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Formation and development of stream potholes in a gorge in Guangdong

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Abstract: The goal of this study is to provide information on the process of pothole growth on a gorge streambed. Pothole geometries were measured in a reach of the Dabu river bed at the head of a gorge more than 200 m deeply incising into a 650–750 m high planation surface formed in the middle Miocene in northern Guangdong, China. Geometric and derivative data of the potholes obtained from fieldwork were interpreted using standard statistical methodologies. Our study shows that the formation and development of a stream pothole were only related to local conditions of a stream reach where the pothole occurs; the weaknesses, which are usually intersect fractures, typically interconnected vertical joints, or triangular pits generated by hitting of rock fragments during floods, initiate the pothole development on a streambed; the geometrical dimensions of the potholes are controlled by tectonic joints developed in bedrock of the stream reach; the radius and the depth of potholes are strongly (log) positive correlated; the pothole shapes and the flow patterns are inconstant during pothole growth; a pothole can be formed within a short period, but cannot be fully developed and maintained for a long time in a strong incision streambed. The finding in our study can improve the understanding of Quaternary environment in Guangdong.

Keywords: Guangdong gorge; stream pothole; morphological feature

Potholes can be produced in various ways and, broadly speaking, any kinds of openings or holes in hard rocks or soft deposits can be called potholes (Zhong *et al*., 2002). According to the researches on the potholes so far in China, stream potholes are found in Guangdong, Hong Kong, Yellow Mountain and lower Yellow River, wave eroded potholes are reported in Hong Kong, Guangdong and Taiwan, and wind eroded and weathered potholes are discovered in Hebei and Inner Mongolia (Zhong *et al*., 2002; Gui *et al*., 1999; Li *et al*., 2001; Zeng, 1958; Zhu, 2000; Hsi, 1974). Also it is worth mentioning that the stream potholes in Guangdong and wind eroded potholes in Hebei and Inner Mongolia are taken for glacier potholes or moulins by some investigators (Han *et al*., 2001; Zhao *et al*., 2006).

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Potholes are a good medium to study the environmental changes (Gui *et al.*, 1999). Study on the process of pothole growth is not only a criterion of judging the geomorphologic importance, but also a significant way to reveal the direction of environmental changes on the earth. For instance, stream potholes are microrelief on the streambeds almost omnipresent in mountainous area of Guangdong. If the stream potholes are assumed as moulins (glacier potholes) formed in ice age, one must suppose that glacier or glacier cover had extended to the region of Guangdong at that time. However, it lies in the difficulty of being compatible with the prevalent understanding of Quaternary environment in Guangdong, the evidences to support which come from ancient deposits, spores, landforms and weathering horizons (Zhong *et al.*, 2002; Gui *et al.*, 1999; Liu *et al.*, 2000; Li *et al.*, 2001; Zhu, 2000; Shi, 2002; Zhou, 2006). Similar arguments between "moulins" and "potholes" occurred in the western world can be traced back to the mid-18th century (Alexander, 1935).

This paper examines potholes on the streambed at the head of a gorge 200 m deep. Statistic analysis of geometric features of the stream potholes measured in the field, combined with related field observations, reveals the origins, formation and development of the potholes. The conclusion of the study can provide valuable information for improving the understanding of Quaternary environment in Guangdong.

1 Study site and geological background

Bedrock of this region is Devonian sandy shale rock, inclining to NNW with obliquity of 5°, some of which exceed 10° in individual places. The Dabu River, the source of which is on the western side of Jingkeng'ao Mountain with elevations of 1100–1200 m, flows eastward through a well-preserved planation surface, where Dabu Town is located. The planation surface is 650–750 m in height and has an area of 20^2 km, and the river suddenly turns to southeast into a deep gorge at a locality 3 km southeast of Dabu Town. The streambed at head of the gorge is more than 200 m lower than the planation surface and the river flows into the gorge as a waterfall (Figure 1). The gorge is narrow with steep slopes on both sides running southwards more than 20 km in distance before flowing into 100–200 m high foothills (Zeng and Huang, 2001).

