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Groundwater drives channel development

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LETTERS

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Growth laws for channel networks incised by groundwater flow

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The re-emergence of groundwater at the surface shapes the Earth's topography through a process known as seepage erosion[1–5]. In combination with flow over land[6], seepage erosion contributes to the initiation and growth of channel networks[1–5]. Seepage processes have also been invoked in the formation of enigmatic amphitheatre-headed channel networks on both Earth[7–11] and Mars[12–14]. However, the role of seepage in producing such channels remains controversial[11,15,16]. One proposed growth law for channel development suggests that the velocity at which channel heads advance is proportional to the flux of groundwater to the heads[17]. Here we use field observations and physical theory to show that this simple model, combined with a second linear response that relates channel branching to the total groundwater flux to the network, is sufficient to characterize key aspects of the growth and form of a kilometre-scale seepage-driven channel network in Florida[18]. We find that the dynamics for the advance of channel heads are reversible, which allows us to estimate the age of the channel network and reconstruct the history of its growth. Our theory also predicts the evolution of the characteristic length scale between channels[19], thereby linking network growth dynamics to geometric form.

Networks of amphitheatre-headed channels known as 'steephead streams'[18] occur abundantly in Liberty County, Florida, east of the Apalachicola River on the Florida panhandle (Fig. 1). The steepheads are incised into 65 m of laterally persistent, medium to coarse, fluviodeltaic and marine sands of Late Pliocene to Pleistocene origin[20], deposited during progradation of the Apalachicola delta[21]. These sands unconformably overlie 15 m of muddy Miocene marine carbonates and sands[20]. Steephead springs occur in the Late Pliocene to Pleistocene sands and examination of the deposit at spring sites reveals no obvious stratigraphic control on their vertical positions[18].

To investigate controls on the horizontal position of springs, we conducted a three-dimensional ground-penetrating radar survey of the water table near a highly bifurcated segment of the channel network (see Supplementary Information). Figure 2a shows that the water table descends as much as 6 m from its highest point midway between channels before reaching the outer contour of the channel network. In general, the height of the water table is a complex function of the spatial distribution of sources (rainfall), sinks (the channel network) and subsurface heterogeneities[22,23]. As rainfall is uniform at this scale, we can test for the influence of heterogeneities by plotting water table height versus the distance to the nearest channel. The good correlation shown in Fig. 2b suggests that distance to the nearest channel, rather than heterogeneities, is the primary determinant of the water table's shape. Consequently the location of springs and the regular structure of this branched drainage network must be a consequence of the intrinsic dynamics of subsurface flow, seepage erosion and sediment transport.

The correlation of Fig. 2b also suggests that the flux of water into any location on the channel network should be proportional to the planform area that is closer to that location than to any other. We call this area the geometric drainage area and plot it in Fig. 3a for each channel tip in the network. Numerical solution of the full three-dimensional hydrodynamic equations for groundwater flow into a periodic array of channels shows that this geometric construction well approximates the relative flux to the tips of channels of varying length (see Supplementary Information).

Howard[17] suggested that the headward erosion rate of a channel tip is proportional to the groundwater flux to the tip. Approximating the flux into the ith tip by the rainfall per unit time into the geometric drainage area a_i associated with that tip then suggests that tip velocity v_i scales as

$$v_i = \beta a_i \tag{1}$$

where β is a transport coefficient (assumed constant) with units $(\mathrm{LT})^{-1}$.

We proceed to test the linear response (1). If it is correct, fast-moving channel tips should be associated with large geometric drainage areas. Figure 3b suggests additionally that larger areas are associated with faster changes in slope as longitudinal valley profiles rise upward from springs towards the relatively flat plain at valley lips. This relation between curvature and area may be understood by assuming that a steady-state longitudinal profile results from a balance between the average erosion rate due to advection and that due to diffusion. Mathematically, this means $\langle v\partial_x h\rangle \sim \langle D\partial^2_{xx} h\rangle$, where h is elevation, D is the topographic diffusivity[24] (assumed constant), v is the horizontal velocity of an elevation contour advancing in the longitudinal direction x, and the angle brackets represent averaging over the upper-slope convexity, which extends a characteristic length r given by its radius of curvature (Fig. 3b). Dimensional analysis of the advection–diffusion balance then yields $v \sim D/r$. Consequently equation (1) predicts that the curvature r^{-1} increases linearly with the geometric drainage area a. Figure 3c tests this prediction for 29 valley heads. The results are indeed consistent with $r^{-1} \simeq \beta a/D$, thereby validating equation (1) and providing an estimate of β/D. Noting that the median radius of curvature is 66 m and assuming

