nature geoscience

LETTERS

PUBLISHED ONLINE: 20 JUNE 2010 | DOI: 10.1038/NGEO894

Rapid formation of a modern bedrock canyon by a single flood event

Michael P. Lamb[1]* and Mark A. Fonstad[2]

Deep river canyons are thought to form slowly over geological time (see, for example, ref. 1), cut by moderate flows that reoccur every few years[2,3]. In contrast, some of the most spectacular canyons on Earth and Mars were probably carved rapidly during ancient megaflood events[4–12]. Quantification of the flood discharge, duration and erosion mechanics that operated during such events is hampered because we lack modern analogues. Canyon Lake Gorge, Texas, was carved in 2002 during a single catastrophic flood[13]. The event offers a rare opportunity to analyse canyon formation and test palaeo-hydraulic-reconstruction techniques under known topographic and hydraulic conditions. Here we use digital topographic models and visible/near-infrared aerial images from before and after the flood, discharge measured during the event, field measurements and sediment-transport modelling to show that the flood moved metre-sized boulders, excavated ∼7 m of limestone and transformed a soil-mantled valley into a bedrock canyon in just ∼3 days. We find that canyon morphology is strongly dependent on rock type: plucking of limestone blocks produced waterfalls, inner channels and bedrock strath terraces, whereas abrasion of cemented alluvium sculpted walls, plunge pools and streamlined islands. Canyon formation was so rapid that erosion might have been limited by the ability of the flow to transport sediment. We suggest that our results might improve hydraulic reconstructions of similar megafloods on Earth and Mars.

Most bedrock river canyons are thought to be cut slowly over millions of years (for example, Grand Canyon, USA; ref. 1) by moderate flows that reoccur every few years[2,3]. Spectacular canyons on Earth and Mars exist, however, that were excavated rapidly in one or a series of cataclysmic flood events[4–12]. Reconstructing flood discharge and duration is difficult, however, because we lack tested morphologic metrics and models of bedrock erosion during megafloods. This is in part because floods capable of rapidly carving bedrock canyons occur infrequently; only a handful of examples exist on Earth and most have been inferred from geologic evidence rather than observed directly[4–12]. Herein we present an extraordinary example of formation of a bedrock canyon, Canyon Lake Gorge, Texas, under known hydraulic and topographic conditions during a single dam-release flood event in 2002.

Before the flood, the 2.2 km unmanaged valley consisted of a short ∼115-m-long concrete canal at its most upstream end, an upper ∼1.2 km reach that was steep (2–8% grade), soil mantled with a small creek and mesquite and oak trees, and a ∼1 km lower sloping (0.6–2% grade) downstream reach (Fig. 1a). The valley was intended to be used as an emergency spillway to connect Canyon Lake reservoir to the Guadalupe River downstream of the dam (US Army Corps of Engineers). In 2002 the spillway was used for the first time and the resulting flood excavated trees, sediment, bedrock and a bridge that crossed the valley (Figs 1b,c, 2a), creating Canyon Lake Gorge[13]. Canyon Lake Gorge has a top width of ∼365 m at its most upstream extent ($x < 0.15$ km, where x is the distance from the spillway entrance) set by the width of the concrete canal (Fig. 1a). The eroded gorge width decreases dramatically over the next 400 m downstream and thereafter is approximately constant at ∼50 ± 10 m. Post-flood topographic data (1 m resolution) in the upper reach of the gorge ($x < 1.2$ km) show that vertical incision was anticorrelated with canyon width, where an average of 2.64 m of incision occurred along the thalweg for $x < 0.5$ km, and an average of 7.2 m of incision occurred for $0.5 \text{ km} < x < 1.2$ km with incision exceeding 12 m locally (Fig. 1c). The stratigraphy in canyon sidewalls indicates that ∼90% of the erosion in the upstream reach ($x < 1.2$ km) is the Cretaceous Glen Rose Formation, consisting of limestone, dolostone and marl[14,15], with ∼10% consisting of overlying soil mantle and alluvium. Erosion in the lower reach ($1.2 \text{ km} < x < 2.2$ km) was into a Quaternary fill terrace of the Guadalupe River consisting of weakly cemented silt and sand[14] (Fig. 1). From differencing pre- and post-flood digital topography, 2.3×10^5 m^3 of sediment and rock were eroded from the upper reach of the spillway ($x < 1.2$ km). Unfortunately, post-flood digital topography was not available in the lower reach ($x > 1.2$ km), but field observations and aerial imagery indicate a similar magnitude of incision (∼7 m) and total volume of erosion (∼2.3×10^5 m^3).

