Response to comments by P. Carling

We are grateful for the constructive comments by Paul Carling (hereafter: reviewer) on our manuscript. Below we respond to all points raised in his review and outline how we changed our manuscript accordingly.

General comments:

Potentially this is a useful contribution to the literature on seepage channels both on Earth and on Mars. The experiments are simple but well designed to address key questions as to the nature of channel network development due to local or distal seepage. The illustrations are informative and of very good quality.

We are happy that the reviewer appreciates the key focus of our paper: an apparently simple experiment to elucidate the complex processes driving valley network development.

However I found the text obfuscated in places and below I try to explain how a clearer argument could be constructed such that the work will be accessible to a wide readership.

We acknowledge these concerns and very much appreciate the suggestions – many of which we have acted upon as detailed below.

Specific comments:

1) A crux issue is the conditions which lead to either theatre-headed channels or V-slot headed channels. The difference in the planform nature of these two morphologies is outlined in Results and the Discussion and the difference in process controls is also alluded to throughout the work. However it would be much better if these two morphologies could be defined in the Introduction together with a planview definition diagram of the channel head morphologies and the likely channel network configurations. The processes which are known to lead to theatre-head or V-shaped channel heads also need introducing at this point. Distinctive hypotheses could then be stated and explored using the data obtained in the experiments. Instead I found the Introduction to be less than specific in orientating the reader as to what to expect in this manuscript.

We agree with the reviewer that there is limited discussion of the formation of V-shaped valley heads. The reason is that the difference between theater-shaped and V-shaped valleys is not the main point of our work. Nevertheless, it is indeed touched upon in the results. On reflection we concur with the reviewer that this needs mentioning in the introduction, which will also make our work more accessible to a wider readership. We have therefore embraced the proposed solution of the reviewer and included a new (figure 2) in the introduction to guide the explanation of the different channel-forming processes.

2) Although the two basic experiments are distinctive I am unsure about the names given to each type as the issues of how to define 'local' and 'distal' are not considered carefully enough and references to 'local groundwater source' as at line 19 Page 132, amongst others, are difficult to evaluate as it is not *clear just what 'local' means. The distal experiment consists of flow emanating from a reservoir 'far' upstream from the break of slope. In contrast the 'local' experiment consists of rainfall evenly distributed over the whole experimental sand box with infiltration occurring but in addition in some experiments overland flow occurred (e.g. line 8 Page 141) so the control is not purely groundwater. Although these two basic experimental conditions provide useful contrasting environments I am not sure if the latter should be termed a local groundwater control. A local groundwater control to me would consist of up-welling of water locally close to the break of slope rather than due to infiltrated rainfall across the whole domain (and with no overland flow). It is not evident why rainfall universally applied over the whole terrain should be termed a 'local' source (line 15 Page 133).*

The terminology for the two experiments requires some further explanation. We chose the terms local and distal since these terms are concise and contrasting, and thus capture the main differences between the experiments, which was the basis for the experimental design. Indeed, more precise terminology for the experimental conditions are 'groundwater seepage from an upstream constant head tank' and 'overland flow and groundwater seepage from precipitation and subsequent infiltration'.

In order to avoid confusion, we changed the names of the experiment to the following short names that represent their boundary conditions better and include the contrasting terms local and distal: 'Distant source and 'Local precipitation'. We explain this more fully in our revised methods section. In the discussion we do now consider broader groundwater systems as analogues.

3) The results in the large are qualitative and this is not a problem but it does lead to problems with the Discussion. I found that the Discussion could have been more focussed and less speculative. The experimental conditions are necessarily constrained and thus these constraints induce limitations to the possible morphological outcomes. It would have been useful if the Discussion could have considered these limitations and further made suggestions as to what additional set-ups might prove additional insight.

This comment follows upon the points discussed in the previous point. We have changed the terminology of the experiments to better reflect what is happening in the experiment, and we extended section 5.2 (first and last paragraph) of the discussion where we discuss the applicability of the experiments. We think that this results in a more rounded and less speculative prose.

4) Line 12 Page 137 you introduce bifurcation angles here but do not provide a methodological reference until the next page. It is important to know just how these are defined. Further in the introduction we have no idea how these should vary between different process domains and so the bifurcation results are difficult to evaluate.

We rephrased this in the methods as: 'At each node of converging valleys, we calculated the angle between the upstream valley segments'.

Indeed, it is problematic that the typical angles for the bifurcations are unknown for the different domains. Previous work has shown a typical value of 72 degrees for uniform infiltration as groundwater source, but such analyses are absent for other domains. Furthermore, many other properties affect such angles.

In our effort to provide a framework of the end-members in a seepage landscape, we want to point out that the above mentioned 72 degree is limited to only one case and is often miss-used for other cases. Furthermore, our work on these angles is explorative and we does not rely heavily on these results. Nevertheless, since these angles are an important part of the network and are often used in recent literature, we did feel this should be part of our manuscript.

In response we changed section 5.4 to make this point clearer and parts of this discussion have been moved from section 5.5 to separate theoretical considerations (as stated above) and consideration of the effect of structural controls.

5) Line 20 Page 23 and Line 3 Page 140 - this cannot be a mudflow as you have sand for a bed. Revise.

Indeed, this was the wrong terminology. We have rephrased this to stick to our observations.

6) Line 26 Page 139 here you indicate the processes show cyclic behaviour. You need to explain why this should be the case and expand on this point in the Discussion

This is explained as: 'These processes showed a cyclic behavior: head collapse only occurred after a destabilization of the head due to the removal of the sediment by fluvial transport. This cycle is essential for the continuation of the process as the channel head would stabilize without such erosion and sediment transport.' In the results section, which we believe is sufficient explanation.

We extended our 5.1 of the discussion to reflect this point.

7) Lines 5 to 6 Page 143. I have some problems here. It is not clear how the water comes to be ponded and then released. Also at line 9 we have pressurized groundwater introduced as a possible explanation. This is very vague and needs further amplification of argument for it to be accepted as a reasonable explanation.

We have rewritten the final paragraph of section 3. We describe the ponding better, which is the result of the sediment becoming saturated and we have removed the confusing reference to pressurized groundwater.

8) Lines 20 to 25 Page 145. In the results there is no mention of hyper-concentrated flows or how this was defined. You cannot argue that this is the controlling process for morphological transition in the Discussion without providing the evidence in the Results prior.

This point relates to point 5, we have indeed no measurements. We rephrased this to stick with our observations.

9) Lines 12 to 15 page 151. Your argument re Martian channels presupposes they have a uniform geology as in your experiments whereas in reality structural controls might control valley alignment.

In addition the meaning is not clear. Higher order channels might have a gradient that <u>*is*</u> *opposite to the main channels though I cannot envisage how this is possible but if they have the 'opposite direction' then they have an identical alignment. Indeed you note structural controls latterly at line 8 page 152 Revise to clarify.*

We agree with the reviewer and can see how this part was unclear given that we mixed up two concepts. We have revised this part and make two separate points now: First is the densely dissected / 'filled' landscape of Louros Valles, which has high-order valleys going in opposite direction of the main valley. We consider this an important clue for the responsible groundwater source. Secondly, we discuss the bifurcation angles. For clarity, we moved the discussion of the applicability of the theoretical 72 degrees and structural control to section 5.4. We show they average around the theoretical 72 degrees but with a huge spread.

10) The Discussion re the Martian systems assumes the reader is familiar with the published arguments as to sources of (ground)water on Mars. However in places it is not clear what arguments are referring to published papers – such as the source of groundwater for Nirgal Vallis (line 9 Page 152) or if this is your speculation. Thus speculation and 'fact' are mixed up – additional citations to Martian literature are required.

We agree with the reviewer on this point. We refer to literature on Martian hydrology (Harrison and Grimm, Clifford) in this part (5.5) and describe this more accurately.

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Groundwater seepage landscapes from distant and local sources in experiments and on Mars

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Abstract. ~~Theater-headed valleys can form by undercutting caused by the seepage of groundwater , but such valleys can also be the~~ Valleys with theater-shaped heads can form due to the seepage of groundwater or as a result of knick-point (waterfall) erosion generated by overland flow. This ~~morphological ambiguity~~ ambiguity in the mechanism of formation hampers the interpretation of ~~formative processes and responsible hydrology of~~ such valleys on Mars, ~~especially due to insufficient~~ particularly since there is limited knowledge of material properties. ~~Instead of single-valley morphology, metrics of the entire landscape~~ Moreover, the hydrological implications of a groundwater or surface water origin are important for our understanding of the evolution of planet Mars and quantification of valley morphologies at the landscape scale may provide diagnostic ~~insight in~~ insights on the formative hydrological conditions. However, flow patterns and the resulting landscapes ~~are different for different~~ produced by different sources of groundwater ~~and~~ are poorly understood. We aim to ~~increase our~~ improve the understanding of the formation of ~~the entire landscapes by seepage from different sources of groundwater and to~~ entire valley landscapes through seepage processes from different groundwater sources that will provide a framework of landscape metrics ~~of such systems to aid~~ for the interpretation of such ~~landscapes~~systems. We study ~~seepage from local and distal sources of groundwater in~~ groundwater seepage from a distant source of groundwater and from infiltration of local precipitation in a series of sandbox experiments and combine our results with previous experiments and observations of the Martian surface. Key results are that groundwater ~~flow-piracy acts on distally-fed valleys , which~~ flow piracy acts on valleys fed by a distant groundwater source and results in a sparsely dissected landscape of many small and a few large valleys~~while locally-fed valleys~~ . In contrast, valleys fed by a local groundwater source, i.e. nearby infiltration, result in a densely dis-

sected landscape. In addition, ~~distally-fed valleys grow into the direction of the groundwater source while locally-fed valleys~~ valleys fed by a distant groundwater source grow towards that source while valleys with a local source grow in a broad range of directions and have a strong tendency to bifurcate, particularly on ~~flat horizontal surfaces. To exemplify our interpretive framework, we apply these results~~ flatter surfaces. We consider these results with respect to two Martian cases~~. The valleys of Louros Valles seem to have formed by seepage erosion from~~: Louros Valles show properties of seepage by a local source of groundwater and Nirgal Vallis shows evidence of a ~~distal sourceof groundwater .~~ distant source, which we interpret as groundwater flow from Tharsis.

1 Introduction

~~Add short section on a step broader: channels, valleys, v-shaped, seepage, sapping. Then elaborate a bit on theatre-shaped valley heads and link with next.~~

Valleys with theater-shaped heads exist in the landscapes of Earth and Mars. On Mars, examples of such valleys are ~~for example~~ Louros Valles (Fig. 1a) and Nirgal Vallis (Harrison and Grimm, 2005). Terrestrial examples can be found in the Atacama Desert in Chile (Fig. 1b), on the Canterbury Plain, New Zealand, on the Colorado plateau and on Hawaii (Schumm and Phillips, 1986; Howard and Kochel, 1988; Craddock et al., 2012). Furthermore, much smaller ~~, but~~ examples that are similar in shape, are valleys that emerge in eroding riverbanks (Fig. 1c) or those on the beach that develop during a receding tide (Higgins, 1982; Otvos, 1999; Fox and Wilson, 2010; Hagerty, 1991).

~~The small valleys on the beach and riverbanks form in several hours by seeping~~ Such theater-headed valleys can form by the seepage of groundwater in ~~unconsolidated sediment . The governing processes and morphology are the same as in groundwater seepage experiments (e.g. Howard and McLane, 1988) and consist of undercutting by erosion by groundwater seepage and resulting head wall collapse. This process is also known to be responsible for the valleys in the Colorado plateau sandstone (e.g. Laity and Malin, 1985), and has long been thought to be the cause of the formation of valleys on Hawaii and on Mars (Kochel and Piper, 1986).However, head-wall retreat due to undercutting by waterfall erosion of a hard cap rock produces similar valley morphology (Lamb et al., 2006)and is probably a better explanation for the~~ erodible sediment (e.g. Howard and McLane, 1988). These valleys form due to headward erosion that is produced by mass-wasting processes where groundwater seeps to the surface (Fig. 2a). In this paper we define *seepage* as the hydrological process of groundwater emerging at the surface and groundwater *sapping* as the geomorphological process of erosion by undercutting which is triggered by seepage, although not all erosion by seepage of groundwater results in undercutting. We define a *valley* as an erosional geomorphological feature, where a *channel* is a body of flowing water. The aim of this study is to investigate valley formation that develops from groundwater seepage that is sufficient to maintain an active channel.

Valley formation by seepage (Fig. 2a) is different from valley formation by overland flow. In the former, headward progression is the result of knickpoint retreat and fluvial incision (Fig. 2b). However, overland flow can also produce similar theater-headed valleys when incising into a substrate with an erosion resistant top-layer (Lamb et al., 2006). This process is a likely candidate for the formation of the theater-headed valleys next to the Snake River in Idaho (Fig. 1d)~~and the Chilean valleys (Irwin et al., 2014).~~

~~The main argument against a groundwater origin of~~ . The ambiguity in the mechanism of formation of the valleys hampers the interpretation of their origin based on their theater-shaped morphology alone. This ambiguity is particularly problematic for the ~~Martian valleys is the limited erodibility by the low seepage discharge (Lamb et al., 2006), but the material properties of Mars are largely unknown, which hinders unambiguous interpretation of the formative mechanism of the theater-headed valleys. Furthermore, small upstream channels feeding the main valleys are expected for waterfall erosion which are visible in terrestrial cases (e.g., Fig. 1e), but evidence for such a source is missing for many Martian cases. Most importantly, formation by either waterfall erosion or groundwater seepage has different implications for the responsible hydrological conditions. Waterfall erosion requires a large flood event or a long period with flowing water on the surface, which requires atmospheric conditions to sustain liquid water. Whereas seepage erosion could occur under surface conditions where liquid water is not stable, as the recharge of groundwater could be far in the past.~~ explanation of theater-shaped valley-heads on Mars where direct field observations and material properties are lacking, and a long period of weathering obscures morphological details.