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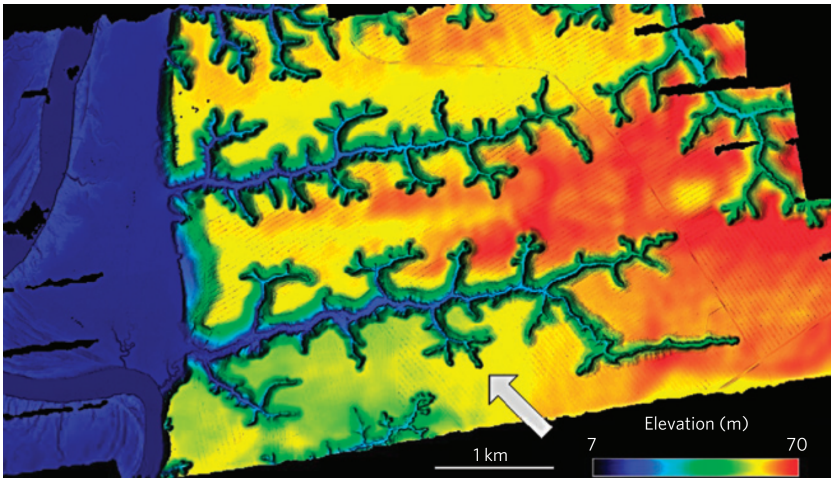

Figure 1 | Topographic map of networks of steephead channels draining into the Apalachicola River, located on the Apalachicola Bluffs and Ravines Preserve, near Bristol, Florida. Topography is shaded with illumination from the east. The arrow points to the location of the water table map in Fig. 2. Mapping data were collected by the National Center for Airborne Laser Mapping. The Universal Transverse Mercator coordinates run from 692000–699000 easting and 3372000–3376000 northing.

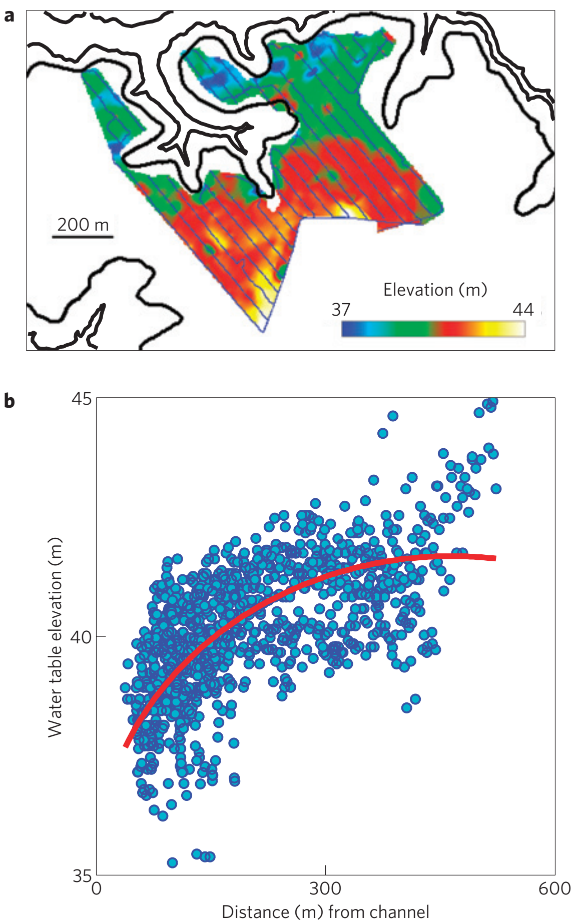

Figure 2 | Water table geometry. a, Elevation of the water table in the region indicated by the arrow in Fig. 1, along with the 35 and 50 m elevation contour of the surface topography (black). The water table was imaged by ground-penetrating radar surveys carried out along transects given by the blue lines. The flat plain away from the channels has a typical elevation of 56 m. **b**, Elevation of the water table plotted against the shortest distance from the 35 m contour. The red curve is the best fitting Dupuit-Forchheimer ellipse[23]. The Spearman rank correlation coefficient $r = 0.69$ ($N = 1{,}065$, $P = 0$). See Supplementary Information.

that the diffusivity $D \simeq 0.02\,\mathrm{m^2\,yr^{-1}}$ (refs 25–28), we find that the headward velocity $v \sim D/r \sim 0.3\,\mathrm{mm\,yr^{-1}}$, consistent with a previous estimate[18].

The water table's shape adjusts continually in response to the advance of channel tips. Given the typical hydraulic conductivity $K \sim 10^{-3}\,\mathrm{m\,s^{-1}}$ for sand[23] and a typical tip area $a \sim 4 \times 10^4\,\mathrm{m^2}$, the timescale for relaxation of the water table is $\sqrt{a}/K \sim 2$ days. Consequently the water table adjusts rapidly—that is, quasistatically—on the timescale of headward growth.