Bedrock in the upper reach of the gorge ($x < 1.2$ km) appears well jointed, blocky and hard (Fig. 2d), with some joints showing karst morphologies indicating widening by dissolution. Near-horizontal joints are the result of bedding planes within the Glen Rose Formation, and individual bed thicknesses are 0.7 ± 0.5 m (ref. 15). The near-vertical joints probably relate to the Balcones fault system, an array of normal faults in the region[16]. Transported boulders within the canyon are large (∼1 m diameter) and tabular, and individual boulders often consist of a single limestone bed (based on similar texture, thickness and fossil content), with the bed thickness composing the short dimension of the boulder (Fig. 2b). Together, these observations indicate that the dominant erosion mechanism was plucking[17]. Although there exist a few linear abrasion marks (∼50 mm in length, ∼10 mm in width and etched <1 mm into bedrock surface; Fig. 1b; Supplementary Fig. S1), abrasion appears to have contributed little to canyon formation in the upper reach because exposed beds can be traced laterally across the canyon with little variation in thickness, they lack flutes or potholes[17] and some show preserved Cretaceous wave-ripple forms with no significant wear (Supplementary Fig. S2).

The canyon floor in the upper reach of the gorge contains many vertical steps or knickpoints at various scales that are composed of one or more limestone beds (Fig. 1c). Some knickpoints were waterfalls, show up to 9 m of relief and now form the headwall

[1]California Institute of Technology, Geological and Planetary Sciences, 1200 E. California Blvd., Pasadena, California 91125, USA, [2]Texas State University, Department of Geography, 601 University Dr., San Marcos, Texas 78666, USA. *e-mail: mpl@gps.caltech.edu.