~~Besides the single-valley morphology, the landscape properties of~~ The morphological properties of entire landscapes with multiple valleys may help in the interpretation of ~~the Martian valleys~~these Martian valleys, when single entities have an ambiguous origin. An important ~~feedback for~~ mechanism for the landscape formation by groundwater seepage is ~~flow piracy,~~ groundwater flow piracy: since valleys are topographic depressions, ~~hence~~ they attract more groundwater from their ~~surrounding, possibly resulting in the abandonment of other valleys(Howard and McLane, 1988).~~ surroundings, resulting in a decrease of discharge to nearby valleys. (Howard and McLane, 1988). As a result, smaller valleys cease to develop in favor of larger valleys. Landscape metrics may ~~provide information on~~ show the presence of ~~feedback mechanisms like groundwater piracy~~this feedback mechanism. Furthermore, ~~the angle of valley bifurcations, and the~~ splitting of valleys during their headward development (headward bifurcation) produces typical angles between valley segments Devauchelle et al. (2012); Glines and Fassett (In case of valley formation by seepage from uniform precipitation, the theoretical angle between valley segments becomes 72° (Devauchelle et al., 2012). Such properties as well as the orientation of valleys ~~could indicate the~~ (Jaumann and Reiss, 2002) can be extracted from the landscape and show the responsible hydrological system~~and the location of the groundwater source (Jaumann and Reiss, 2002; Devauchelle et al., 2012; G~~

Our knowledge of ~~the groundwater sapping~~ groundwater seepage processes and their relation to landscape evolution is ~~rather~~ limited. Particularly as systems with only groundwater processes are absent on Earth and previous ~~experimental~~ studies were mostly limited to the same boundary conditions of groundwater from ~~a~~ an upstream constant-head tank (e.g. Howard and McLane, 1988; Lobkovsky et al., 2004; Schorghofer et al., 2004; Pornprommin et al., 2010; Marra et al., 2014a). These experiments simulated a distant groundwater source and showed the basic morphology of ~~sapping valleys , revealing~~ valleys formed by groundwater seepage and also revealed the importance of groundwater flow piracy as a key process for valley evolution. However, alternate hydrological systems exist where other processes ~~play a role, which results~~ are significant and result in a different landscape evolution. ~~For example, in~~ In contrast to a ~~ ~~distant groundwater source, ~~a local groundwater source can release water from a shallow aquifer, generated by local~~ groundwater seepage could come from nearby infiltration of precipitation. Such systems exist on Earth (Abrams et al., 2009; Fig. 1f) and have been studied in experiments to some extent (Berhanu et al., 2012), but require more attention in terms of their morphological impact on landscape dynamics. We hypothesize that a local groundwater source, e.g. as result of locally infiltrated precipitation, results in less groundwater flow piracy compared to groundwater that first travels some distance ~~, because a local~~ before seepage to the surface, because seepage from a nearby source is less influenced by the ~~regional topographic gradient~~ topographic gradient responsible for flow piracy. Since flow piracy is an important mechanism in the formation of ~~theater-headed~~ valleys by groundwater seepage, we expect ~~a different~~ different and distinct morphological development for ~~locally-fed sapping valleys .~~ valleys formed by seepage from a local source compared to those produced by distally fed systems. Specifically, distant sources of groundwater produces landscapes with abandoned valleys whereas in landscapes produced by local sources of groundwater, there are no or hardly any abandoned valleys.

In this paper, we aim to ~~increase~~ improve our understanding of groundwater seepage processes, specifically on the resulting valley formation ~~. In order to expand our knowledge on the possible range of processes, we~~ at a landscape scale using morphological experiments. We specifically study the difference in morphological development of valleys that ~~emerge from distant and local sources of groundwater in sealed experiments~~result from a distant groundwater source (simulated with an upstream constant-head tank), and a local groundwater source (simulated by infiltrating precipitation). Furthermore, we combine our experimental insight with previous studies in order to ~~cover~~ show a complete range of ~~possible sapping systems~~landscapes formed by groundwater seepage under different conditions. The objective is ~~essentially~~ to provide a framework that shows the arrangement of multiple valleys, i.e., the orientation and length distribution that ~~result~~ results from different hydrological boundary conditions. These properties will aid in the identification of the formative processes when the single valley morphology is ambiguous, and will constrain the ~~hydrological and climate conditionsduring formation. As an example, we apply our developed framework to two often-cited~~ underlying hydrological conditions. To demonstrate the application of this framework for landscape interpretation, we use two frequently cited cases of groundwater seepage on Mars, Nirgal Vallis and Louros Valles, and relate their landscape metrics to the possible sources of groundwater.

2 Methods

2.1 Experimental design

~~We conducted several~~ We conducted a series of flume experiments in the Total Environmental Simulator (TES) facility at the University of Hull to ~~study~~ investigate the morphological development of theater-headed valleys by ~~seeping groundwater~~ groundwater seepage. Moreover, with these experiments we ~~studied the effect of groundwater seepage from a local and from a distal source . We simulated groundwaterseeping from a distal source by~~ simulated the difference between groundwater seepage generated by a distant source of groundwater, using a ~~fixed-head~~ constant groundwater level at the upstream end of the ~~setup. As a local source of groundwater, we applied precipitation on the entire experiment domain, using an intensity~~ experimental setup, and groundwater seepage produced by infiltration of precipitation applied over the entire experimental domain. The distant groundwater source was maintained using a constant-head reservoir at a level below the sediment surface and the precipitation was generated using an array of nozzles spraying water at a rate lower than the infiltration capacity of the sediment. We repeated both experiments with an idealized initial morphology and with a heterogeneous initial morphology that was the result of a previous experiment. In this section, we present the setup, the initial topography and applied boundary conditions across the experimental set.

The initial idealized morphology consisted of a volume of sand with a median grain size of 0.7 mm, that comprised (1) a flat area of 1.7 m upstream and (2) a slope of 0.22 $\mathrm{m\,m^{-1}}$ for 3.5 m (Fig. 3), which was ~~equal~~ uniform over a width of 4 m. ~~The~~ We used natural, moderately angular sand to mimic natural groundwater and surface flow processes. The grain size was such that groundwater flow was neither too rapid nor too slow for the formation of valleys within a reasonable period of time. The sloping section ensured seepage of groundwater from a hydrostatic groundwater level, ~~i. e. not pressurized.~~ that is, without applying extra pressure to the groundwater.

The sediment was placed on top of a partially sloping impermeable floor to increase groundwater flow in the downstream half of the setup and to reduce the amount of sediment required. This floor was flat for 2.6 m and the slope was 0.11 $\mathrm{m\,m^{-1}}$ for 2.6 m. Pond liner ensured the impermeability of the floor and walls. A rough cloth on top of the pond liner prevented the entire block of sediment from sliding down the smooth pond liner surface. The total sediment depth was 0.5 m in the upstream flat part, sloping towards the downstream end. At the downstream end, a row of 6 cm high bricks truncated the wedging slope to prevent the sediment from sliding down. In addition, the small spaces between these 10 cm wide bricks acted as initial surface perturbations. This ensured ~~evenly distributed channel initiation~~ valley initiation was evenly distributed over the entire width of the sediment surface.

~~To simulate a groundwater system from a distal source , we used a constant head tank at the upstream end of the setup. This constant head tank was constructed over~~ The constant-head tank was designed to simulate a distant groundwater source and was constructed opposite of the sloping wedge of sediment. It spanned the entire width ~~of the setup using~~ and depth of the sediment fill with a 0.6 mm mesh fabric, braced with chicken wire and steel gratings ~~. To simulate a local groundwater system~~at the water-side to retain the sediment and avoid collapse into the reservoir under the weight of the sand. This setup enabled water from the constant-head tank to enter the body of sediment over the entire width and depth at the upstream side of the flat section of the sediment fill.

For the experiment with precipitation as the water source, we used ~~a series~~ an array of spray nozzles above the setup to supply water over the sediment surface. These nozzles were ~~set to spray at such discharge~~ fed with a discharge such that the water ~~infiltrated, which corresponds with a discharge~~ spray infiltrated in the flat area and seeped-out on the sloping wedge. The discharge feed was slightly lower than the infiltration capacity of the sediment. A rising groundwater table induced seepage, but, in contrast to the constant head tank, the seepage areas were fed by ~~locally~~ nearby infiltrated groundwater. Twelve spray nozzles with square spray patterns were used ~~, which were pressurized~~ to ensure uniform spray distribution and pressurized water was fed from a ring main to ensure equal spray rates for all nozzles.

We carried out five experiments with the above described boundary condition combinations (Table 1) ~~. Experiment "Distal"~~ under terrestrial conditions. The experiment labelled *Distant source* was carried out ~~entirely with the constant head tank as boundary condition~~with the constant-head tank throughout as the boundary condition using the initial topography described above. The final ~~morphology of this~~ surface morphology from the *Distant source* experiment was used as initial morphology of ~~experiment "Local after Distal"~~the experiment labelled *Local after distant*, which was run with water input from the spray nozzles. ~~Experiments "Local"~~ The experiment labelled *Local precipitation* was run with water input from the spray nozzles on the above-described initial topography. ~~Experiment "Local 2" was only~~ The experiment labelled *Local precipitation 2* was run to generate an initial morphology with the same conditions as ~~"Local", but~~ *Local precipitation* and this experiment was ceased early. The final morphology of ~~"Local 2"~~ *Local precipitation 2* was the initial morphology of ~~"Distal after Local"~~*Distant after local*, which was subject to groundwater flow ~~from the constant head~~ generated by the constant-head tank.

2.2 Experimental imagery and elevation models

We captured the morphological development of the experiments using time-lapse photography. These images ~~allowed~~ enabled us to study the experiments in detail from different angles. Moreover, we derived ~~channel~~ valley dimensions from orthorectified time-lapse images. The time-lapse setup consisted of six cameras (Canon PowerShot A640), mounted around the experimental setup (see C1–C6 in Fig. 3), which were ~~synchronously triggered~~ triggered synchronously at set intervals. These intervals ~~differed~~ ranged from 30 s to 5 min, based on the ~~pace of the morphological development in~~ rate of morphological development during the ongoing experiment (values in Table 1).

For each experiment, time-lapse imagery from four ~~angles were processed to a single orthorectified image. Camera's~~ cameras (C1, C2, C4 and C5) were processed to construct a single orthorectified photograph (Fig. 3)~~were used to construct orthorectified images~~. Orthorectification was ~~conducted on the initial surface elevation model. Using~~ implemented using the 'Image Processing' and the 'Camera Calibration' Toolboxes in the MATLAB software suite. Orthorectification was performed using the initial surface elevation ~~, the orthorectified images were distorted in morphologically altered areas . However, the dimensions of erosional features, such as the valleys in our experiments, remain correct~~ model, due to absence of elevation data at each time-step. This method resulted in warped imagery in areas with elevation change, i.e. within the valleys. However, these images were used to extract valley lengths and widths which are calculated from the distances between non-eroded valley walls. The outside edge of these walls form in the original surface and are therefore correctly represented in the orthorectified photograph using this method. ~~We performed time-lapse orthorectification in MATLAB, using the Image Processing Toolbox and the Camera Calibration Toolbox for MATLAB.~~

For detailed morphological analysis~~and morphometrical analysis, we collected~~ , we generated digital elevation models and orthorectified images at the end of each experiment using a large set of images and a structure-from-motion (SfM) algorithm (Forsyth and Ponce, 2011). In addition, we also acquired these data ~~several times during the Distal and Distal-after-Local~~ every day during the *Distant source* and *Distant after local* experiment at irregular intervals (Table 1).

~~Elevation models were acquired at the end of each experiment and during the experiments Distal and Distal-after-Local every day of the experiment (see Table 1) using SfM For each~~ Each digital elevation model and associated orthorectified image ~~, we took a set of about 70–100~~ were derived from 70 to 100 digital images with about 80 % overlap. We took these images by hand, allowing us to capture the area of interest. Twenty-four targets with known coordinates within the experimental setup enabled referencing of the images. Camera positions and orientations were solved using these known target coordinates and matched features between images. To ~~increase~~ improve the quality of the result, we removed features in wet areas ~~in order~~ to eliminate faulty matches in reflective areas due to different lightning angles between images. Elevation models were generated for each set of images, which were processed to a gridded elevation model with 1 mm cell size and a 0.5 mm orthorectified images. We used a Canon 550D DSLR camera with an 18–55 mm f/2.8 lens to take the photos, which we processed in RAW format to 16 bit TIF images to eliminate compression artifacts. We used Agisoft PhotoScan for SFM processing (Agisoft, 2014).

~~In addition, we used a~~A laser scanner ~~to obtain~~ was also used to obtain digital elevation models at the end of each experiment. Point-cloud elevation data of the final morphology were ~~obtained using a laser scanner from two~~ scanned from two different angles in order to eliminate data shadows outside the line-of-sight of the laser scanner (see Fig. 3). These point-clouds were oriented and merged using fixed targets in the experimental setup ~~. The combined scans were gridded to~~ to produce a combined scan gridded onto a digital elevation model with a 2 mm ~~elevation models~~cell size. We used a Leica ScanStation 2 laser scanner for data acquisition, CloudCompare for point-cloud orientation and ArcGIS for gridding of the point-cloud data.

2.3 Valley development and ~~eroded volume~~erosion rates

To quantify the morphological development, we plotted measured valley widths, lengths and depths during the experiments. Based on these data, we calculated valley shapes, and erosion rates and compared the latter to measured sediment output.

The length L (m) and width W (m) of each valley that formed during the experiments were determined for each time-lapse interval from the orthorectified time-lapse images. The valley width was taken just downstream of the valley-head where the valley walls were parallel. Valley depth D (m) was defined as the deepest point of each valley, i.e. the largest elevation difference between the original surface and the eroded surface. Valley depth was measured at each SfM interval. The final valley floor slope S_f ($\mathrm{m\,m^{-1}}$) was extracted from the final DEM. We defined the valley floor as the lowest point in each valley cross section. We estimated the erosion rates of each valley during the experiments by combining the valley dimensions and valley shapes.