This mundane observation has a profound implication: the headward growth described by equation (1) is reversible. We therefore evolve the network backwards in time by retracting tips i at velocity $-\beta a_i$, continuously updating the a_i values as the network geometry changes. Reversing the process yet again so that time marches forward then provides a reconstruction of the network's growth. Figure 4 shows that new channel tips are generated by both side-branching and tip-splitting events. Computer animation (see Supplementary Information) shows the process dynamically.

An immediate consequence of the reconstruction is an ability to estimate the age of the network. Letting ℓ be the length of a stream and t the time it takes to grow with time-averaged tip velocity $\bar{v}$ and tip area $\bar{a}$, we have

$$t = \frac{\ell}{\bar{v}} = \frac{\ell}{\beta \bar{a}} = \frac{1}{D}\left(\frac{D}{\beta}\right)\left(\frac{\ell}{\bar{a}}\right) \qquad (2)$$

where the second equality follows from averaging equation (1) over time. For the longest channel of the modern network, $\ell \simeq 3.9 \times 10^3$ m and $\bar{a} \simeq 8.3 \times 10^5\,\mathrm{m^2}$. Inserting into equation (2) our previous estimate[25–28] of the diffusivity D and our estimate of D/β from Fig. 3c, we then obtain $t \simeq 0.73$ Myr, roughly accurate within a factor of two, and consistent with the Pliocene–Pleistocene age ($\sim$2 Myr) of the sand. These numbers imply that the time-averaged tip velocity is about $5.3\,\mathrm{mm\,yr^{-1}}$. Averaging over all channels for the last 10,000 yr of the network's evolution, however, shows that the current network is growing more slowly, at about $0.5\,\mathrm{mm\,yr^{-1}}$, which represents a refinement of our previous estimate using the curvature–area relation of Fig. 3c.

More fundamentally, the reconstruction also shows an approximate rate law for the generation of new channels by tip-splitting and side-branching. Let $A(t)$ equal the total area drained by the network. Then $\dot{N}/L$ is the production rate, per unit length, of new tips, and A/L is the drainage area, per unit

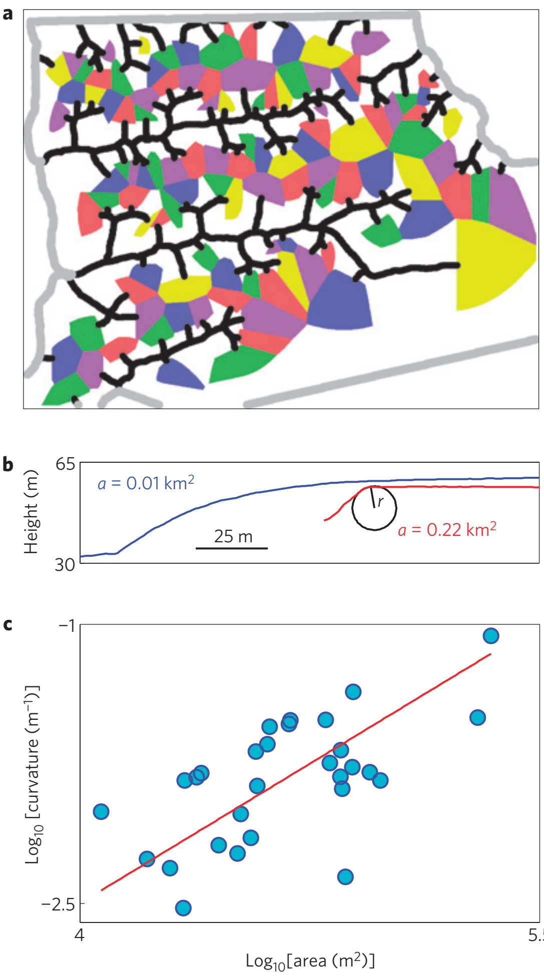

Figure 3 | Geometric drainage areas and the curvature–area relation. **a**, Backbone of the network of Fig. 1 (black) along with the geometric drainage area a (coloured polygons) associated with each channel tip. Grey lines indicate boundaries used to delineate the overall basin. **b**, Longitudinal valley profiles associated with small (0.01 km^2) and large (0.22 km^2) geometric drainage areas. In the latter case, the radius of curvature, r, of the upper-slope convexity is indicated. Horizontal axis is only for scale. Profiles rise upward from springs and terminate at the flat plain. **c**, Log–log plot of the curvature r^{-1} versus geometric area a for isolated non-bifurcating valley heads. The Pearson correlation coefficient $r = 0.62$ ($N = 29$, $P < 0.001$). The straight line is the best fit to $r^{-1} = (\beta/D)a$, providing the estimate $\beta/D = 3.2 \pm 0.7 \times 10^{-7}$ m^{-3}. The valley profiles of **b** correspond to the smallest and largest areas in **c**. See Supplementary Information.

length, into the entire network. The generation of new channel tips must ultimately derive from a three-dimensional erosional instability[1–5,29,30]. We know of no theory for this instability, but the mechanism that drives it must be drainage into the network. Consequently we expect that A/L is proportional to a force density that creates new tips at rate $\dot{N}/L$ per unit length. Hypothesizing a linear response, we obtain

$$\frac{dN}{dt} = \alpha A \tag{3}$$

where α is a rate constant per unit area, with units $(\mathrm{L}^2\mathrm{T})^{-1}$. We test the integral form of equation (3) by plotting $N(t)$, the number of channel tips, versus $\int_0^t A(t')\,dt'$. The result, shown in the inset of Fig. 4, is consistent with the linear response equation (3); the slope gives the rate constant α.