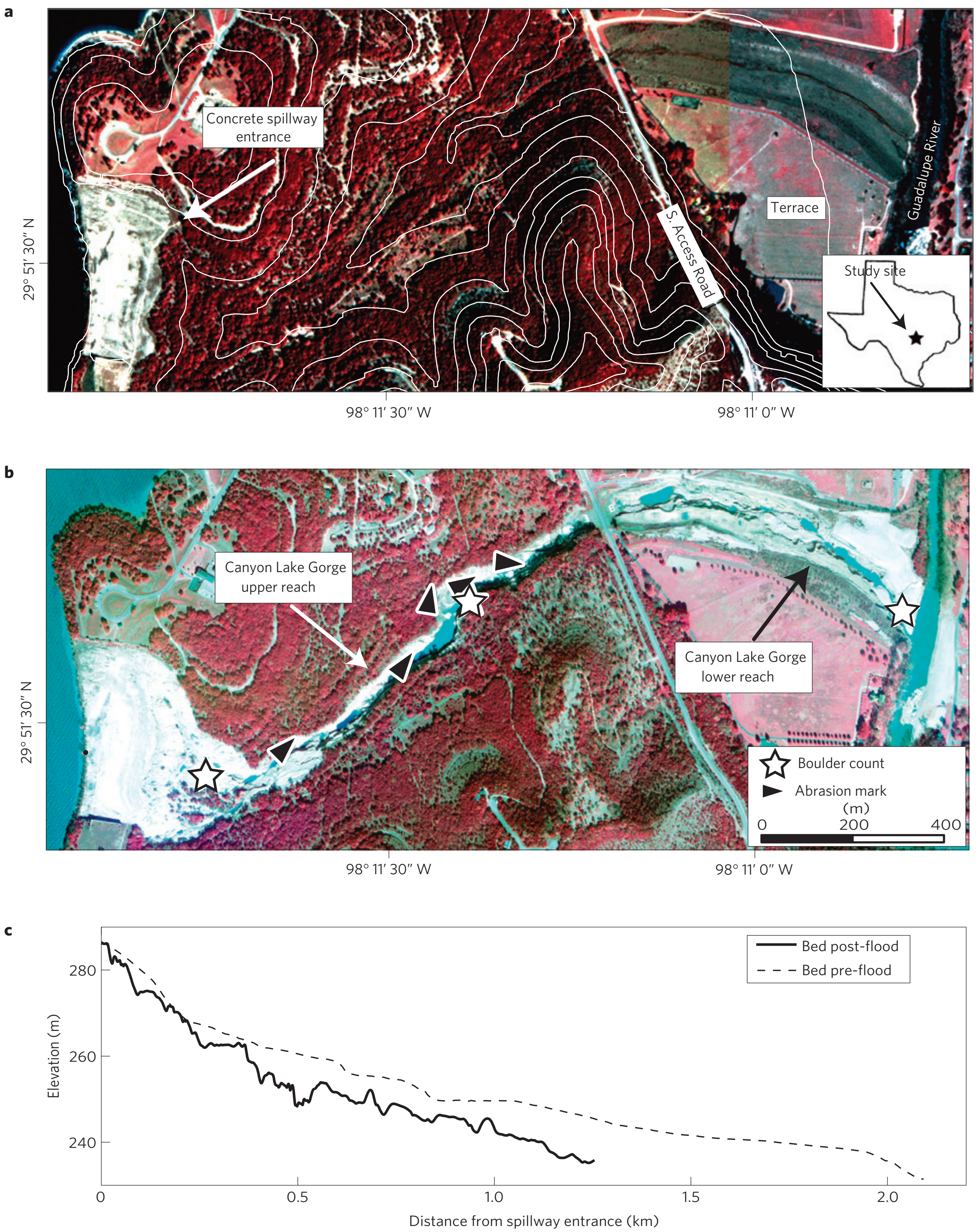

Figure 1 | Pre- and post-flood topography and imagery. a, Canyon Lake Gorge in 1995 before the flood event (1-m-resolution digital visible/near-infrared orthophotograph; NAD1983 datum, and UTM projection; US Geological Survey) showing Canyon Lake (black), concrete spillway entrance (white), South Access Road, vegetated valley (red), alluvial terrace and Guadalupe River. White lines are 10 m topographic contours. **b**, Canyon Lake Gorge in 2007 after the flood event (1-m-resolution NAIP aerial imagery, US Geological Survey) showing particle-size-measurement locations and abrasion marks. **c**, Longitudinal thalweg profile, pre- and post-flood (1-m-resolution post-flood topography, Guadalupe Blanco River Authority, Texas).

of an inner channel with horizontal bedrock terraces on either side (Fig. 2c,d). There is no evidence of prominent undercutting at the base of the headwalls that is typically associated with waterfall retreat[18]. Instead, erosion appears to have occurred through plucking or sliding of slabs of bedrock exposed at vertical faces where beds were unconstrained at their downstream boundaries.

The cemented alluvium in the lower reach ($1.2 < x < 2.2$ km) is massive and lacks the prominent bedding planes and vertical

Figure 2 | Photographs of Canyon Lake Gorge. a, Canyon Lake and upper spillway near peak discharge (credit Comal County, Texas). **b**, Imbricated boulders, $x = 0.35$ km, 3 December 2006. **c**, ∼9-m-high waterfall, $x = 0.5$ km, 27 July 2002 (credit Richard Sears). **d**, ∼7 m waterfall headwall, $x = 0.25$ km, 22 August 2008. **e**, Sculpted islands, $x = 1.6$ km, 22 August 2008. **f**, Potholes, sculpted islands and boulders (white), $1.55 < x < 1.75$ km (0.15-m-resolution aerial orthophotograph, US Geological Survey). Flow is left to right in all images.

joints of the upper reach. It is strong enough to support a vertical face, but collapses under the blow of a rock hammer. The result is that the longitudinal profile lacks knickpoints and steps, and the flood pathway contains two or more interweaving channels with ∼20-m-long and ∼2-m-wide streamlined islands of cemented alluvium in between (Fig. 2e,f), which are similar to some ancient megaflood features on Earth and Mars[4–7,11]. The canyon also has undular walls that appear to be remnants of large potholes (10–25 m diameter; Fig. 2f) indicating erosion by abrasion[17]. Significant numbers of large limestone boulders eroded further upstream were transported through the lower reach of the canyon; some of these now cover the canyon floor (Fig. 2f). Although large boulders must have impacted the streamlined islands with substantial force, the smooth morphology suggests that abrasion by finer particles, potentially transported in suspended load[17,19], dominated erosion in this reach. Despite the fact that bedrock type and the apparent dominant erosion process change abruptly from the upper to the lower reach, the eroded width and depth are surprisingly constant across this transition.