First, the eroded volume V ($\mathrm{m^3}$) was estimated as:

$$V = W \cdot L \cdot D \cdot \mathrm{SI_c} \cdot 0.5, \tag{1}$$

for which W and L were taken at each time-lapse interval, D (m) is the ~~channel~~ valley depth that was interpolated between ~~measurements at~~ SfM measurements for each time-lapse interval. $\mathrm{SI_c}$ is the shape-index of the valley cross-section, which is the average ratio of the actual valley cross section to the square cross-section of $W \times D$. The factor 0.5 corrects for the longitudinal profile of the valley, which is in all cases ~~an approximate triangle~~approximately triangular. Valley volume was transformed ~~to~~ into an erosion rate E ($\mathrm{g\,s^{-1}}$):

$$E = \frac{\Delta V \rho_\mathrm{s}(1-n)\cdot 10^{-3}}{\Delta T}, \tag{2}$$

where ΔV is the change in volume, ρ_s is the density of sand (2300 kg m~~$^{-1}$~~$^{-3}$), n the porosity of the sediment (0.3) and ΔT (s) is the time over which the change in volume occurred. Cumulative erosion was compared to sediment output measurements ~~using buckets~~collected from bucket traps.

2.4 Martian landscape metrics

We constructed elevation profiles and extracted the orientation in degrees from North (i.e. azimuth) of valley segments, the ~~bifurcation angles~~ angles between converging valleys and valley lengths of Louros Valles and Nirgal Vallis. ~~Channel segments were digitized based on~~ Elevation profiles were extracted from HRSC image H0380_0001 (125 m resolution DEM) for Louros Valles, valleys of Nirgal Vallis were too small to produce elevation profiles. Valley segments for both systems were digitized from THEMIS Daytime Infrared Mosaic (Fergason et al., 2013) and HRSC (Jaumann et al., 2007) imagery. We distinguished different stream-orders, based on the Hack stream ordering number (Hack, 1957). In this system, the first-order is the main, downstream, valley; the first tributary is the second order and so on. We choose this system since it represents the chronology of valley formation by headward erosion. ~~Elevation profiles were extracted from HRSC image H0380_0001 (125 resolution DEM) for Louros Valles, valleys of Nirgal Vallis were too small to produce useful profiles.~~

The dataset of ~~channel~~ valley segments was transformed to a network-topology to distinguish between upstream and downstream ~~direction~~directions, using logical operators based on the methods described in Marra et al. (2014d) using ArcGIS and MATLAB. In this dataset, we identified ~~bifurcations~~converging valley segments, valley heads and outlets based on the ~~topology of the network . From this dataset~~network topology. Building upon the work of Jaumann and Reiss (2002), the orientation relative to north of each valley segment was extracted for each stream order ~~(building upon the work of Jaumann and Reiss, 2002)~~identified in the dataset. Orientation distributions were normalized per stream order to ~~better show the difference and reveal the effect of bifurcations of valley orientation~~clearly show the differences between valley orientations of different stream-orders. At each ~~bifurcation~~node of converging valleys, we calculated the ~~bifurcation~~ angle between the upstream ~~channel~~ valley segments (following Glines and Fassett, 2013). ~~Furthermore, for each valley head in the network, we calculated the distance to the first lower-order valley segment.~~

~~What we here refer to as bifurcation is a valley that splits in upstream direction. This~~ Such converging valleys is referred to as *headward bifurcation*, this definition relates to the chronological order of events in valley formation. In active rivers, the term bifurcation is used for a ~~channel that slits into two channels in~~ fluvial channel that splits into two in the downstream direction, which relates to the ~~motion~~ direction of water ~~.~~movement. Furthermore, for each valley head in the network, we calculated the distance to the first lower-order valley segment.

3 Experimental results

In the following section, we first describe the observed morphological development during the experiments, and then we link this morphological development to the acting processes. Time-lapse imagery and elevation models support these observations (time-lapse movies are available in the ~~Supplement~~online supplement).

3.1 ~~Distal groundwater~~ Distant source

~~The distal groundwater experiment~~ The experiment with seepage from a distant constant-head tank was characterized by slowly developing valleys. This experiment took over three days to complete and was carried out with a constant discharge of 2.4 liter per minute (Table 1).

The sediment saturated in the first hours of the experiment. During this stage, a visible wetting front at the surface progressed from the upstream constant head tank in downstream direction. The sediment became fully saturated at the foot of the slope where seepage occurred after 2.5 h over the full width of the sediment surface (Fig. 4a-i). The initial seepage pattern remained roughly the same, though the seepage area extended upslope to about 1 m from the foot of the slope. Initially, the seepage was too low for fluvial transport to occur. As the seepage rate increased, fluvial transport started after 4 h and the first ~~valleys~~ channels started to form at the foot of the slope within the seepage area.

The initial ~~valleys that formed~~ channels at the foot of the slope featured a combination of mass-wasting and fluvial processes. Mass-wasting of saturated sediment at the head caused headward erosion, and fluvial processes ~~removed the material from the valley~~ in the channel resulted in incision and the formation of valleys (Fig. 4a-iii). As the valleys developed in upstream direction, the seepage area retreated and seepage focused within the valleys as shown by drying of the sediment between the valleys and a concurrent increase of discharge within the valleys (Fig. 4a-iii). Seepage was limited to a declining number of valleys, as the valleys that reached ~~furthermost~~ most upstream progressively attracted more groundwater. From the ten valleys that started to form in the initial stage of the experiment, only six remained active after a few hours (Fig. 4a-iv), and only three remained active for several days (Fig. 4a-v).

The decreasing number of ~~active valleys testifies to the presence of groundwater piracy, which is typical for the process of groundwater sapping. This groundwater piracy~~ actively developing valleys illustrates the process of groundwater flow piracy as the largest valleys attract most of the groundwater flow since these are the deepest point in the landscape. As a result, more groundwater is directed to those largest valleys, which are therefore more active and smaller valleys cease developing. This feedback resulted in a final morphology ~~comprising~~ with a few large and several small valleys (Fig. 5). ~~The valleys did not bifurcate, which is the result of the high initial slope (Pornprommin et al., 2010).~~

The remaining valleys grew and as they became deeper, the head- and side-walls gained strength by cohesion as the sediment was moist. As a result, the head-wall retreat was governed by collapse due to undercutting at the toe, in contrast to the slumping of the entire valley head before the development of this cohesive top layer. In this process, the toe of the head wall was destabilized by fluvial erosion, resulting in collapse of the head-wall. The collapsed material ~~transformed into a mudflow. Therefore, the collapsed material~~ spread over a distance of 0.1 to 0.2 m into the valleys. Fluvial transport removed this material from the upstream end to the downstream end of the experimental setup. These processes showed a cyclic behavior: head collapse only occurred after a destabilization of the head due to the removal of the sediment by fluvial transport. This cycle is essential for the continuation of the process as the ~~channel~~ valley head would stabilize without such erosion and sediment transport. The final morphology shows the former presence of these various processes. In the three most developed valleys, the upstream end had a steeper slope than the downstream sections with a ~~clear knick-point~~ break in slope separating the two (Fig. 6a). This ~~corresponded to mudflow and fluvial flow dominating in these areas, respectively~~change in slope is the result from the transition of mass-wasting processes upstream to fluvial processes downstream.

The collapse of unsaturated material at the valley heads resulted in steep head walls (Fig. 5). The step-wise increase of valley width and length shows ~~this cyclic behavior~~ distinct peaks of collapse (Fig. 7a and b) and ~~results in peaks in the estimated instantaneous~~ erosion rates (Fig. 7d). Steps in width and depth of the valleys are not simultaneous, which shows that collapse of the head- and side-walls occur at different moments. Although erosion takes place in distinct peaks of activity, ~~the distally-fed~~ these valleys show a linear trend in valley length and width during most part of their development. Not only the length and width ratio of a single valley remain the same, but this ratio is the same for the three main valleys (Fig. 8a).

3.2 ~~Effect of initial morphology on Distal experiment~~Local precipitation

~~We studied the effect of an initial morphology on the valley development in experiment Distal-after-Local by repeating the experiment on an initial morphology. This initial morphology was the result of experimentLocal-2, which consists of multiple parallel shallow valleys created by overland flow (Fig. 9).~~

~~Experiment Distal-after-Local showed the same general characteristics and development as the Distal experiment. The main difference is valley initiation processes. We consider other differences as natural variations, which could have occurred without the altered initial morphology as well. In the Distal-after-Local experiment , initial seepage at the downstream end focused within the valleys of the initial morphology. However, due to groundwater flow piracy, only a limited number of these valleys fully developed. Six valleys started to form, but only two valleys fully developed (Fig. 5c). Development in the two remaining valleys was the same as described above. In the early stages of valley development, the valleys followed the path of the existing valleys in the initial morphology. When they became larger, they still followed the path of the initial valleys, although these were straight at this stage and the new valleys were much wider than the initial valleys. In our view, these mature valleys seemed to develop independently from the initial morphology.~~

3.3 ~~Local groundwater source~~

~~The local groundwater experiment took one hour and~~ The *Local precipitation* experiment took one hour and 50 ~~min with an average discharge of~~ min with an average discharge of $11.9\,\mathrm{L\,min^{-1}}$. This discharge is higher than in the *Distal source* experiment. A part of the precipitation fell directly into the valleys since the precipitation was distributed evenly over the experimental domain. Furthermore, the groundwater table in the *Local precipitation* experiment was close to the surface compared to a relative deep groundwater table in the *Distal source* experiment. As a result this setup allowed for more seepage due to the higher seepage area, explaining the higher discharge and shorter run of this experiment. In this experiment we distinguished two stages in valley development. In roughly the first half of the experiment, overland flow was the main source of water for valley development. In the second half, groundwater fed the valleys at their heads.

In the first stage of the experiment, the sediment in the downstream part of the slope saturated rapidly due to the limited sediment thickness (Fig. 4b-i). On this saturated sediment, precipitation transformed directly into runoff, which in turn induced valley formation by fluvial processes. These valleys started to form over the entire width of the sediment and showed valley heads with a v-shaped planform (Fig. 4b-ii). During this stage, valleys developed in headward direction by fluvial erosion and valley heads were within the area of saturated sediment. Seepage inherently occurred in the valleys due to the setup of the experiment. However, the overland flow processes dominated the seepage processes.

As the groundwater table rose during the experiment, the boundary of saturated sediment moved upslope. This progression of the saturated area slowed down as it progressed. In the first stage, valley development did not keep up with this moving front. However, the valleys caught up and developed upstream of the saturated area as the experiment progressed (Fig. 4b-iii). This marks the second stage in valley development wherein groundwater seepage rather than surface runoff fed the valley heads. From the moment the valley heads were fed by groundwater, their planform changed from v-shaped to theater-shaped (Fig. 4b-iv and b-v). This change indicates a change from fluvial flow to mass-wasting processes at the ~~head wall~~headwall. The headward growth showed similar characteristics as in the ~~distal seepage experiment~~ experiment with seepage from a distant source: growth governed by failure of the headwall and fluvial transport that removed the failed material. Similar to the ~~distal~~ *Distant source* experiments, there was also a distinguishable difference in slope in the upstream and downstream half of the valleys (Fig. 6), although this difference was less pronounced.

The valleys in the ~~local~~ *Local precipitation* experiment were shallow compared to the valleys in the ~~distal~~ *Distant source* experiment. In both cases, the valleys developed around the groundwater table, which was close to the surface in the ~~local~~ *Local precipitation* experiments. The limited depth was presumably the result of the high groundwater table, there was no zone of unsaturated sediment resulting in valleys without steep walls (Figs. 5b and 6a).

The valleys in the ~~local~~ *Local precipitation* experiment became longer and slightly wider by lateral erosion during the experiment (Fig. 7f and g). An important difference with the ~~distal~~ *Distant source* case was that all valleys remained active and had similar sizes during the experiment (Fig. 7i). This is due to the absence of groundwater flow piracy since each ~~channel~~ valley was fed by locally infiltrated groundwater (Fig. 5). In contrast to the ~~distally-fed valleys~~ valleys from a distant, the relation between valley length and width in the locally-fed valleys is not linear and different valleys do not have the same ratio (Fig. 8b).

3.3 Effect of initial morphology on Local experimentseepage from a distant source

We studied the effect of an initial morphology on the valley development in experiment *Distant after local* by repeating the experiment on an initial morphology. This initial morphology was the result of experiment *Local precipitation 2*, which consists of multiple parallel shallow valleys created by overland flow (Fig. 9).

In the Local-after-Distal experiment, Experiment *Distant after local* showed the same general characteristics and development as the *Distant source* experiment. The main difference is valley initiation processes. We consider other differences as natural variations, which could have occurred without the altered initial morphology. In the *Distant after local* experiment, initial seepage at the downstream end focused within the valleys of the initial morphology. However, due to groundwater flow piracy, only a limited number of these valleys fully developed. Six valleys started to form, but only two valleys fully developed (Fig. 5c). Development in the two remaining valleys was the same as described for the distant experiment. In the early stages of valley development, the valleys followed the path of the existing valleys in the initial morphology. When they became larger, they still followed the path of the initial valleys, although these were straight at this stage and the new valleys were much wider than the initial valleys. In our view, these mature valleys seemed to develop independently from the initial morphology.

3.4 Effect of initial morphology on local precipitation experiment

In the *Local after distant* experiment, we studied the effect of the initial morphology in the opposite way as in the Distal-after-Local *Distant after local* experiment; the final morphology of Distal the *Distant source* experiment acted as the initial morphology of this run (Fig. 5a). The same processes acted in this experiment, though the initial morphology had a much larger effect on the final morphology in this case.

In the first stage of the Local-after-Distal *Local after distant* experiment, the present valleys reactivated as the sediment saturated. Due to the rising groundwater level, the steep side- and headwalls of the previous valleys became instable and collapsed. This resulted in a decreasing valley depth and increasing width. The valleys that were abandoned in the Distal *Distant source* experiment due to groundwater flow piracy reactivated as they were fed by local precipitation and subsequently infiltrated groundwater, resulting in a smaller difference in valley size (Fig. 5d), compared to the initial situation (Fig. 5a). Collapse of the head-wall caused headward erosion and lateral erosion caused widening of the valleys. These are the same processes as in the Local run *Local precipitation experiment* with no initial morphology, but the final morphology showed much wider valleys. The initially present valleys were relatively deep in comparison to the final valleys. The reduction in depth of these valleys corresponded with this widening.