The study site is a 400 m long reach of a gorge stream near the head of the gorge from Pubutan Pool to Huanglongtan Pool with an altitude descending from 410 m to 380 m (measured using a barometer). The term of "Pool" herein is a local name for a big waterfall. Five groups of vertical joints were developed on the bedrock of the streambed as a result of tectonic actions. The strike directions of the joints measured in the field are 5º–20º, 35º–50º, 60º–70º, 270º–280º and 315º–335º with dip angles of 70º–88º. The result of the measurement is similar to the work of previous investigators (Zeng and Huang, 2001). In a longitudinal direction, the streambed has flat rocky surfaces combined with steps and cascades which constitute a great streambed gradient. The transverse section of the streambed displays a combination of rocky deep channels and shallow shoals called low water and high water streambeds respectively by Zeng (1958) (Figure 1).

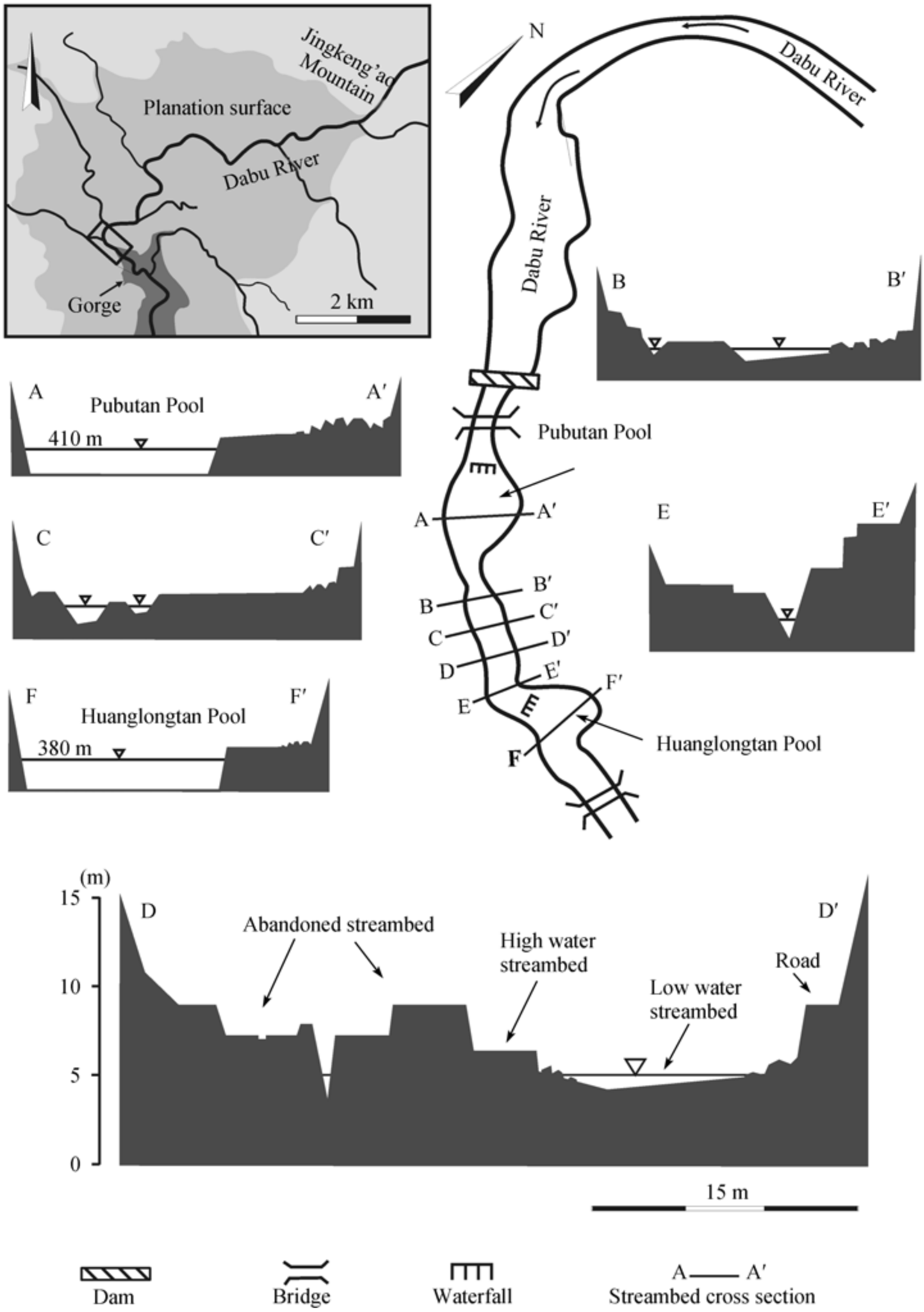

Figure 1 Location of the study area and cross sections along the study reach of the Dabu River

