial deposit in arid climate**

Elevation (meters above sea level)

5 **485 m a.s.l.**

Burial depth (meters from surface)

**~ 1.5 m**

Sample No. **SEY4**

10 Sample Location (lat. and long required, country, state, county optional)

**LAT: 33° 13.197'N; LONG: 47° 18.382'E – WESTERN IRAN**

Sample depositional environment (e.g. eolian-medium sand, alluvial fan):

**VARVED LACUSTRINE DEPOSIT.**

15 Stratigraphic and/or geomorphic context, sketch below (or attach photo):



Estimate of burial moisture content:

**The one expected for a lacustrine deposit in arid climate**

Elevation (meters above sea level)

5 **590 m a.s.l.**

Burial depth (meters from surface)

**~ 25 m**

Sample No. **SEY5**

Sample Location (lat. and long required, country, state, county optional)

10 **LAT: 33° 13.437'N; LONG: 47° 18.219'E – WESTERN IRAN**

Sample depositional environment (e.g. eolian-medium sand, alluvial fan):

**ALLUVIAL PLAIN DEPOSIT. WE SAMPLED A SANDY LAYER.**

Stratigraphic and/or geomorphic context, sketch below (or attach photo):

**TERRACED ALLUVIAL DEPOSIT (LEVEL 1 OF 3 – same sequence of SEY6 and SEY8)**



Estimate of burial moisture content:

**The one expected for an alluvial deposit in arid climate**

5 Elevation (meters above sea level)

**607 m a.s.l.**

Burial depth (meters from surface)

**~ 1.5 m**

Sample No. **SEY6**

10 Sample Location (lat. and long required, country, state, county optional)

**LAT: 33° 13.291'N; LONG: 47° 18.358'E – WESTERN IRAN**

Sample depositional environment (e.g. eolian-medium sand, alluvial fan):

**ALLUVIAL PLAIN DEPOSIT. WE SAMPLED A SANDY LAYER.**

15 Stratigraphic and/or geomorphic context, sketch below (or attach photo):

**TERRACED ALLUVIAL DEPOSIT (LEVEL 3 OF 3 – same terrace sequence of SEY5 and SEY8)**



Estimate of burial moisture content:

**The one expected for an alluvial deposit in arid climate**

5 Elevation (meters above sea level)

**587 m a.s.l.**

Burial depth (meters from surface)

**~ 5 m**

Sample No. **SEY8**

10 Sample Location (lat. and long required, country, state, county optional)

**LAT: 33° 7.402'N; LONG: 47° 28.795'E – WESTERN IRAN**

Sample depositional environment (e.g. eolian-medium sand, alluvial fan):

**SANDY-GRAVELLY ALLUVIAL PLAIN DEPOSIT. WE SAMPLED A SANDY LAYER**

15 Stratigraphic and/or geomorphic context, sketch below (or attach photo):

**TERRACED ALLUVIAL DEPOSIT (LEVEL 2 OF 3 – same sequence of SEY5 and SEY6)**



Estimate of burial moisture content:

- 5 **The one expected for an alluvial deposit in arid climate**

Elevation (meters above sea level)

**561 m a.s.l.**

Burial depth (meters from surface)

**~ 2.5 m**

- 10 Sample No. **SEY9**

Sample Location (lat. and long required, country, state, county optional)

**LAT: 33° 4.462'N; LONG: 47° 34.197'E – WESTERN IRAN**

Sample depositional environment (e.g. eolian-medium sand, alluvial fan):

**SANDY-GRAVELLY ALLUVIAL DEPOSIT. WE SAMPLED A SANDY LAYER**

- 15 Stratigraphic and/or geomorphic context, sketch below (or attach photo):



Estimate of burial moisture content:

**The one expected for an alluvial deposit in arid climate**

5 Elevation (meters above sea level)

**570 m a.s.l.**

Burial depth (meters from surface)

**~ 1.5 m**

Sample No. **SEY10**

10 Sample Location (lat. and long required, country, state, county optional)

**LAT: 32° 59.335'N; LONG: 47° 46.071'E – WESTERN IRAN**

Sample depositional environment (e.g. eolian-medium sand, alluvial fan):

**SANDY-GRAVELLY-CONGLOMERATIC ALLUVIAL PLAIN DEPOSIT. WE SAMPLED A SANDY LAYER**

Stratigraphic and/or geomorphic context, sketch below (or attach photo):

**TERRACED ALLUVIAL DEPOSIT (LEVEL 3 OF 4 - same sequence as SEY3 and SEY11)**



Estimate of burial moisture content:

- 5 **The one expected for an alluvial deposit in arid climate**

Elevation (meters above sea level)

**436 m a.s.l.**

Burial depth (meters from surface)