At the end of the ~~Local-after-Distal experiment, a body of ponding water at the flat area upstream of the valleys was released in the central valley. This resulted in the development of a feather-shaped drainage network upstream of the valley head~~ *Local after distant* experiment, water ponded at the upstream flat section of the experimental setup. This ponding seemed to be the result of the sediment becoming fully saturated towards the end of the experiment. The headward developing valleys tapped into this shallow reservoir, resulting in a final slightly catastrophic stage of erosion due to the breach of this reservoir (Fig. 5d). ~~We do not further consider this event in this paper, but a similar morphological feature develops after the overflow of a shallow lake as result from pressurized groundwater outflow, which is discussed in Marra et al. (2014c)~~This stage is not representative for the main objectives of this paper and therefore not further considered here.

4 Examples of Martian valley systems

In this section, we show the morphology of Louros Valles and Nirgal Vallis (Figs. 10 and 11), two Martian valley systems that were previously attributed to a groundwater seepage origin (e.g. Jaumann and Reiss, 2002; Harrison and Grimm, 2005; Glines and Fassett, 2013). These two system serve as an example on how to apply our experimental results and have received much attention in recent literature. Furthermore, these systems show branching valleys which also aids the interpretation of these systems. In this section, we describe Louros and Nirgal Valles, their interpretation is part of the discussion.

4.1 Louros Valles

Louros Valles are located at the north and south flanks of Valles Marineris. These valleys have circular valley heads cutting into flat plains. The valleys have a total relief of several kilometers and are between 10 and 100 km long (Fig. 10b and c). Upstream of the valley heads, there are no visible tributaries or depressions in the elevation data or imagery. Downstream of the valleys, in Valles Marineris, there are no clear deposits associated with these valleys. Sediment output in ~~the experiments was constantly removed, in the Martian case slow could have removed the produced sediment. Alternatively, deposits could~~ this case could be spread over a large area on the floor of Ius Chasma as a thin veneer ~~layer~~ and not recognizable as fluvial deposits. The valleys on the northern flank are shorter than the valleys at the south. Of the southern valleys, there are two larger valleys in the west; all other valleys are approximately equal in size. The valleys are closely spaced and several valleys touch or intersect, resulting in a relatively densely dissected plain (Fig. 10c and d).

As an example, we show an elevation profile of the largest valley of Louros Valles (Fig. 10e). These and other elevation data show a rough profile with many bumps, likely related to post-valley formation wall collapse or tectonism. At the ~~distal~~ downstream end of the valley, the elevation quickly drops, which shows the onset of Valles Marineris. Based on a 10 km moving average, we show the valley has a change in slope about halfway to a lower slope than the upstream part (Fig. 10e). However, the irregular elevation data limits the interpretation of these observations.

All valleys show ~~headward-bifurcations~~headward bifurcations. For the northern valleys, the orientation of the first-order valleys varies from northwest to northeast with most valleys oriented to the north-northeast (Fig. 12). The first tributaries, or second order (Hack, 1957) valleys have a similar spread in orientation, but most valleys are oriented to the west-northwest. For the southern valleys, most first-order valleys are oriented towards the southwest while higher-order valleys are directed towards the south-southwest or towards the west-southwest (Fig. 12b). Interestingly, a few third- and fourth-order segments are oriented in opposite direction (180°) as the first-order valleys (e.g. Fig. 10d).

The lengths of the tributaries range between 5 and 15 km (the main valleys are longer, but most are outside the graph), with no specific trend in the distribution of valley length (Fig. 12d). Mean heaward bifurcation angles of the different stream-orders are between 70 and 90° (Fig. 12f).

4.2 Nirgal Vallis

Nirgal Vallis consists of one more than 500 km long main valley and several sparsely distributed side valleys of various sizes (Fig. 11). Valley depths range from several tens to several hundreds of meters. The valley cuts into the plateau through several north-to-south oriented wrinkle ridges, which are in places the highest points in the landscape. Several side-valleys align with these wrinkle ridges (Glines and Fassett, 2013).

The orientation of the main valley is dominantly west-northwest, the first-order tributaries have the same dominant orientation, but a large part is deflected north- and southward (Fig. 12c). This tendency of dominantly westward-oriented ~~channels~~ valleys is shown in the landscape (Figs. 11d and 12c). There a few larger side valleys, but most side-valleys are very short (Figs. 11d and 12e). This results in the sparsely dissected landscape. The mean heaward bifurcation angle between valleys is 70.7° with a standard deviation of 18.6 (Fig. 12g), similar but slightly less than the results of Glines and Fassett (2013) for the same valley network but with less measured junctions. ~~Bifurcation~~ Headward bifurcation angles are similar for different stream orders.

5 Discussion

5.1 Valley morphology related to groundwater source~~character~~

~~In this paper, we aim to find morphological properties related to different sources of groundwater in the formation of valleys by groundwater seepage. The general morphology of our experimental valleys agrees well with previous studies on sapping valleys (e.g. Howard and McLane, 1988; Hagerty, 1991; Dunne, 1980; Fox et al~~

~~These valleys consist of~~ The valleys in experiments with a distant source of groundwater have half-round, theater-shaped ~~,~~ valley heads with a sharp transition to the upstream, ~~uneroded surface. They develop in~~ un-eroded surface. These are similar to those found in previous studies on valleys formed by groundwater seepage (e.g. Howard and McLane, 1988; Hagerty, 1991; Dunne, 1980; Fox et al., 2006; Pornprommin et al., 2010). Valleys in our experiment fed from nearby infiltrated precipitation also featured round valley-heads but lacked the steep theater-shaped head wall. The valleys from both boundary conditions developed in a headward direction by destabilization of the ~~channel head , which results from~~ valley head due to either undercutting or slumping. The eroded material is transported ~~though~~ along the valley by fluvial processes. These two main processes showed a cyclic behavior as the fluvial erosion in the valley was the trigger for collapse at the valley head. Furthermore, in both experiments, the slope in the upstream section of the valley floor ~~is~~ was steeper than in the downstream ~~end~~ valley floor (Fig. 6), which ~~results from the transition of hyper-concentrated flow with high sediment availability at the channel heads to regular fluvial flow further~~ relates to the transition from mass-wasted material released at the valley head to the fluvial transport of material downstream.

The morphological similarity between theater-headed valleys in groundwater sapping features (undercutting and failure by groundwater seepage erosion) at the beach (Higgins, 1982), in sand-box experiments (Howard and McLane, 1988), on the Colorado plateau (Laity and Malin, 1985) and ~~valleys~~ on Mars is often used as an argument for a groundwater origin of the Martian valleys (e.g. Schumm and Phillips, 1986; Mangold and Ansan, 2006; Harrison et al., 2013). A complication in the study of such morphology on Mars is that different processes yield a similar morphology~~, for example~~. For example, waterfall erosion (Lamb et al., 2006) or groundwater weathering (Pelletier and Baker, 2011) can also produce theatre-headed valleys. We do not solve ~~that~~ this controversy in this paper since the experiments here do not explore the morphological ~~difference between different~~ differences between all these possible processes. Here, we focus on ~~groundwater processes~~ morphology related to groundwater flow processes and subsequent erosion in further detail and provide metrics of entire landscapes to aid the interpretation of Martian landscapes.

In the following discussion, we start by considering the applicability of our experiments. Then, we propose different end-member landscapes based on knowledge from our experiments combined with previous experimental ~~and~~ work, modeling results and theoretical considerations. The main landscape properties are the distribution of valley lengths, valley order, valley ~~spacing and bifurcations. We interpret the~~ orientation and the angle between valley segments. We close the discussion with an interpretation of the Martian valleys described ~~above in this framework and end with considerations on the applicability of scaled experiments of such systems.~~ using the proposed landscape metrics framework.

5.2 Scalability of experimental results

The experiments described in this paper are not dimensionally scaled or direct analogues to the Martian case studies. Instead, the experiments provide insights into the fundamental processes that result from groundwater seepage and the resultant morphology. These experiments were devised to contrast distinct sources of groundwater and complement previous work. The experimental setup was designed to be simple in order to show clearly the effect of different hydrological boundary conditions. Different initial conditions will produce different landscapes, but again, our work is focused on the essential underlying processes and representative morphological features.

The experiments presented in this paper, and previous work on seepage erosion, applies to landscapes formed by groundwater and thus landscapes that form in porous and erodible material. The overall patterns are expected to be similar on different scales and for different materials that meet these conditions, but details will differ. Our analyses are therefore limited to the large-scale patterns in the landscapes and not expected to explain details. Below we point out the scale-effects in our experiments and how we take these into account.

An important difference between the distal and local groundwater *Distant source* and *Local precipitation* experiments was the steepness of the valley heads and sidewalls, which were much steeper in the distal groundwater *Distant source* case. In the Distal *Distant source* experiment, the groundwater table was deeper, resulting in an unsaturated (moist) top layer above the groundwater table, which has more apparent cohesion than the saturated (wet) top layer in the locally infiltrated groundwater case*Local precipitation* experiment. In natural systems, such properties show contrasts in material strength arise from differences in soil or substrate properties rather than formative processes. The depth of the unsaturated layer relates to capillary forces, which are scale-independent and thus relatively small for large experimental valleys (see discussion in Marra et al., 2014a). Nevertheless, theater head formation took place in both cases with and without an unsaturated top-layer, which indicates that this process takes place under both conditions and is not the result of this scale-effect.

Destabilization of the headwall is a necessary condition for the development of sapping valleys valleys by seepage. This only takes place if sufficient sediment is removed from the toe of the headwall, which requires enough discharge for sediment transporterosion and transport along the entire valley length. In previous smaller sapping experiments(Marra et al., 2014a), there were problems with sustaining the process without artificial removal of sediment. In our current experiment, the discharge was sufficient to allow continuous downstream sediment transport. Marra et al. (2014a) smaller-scale experiments, (Marra et al., 2014a), report on experiments in a $1 \times 3\,\mathrm{m}$ setup flume with sand where the valleys clogged due to the absence of downstream sediment removal(these are not the main experiments reported in that paper, they are mentioned in the discussion). Their solution to keep the sustain upstream processes and valley formation going was to flush away sediment at the downstream end. In that same setup, sapping valleys valleys from groundwater seepage did develop when lightweight plastic sediment was used, resulting in which enabled sufficient sediment transport due to the lower material density. In other words, sufficient downstream erosion by fluvial processes is essential to keep the cyclic formation characteristic for seepage valleys going. ~~Similarly, the larger experiment by Howard and McLane (1988) featured a downstream gutter to remove the sediment and maintain the process of sediment evacuation from the growing valley.~~ In the experiments described in this ~~study~~paper, sediment was not flushed at the downstream end~~and the downstream elevation is kept constant by a row of bricks. In other words, the processes that occurred were not forced by the removal of downstream sediment,~~ , which shows that the scale-effect of having a ~~too low~~ insufficient discharge for sediment erosion and transport was overcome in our setup.

5.3 ~~Groundwater piracy, valley spacing and length distribution~~

Additional work is required to understand the morphological details of valleys formed by groundwater seepage. In particular, we expect important effects on valley shapes to result from layered substrates with alternations in material erodibility. These effects can be studied experimentally, but to model erosion rates on larger scales than can be represented in the laboratory, numerical modelling will be more informative about the formative time-scales of such systems and may elucidate on terraces found in Martian valley systems. Furthermore, using such models, Martian scenarios with a thick layer of permafrost can be simulated which are unpractical to recreate in most laboratories.

5.3 Groundwater flow piracy, valley spacing and length distribution

The morphology of the entire landscape shows important differences that are related to subsurface groundwater flow processes. In the ~~distally-fed~~ *Distant source* experiment, a decreasing number of ~~channels~~ valleys remained active when ~~small~~ smaller valleys ceased to develop. This behavior ~~is related to groundwater piracy of~~ relates to groundwater flow piracy by the larger valleys~~and results in an increase of valley spacing. The valleys are depressions and therefore~~ , since these depressions attract groundwater. Due to the travel distance and direction of the groundwater, areas downstream of large valleys receive less ~~groundwater~~or even no groundwater as shown by surfacing drying. The resulting landscape consists of ~~a few large and several small valleys in between, which ceased developing due to this cutoff of groundwater~~ several small inactive valleys with no groundwater supply (Fig. 5a) ~~, and valleys are mainly~~ in between a few large active valleys oriented towards the groundwater source (Fig. 13a). In contrast, the ~~locally-fed channels~~ *Local precipitation* experiments did not feature groundwater flow piracy ~~, which results in a~~since the groundwater source is distributed everywhere and therefore cannot be captured by nearby valleys. The resulting landscape is densely dissected ~~landscape~~ with valleys of similar size in close proximity ~~of~~ to each other (Figs. 5b and 13b). ~~The close proximity is a strong indication that the availability of water was not limiting and piracy can therefore not have been important.~~

An important parameter for groundwater flow piracy is the fraction of the groundwater flow that a valley captures. This is controlled by the ~~fraction~~ ratio of cross-stream to downstream groundwater flux (Pelletier, 2003; Schorghofer et al., 2004), which is proportional to the groundwater gradient in isotropic conditions. In the case of ~~sapping valleys~~ valleys formed by groundwater seepage, the emerging valley itself leads to a topographic low that introduces a cross-stream groundwater slope, which increases the flow towards that valley. This morphological feedback causes flow piracy when a valley attracts enough flow to cease the development of another valley. This feedback and tendency for flow piracy, is stronger for ~~lower regional slopes as a perturbation~~ flat surfaces in contrast to valley formation on a slope, since a depression in a flat surface has a ~~relative large~~ larger effect on the convergence of groundwater flow (Pornprommin et al., 2010).