2 Field recording and calculating methods

The potholes developed at Dabu gorge streambed are different in geometry and size. The mouths of the potholes vary considerably in shape which may be circular, elliptic, triangular, polygonal or elongate (Figure 2). The length and direction of the 3 edges as well as the depth of each triangular pothole were measured using metric tapes. The caliber or mean diameter of a triangular pothole was determined by the average of the 3 edges' lengths. For other potholes, depth as well as direction and length of long and short axes were measured and the caliber of these potholes was represented by the average of the long and short axes (the short axis was perpendicular to the long axes). If the ratio of the long axis to the short one was 2 standard deviations larger than the mean value, the pothole was elongate in shape, called

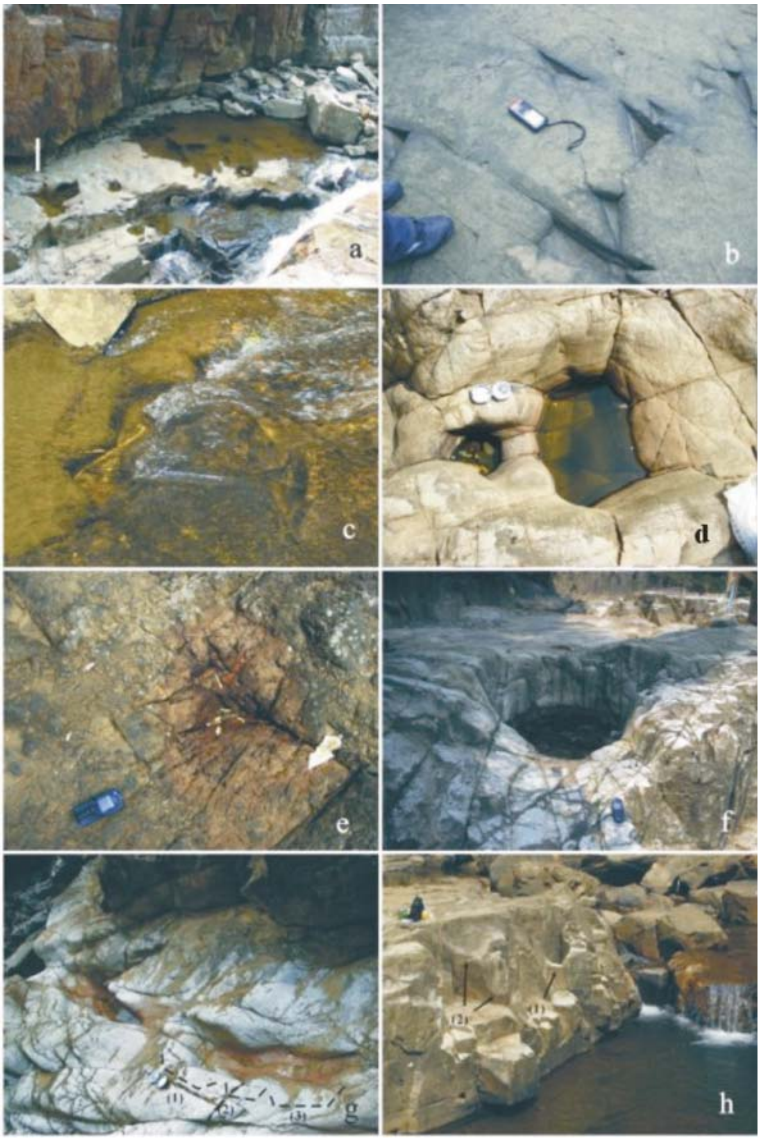

Figure 2 Morphological features of potholes

a. Potholes on the streambed; b. Triangular pits with abraded edges on downstream sides (the lower reach is pointed by a GPS); c. Flow pattern over triangular pits; d. A pothole with the shape controlled by Joints; e. The rough and cracked surface of a dish-like abandoned pothole marked with weathered joints. The mouth of the pothole is rounded with a bottom (deep-brown in color) still triangular in shape (the mobile phone pointing to the lower reach); f. A cylindrical abandoned pothole with rough and cracked wall, rim and floor; g. A trough coalesced by potholes connected by a joint. The concaves ((1), (2) and (3)) on the trough floor are the localities of the original potholes and lead to the floor waving up and down (the compass pointing downstream); h. Potholes on the lee side of steps. (1) A pothole with a lower rim on the downstream side and a joint going across the pothole. (2) Two vertical half potholes showing their vertical cross shape. Both (1) and (2) have smooth wall, rim and floor which are quite different from those of abandoned potholes in e and f.