Canyon Lake Gorge offers a rare opportunity to test techniques used to reconstruct ancient megafloods on Earth and Mars because it was formed under known discharge, flood duration, and pre- and post-flood topography. We made these calculations in the upper reach of the canyon where post-flood topography was available (Methods). Minimum flood discharge during canyon excavation is often estimated by the necessary bed stress to begin sediment motion[6,8,9,12,20,21]. The sizes of transported boulders were measured using a point-count method[22] and the median particle diameter at $0.15 < x < 0.25$ km was found to be 0.65 m. Incipient motion of these particles requires a necessary flow discharge of $Q = 380$–$550\ \mathrm{m^3\ s^{-1}}$ (assuming a range in bed-roughness scales: $0.05\ \mathrm{m} < k_s < 0.5\ \mathrm{m}$, Methods). This indicates that canyon erosion occurred for 2.8–3.7 days when the flood exceeded this discharge (that is, 7/4–7/8 in Fig. 3a), which is consistent with eye-witness reports (Supplementary Information).

To estimate the peak in flood discharge, we used two common methods that rely on the observation of sediment inferred to be in suspension during the flood, which for the case of Canyon Lake

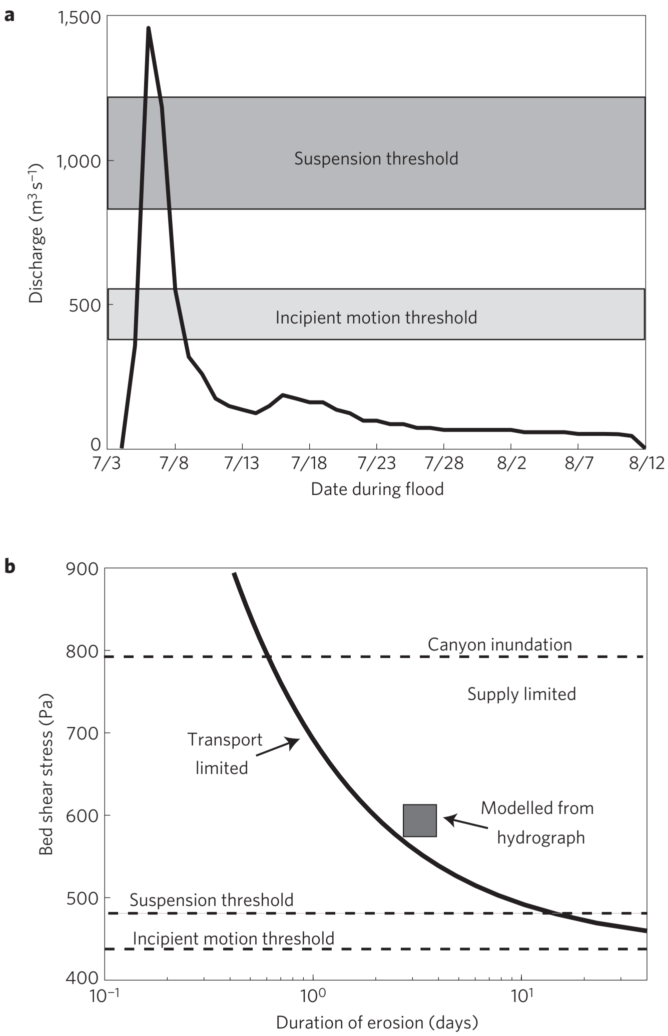

Figure 3 | Observed discharge and hydraulic reconstructions. a, Observed discharge and modelled discharge range to mobilize boulders and suspend sediment. **b**, Flow-duration and average-bed-shear-stress combinations required to transport excavated volume of Canyon Lake Gorge (solid line), and peak stress hydraulic reconstruction estimates for canyon inundation and suspension (Methods). The rectangle represents the range in duration and average bed shear stress during canyon formation as calculated from the observed flood discharge (Methods).