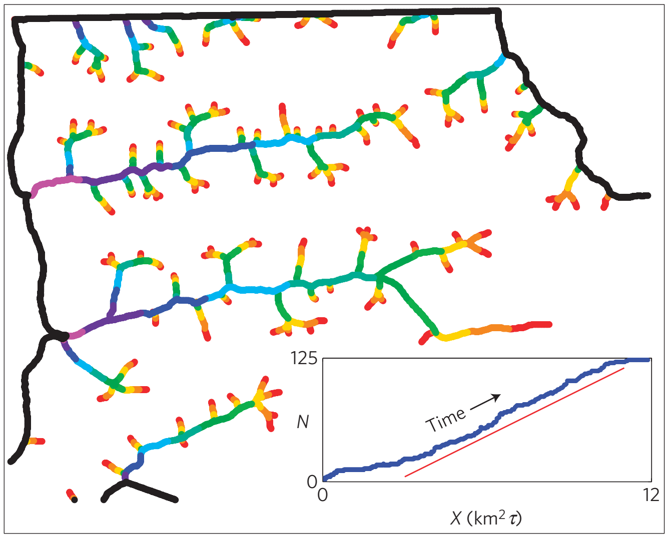

Figure 4 | Reconstruction of network growth. Each coloured segment corresponds to one-tenth of the elapsed time of growth. Black segments represent initial conditions. Computer animations are available in Supplementary Information. Inset: Plot of the number of reconstructed channel tips, N, versus $X = \int_0^\tau A(\tau')d\tau'$, where $\tau = t/t_{max}$. After an initial transient the growth is approximately linear, thereby validating equation (3).

The linear response relations (1) and (3) provide, respectively, the growth and birth rates of channels. The ratio of the transport coefficient β to the rate constant α is a length scale that represents the characteristic growth of the network's total length L during the characteristic time between the birth of new channels. We can obtain β/α explicitly by noting from equation (1) that $\dot{L} = \beta \sum_i a_i$ and integrating to obtain $\beta t = L/\sum_i \bar{a}_i$. On the other hand, integration of equation (3) yields $\alpha t = N/\bar{A}$, where $\bar{A}$ is the time-averaged area draining into the entire network. Then

$$\frac{\beta}{\alpha} = \frac{L(t)}{N(t)}\left(\frac{\bar{A}(t)}{\sum_i \bar{a}_i(t)}\right) \tag{4}$$

Note that all terms on the right-hand side depend on time, but the left-hand side does not. Thus, lengths, areas and the number of channels must evolve such that β/α is constant. Our reconstruction confirms this prediction: over the last half of the network's growth, $\beta/\alpha \simeq 461$ m with a root-mean square fluctuation of less than 3%.

To further understand the length scale β/α, we define the dimensionless 'screening efficiency' $S = \sum_i \bar{a}_i/\bar{A}$. Substitution into equation (4) and rearranging then yields

$$L = \left(\frac{\beta}{\alpha}\right) SN \tag{5}$$

The screening efficiency $0 \le S \le 1$ is the fractional extent to which tips draw groundwater away from channel sidewalls. In the limit in which all groundwater flows to tips, $S = 1$ and each tip contributes a length β/α to the total channel length L, consistent with our dimensional argument. Less efficient screening ($S < 1$) implies less length per tip. (Here we find $S = 0.59 \pm 0.01$ while $\beta/\alpha \simeq$ const.) But the fundamental length scale that must determine all other lengths is β/α.

Foremost among network length scales is the average distance A/L between any point on the network and the closest groundwater divide. This 'dissection' scale[19] is the inverse of Horton's drainage density[6] L/A. It is typically studied in the context of mature, static networks in which the tips no longer gather sufficient water to grow[19]. Here we instead provide a dynamic view. Dividing both sides of equation (5) by A, it can be seen immediately that the drainage density increases as the number N of tips grows.