trough or trough pothole herein. Thus the potholes in this study could be divided into 3 types: triangular potholes, trough potholes and normal potholes. For determining the locations of the potholes on the streambed, the measurement and recording began in sequence from Bubutan Pool at head of the gorge, continued downstream and ended at Huanglongtan Pool. In this study, 227 potholes including 56 triangular ones, 18 trough ones and 153 normal ones were measured. Strike directions of the joints visible on the bedrock of the streambed surface were measured simultaneously with the measurements of the potholes.

The observed data were calculated for their statistical features, such as means, standard deviations and distribution features, to interpret the pothole dimensions using standard statistical methods (Chen *et al*., 2002). The relationship between the pothole dimensions and their derivative process was quantified using correlation and regression analysis.

3 Results

3.1 Pothole morphology and localities

Since the Dabu River was blocked before running into the gorge for tourism purposes by local government, only small amount of water was still kept in deep water channel (low water streambed) and, therefore, most of the potholes formed on the streambed surface were exposed during the field work. However, potholes were not usually found in the low water streambed and most of them were developed on the high water streambed surface or the lee side of steps or cascades. The potholes changed irregularly in size, shape and depth from the upper reach to the lower reach (Figure 3). It meant that the pothole development was only agreeable to the local conditions, such as geology, geomorphology and flow patterns, of the very reach where the potholes appeared and unrelated to mean values of water velocity and discharge, which, in general, changed downstream regularly.

Most of the normal potholes which were usually formed in the high water streambed had diameters larger than 10 cm and those larger than 25 cm represented only 15% of the total (Figure 4a). The potholes which could be dish-like or cylindrical in shape varied with different lateral views. Potholes with a bigger diameter at middle depth were not found herein. The column shaped potholes generally had pothole wall nearly circular and parallel to

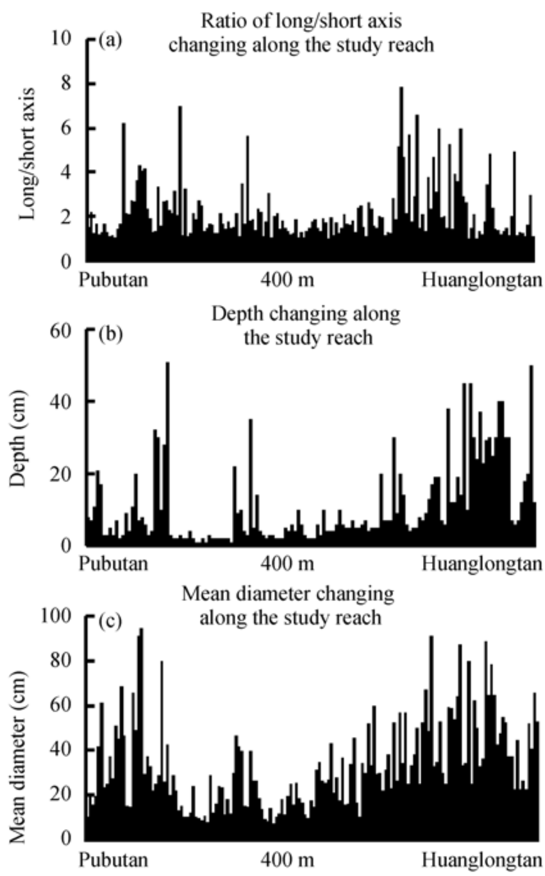

Figure 3 Changes in pothole shapes, depths and sizes along the study reach of the Dabu River

the rim with diameters larger than the depths. The dish shaped potholes had slightly concaved floor without pothole wall, and the depth of them was much smaller than the diameter. The potholes located at lee side of steps or cascades of the streambed were round with the depth usually much larger than the diameter. The rim of the lee side potholes on the upstream side was much higher than that of the downstream side (Figure 2h).