Our experiments show that the valley width-to-length ratio is similar for valleys formed by a ~~distal~~ distant source of groundwater (Fig. 8a), ~~which was~~ but this is not the case for ~~the locally-fed valleys~~ valleys generated by a local groundwater source (Fig. 8a). ~~Such~~ The similarity in the development of several distally-fed valleys is indicative for valley formation by the same source of groundwater. The size of the ~~valleys dominantly control~~ valley is the dominant control on the amount of water delivered to that valley since a larger ~~valley source yields more~~ and deeper valley yields more groundwater seepage. In turn, the amount of erosion relates to the size of the valley and hence, the morphological development is similar for the different valleys. The amount of water delivered to the ~~locally-fed channels~~ valleys fed by local precipitation is only partly controlled by this mechanism. In this case, the amount of groundwater delivered to the valley head also depends on upstream area and local watersheds.

Initial conditions may affect the location ~~and thus~~ of valley initiation and thereby the spacing of valleys in the final landscape. In our ~~distally-fed~~ *Distant after local* experiment with minor initial morphology ~~(Distal-after-Local)~~and a distant groundwater source, the initiation of ~~sapping valleys seemed~~ valleys appeared to be related to the initial perturbation of the surface, but the resulting processes and the final landscape was similar to the experiment with no initial perturbations. This shows that seepage is robustly driven by the subsurface flow pattern and agrees with the observations of Schumm and Phillips (1986) ~~:~~ that valleys of a composite origin dominantly reflect the last process. In contrast, in the ~~locally-fed experiment withinitial perturbations (Local-after-Distal)~~*Local after distant* experiment with, there was a ~~major effect~~ significant effect of the initial morphology as old valleys reactivated~~and dominated the final morphology.~~

~~The strong difference of local effects is the result of the groundwater flow patterns : in the locally-fed experiments, local perturbations affect the flow pattern, while groundwater from a distal source is driven dominantly by the large-scale morphology. Furthermore, flow piracy dampens the development of small perturbations. An important~~ . Importantly, the valley patterns in the *Distant after local* experiment are similar as in the *Distant source* experiment, an hardly influenced by the initial morphology. An implication is that the location and orientation of ~~distally-fed sapping valleys strongly~~ valleys fed from a distant source relate to the hydrological system and ~~can thus be used as an indicator of~~ thereby provide an indicator for the possible source of groundwater.

5.4 Headward ~~channel~~ bifurcations

Our experimental valleys did not bifurcate at their ~~channel~~ valley head, which is considered a typical property for ~~sapping valleys~~ valleys fed by groundwater seepage (e.g. Howard and McLane, 1988). The absence of headward bifurcations in our experiments is the result of the steep slope in the downstream half of the setup. Pornprommin et al. (2010) showed that ~~a low regional slope, and thus lower morphological feedback, resulted~~ for valleys that formed in a flat surface, result in more seepage at the flanks of the valley head, which increased the tendency of the valleys to ~~bifurcate~~split when growing in a headward direction. Our results show that seepage on a ~~relatively~~ steep slope suppresses the tendency to form such headward bifurcations, compared with similar experiments ~~with a horizontal surface~~on horizontal surfaces, which do show headward bifurcations (Fig. 13a and c; e.g. Berhanu et al., 2012).

Besides the ~~regional~~ initial slope, Berhanu et al. (2012) showed that valleys fed from a local source have a higher tendency to bifurcate in a headward direction. This tendency relates to the groundwater flow that enters the ~~channel~~ valley head from a wide range of directions and not mainly from upstream ~~of the valley. The typical flow field that results from local infiltration in a flat substrate results in bifurcations with a typical angle of 72(Devauchelle et al., 2012). In such system, the valleys would have many~~ or the direction of the groundwater source. As a result, valleys formed by seepage from a local source on a flat topography have many headward bifurcations which results in a densely dissected landscape (Fig. 13d)~~,~~. This pattern is similar to the Apalachicola Bluffs (Florida) which ~~were~~ have been shown to be formed by seepage of locally infiltrated precipitation (Abrams et al., 2009). ~~The valleys in this system could be subject to flow piracy, but as a result by other valleys cutting each other off. This mechanism of piracy is different from the piracy by groundwater flow capture, which acts on a larger distance and is typical for distally-fed valleys~~

The flow field that results from local infiltration into a flat substrate results in heaward bifurcations angles of 72° (Devauchelle et al., 2012). This value has been considered as evidence for a groundwater origin of Nirgal Vallis by Glines and Fassett (2013), but this value is only characteristic for seepage from uniform precipitation on a flat surface and is therefore not universally applicable. Furthermore, structural controls from tectonics may also dictate the angles between valleys (Luo et al., 1997), which is also likely the case for Nirgal Vallis (Glines and Fassett, 2013).

The combined occurrence of developing headward bifurcations and groundwater flow piracy results in the formation of typically stubby tributaries. When a valley bifurcates in headward direction, there are two ~~channel~~ valley heads close to each other, which will in ~~many cases~~ result in abandonment of one of the two (Fig. 13c) due to the presence of groundwater flow piracy. This behavior and the resulting morphology is indicative of ~~sapping~~ valley formation by seepage from a ~~distal~~ distant groundwater source.

5.5 Origin of Martian examples

~~In this paper, we~~ We analyzed the landscape of Louros and Nirgal Vallis, two valley systems often attributed to groundwater seepage. Two additional examples are shown in Fig. 13a and b and these examples are described below to serve as an illustration of how the morphology can appear, but are not analyzed further. The valleys in Noctis Labyrinthus (Fig. 13a) show valleys with no headward bifurcations and a few small valleys in between larger valleys. Although the plateau where these valleys cut into is flat, there is a strong gradient between valley head and outflow point, which ~~is what we mean with~~ illustrates our contention that a steep slope ~~and which is what~~ suppresses the tendency ~~to bifurcate~~for headward bifurcation to form. The small valleys in Gale Crater (Fig. 13b) are similar in size, shallow and ~~the~~ there is a regional slope. ~~These examples serve as an illustration on how the morphology can appear, but are not further analyzed here.~~

Alternate hypotheses for similar valley ~~formation~~ formations are bedrock erosion by catastrophic release of surface water (Lamb et al., 2006) or bedrock weathering ~~rather~~ and erosion by groundwater (Pelletier and Baker, 2011)~~. The latter would yield a similar morphology as sapping in unconsolidated material, and the two processes would likely act~~ , which would result in the same ~~systems as the weathered bedrock material is further removed by seeping groundwater. However, weathering in bedrock could result in steep slopes, which are not likely for large valleys in case of seepage erosionin unconsolidated material (Marra et al., 2014a)~~combination of boundary conditions and morphology as seepage in unconsolidated materials. Another hypothesis for the formation of Louros Valles is focused erosion by meltwater in between patches protected from erosion by the presence of an ice-cover ("glacial selective linear erosion", Lee, 2000).

The evidence in favor of a groundwater origin ~~on both cases~~ over surface flow in both Nirgal and Louros, is the absence of upstream feeder channels ~~to~~ into the main valleys. However, billions of years of weathering and a dust cover could have obscured such small channels. The elevation profile of one of the Louros Valles is bumpy (Fig. 10e), likely due to later activity. ~~Based on filtered elevation profile, the valley shows a lower slope downstream, similar to the experiments, but the implication of this is limiteddue to the bumpiness of the profile~~Consequently, the interpretation of such profile in comparison to elevation profiles of the experiments (Fig. 6) is limited. Therefore, we use the properties of multiple valleys and valley segments in the entire landscape rather than single-valley morphology for our interpretation.

The orientation of valley segments of Louros Valles is diverse ~~with wide bifurcation angles and~~ and has a broad range of valley lengths, resulting in a densely dissected landscape (Fig. 10). Such a landscape is typical for a local groundwater source (Fig. 13d). ~~The bifurcation angles have a much broader distribution than the theoretical value for such system. This could be the effect of valleys aligning with the tectonic structure, which would result in 90angles (Luo et al., 1997).~~ Furthermore, in Louros Valles, some higher-order valley segments are oriented in ~~opposite direction~~ downstream direction with respect of the main valleys (Fig. 10d), which can ~~only be explained by~~ be the result of a local source of groundwater and not ~~by surface flow following the topography~~groundwater coming from greater distances. Additionally, the presence of valleys on both sides of Valles Marineris suggests a local groundwater source and not groundwater coming from a great distance.

A possible local source of groundwater for Louros Valles is precipitation; melt of snow, ice or permafrost; or upwelling groundwater from a cryosphere-confined aquifer ~~. Another source of water could be vertical upwelling groundwater from an aquifer . Such aquifer~~ (e.g. *Clifford*, 1993). The presence of this type of aquifer in this region may ~~relate to the~~ also have been the source of water for the outflow channels further northeast ~~, although the~~ which are likely to have formed by the release of pressurized groundwater from a confined aquifer. The timing of events here is crucial ~~. The~~ since the presence of Valles Marineris, and the clear formation of Louros Valles after the opening of Valles Marineris, suggest that this aquifer was at that point cut-off ~~, and in fact split between~~ and split between the north and south. Seepage at Louros Valles rather than the formation of an outflow channel could represent ~~a~~ low aquifer pressure, which fits a trend of lower groundwater pressures at higher elevations in Ophir and Lunae Plana (Marra et al., 2014b). ~~An alternate hypothesis for the formation of Louros Valles is by focussed erosion of meltwater in between patches protected from erosion by the presence of an ice-cover ("glacial selective linear erosion", Lee, 2000)~~Furthermore, the subsidence of Valles Marineris into the aquifer may have been a trigger for outflow or upwelling of groundwater. This hypothesis could be further explored and the asymmetry between the valleys on the North and South flank may provide additional insight into the nature of such aquifer.

~~Nirgal Vallis cuts through some ridges in the landscape where surface runoff would have flowed around. If this landscape is indeed formed by groundwater, the sourceis likely distal~~The landscape of Nirgal Vallis is an exemplar of valley formation by seepage from a distant source, given the large number of small valleys typical for groundwater ~~piracy due to a distal source~~ flow piracy (Figs. 11, 5a, 13a and c). The groundwater source was likely to have been west of the valley due to the orientation of most valleys towards that direction. ~~The average bifurcation angle is close to 72, which is considered a typical angle for groundwater-seepage valleys and mentioned as evidence for a groundwater origin by Glines and Fassett (2013). However, this value is only valid for valleys formed by a local source of groundwater (Devauchelle et al., 2011), which is not the case here, and such value is heavily influenced by subsurface conditions like tectonic structures (e.g. Luo et al., 1997).~~

A possible source of groundwater ~~for Nirgal Vallis is groundwater~~ flow from the west ~~, which is ultimately recharged from Tharsis~~ could be recharge in the Tharsis region (*Harrison and Grimm*, 2004). Seepage of groundwater ~~could have taken~~ likely took place before the formation of a ~~confining cryosphere. Alternatively, if the cryosphere was already present, discontinuities or rupture could have triggered outflow from a confined aquifer. However, in this case the groundwater should have flown laterally first to account for the morphology, which would be~~ global confining cryosphere, which is considered a requirement for aquifer pressurization for the Martian outflow channels in the Hesperian (*Clifford*, 1993; Marra et al., 2014c). Alternatively, a regional discontinuity may be the reason for seepage at Nirgal Vallis. In that case, seepage took place during an early stage in the ~~case if the groundwater pressure was not sufficient to induce artesian seepage. Seepage would then occur further downstream at topographic depressions~~formation of the cryosphere. The climatic implications are the presence of precipitation in the source region which could be aqueous or icy (Wordsworth et al., 2013), but widespread precipitation is not required and a groundwater system as the dominant element of the hydrology shows that these valleys could form in the absence of a long-lived hydrological cycle at the surface.

Based on our and previous experiments, this study now provides a framework ~~which links the landscape~~ that links landscape properties to the groundwater source ~~characteristics~~location. The two Martian examples shown, further illustrate this link. Although different processes could produce similar valley morphologies, the strong correspondence of the landscape metrics of these examples and those produced by ~~sapping hints~~ seepage points towards at a groundwater origin. ~~Particularly~~ In particular the distant groundwater source of Nirgal Vallis implies a well-developed groundwater system. Perhaps most significantly, outflow and valley formation of such a system could have taken place regardless of climate conditions ~~optimal for~~ being optimal for the sustained presence of liquid water on the surface.

6 Conclusions

We studied groundwater seepage processes and subsequent valley formation using a series of large sandbox experiments. Our experiments focused on the difference between ~~locally- or distally-fed valleys on a steep slope~~valleys fed from groundwater originating from a distant source or from infiltrated local precipitation. In both cases, valley heads developed in headward direction by mass-wasting processes triggered by steepening due to fluvial sediment transport out of the valley.

Combined with previous experimental work, we provide a framework of driving processes and resulting landscape metrics for ~~sapping~~ valleys fed by a ~~distal and local source~~distant source and local precipitation, and for a steep and flat topography. Their main characteristics are as follows. (1) Due to groundwater flow piracy, seepage erosion from a distant groundwater source results in a sparsely dissected landscape with a few large and many small valleys. Valleys fed ~~by a local groundwater source~~ from a local source of groundwater, e.g. precipitation, ~~for example infiltrating precipitationor melt of ground ice,~~ are not characterized by flow piracy and have a range sizes, resulting in a densely dissected landscape. (2) Valley formation in horizontal surfaces promote the development of headward bifurcations in contrast to steep surfaces where this tendency is suppressed. For ~~distally-fed sapping~~valleys fed by a distant source of groundwater, the combined occurrence of bifurcating valleys and flow piracy results in valley systems with stubby tributaries. ~~Locally-fed sapping valleys~~ Valleys fed by locally infiltrated groundwater on horizontal surfaces grow in a wide range of directions due to the ~~occurrence and prevalence of bifurcations~~development of many headward bifurcations which remain morphologically active.

As an example, we applied these characteristics to two Martian systems. Firstly, Louros Valles shows a densely dissected landscape with a broad range of valley orientations and valley lengths. This landscape is typical for a local groundwater source. Such local source could relate to an aquifer that fed the outflow channels, but is more likely related to local precipitation or melt of ice or snow. Secondly, Nirgal Vallis ~~whos~~ illustrates a sparely dissected landscape with many small and only a few large valleys ~~that are oriented dominantly to the west~~with a single dominant orientation. This indicates a ~~distal~~ distant groundwater source in the west, which is likely produced from recharge at Tharsis. Further study of similar landscape properties as a result of overland flow is required to ~~further resolve~~ advance the ambiguous interpretation of these valleys.