Decades ago, Dunne[1,3,4] advanced a conceptual model for the development of seepage-driven networks. Its principal components—headward growth due to groundwater focusing and generation of new channel heads by tip-splitting and side-branching—are encoded here in terms of two linear response relations. After validating these linear laws by analysis of the Florida network's present and past development, we find that the evolution of lengths, drainage density and number of tips is slaved to the transport coefficient β and rate constant α that set the respective timescales for the network's growth and ramification. This result provides an explicit link between the dynamics of a network and its static structure. Although this link does not by itself provide an immediate method for resolving the mysterious provenance of other amphitheatre-headed channels[7–16], we expect that the growth laws on which it is based will be useful for understanding the mechanisms that produce such shapes in addition to providing further reconstructions of past network growth.

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References

1. Dunne, T. *Runoff Production in a Humid Area*. Thesis (Johns Hopkins Univ., 1969). Also published as US Department of Agriculture Report ARS 41–160 (1970).
2. Dunne, T. in *Hillslope Hydrology* (ed. Kirkby, M. J.) 227–293 (Wiley, 1978).
3. Dunne, T. Formation and controls of channel networks. *Prog. Phys. Geogr.* **4**, 211–239 (1980).
4. Dunne, T. in *Groundwater Geomorphology: The Role of Subsurface Water in Earth-Surface Processes and Landforms* Vol. 252 (eds Higgins, C. G. & Coates, D. R.) 1–28 (Geol. Soc. Am. Special Paper, Geological Society of America, 1990).
5. Dietrich, W. E. & Dunne, T. in *Channel Network Hydrology* (eds Beven, K. & Kirby, M. J.) 175–219 (Wiley, 1993).
6. Horton, R. E. Erosional development of streams and their drainage basins: Hydrophysical approach to quantitative morphology. *Geol. Soc. Am. Bull.* **56**, 275–370 (1945).
7. Wentworth, C. K. Principles of stream erosion in Hawaii. *J. Geol.* **36**, 385–410 (1928).
8. Laity, J. E. & Malin, M. C. Sapping processes and the development of theater-headed valley networks on the Colorado plateau. *Geol. Soc. Am. Bull.* **96**, 203–17 (1985).
9. Orange, D. L., Anderson, R. S. & Breen, N. A. Regular canyon spacing in the submarine environment: The link between hydrology and geomorphology. *GSA Today* **4**, 1–39 (1994).
10. Schorghofer, N., Jensen, B., Kudrolli, A. & Rothman, D. H. Spontaneous channelization in permeable ground: Theory, experiment, and observation. *J. Fluid Mech.* **503**, 357–374 (2004).
11. Lamb, M. P. *et al.* Can springs cut canyons into rock? *J. Geophys. Res.* **111**, E07002 (2006).
12. Higgins, C. G. Drainage systems developed by sapping on Earth and Mars. *Geology* **10**, 147–152 (1982).
13. Malin, M. C. & Carr, M. H. Groundwater formation of martian valleys. *Nature* **397**, 589–591 (1999).
14. Malin, M. C. & Edgett, K. Evidence for recent groundwater seepage and surface runoff on Mars. *Science* **288**, 2330–2335 (2000).
15. Lamb, M. P., Howard, A. D., Dietrich, W. E. & Perron, J. T. Formation of amphitheater-headed valleys by waterfall erosion after large-scale slumping on Hawaii. *GSA Bull.* **19**, 805–822 (2007).
16. Lamb, M. P., Dietrich, W. E., Aciego, S. M., DePaolo, D. J. & Manga, M. Formation of Box Canyon, Idaho, by megaflood: Implications for seepage erosion on Earth and Mars. *Science* **320**, 1067–1070 (2008).
17. Howard, A. D. in *Sapping Features of the Colorado Plateau: A Comparative Planetary Geology Field Guide* (eds Howard, A. D., Kochel, R. C. & Holt, H. E.) 71–83 (NASA Scientific and Technical Information Division, 1988).
18. Schumm, S. A., Boyd, K. F., Wolff, C. G. & Spitz, W. J. A ground-water sapping landscape in the Florida Panhandle. *Geomophology* **12**, 281–297 (1995).
19. Montgomery, D. R. & Dietrich, W. E. Channel initiation and the problem of landscape scale. *Science* **255**, 826–830 (1992).
20. Schmidt, W. *Alum Bluff, Liberty County, Florida*. Open File Report 9 (Florida Geological Survey, 1985).
21. Rupert, F. R. *The Geomorphology and Geology of Liberty County, Florida*. Open File Report 43 (Florida Geological Survey, 1991).
22. Polubarinova-Kochina, P. I. A. *Theory of Ground Water Movement* (Princeton Univ. Press, 1962).
23. Bear, J. *Dynamics of Fluids in Porous Media* (Dover, 1972).
24. Culling, W. E. H. Analytic theory of erosion. *J. Geol.* **68**, 336–344 (1960).
25. McKean, J. A., Dietrich, W. E., Finkel, R. C., Southon, J. R. & Caffee, M. W. Quantification of soil production and downslope creep rates from cosmogenic ^{10}Be accumulations on a hillsope profile. *Geology* **21**, 343–346 (1993).
26. Rosenbloom, N. A. & Anderson, R. S. Hillslope and channel evolution in a marine terraced landscape, Santa Cruz, California. *J. Geophys. Res.* **99**, 14013–14029 (1994).
27. Fernandes, N. F. & Dietrich, W. E. Hillslope evolution by diffusive processes: The timescale for equilibrium adjustments. *Wat. Resour. Res.* **33**, 1307–1318 (1997).
28. Small, E. E., Anderson, R. S. & Hancock, G. S. Estimates of the rate of regolith production using ^{10}Be and ^{26}Al from an alpine hillslope. *Geomorphology* **27**, 131–150 (1999).
29. Howard, A. D. & McLane, C. F. Erosion of cohesionless sediment by groundwater seepage. *Wat. Resour. Res.* **24**, 1659–1674 (1988).
30. Lobkovsky, A. E., Jensen, B., Kudrolli, A. & Rothman, D. H. Threshold phenomena in erosion driven by subsurface flow. *J. Geophys. Res.-Earth* **109**, F04010 (2004).