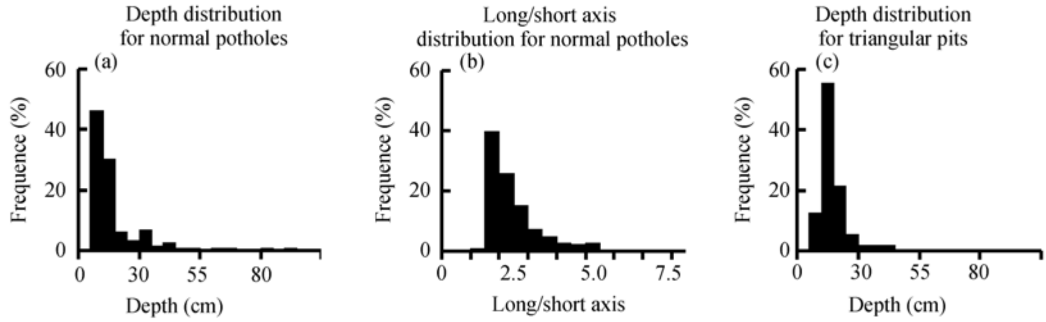

Figure 4 Histograms of depth and ratios of long to short axis of normal potholes and triangular pits

3.2 Pothole morphology and tectonic joints of streambed

The potholes developed on the streambed surface or on the lee side of the steps were usually located at the intersection of the joints or along the joints (Figure 2d, h). Less than 1 % of all the normal potholes observed in the field had a ratio of long to short axis equaling to 1 (totally round in shape) and the potholes with a ratio of 1.5 took up 45% of the total (Figure 4b). Two main joint systems identified in the field were orthogonal to each other. Most of the joints had directions ranging 315º–335º and paralleled to the gorge, while the others had ones between 40º–50º. Apparently they were coincided with the long and short axes of the potholes respectively (Figure 5a). The pothole features described above indicated that the pothole developed from the weaknesses, which were usually intersect fractures or, typically, interconnected vertical joints on the rocky streambed surface, and the pothole shapes were thus controlled by the tectonic joints and the flow directions.

Although most of the triangular potholes or pits were also found on the streambed surface, they did not developed at the weaknesses of the streambed. The directions of the 3 edges of the pits were fixed and coincided with those of the joint sets of the bedrock (Figure 5b). The triangular potholes looked like the triangle shaped mechanical impact pits on the quartz grain surface being observed under the scanning electrical mi-

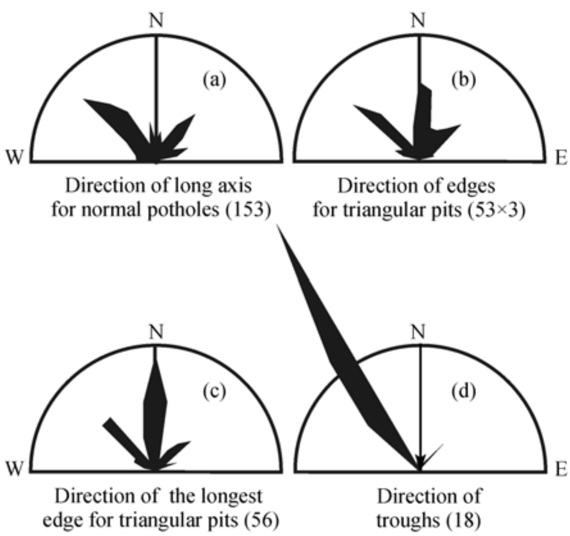

Figure 5 Directions of long axes of potholes, each edge and the longest edge of triangular pits, and trough potholes. The number in the bracket is sample numbers

croscope (Figure 2b), although their sizes were not same in scale. The phenomenon indicated that the potholes were resulted from fractures along the bedrock joints broken by impacting of rock fragments or blocks on the streambed surface during flood periods (Figure 6).