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~~Experimental runs, their duration, discharge setting and data acquisition intervals, video number corresponds with videos in the Supplement.~~

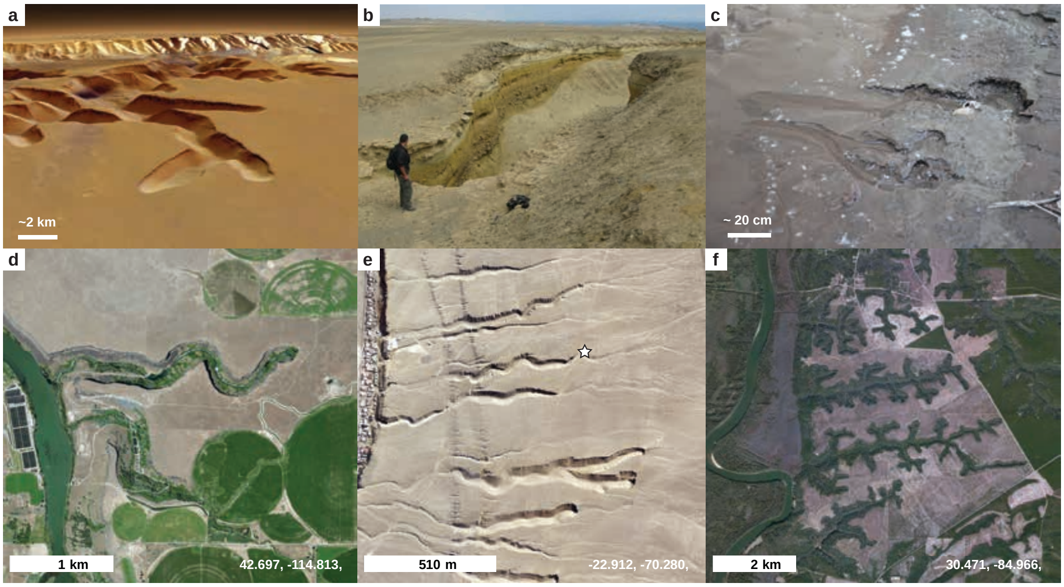

Figure 1. Examples of theater-headed valleys. ~~(a)~~ (a) Louros Valles on Mars, (perspective view); ~~(b)~~ (b) valleys on the coast of the Atacama Desert, Chile (oblique photo, human for scale); ~~(c)~~ (c) a -riverbank (oblique photo); ~~(d)~~ (d) Side valleys of Snake River, Idaho, USA (orthorectified image); ~~(e)~~ (e) valleys on the coast of the Atacama Desert, star indicates position of viewpoint of ~~(b)~~ panel b (orthorectified image); ~~(f)~~ (f) Apalachicola bluffs near Bristol, Florida, USA (orthorectified image). Image credits: ~~(a)~~ (a) Google Earth (NASA/USGS, ESA/DLR/FU Berlin~~)~~, ~~(b)~~ (b) Tjalling de Haas, ~~(c)~~ (c) Wouter Marra, ~~(d, f)~~ (d,f) Bing Maps Imagery, ~~(d)~~ (d) Courtesy of GFZ Potsdam.

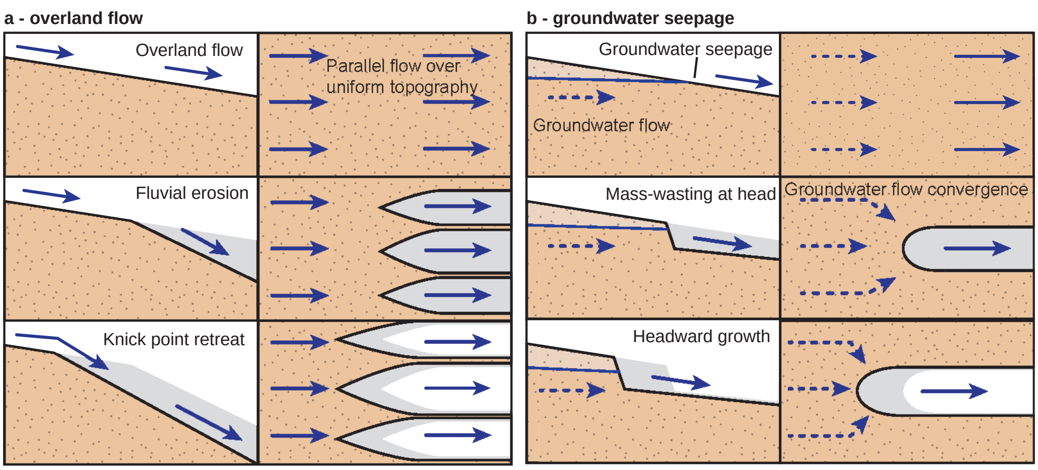

Figure 2. Fundamental processes at valley heads for overland flow and groundwater seepage. (a) Valleys formed by groundwater seepage extend in headward direction by mass-wasting processes. (b) Valleys by overland flow deepen by fluvial incision and extend in headward direction by knickpoint retreat.

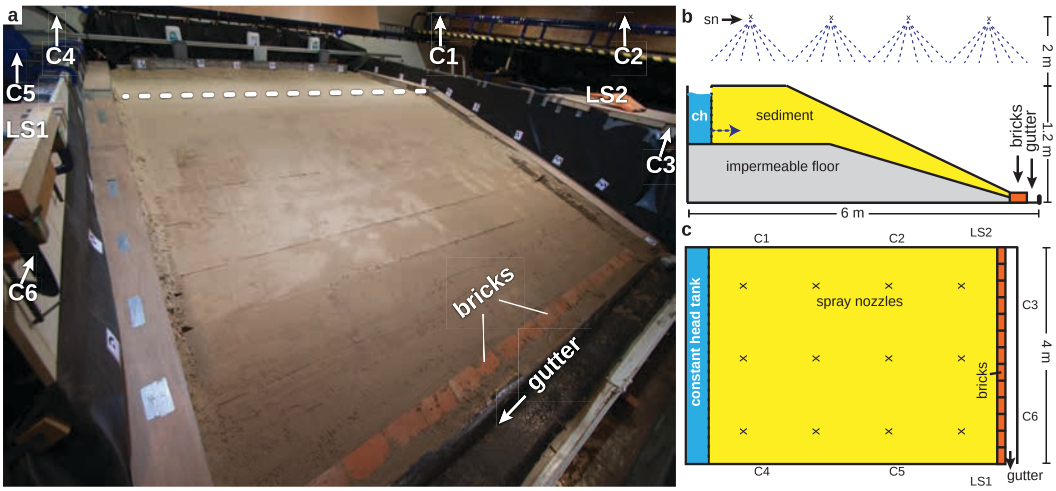

Figure 3. Setup of the ~~sapping~~ experiments. ~~(a)~~ (a) Oblique photo from downstream end of the flume, showing the initial sediment surface, gutter and constant head tank in the back. The rain simulators and cameras are above the photographed area; their approximate locations (~~C1–C6~~C1-C6) are shown. ~~(b)~~ (b) Cross section showing setup with impermeable floor, constant head tank (ch), gutter, approximate location of spray nozzles (sn) and brickwork. ~~(c)~~ (c) Plan view showing the locations of the rain simulators (x), camera locations (~~C1–C6~~C1-C6) and positions of the laser scanner (LS1, LS2).

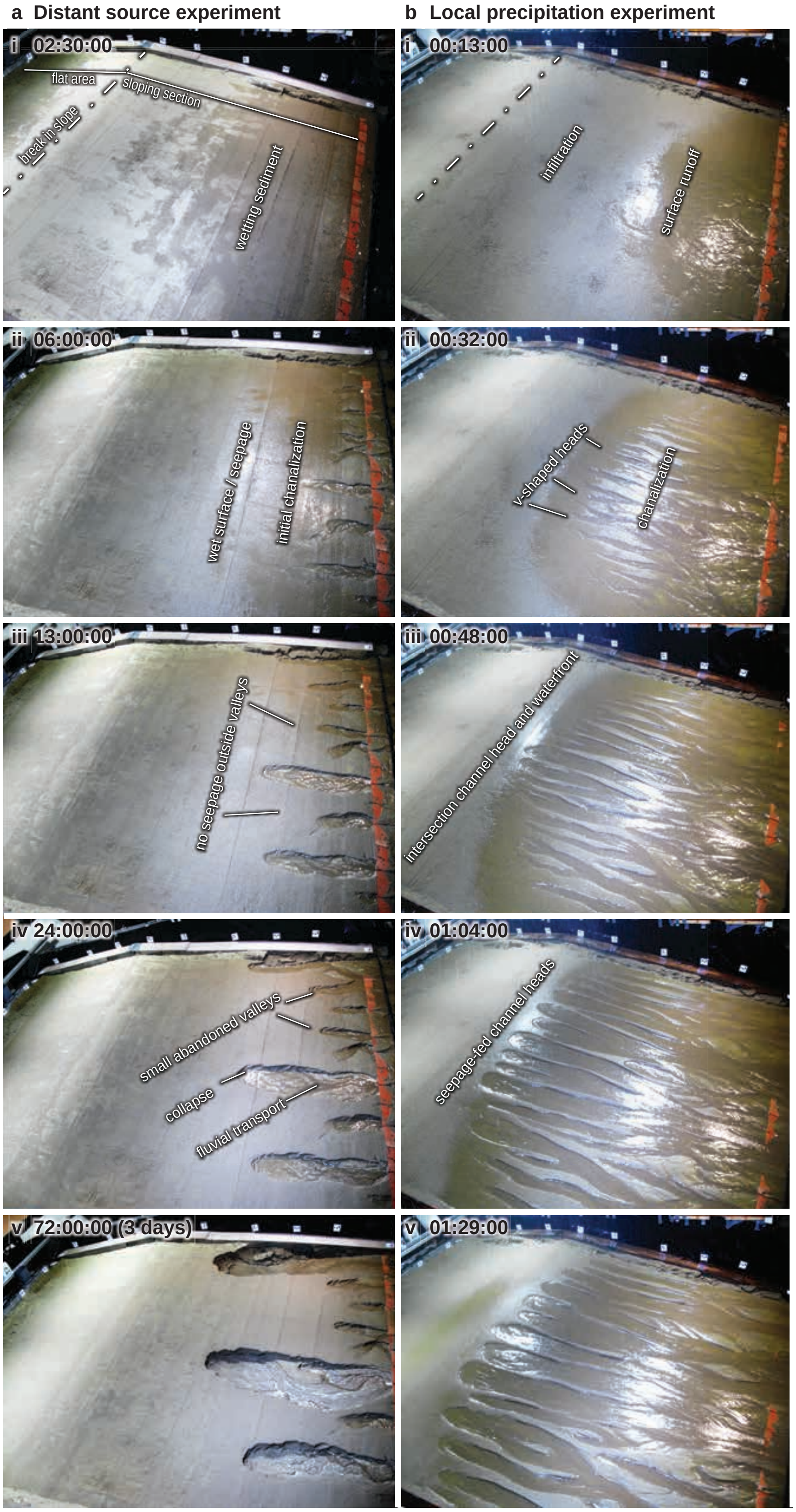

Figure 4. Stills from time-lapses of the experiments showing the main morphological development. Full time-lapse movie are available in the ~~Supplement~~online supplementary materials.

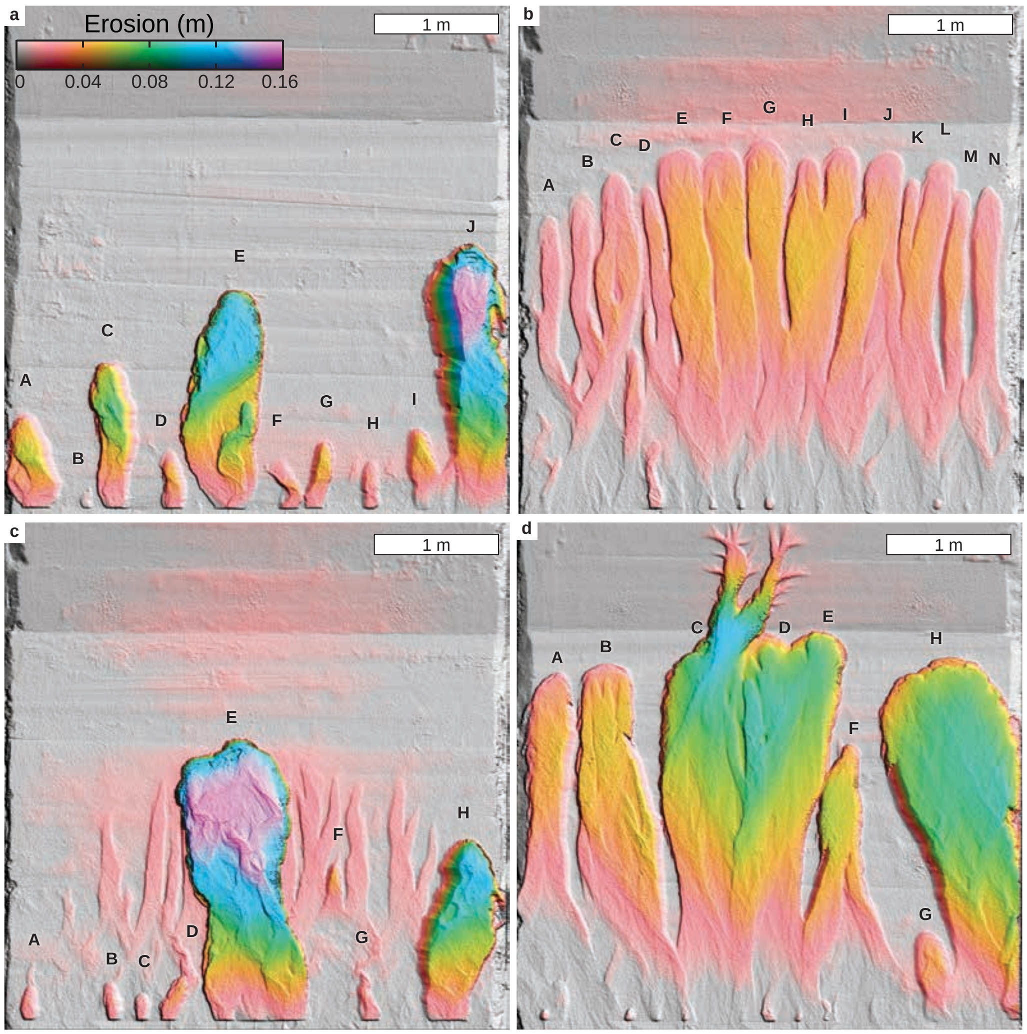

Figure 5. Erosion maps / final morphology of the experiments showing valley letters used in subsequent figures. ~~**(a)** Distal~~ (a) Distant source experiment, ~~**(b)**~~ (b) Local precipitation experiment ~~**(c)** Distal~~ (c) Distant after ~~Local~~ local and ~~**(d)**~~ (d) Local after ~~Distal~~distant.