Gorge were found along the canyon rim at $0.93 < x < 1.03$ km (Fig. 1). First it was assumed that the entire canyon cross-section was inundated at $0.93 < x < 1.03$ km during the flood peak[6,8,11], which results in a discharge of 2,660–3,900 $m^3\,s^{-1}$ (for $0.05\,m < k_s < 0.5\,m$, Methods). This necessarily overestimates the discharge because it assumes that the canyon bed was fixed at its post-flood elevation during the flood peak. The second palaeo-hydraulic technique assumes that the particles were at the threshold for suspension during the flood peak[8,20], which could underestimate the flood peak if stresses exceeded this threshold. This results in a necessary bed stress of 480 Pa and a discharge of 830–1,220 $m^3\,s^{-1}$ to suspend the 50 mm particles (Methods; Supplementary Fig. S3). As expected, the two methods bracket the observed flood peak, although the latter yields a more reasonable estimate (Fig. 3a).

It is difficult to identify morphologic features in Canyon Lake Gorge that indicate canyon formation during a 3 day event, versus a longer-lived flood or multiple events. For example, inner channels, knickpoints and terraces are often formed slowly over geologic time in response to shifting climate or tectonic forcing[23], but in Canyon Lake Gorge and other megafloods[4–12] they must have formed rapidly through intrinsic instabilities in the erosion processes. A narrow gorge is sometimes inferred to represent slow persistent erosion[7], whereas Canyon Lake Gorge was formed in a matter of days. It is clear that models for the rate of bedrock erosion are needed to calculate the duration of flooding necessary to excavate a canyon of known volume. Although notable progress has been made[24,25], there are no well tested mechanistic models of bedrock erosion via plucking during megafloods. Instead, models for sediment flux can be used[12,20], which give a minimum estimate for duration if the rate of canyon formation was limited by the erosion of bedrock rather than the transport of sediment. We used the measured volume of excavation in the upper reach, a semi-empirical theory for sediment transport capacity[26] and our bed stress estimates from palaeo-hydraulic reconstructions to calculate the flood duration (Methods). This analysis yields a timescale of canyon excavation of 0.6 days assuming the canyon was inundated and 15 days using the threshold for sediment suspension (Fig. 3b), which bracket the actual duration of canyon formation of ∼3 days.

It is surprising that this result is fairly reasonable given that supply-limited erosion theories are most often applied to bedrock rivers[23]. The estimated average bed stress during canyon excavation is 578–607 Pa using the measured flood hydrograph (Methods), which places it very close to the theoretical prediction for transport-limited erosion (Fig. 3b). We suspect that well developed vertical and horizontal joints at Canyon Lake Gorge define blocks of bedrock that have little interlocking along their boundaries, rendering their behaviour similar to an alluvial bed when the critical stress for mobility is surpassed[4,17,25]. Indeed, the smooth longitudinal profile of canyon depth and width from the upper limestone reach to the lower cemented alluvium suggests that bedrock strength did not limit the rate of erosion. Thus, it seems plausible that erosion of well-jointed rock by large floods might be extremely rapid, such that canyon formation is limited by the capacity of the flood to transport plucked blocks rather than by the plucking processes itself.

Methods summary

Minimum-flow indicators. To estimate the discharge to transport boulders, we assumed hydraulically rough, steady and uniform flow, and calculated the discharge as[27]

$$Q = UA = 8.1\,A\left(\frac{\tau_b}{\rho}\right)^{1/2}\left(\frac{h}{k_s}\right)^{1/6} \qquad (1)$$

where A is the cross-sectional area of the flow, U is the depth-averaged velocity, ρ is the fluid density (1,000 $kg\,m^{-3}$), h is the flow depth and k_s is the roughness-length scale of the bed. The bed shear stress was found from

$$\tau_b = \rho g h_R S \qquad (2)$$

where g is the acceleration due to gravity, h_R is the hydraulic radius and S is the bed-slope gradient. Because roughness is highly variable in the canyon and ranges from relatively smooth bedding-plane surfaces to boulder bars, we used a range of bed-roughness length scales in the model ($0.05\,m < k_s < 0.5\,m$). Although this hydraulic model is oversimplified, most palaeo-hydraulic reconstructions do not warrant more complex flow solvers because the evolutions of bed topography, bed roughness and flood discharge with time are not known. We tested our uniform-flow model predictions against a quasi-one-dimensional, steady, non-uniform, flow algorithm (Hydrologic Engineering Centers River Analysis System) and found similar results, generally within the scatter introduced by the range in bed roughness investigated.