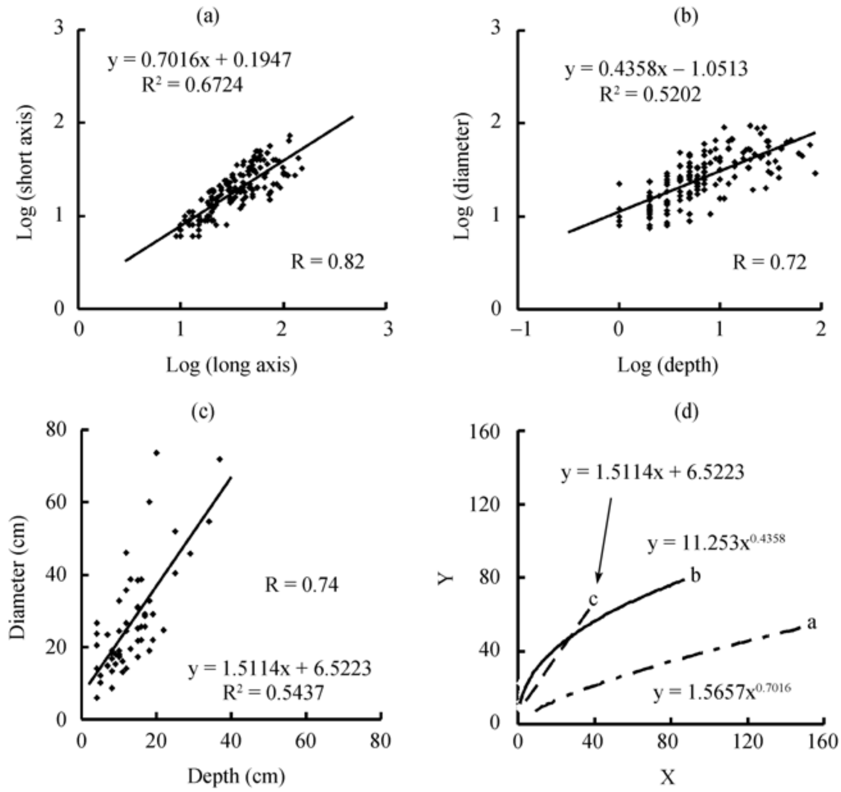

Figure 6 Plots of long-axis versus short-axis for potholes (a), depth versus size for potholes (b) and triangular pits (c), and regression lines for the pots a, b and c (d)

Most of the trough potholes were elongated in the direction of the stream flow (Figure 5d). Sometimes a trough pothole was not a simple long and narrow trough, but a coalescence of a string of potholes connected by a tectonic joint. It was supported by the vertical and lateral views of the trough (Figure 2g). Obviously, it was the result of erosion by stream fluid running along the joint, continuous enlargement of which led to coalescence of the potholes.

3.3 Pothole morphology and growth

After logarithmic transformation of the data, a strong positive correlation was shown between the long and short axes of the normal potholes (R=0.82), indicating that the relation between the 2 axes was log linear or nonlinear (Figures 6a and 6d). Therefore, the growth of a pothole could be described as a regression curve with an exponent < 1 (curve a in Figure 6d), indicating that the long axis elongated faster than the short one during pothole growth, and, therefore, the pothole perimeter outline was not apt totally round. It furnished corroborating evidence for the control actions of the tectonic joints on the pothole development.

Although the 3 edges of a triangular pothole coincided with the structural joints, the direction of the longest edge was uncertain because it could be one of the 3 edges (Figure 5c). However, no matter what the orientation it had, the pothole's rims on the downstream side were more eroded than those on the other sides (Figure 2b). Hydromechanics indicates that flow separation occurs at the bottom surface with a big curvature radius (Li and Ma, 1985). Comparing to water flow features in Figure 2c, it could be inferred that the stream flow separated due to the streambed floor turning down suddenly at the pothole rim on the upstream side, which was therefore suffering less erosion than other edges of the same pothole (Figures 2c and Figure 7). The flow separation weakened after the edges on the downstream side were moved downstream by water abrasion. It in turn led to erosion on the upstream side edges which therefore retreated upstream. As a result, the triangular pit increased its mouth and became a round pothole (Figure 7). Potholes with round mouths and triangular bottoms were observed in the field (Figure 2e).

