A criteria-based methodology for determining the mechanism of transverse drainage development, with application to the southwestern United States

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ABSTRACT

The study of how rivers cross obstructing mountains, once popular in the early twentieth century, has seen a dramatic resurgence in the last decade. Since Hutton's scholarly introduction to a possible cause for transverse drainage, however, no single study has compiled all of the various criteria that can be used to discriminate among the four possible mechanisms of antecedence, superimposition, overflow, and piracy. This paper presents the first such compilation and related methodology to apply these criteria both in tabular and graphical formats, as well as an online interactive tool in the data repository. Combining nominal and ordinal data sources, this methodology generates an objective, reproducible assessment for the mechanism most likely to have established the transverse drainage at five ordinal levels of confidence. When applied to southwestern U.S. sites, randomly selected through an objective spatial procedure, four general observations emerged on the relationship between the development of transverse drainage and landscape evolution. (1) Streams persisting through lengthy periods of extension develop antecedent canyons. (2) In order to reestablish through-flowing channels, streams overflow closed basins as active extension wanes. (3) Following a drop in base level related to the newly developed trunk channels, streams tributary to the trunk channels incise into basin-fill deposits—sometimes leading to the development of superimposed drainages. (4) Tributaries eroding headward, in response to the integration of two or more closed basins, can capture and redirect drainage; this permits transverse drainage through both piracy and superimposition upstream of the capture event. Because extant criteria use nominal and ordinal data almost entirely, considerable potential exists to refine this approach through future strategies that incorporate interval data. Future use of a criteria-based method has the potential to inform on prior geomorphic studies by providing a new perspective with which to study how basins evolve in active tectonic regions, the analysis of related basin sedimentation, the hydrological and biological aspects of drainage evolution, and transverse drainage found in Martian crater fields.

Keywords: antecedence, basin analysis, drainage evolution, overflow, piracy, superimposition, tectonic geomorphology, planetary geomorphology, transverse drainage.

INTRODUCTION

Rivers flow downhill. The only exceptions to this rule occur over relatively short distances where the stream's momentum may allow it to flow over a local high spot, or where a stream's water surface slopes opposite to its bed. Except in the case of very small bed slopes, these conditions cannot extend very far downstream. Yet many transverse streams incise unexpectedly across highlands such as anticlines, upwarps, cuestas, or horsts. Many of the world's largest river systems have incised gorges across structural and topographic highs (Fig. 1).

Since at least the eighteenth century, a number of scholars have described and debated causes of transverse drainage (Hutton, 1795; Playfair, 1802; Powell, 1875; Gilbert, 1877; Dutton, 1882; Davis, 1898b; Lane, 1899; Thornbury, 1957; Oberlander, 1965; Twidale, 1966; McKee et al., 1967; Hunt, 1969). Transverse drainages have also been termed gaps, transverse valleys, transverse gorges, water gaps, transverse river gorges, drainage anomalies, transverse trunk valleys, and boxes. In the past decade there has been a resurgence of interest in transverse drainage (Young and Spamer, 2001; Mayer et al., 2003; Nesci and Savelli, 2003; Stokes and Mather, 2003; Twidale, 2004), aided by the desire to link fundamental research on such diverse topics as the genetic distribution of freshwater species (Bishop, 1995; Burridge et al., 2006; Craw et al., 2007), and possible drainage in crater fields on Mars (Irwin et al., 2002).

Often, transverse drainage develops during or following a period of significant tectonic activity. Thus, knowledge of the mechanism and timing of the inception of transverse drainage can be useful in exploring links between tectonics, climate, and surface processes (Humphrey and Konrad, 2000; Marshall et al., 2003; Clark et al., 2004; Simpson, 2004; Brocard et al., 2005; Bishop, 2007). A number of numerical landscape evolution models have been developed that are able to reproduce many significant landscape features such as morphometrically realistic drainage networks, river concavity, and hilltop convexity (e.g., Willgoose et al., 1991; Howard, 1994; Tucker et al., 2001). With the possible exception of antecedence, however, none of these landscape evolution models has yet simulated the development of transverse

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GSA Bulletin; March/April 2009; v. 121; no. 3/4; p. 586–598; doi: 10.1130/B26131.1; 6 figures; 5 tables; Data Repository item 2008163.