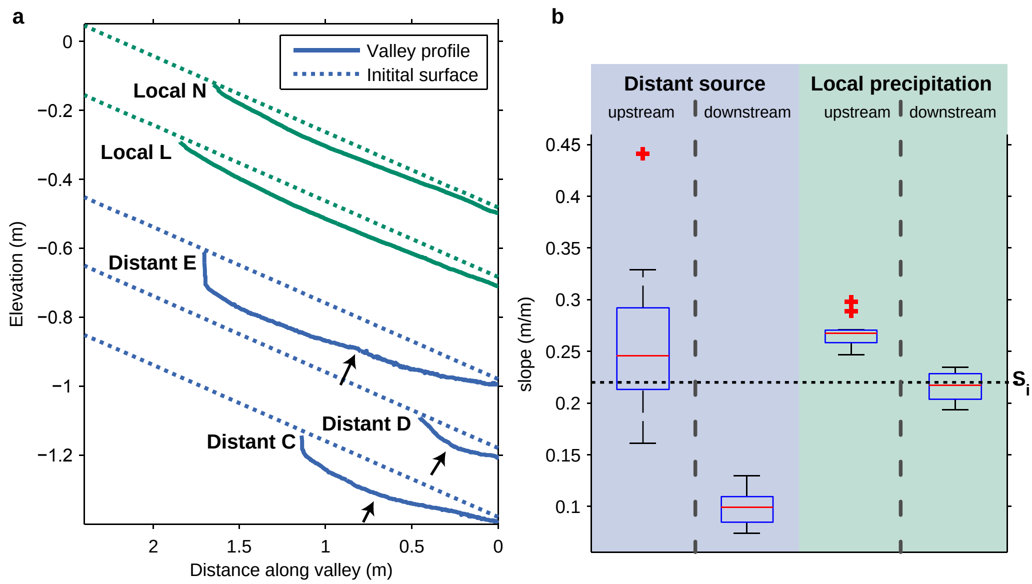

Figure 6. Channel profiles and slopes. ~~(a)~~ (a) Channel profiles of valleys C, D and E of ~~distal~~ the distant source experiment and valleys N and L of local precipitation experiment, displayed with factor 2 vertical exaggeration. Elevations are arbitrary and plotted with offset for clarity. The three ~~distal~~ distant source experiment profiles show three arrested stages of development also seen in larger valleys: incipient ~~sapping~~ valley without a steep valley head (D), developing valley with moderate steep valley head (C) and developed valley with steep valley head and reduced valley floor gradient (E), arrows indicate break in slope at the valley floow. ~~(b)~~ (b) Boxplot of slope in upstream and downstream part of all valleys ~~in distal~~ of the distant source (~~$n = 9$~~ n = 9) and local precipitation (~~$n = 14$~~ n = 14) experiments. The horizontal dotted line shows the initial surface slope ~~$S_i = 0.22$~~ $S_i = 0.22$.

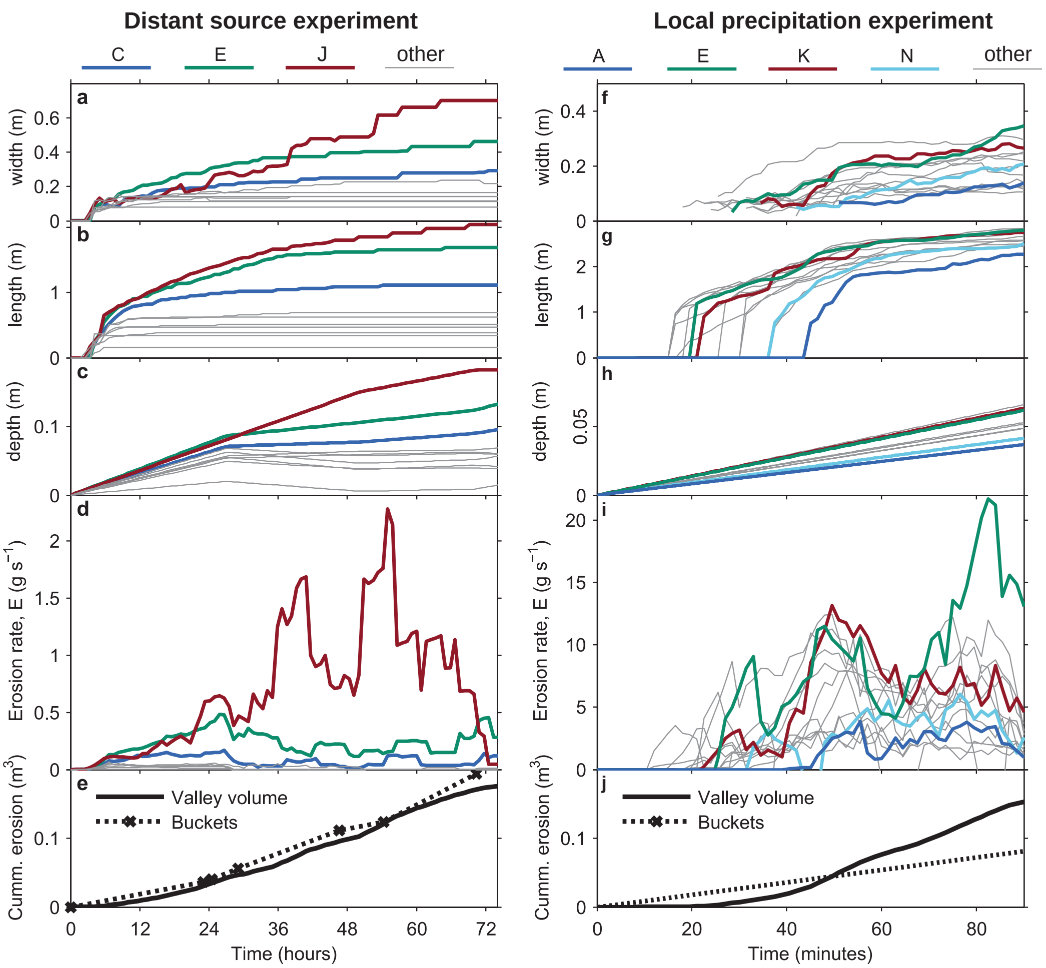

Figure 7. Valley development in the ~~distal~~ distant source (left panel) and local precipitation (right panel) ~~experiment~~experiments. Main valleys indicated with colors, letters in legend correspond with letters in ~~Fig.~~Figure 5. ~~**(a, f)**~~ (a,f) Valley width and ~~**(b, g)**~~ (b,g) length derived from orthorectified time-lapse imagery, ~~**(c, h)**~~ (c,h) valley depth derived from SFM-dems, ~~**(d, i)**~~ (d,i) estimated erosion rated from these properties and ~~**(e, j)**~~ (e,j) total cumulative erosion estimate from valley volume compared to measured sediment output.

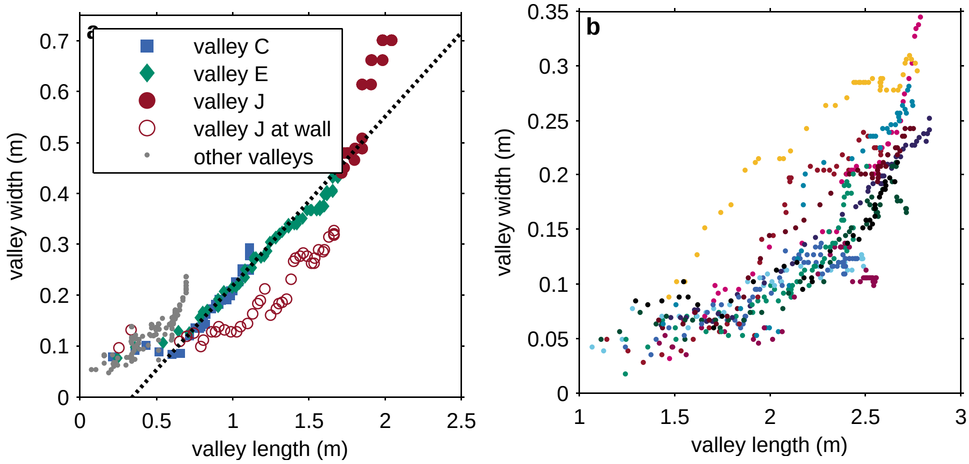

Figure 8. Development of valley width ~~vs.~~ versus length of the ~~(a) distal~~ (a) distant source and ~~(b)~~ (b) local precipitation experiment. Colored symbols in panel a represent the three main valleys. Values are plotted for all time-lapse intervals (valley dimensions increase with time). The open symbols in panel a represent valley dimensions when the measured valley section flowed at the side wall which influenced the valley width. Dotted line indicates trend of the three persisting valleys when the flume wall did not influence their width.

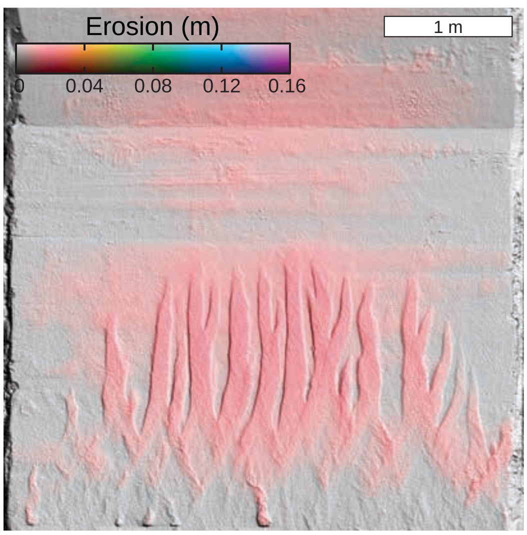

Figure 9. Final morphology of experiment Local precipitation 2, which is the initial morphology of experiment ~~Distal~~ Distant after ~~Local~~local.

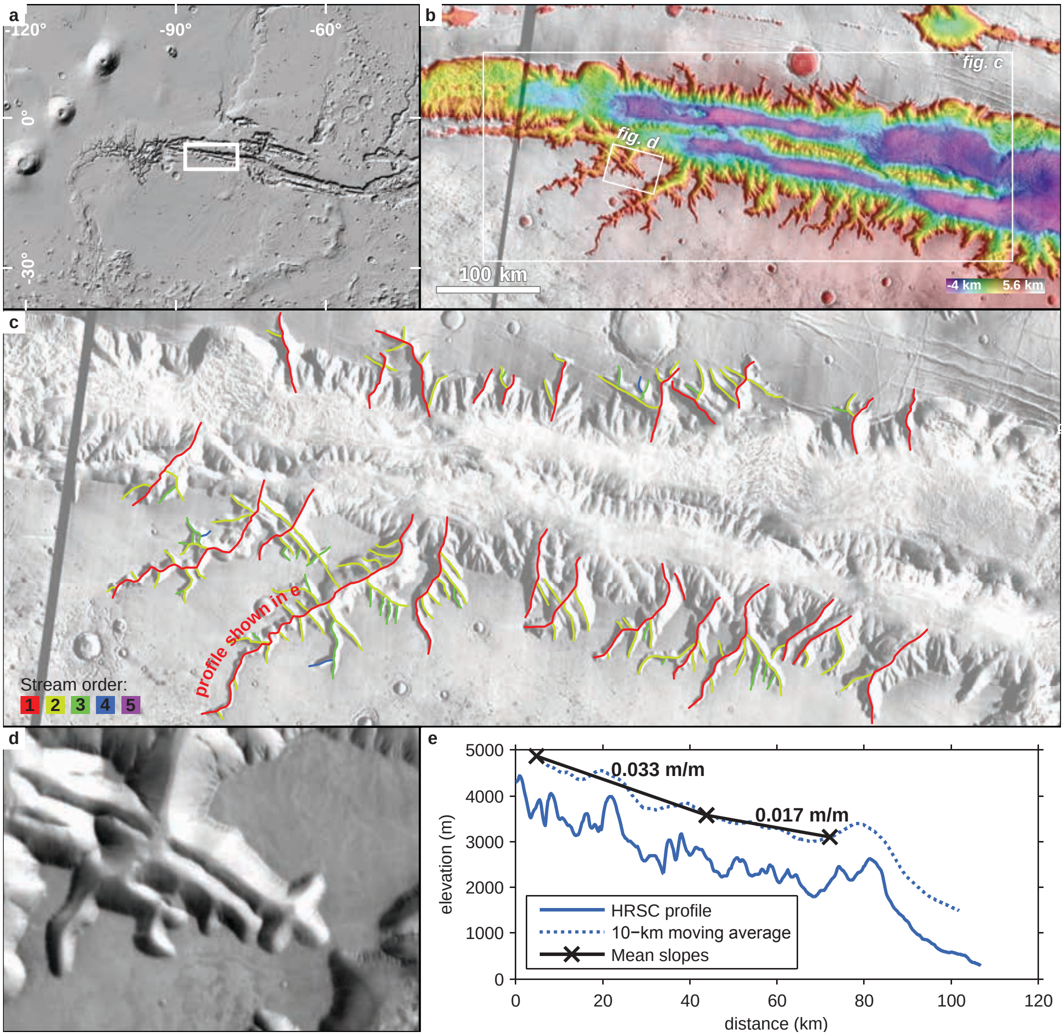

Figure 10. Maps and profile of Louros Valles. ~~(a)~~ (a) Overview map showing location of ~~(b)~~ panel b (MOLA shaded relief). ~~(b)~~ (b) THEMIS daytime infrared mosaic with color-coded MOLA DEM, showing location of ~~(c~~ panels c and ~~d)~~d. ~~(c)~~ (c) Valley centerlines, color-coded with stream-order on THEMIS day-IR mosaic. ~~(d)~~ (d) Detail of the network showing a ~~-~~densely dissected landscape and bifurcating valleys. ~~(e)~~ (e) Elevation profile based on HRSC data, moving average using a ~~10~~ 10-km window (plotted with 1000~~-~~ m vertical offset) and slopes of two segments. Location of this profile is the first order valley indicated in ~~(c)~~panel c.