The linear correlation coefficient between the depth and the diameter of the triangular potholes equaled 0.74. The linear regression coefficient was >1, indicating that increase of the diameter was faster than the depth during triangular pothole growth (Figure 6c). It coincided with what observed in the field. It seemed that deepening of a triangular pit could not exceed some threshold because only 6% of the triangular potholes had a depth larger than 25 cm (Figure 4c). Linear correlation between depths and diameters was not clear for the normal potholes (R=0.49) and, however, the value of R increased to 0.72 after a logarithmic transforming of the data. Transforming the results back to the original scale of the measurements yielded a regression curve with an exponent <0.5 (curve b in Figure 6), indicating that in the initial stage of pothole growth the increase of the radius was faster than the depth and later on it inversed. The increase in depth produced pothole wall for the potholes.

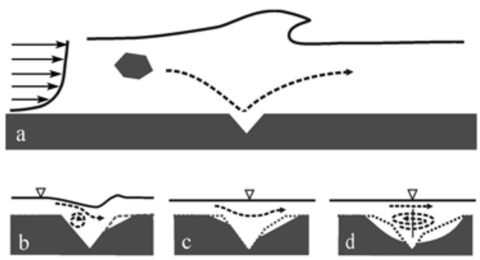

Figure 7 A schematic illustration for the development of a triangular pit

The localities of lee side potholes implied that the potholes initiated from vertical hits of stream water at the weakness (joints or intersected joints) immediately downstream the steps or water falls. These deep potholes with the depth much larger than the radius denoted that the vertical erosion was stronger than the lateral erosion produced by water plunging vertically downward. Therefore the control of the tectonic joints on the geometries of these potholes was not so strong as on other potholes. As a result, the lee side potholes, even in their initiate stage when the potholes formed without wall, had always a round or near rounded shape.

3.4 Pothole morphology and death

An original high water streambed becomes an abandoned one when it is uplifted to exceed the flood water level resulting from channel incision (Zeng, 1958). The potholes on the abandoned streambed were therefore no longer acted by stream water. The potholes thus stopped to grow and became abandoned ones. The typical feature of an abandoned pothole was its floor, wall and rims being marked with weathered joints and, therefore, rough and cracked (Figures 2e and 2f). In contrast, those of the potholes still undergoing stream water erosion were smooth (Figure 2h). The abandoned potholes would eventually be worn out by weathering.

The vertical half of potholes kept on the step cliff was usually observed in the field (Figure 2h). It indicated that the downstream half of the lee side potholes was damaged by stream water erosion or rock collapse while the step was retreating upstream. As a result of step withdrawing, the lee side potholes were destroyed and the streambed downstream of the step was lowered down. It was clear that the pothole development was one of the ways of river headward erosion.

As described above, some of the trough potholes were actually a string of potholes connected by a tectonic joint. The coalescence with those potholes by flow erosion also led to a disappearance of the original potholes (Figure 2g).

4 Discussion and conclusions

Opinions are mixed on whether a causal relation of tectonic joints to the formation of stream potholes exists. The investigation on upper Dingjiang River shows that the pothole developed in granite streambed has no relations to the joints (Zeng, 1958). In contrast, the study of Shiduxi River indicates that the geometries of the stream potholes, also formed in granite streambed, are controlled by joints (Zhu, 2000), and however, the same potholes are taken for moulins by other investigators, who believe that there is no relation between the moulins and the joints (Han *et al*., 2001). Similarly, the long axis of wind-formed potholes developed on granite rock in the inland of northern China is considered to be selective and affected by climate factors (Gui *et al*., 1999), while there are other investigators who think that the rock for the formation of any kind of potholes, including moulins, must be homogeneous and easily weathered (Zhao *et al*., 2001). Our study clearly shows that stream potholes are formed in sandy shale rock which is stratified and, furthermore, both of their geometries and development are controlled by the tectonic joints. It is supported by sufficient samples.