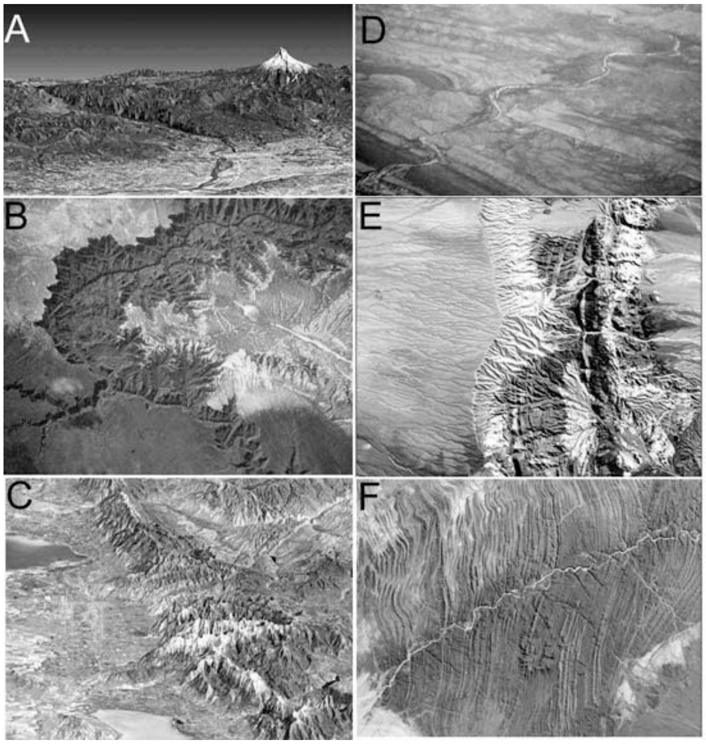

Figure 1. Examples of transverse streams in the United States (A–C) and the world (D–F). Images are courtesy of National Aeronautics and Space Administration and the authors. (A) The Columbia River crosses the bedrock highland of the Cascade Mountains through the narrow canyon of the Columbia River Gorge, Oregon-Washington border. (B) The Grand Canyon where the Colorado River incises into the Kaibab Plateau, Arizona. (C) Streams that cut across the Wasatch Range between Provo and Salt Lake City, Utah. (D) The McDonnell Ranges in Australia host transverse drainages. (E) Erosion of a covermass of volcanic sediments superimposes transverse drainages across folds in the Altiplano, northern Chile. (F) The Ugab River cuts across resistant hogbacks in Namibia.

drainage. This is not surprising, because landscape evolution models remain unable to simulate many dynamic features of landscapes. For example, ridges migrate even under relatively steady-state climatic and tectonic conditions (Hasbargen and Paola, 2000; Mudd and Furbish, 2005), and ridge migration may be an important factor in the formation of transverse drainage by piracy (Davis, 1898a). A methodology that is able to correctly and efficiently determine the basic mechanism of transverse drainage over large areas thus has the potential to provide clues about the evolution of a landscape and, therefore, to improve landscape models.

Early scholars proposed four general mechanisms to explain the formation of transverse drainage: antecedence, superimposition, overflow, and piracy (Hutton, 1795; Newberry, 1861; Medlicott, 1864; Gilbert, 1877; Davis, 1898a). In this paper we first introduce the different mechanisms in detail and briefly describe the relevance of transverse drainage development to the broader topic of landscape evolution. We then explain our methodology and results for 20 randomly selected sites in a portion of the southwestern United States. Lastly, we interpret southwestern U.S. drainage development from a transverse drainage perspective, where regional tectonic history influences the mechanism of transverse drainage development.