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Author contributions

D.M.A., A.E.L., A.P.P., K.M.S. and D.H.R. contributed equally to this work. D.M.A., A.E.L., A.P.P. and D.H.R. developed theory and carried out field work and data analysis. K.M.S. and A.K. carried out field work and data analysis. B.M. and D.C.M. carried out field work and analysed regional sedimentology. D.H.R. wrote the paper, with input from D.M.A., A.E.L., A.P.P., K.M.S. and B.M.

Additional information

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Unearthing the flow

Daniel Rothman and colleagues imaged underground water and made friends with a hatchet-wielding prisoner during their attempt to understand the mechanics of stream development.

Daniel Rothman (left) and Kyle Straub during an early attempt to obtain ground-penetrating radar data to map the water table.

What was the objective of the work?
Most studies of stream growth concern how channels develop following the flow of water over land. However, when groundwater seeps through to the surface it can also create channels. We initially went to our Florida field-site to better understand how this often neglected process of groundwater seepage affects the shape of individual channels. Our goal of comparing our theoretical predictions and experimental results with field observations was quickly met. Yet, the beauty of the site immediately motivated investigations into how entire networks of channels evolve.

Why did you choose this particular location for the fieldwork?
We were seeking the simplest possible large-scale manifestation of channels generated by groundwater seepage. After reading a paper by Stan Schumm, of Colorado State University, on seepage channels in the Florida Panhandle, we decided to head there. We found some of the nicest examples in The Nature Conservancy's Apalachicola Bluffs and Ravines Preserve. This was especially fortunate because The Nature Conservancy provided unfettered access to the preserve.

What sorts of data were you after?
First and foremost we needed topographic data. The usual digital elevation maps were insufficiently resolved for our purposes, so we asked the National Center for Airborne Laser Mapping to construct a map of the region with a 1-metre horizontal resolution. However, we also required another kind of topographic map — one that gives the shape of the water table. For that we conducted our own ground-penetrating radar survey.

Did you encounter any difficulties?
Absolutely: a lack of field experience. In fact, most of us had no idea what we were doing! But, we had the great fortune of working with some highly experienced colleagues, and we learnt rapidly.

Did you have any dangerous encounters?
Almost. Inmates from a nearby prison often work on the site. We hardly ever saw them, but once one of the inmates approached some members of our group with a hatchet. As it happened, he only wanted to chat.

Any lowpoints, close misses?
Most of the data we collected are useless. Sometimes the problem was faulty equipment — our first attempt to collect ground-penetrating radar data recorded only the sign of the reflected radar wave, not its amplitude. Other times we encountered the time-honoured problem of natural variability; for example, measuring the water flux coming out of the ground in a way that is not strongly influenced by local, small-scale heterogeneities turned out to be very difficult. If the work wasn't fun we would have quit from frustration long ago.

What was the highlight of the expedition?
For a group mostly based in Cambridge, Massachusetts, it is hard to beat the pleasures of Florida in January.

Did you learn anything new about yourself or your team members?
Those of us who hadn't done fieldwork before learnt how much fun it can be, but how awfully hard it is to obtain results worth showing anyone else. The more experienced members of our group cultivated patience when working with inexperienced theoreticians.

Did the trip give you any ideas for future research projects?
Although we've learnt how to reconstruct the growth of a highly branched channel network, we do not yet understand the mechanisms through which the branching process is initiated. The Florida network provides an abundant supply of active branching events. At present we are refining our theoretical and experimental models to better understand the conditions that favour branching. We will then take our predictions to Florida to see how they stack up against the real world.

This is the Backstory to the work by Daniel Rothman and colleagues, published on page 193 of this issue.