Springer (2005; 2006) considers the relationship between depth and mean radius or diameter of stream potholes is log-linearity which expresses itself as linear trends in a log–log plot. Transforming the data back, the best regression is a power function equation, the curve of which is non-linear, and the power and coefficient of the equation are different in the areas with different rock (Springer *et al*., 2005, 2006). We also get the similar relationship between pothole depth and mean diameter in our study, denoting that the equation expresses a general rule for stream pothole development. Determination coefficient of our regression equation is > 0.5, indicating that the growth of more than 50% of potholes measured in our study can be described by the equation, although Springer has a higher coefficient (> 0.75) for his equation. Springer considers that a pothole will increase and never decrease the radius in its growth and meanwhile the depth of the pothole may be reduced due to vertical incision of the streambed (Springer *et al*., 2006). It will generate a data distribution that is not log-normal (Springer *et al*., 2006). A further study is needed to obtain if the smaller determination coefficient in our study is the result of a fast vertical incision of the gorge streambed. However, in our study, only 15% of potholes have a diameter > 25 cm, indicating that the potholes growing in a streambed suffering such rapid and strong incision can not get a full development.

Previous studies showed that the planation surface where the Dabu River was running through was formed during the period between late Oligocene and middle Miocene (Zeng, 1958; Zhang and Huang, 1995). The study reach more than 200 m deeper than the planation surface has witnessed a rapid and strong vertical incision. Potholes formed within a period of 60 years have been reported by Kale and Joshi (2004). As one of the efficient means for deepening of stream channels, the potholes play an important role in gorge incision (Whipple *et al*., 2000; Whipple *et al*., 2002). The potholes developed in a gorge suffering a rapid vertical incision can be formed quickly and, or else the rapid incision can not be yielded. On the other hand, the potholes in the study reach can not be kept for a long time also because of the rapid vertical incision. Both dish-like and cylindrical abandoned potholes found at same reach indicate that some of the potholes have become abandoned ones before they developed into mature ones, which more or less have a cylindrical shape (Figures 2e and 2f). The potholes herein were formed and died out constantly because the process of more than 200 m vertical incision by the Dabu River has experienced many times of step withdrawal, pothole coalescence and transformations of low water streambeds into high water ones. As long as a pothole in such a streambed is formed it can not be buried until someday when river water washes it out. The potholes are formed at present as in the past and the potholes formed in the modern streambed are modern ones.

Alexanda (1935) classifies stream potholes into three types according to the mechanics of streamflow involved in the pothole production. The first is eddy holes caused by eddying action of water with a vertical vortex axis. The second is gouge holes produced by impacts of swift currents passing through the holes. A gouge hole may be elongated in shape with its longitudinal axis several times longer than the transverse one. The third is plunge holes produced by water plunging vertically downward (Alexanda, 1935). In Alexanda's experiment eddy flow or spiral vortex occurs in a glass cylinder that was similar to a cylindrical pothole with well developed pothole wall (Alexanda, 1935).

The regression equation for the triangular pits is a linear one with a coefficient > 1, indicating that the development of the triangular potholes is quite different from that of the normal potholes which has a nonlinear regression curve (Figure 6). The triangular pits are one kind of immature potholes or initial depressions for pothole development because only 5% of them have a depth larger than 25 cm. Observation in the field reveals that the stream water flows over triangular potholes as it does over gouge holes, in the same way as described by Alexanda (1935) (Figure 2d).

The comparison of the two regression models reveals that either the triangular pits or the small concavities developed at the weaknesses on the streambed have small depth without well developed pothole wall (Figure 6d). They are initial depressions acting as pothole seeds with a planar or hemispherical or dish-like cross section, and belong to gouge holes according to the flow pattern running over them. As a result of the potholes growing from immature ones to mature ones, pothole wall is formed with increase of pothole depth, and the initial depressions are eventually converted to eddy holes with more or less a cylindrical shape. If the potholes develop along a structural joint, they may coalesce into a trough pothole and thus become a gouge hole again. It means that the pothole shapes and the flow patterns are inconstant in the process of pothole development.

The following conclusions are drawn:

(1) The formation and growth of stream potholes relate only to local conditions, such as geology, geomorphology and flow patterns, of a stream reach where the potholes appear.

(2) The growth of a pothole begins from an initial depression which is a weakness or a triangular impact pit on a streambed. The geometries of a pothole are controlled by tectonic joints.

(3) Log correlation exists between depth and mean radius of potholes. Transforming the data back, the best regression between them is a power function equation with an exponent

< 1.

(4) Pothole shapes and flow patterns are inconstant during pothole growth.

(5) The process of pothole growth is one of the means to wear down a streambed. In a strong incision streambed, a pothole can be formed within a short period, but cannot be fully developed and well kept without any changes for a long time. The potholes developed in the modern streambed are modern potholes.

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