Sediment moves when the Shields parameter (τ_*) exceeds a critical value for incipient motion (τ_{*c}), which we calculated as a function of bed slope following[28] $\tau_{*c} = 0.15\,S^{0.25}$, where $\tau_* = \tau_b/((\rho_s - \rho)g\overline{D_2})$, $\rho_s = 2{,}500\,kg\,m^{-3}$ is the density of sediment, D_2 is the length of the intermediate particle axis and the overbar denotes the median particle size.

The bed slope (following the path of steepest decent and smoothed using a 200 m moving-average window) and cross-sectional geometries (spaced every 30 m) were extracted from the 1 m post-flood topographic data provided by the Guadalupe Blanco River Authority, TX. Given this information, and $\overline{D_2} = 0.65$ m

(Supplementary Information), the discharge was calculated using an iterative numerical scheme because the hydraulic radius (h_R) and cross-sectional area of the flow (A) are functions of flow depth (h) for a given channel cross-section.

Peak-flow indicators. We evaluated sediment deposits along the canyon rim at $x = 930$ m as potential peak-flow indicators. First, we assumed that the entire cross-section at this location was fully inundated, measured the flow depth and slope from the topographic data and applied equations (1) and (2), and found a discharge of 2,660–3,900 $m^3 s^{-1}$ for $0.05 m < k_s < 0.5 m$. Second, we assumed that the particles deposited along the canyon rim were at the threshold of suspension during the flood. The necessary bed stress to suspend the measured particle size ($\overline{D_2} = 0.05$ m, Supplementary Information) can be found from $\tau_b = \rho(0.8w_s)^2$, where w_s is the particle settling velocity[29]. The settling velocity was found to be 0.87 $m s^{-1}$ using the empirical relationship of ref. 30 for natural sediment (Corey shape factor = 0.8, power scale = 3.5), which yields a critical stress for suspension of 480 Pa. This was combined with equations (1) and (2) to calculate the discharge of 830–1,220 $m^3 s^{-1}$ for $0.05 m < k_s < 0.5 m$.

Flood duration. We calculate the necessary flood duration to carve the canyon by assuming that the flow was carrying its full capacity of sediment. The volumetric sediment transport capacity was calculated as[26] $Q_b = 5.7\, w(Rg\overline{D_2}^3)^{1/2}(\tau_* - \tau_{*c})^{3/2}$, where $w = 53.5$ m is the average canyon width, $R = 1.5$ is the submerged specific density of the sediment, $\overline{D_2} = 0.49$ m (Supplementary Information) and $\tau_{*c} = 0.06$ based on the average bed slope in the upper reach of the canyon[28]. The total duration in Fig. 3b was calculated as $\Delta t = V/Q_b$ where V is the volume of the eroded canyon ($V = 2.3 \times 10^5$ m^3 in the upper limestone reach of the canyon from differencing 10-m-horizontal-resolution digital elevation data from before and after the flood event). The Shields number during peak flooding was calculated from our peak-stress estimates for canyon inundation and the threshold for sediment suspension. In addition, we estimated the average shear stress during canyon formation to be 580–610 Pa for $0.05 m < k_s < 0.5 m$ from the measured discharge (when greater than that required for incipient motion) and equations (1) and (2).

Received 23 December 2009; accepted 18 May 2010; published online 20 June 2010

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Acknowledgements

Fieldwork was completed with permission from the Canyon Lake Gorge Preservation Society and the US Army Corps of Engineers. We are indebted to Bill Ward for facilitating this access, sharing his field notes and discussions. We thank B. McElroy, P. Myrow, R. Ewing, J. Shaw and D. Mohrig for field assistance. R. Sears provided photographs taken during the flood event.

Author contributions

M.P.L. was primarily responsible for field measurements, sediment-transport modelling, palaeo-hydraulic analysis and drafting the manuscript. M.A.F. provided field observations immediately following the flood, preliminary hydraulic modelling and assisted in manuscript preparation.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to M.P.L.