HYDROLOGY

Forming valleys from below

Surface water is known to shape the formation and growth of valleys and channels. However, in some geologic settings, groundwater seeping upwards is important for the development of channel networks.

Alan D. Howard

Stream valleys cross the surface of terrestrial planets. Some still carry water, whereas others are remnants from earlier climates. The channels primarily form through runoff from the surrounding catchment, either directly from precipitation or from melting snow. However, runoff alone cannot explain the formation of all channel networks — in some geologic settings, the seepage of groundwater can be the dominant factor. On page 193 of this issue, Abrams and colleagues[1] use field observations and physical theory to generate a model for the growth of such channel networks, and apply the model to an extensive network of channels in Florida that were excavated by groundwater.

Groundwater can influence the development of valleys in a number of ways. In the simplest mechanism, flowing groundwater enters cracks and fissures in soft sediments, creating subsurface channels through scouring — a process directly analogous to erosion by surface flows. This is common in arid landscapes, in badlands or on stream terraces. Scouring also occurs locally in headwater hollows in more humid landscapes. Alternatively, groundwater can dissolve rocks composed of soluble minerals, such as limestone and gypsum, forming cavernous subsurface networks that can extend surface drainage though collapse processes, such as sinkholes.

Groundwater often re-emerges to the surface as a seep. This process tends to be strongest at the headward tips of stream networks, where subsurface flows often converge. It has been proposed that seepage is important in the extension of valley networks in a number of terrestrial and planetary settings, although this interpretation remains controversial[2]. For groundwater seepage to drive valley extension, the processes that produce loose sediment at the valley head, and the processes of fluvial transport that remove that sediment, must work in perfect harmony. The most intensive debate surrounds the role of groundwater in the extension and incision of valleys in hard rock. It has been proposed that such groundwater seepage in both rock weathering and transport is important in a number of settings, including sandstone canyons in the southwestern United States, deep Hawaiian valleys and short valleys fed by springs in Idaho.

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Figure 1 | The Florida channel networks. This aerial photograph shows the well-developed intricately branching channels that are formed by groundwater seepage. Abrams and colleagues[1] show that the seepage rate and the amount of water discharged control the shape and formation of these channels.

The valleys in Hawaii and Idaho are cut into basaltic bedrock. These valley systems share the common characteristics of deep canyons: stubby branches and headward termination in abrupt, sometimes rounded, headwalls known as amphitheatres. These valleys have been thought to be excavated entirely by the modest flows contributed by groundwater. This interpretation formed an attractive explanation for valley networks on Mars, partly because atmospheric scientists have had difficulty accounting for a warm climate and heavy precipitation early in martian history.

Recent studies have called into question the role of groundwater in the terrestrial valley systems cited as seepage archetypes[2]. Runoff from precipitation clearly dominates transport of sediment in both the southwestern sandstone canyons and the Hawaiian basalt canyons[2]. In Hawaii, plunge-pool erosion has been suggested as the dominant erosive process, although seepage weathering may be prevalent in the sandstone canyons. Large-volume flows also emanate from the springs at the head of the Idaho basalt valleys, but they are insufficient to transport the large boulders that form the channel beds. It thus seems that one or more megafloods poured over the headwall of these valleys, probably contributing to valley extension[3].

Despite the controversial role of groundwater in some valley systems, Abrams and colleagues[1] find that emerging groundwater is directly involved in forming extensive channel networks in the Florida panhandle (Fig. 1). The extensive deposits of loose sandy sediment in this region have permitted the development of elaborately branched seepage valleys several kilometres in extent[4], which Abrams and colleagues have used as the basis for their field studies of seepage erosion. The group was able to develop a mechanistic model using a combination of theory, experimentation and field study of this unusual site[5–7].

Abrams and colleagues use detailed mapping of the surface topography to estimate the rate at which the head of the valley grew forward, based on the magnitude of the diffusivity of soil creep. The authors also propose that the rate of valley head extension is proportional to the seepage rate. This implies that the rate of growth should slow as the tributary heads approach the drainage divides, where inflow is reduced. As seepage channels erode and grow towards divides, they also elaborate into a network by branching at their tips. The authors suggest that the creation of new tributaries is directly related to the size of the contributing drainage area. This results in a linear increase in the branching of the networks with increasing drainage area.

The rate of channel growth that Abrams and colleagues describe has the interesting property of being 'reversible', which means the equation can be solved for the starting values. Thus, it can be used to calculate the age and timing of the network development. Using this interpretation, they find that the channel network is roughly 0.73 million years old, which is broadly consistent with the age of the sediments. The quantification of such a relationship allows the history of seepage-driven networks to be defined, and could provide a means for estimating the age of surface features on Earth and on Mars.