**~ 2 m**

- 10 Sample No. **SEY11**

Sample Location (lat. and long required, country, state, county optional)

**LAT: 32° 59.265'N; LONG: 47° 45.869'E – WESTERN IRAN**

Sample depositional environment (e.g. eolian-medium sand, alluvial fan):

**SANDY-GRAVELLY-CONGLOMERATIC ALLUVIAL PLAIN DEPOSIT. WE SAMPLED A SANDY LAYER**



Stratigraphic and/or geomorphic context, sketch below (or attach photo):

**TERRACED ALLUVIAL DEPOSIT (LEVEL 4 OF 4 - same sequence as SEY3 and SEY10)**



Estimate of burial moisture content:

**5 The one expected for an alluvial deposit in arid climate**

Elevation (meters above sea level)

**400 m a.s.l.**

Burial depth (meters from surface)

**~ 1 m**

**10 References**

[Blanc, E. J.-P., Allen, M. B., Inger, S. and Hassani, H.: Structural styles in the Zagros Simple Folded Zone, Iran, J. Geol. Soc. London, 160Bisbal, 401–412. Available from: Blanc et al 2003.pdf, 2003.](#)

- Hatzfeld, D., Authemayou, C., Van der Beek, P., Bellier, O., Lavé, J., Oveisi, B., Tatar, M., Tavakoli, F., Walpersdorf, A. and Yamini-Fard, F.: The kinematics of the Zagros Mountains (Iran), Geol. Soc. London, Spec. Publ., 330(1), 19–42, doi:10.1144/SP330.3, 2010.
- 5 Homke, S., Vergés, J., Garcés, M., Emami, H. and Karpuz, R.: Magnetostratigraphy of Miocene-Pliocene Zagros foreland deposits in the front of the Push-e Kush Arc (Lurestan Province, Iran), Earth Planet. Sci. Lett., 225(3–4), 397–410, doi:10.1016/j.epsl.2004.07.002, 2004.
- Leturmy, P. and Robin, C.: Tectonic and stratigraphic evolution of Zagros and Makran during the Mesozoic-Cenozoic: introduction, Geol. Soc. London, Spec. Publ., 330(1), 1–4, doi:10.1144/SP330.1, 2010.
- 10 McQuarrie, N.: Crustal scale geometry of the Zagros fold-thrust belt, Iran, J. Struct. Geol., 26(3), 519–535, doi:10.1016/j.jsg.2003.08.009, 2004.
- Navabpour, P., Angelier, J., and Barrier, E.: Mesozoic extensional brittle tectonics of the Arabian passive margin, inverted in the Zagros collision (Iran, interior Fars), Geol. Soc. London, Spec. Publ., 330(1), 65-96, doi:10.1144/SP330.5, 2010.
- Paul, A., Hatzfeld, D., Kaviani, A., Tatar, M. and Péquignat, C.: Seismic imaging of the lithospheric structure of the Zagros mountain belt (Iran), Geol. Soc. London, Spec. Publ., 330(1), 5–18, doi:10.1144/SP330.2, 2010.
- 15 Rajabi, A. M., MahdaviFar, M. R., Khamsehchiyan, M. and del Gaudio, V.: A new empirical estimator of coseismic landslide displacement for Zagros Mountain region (Iran), Nat. Hazards, 59(2), 1189–1203, doi:10.1007/s11069-011-9829-1, 2011.
- Saura, E., Verges, J., Homke, S., Blanc, E., Serra-Kiel, J., Bernaola, G., Casciello, E., Fernandez, N., Romaine, I., Casini, G., Embry, J. C., Sharp, I. R. and Hunt, D. W.: Basin architecture and growth folding of the NW Zagros early foreland basin during the Late Cretaceous and early Tertiary, J. Geol. Soc. London., 168(1), 235–250, doi:10.1111/j.1601-
- 20 5037.2004.00096.x, 2011.
- Sepehr, M. and Cosgrove, J. W.: Structural framework of the Zagros Fold-Thrust Belt, Iran, Mar. Pet. Geol., 21(7), 829–843, doi:10.1016/j.marpetgeo.2003.07.006, 2004.
- Tatar, M., Hatzfeld, D., Martinod, J., Walpersdorf, A., Ghafori-Ashtiany, M. and Chéry, J.: The present-day deformation of the central Zagros from GPS measurements, Geophys. Res. Lett., 29(19), 33-1-33–4, doi:10.1029/2002GL015427, 2002.
- 25 Yamini-Fard, F., Hatzfeld, D., Tatar, M., and Mokhtari, M.: Microearthquake seismicity at the intersection between the Kazerun fault and the Main Recent Fault (Zagros, Iran), Geophys. J. Int., 166(1), 186-196, doi:10.1111/j.1365-246X.2006.02891.x, 2006.