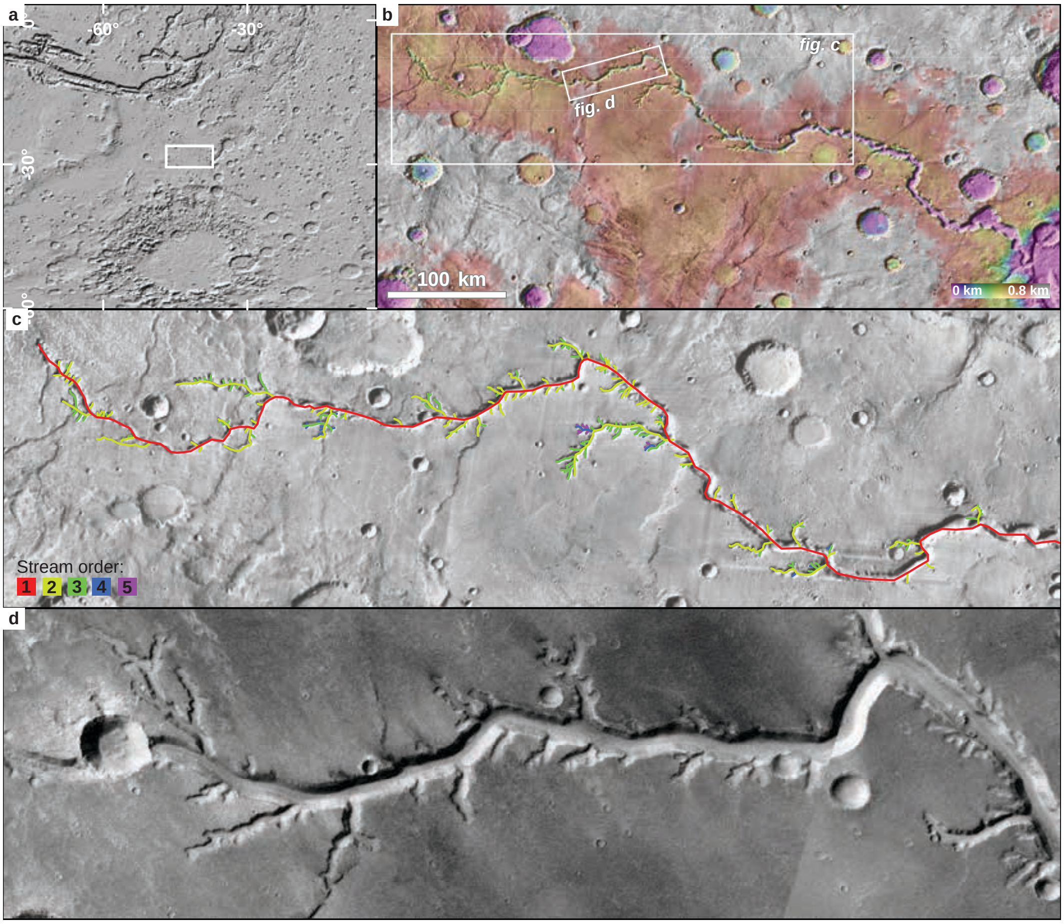

Figure 11. Maps of Nirgal Vallis. ~~(a)~~ (a) Overview map showing location of ~~(b)~~ panel b (MOLA shaded relief). ~~(b)~~ (b) THEMIS daytime infrared mosaic with color-coded MOLA DEM, showing location of ~~(c~~ panels c and ~~d)~~d. ~~(c)~~ (c) Valley centerlines, color-coded with stream-order on THEMIS day-IR mosaic. ~~(d)~~ (d) Detail of the network showing a sparsely dissected landscape with many small and a few large valleys.

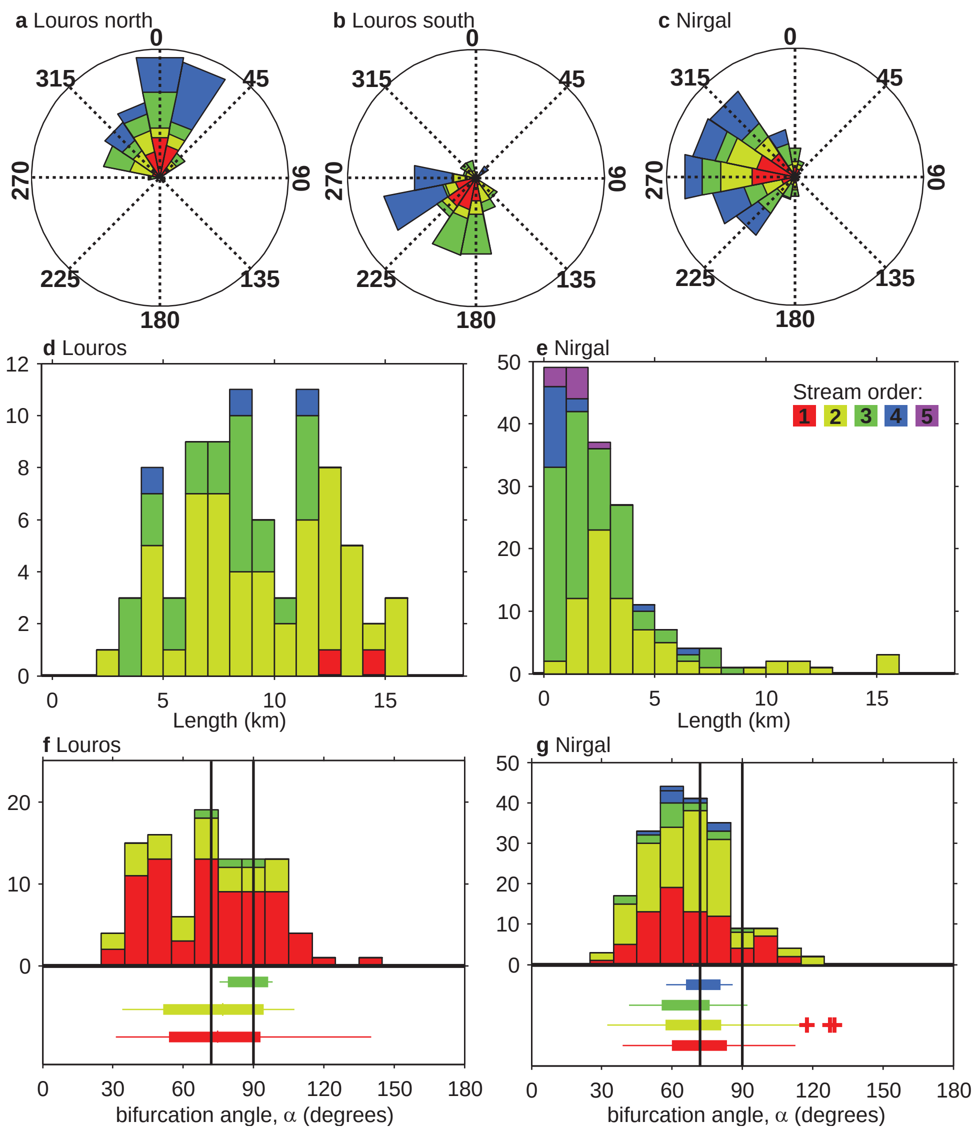

Figure 12. Landscape metrics of Louros and Nirgal Vallis. ~~(a–c)~~ (a-c) Valley orientation for valleys on the north ~~(a)~~ (a) and south flank ~~(d)~~ (d) of Louros Valles and Nirgal Vallis ~~(c)~~(c). (~~**d** and **e**~~d-e) Valley length (distance to lower-order valley) distribution for different stream orders, most main valleys (order 1) plot far outside the shown window for ~~(d)~~ (d) Louros and ~~(e)~~ (e) Nirgal Vallis. (~~**f** and **g**~~f-g) Distribution of bifurcation orientation and boxplots per stream order for ~~(f)~~ (f) Louros and ~~(g)~~ (g) Nirgal Vallis.

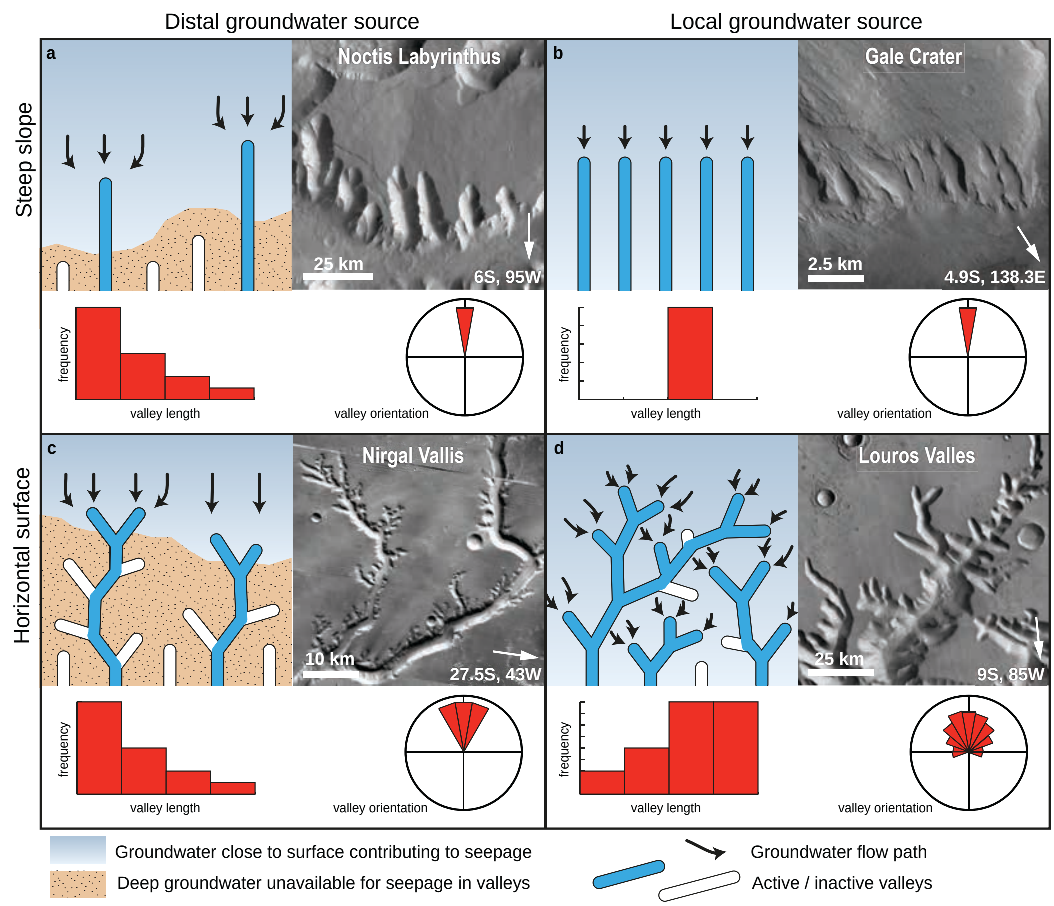

Figure 13. Landscape end-members formed by groundwater seepage as result from a ~~distal~~ distant source or local ~~source~~precipitation, and steep or horizontal surface. Each panel shows a schematic diagram (upper left), an Martian case showing a similar morphology (upper right) as an example and the expected valley length distribution and valley orientation (bottom). A ~~distal~~ distant source ~~(a, c)~~ (a,c) results in valley abandonment due to upstream capture of groundwater, ~~where~~ whereas a local groundwater source ~~(b, d)~~ (b,d) is less prone to flow piracy. Horizontal surfaces ~~(c, d)~~ (c,d) have a strong tendency to from valley bifurcations in contrast to steep slopes ~~(a, b)~~(a,b). ~~Distally-fed valleys~~ Valleys emerging from a distant groundwater source result in an open landscape as no valleys develop downstream of large valleys. Similar Martian landscapes in ~~(a)~~ (a) Noctis Labytinthus (THEMIS image), ~~(b)~~ (b) Gale Crater (CTX image), ~~(c)~~ (c) Nirgal Vallis (THEMIS image) and ~~(d)~~ (d) Louros Valles (THEMIS image).

Table 1. Experimental runs, their duration, discharge setting and data acquisition intervals, video number corresponds with videos in the online supplementary materials. Abbreviation used: d=days, h=hours, min=minutes.

Experiment	**Duration**	**Mean Q (l/min)**	**Cumm. Q (m^3)**	**Time-lapse interval**	**SfM interval**	**video**
Distant source	3 d. 3 h.	2.4	10	5 min.	1 d. 3 h. 2 d. 2 h. 2 d. 22 h. 3 d. 3h.	video 1
Local precipitation	1 h. 50 min.	11.9	0.95	30 s.	end of exp.	video 2
Local precipitation 2	40 min.					
Local after distant	3 h. 10 min.	10.5	1.9	30 s.	end of exp.	video 3
Distant after local	3 d. 16 h.	2	10	5 min.	2 h. 21 h. 2 d. 0 h. 2 d. 20 h. 3 d. 16 h.	video 4