However, further study is required to substantiate the relationships proposed by Abrams and colleagues[1]. Both the linear relationship between seepage and growth rate, and the proportional relationship between branching rate and contributing area, are based on model assumptions that require verification. Simulation modelling indicates that the degree of branching in seepage valleys may depend on the functional relationship between seepage flux and the rate of valley extension[8]. Measurements of water and sediment fluxes in the Florida drainage network, estimation of erosion rates and history (using cosmogenic isotopes and other methods), and detailed study of the geologic context should help with testing these relationships. ❐

References

1. Abrams, D. M. *et al. Nature Geosci.* **2,** 193–196 (2009).
2. Lamb, M. P. *et al. J. Geophys. Res.* **111,** E07002 (2005).
3. Lamb, M. P. *et al. Science* **320,** 1067–1070 (2008).
4. Schumm, S. A., Boyd, K. F., Wolff, C. G. & Spitz, W. J. *Geomorphology* **12,** 281–297 (1995).
5. Schorghofer, N., Jensen, B., Kudrolli, A. & Rothman, D. H. *J. Fluid Mech.* **503,** 357–374 (2004).
6. Lobkovsky, A. E., Jensen, W., Kudrolli, A. & Rothman, D. H. *J. Geophys. Res.* **109,** F04019 (2004).
7. Lobkovsky, A. E., Smith, B. E., Kudrolli, A., Mohrig, D. C. & Rothman, D. H. *J. Geophys. Res.* **112,** F03S12 (2007).
8. Howard, A. D. *Geomorphology* **12,** 187–214 (1995).

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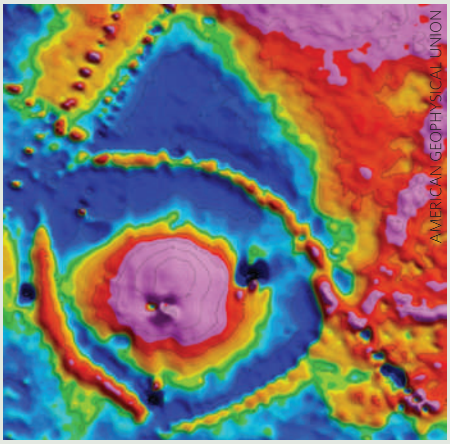
GEOMORPHOLOGY

Crater or not?

Chance physical phenomena can intersect with human civilization in unexpected ways. One such phenomenon is a putative meteorite impact in Italy's Sirente region dated to around AD 400: it has been speculated that the fiery arc traced by the meteorite fragments in the sky was instrumental in triggering a chain of events that eventually led to Christianity displacing pagan beliefs in the Roman Empire.

The primary evidence for an impact in this region is the presence of an approximately 100-metre-wide sag or depression, accompanied by other smaller sags. The morphological attributes and distribution of these features have been considered consistent with crater formation due to a meteorite shower. However, this interpretation is by no means unique. Several features typical of impacts, such as shocked minerals and high concentrations of certain metals, have not been found, and the craters have alternatively been proposed to be mud volcanoes, pits dug by humans or sink holes, that is pit-like features that commonly form when water dissolves lime.

Resolution of the craters' origins requires detailed information about the subsurface structure of the sags, which is now presented by Speranza and colleagues (*J. Geophys. Res.* doi: 10.1029/2008JB005759; 2009).



According to the team, the electrical and magnetic properties of the area's sediments and rocks show unambiguously that none of the crater-like structures were formed by an impact. Furthermore, geological and geochemical data — such as the absence of methane or carbon dioxide reservoirs at depth — rule out a mud volcano origin.

The survey shows that the sags are underlain by a thin sedimentary package that rests on a series of ridges and valleys cut into a limestone substrate. Sediment-filled depressions in the subsurface ridges, indicative of sink holes, underlie many of the smaller sags. The researchers conclude that water seeping through the sediments led to the formation of sinkholes at depth, which ultimately caused the surface to cave in.

The main crater-like feature is now occupied by a lake. Layers of sediments within and underlying this lake show no sign of being disturbed and are more or less horizontal, which is inconsistent with an impact. The properties of these sediments and those surrounding this sag are rather similar and it is therefore unlikely that sediments in the structure represent impact crater fill. Moreover, the magnetic signature of the material at the bottom of the main sag is quite the opposite of what would have been expected for a buried meteorite.

Depressions with a size similar to the main Sirente sag are also found in nearby hill ranges; the researchers have previously proposed that these are man-made. The region's economy has depended on sheep rearing for thousands of years: water flowed from springs and accumulated in these sags, which served as a drinking trough. Speranza and colleagues suggest that the Sirente crater served a similar purpose and is in fact a water reservoir made by humans.

The Sirente sags appear to have been emplaced under far calmer circumstances than a meteoritic impact. Their birth is unlikely to have swung Roman history, but probably helped satisfy many a thirsty lamb.

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