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


FLORIDA DEPARTMENT OF REVENUE

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.

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.

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).

Alan D. Howard is at the Department of Environmental Sciences, PO Box 400123, University of Virginia, Charlottesville, Virginia 22904–4123, USA. e-mail: ah6p@virginia.edu

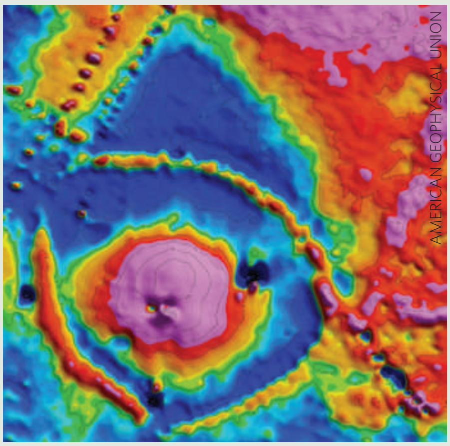
GEOMORPHOLOGY

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).


AMERICAN GEOPHYSICAL UNION

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.

NINAD BONDRE