MECHANISMS

Antecedence

For antecedence to take place, a stream must drain across and erode a channel into an uplifting bedrock structure (Fig. 2). Researchers have studied the basic mechanics of antecedence with numerical modeling (Humphrey and Konrad, 2000; Simpson, 2004) and stream table experiments (Ouchi, 1983, 1985; Douglass and Schmeeckle, 2007). These numerical and experimental models show that antecedence takes place when a channel has the capacity to erode into a rising bedrock structure and continue to transport sediment downstream without periods of prolonged aggradation. Humphrey and Konrad (2000) showed that knickpoints must retreat across the rising bedrock structure at a rate that prevents aggradation upstream of the bedrock structure. Otherwise, the channel upstream of the bedrock structure could be diverted to a new path. Ouchi's (1983, 1985) experiments demonstrate that aggradation also occurs downstream of a rising structure. Downstream aggradation develops when a stream lacks the capacity to erode through a rising structure *and* transport the eroded bedrock material downstream. In the experiments of Douglass and Schmeeckle (2007), aggradation downstream of the rising structure reduced channel gradient to such an extent that the channel's erosive capacity was insufficient to maintain its path across the rising structure. As a result, the channel was deflected to a new location upstream of the rising structure.

Because an antecedent stream drains across a rising structure, highlands where the stream originates must predate surface exposure of the uplifting mountain range, an important method to estimate the relative ages of mountain ranges (Schumm et al., 2000). As rivers flow across rising mountain ranges they develop offset and flexed fluvial terraces. Using offset and flexed terraces, Lavé and Avouac (2000) quantified the rate of active faulting in the Siwaliks Hills, central Nepal. Not all streams that cross a rising mountain can maintain their course, and the stream's course is either deflected or ponded by the rising mountain. Higher order channels, with greater discharges, should be more likely to develop and maintain antecedent canyons. As streams erode into rising mountains, accelerated removal of rock from the antecedent canyon causes the crust to respond isostatically, resulting in further rock uplift and curious double-plunging anticlines bisected by rivers (Simpson, 2004). Thus, antecedent streams both influence and are influenced by active tectonic processes and landscape evolution (Tables 1 and 2).

Superimposition

Superimposed streams can also be associated with active tectonics. Superimposition requires that a stream flow atop a covermass that buries a comparatively resistant bedrock structure (Fig. 2). The covermass can consist of alluvium, erodible bedrock, marine

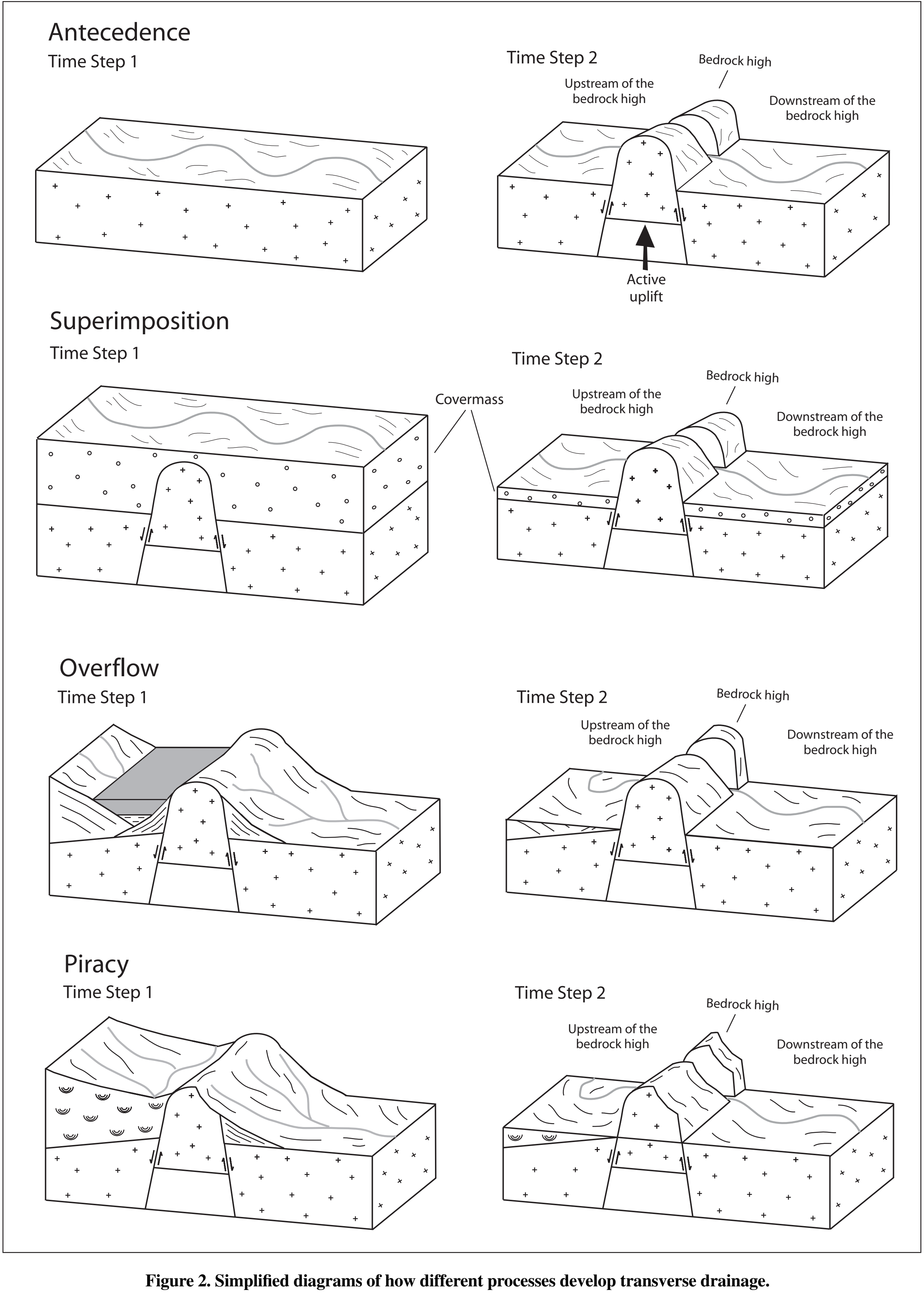

Figure 2. Simplified diagrams of how different processes develop transverse drainage.

TABLE 1. BASIC DESCRIPTIONS OF THE TRANSVERSE DRAINAGE MECHANISMS AND THEIR RELATIONSHIP TO ACTIVE TECTONICS

Mechanism	Generally located where:	Suggests mode of active tectonics that:	Relationship to stream order:
Antecedence	Streams flow across active or formerly active highlands with a capacity for erosion greater than the rock uplift rate.	Uplifts bedrock across the path of a through-flowing river.	Tend to be higher stream order channels because they require the capacity to erode through rising bedrock.
Superimposition	Streams develop transverse to resistant bedrock outcrops buried by nonresistant strata, alluvium, or lacustrine deposits and later become exposed following prolonged erosion.	Exposes strata, develop active mountain fronts flanked by alluvial fans, or disrupt fluvial systems and form interior-drained basins, which then experience extensive sedimentation.	Any stream order channel can be superimposed if the stream develops transverse to resistant bedrock buried by an erodible covermass.
Piracy	Streams flow in an indirect pattern with respect to regional topography and become captured across interfluves by channels with steeper gradients.	Disrupts drainage patterns such that streams have lower gradients than other potential stream paths.	Any stream order channels can be pirated as a drainage network becomes reorganized.
Overflow	Streams become ponded in interior-drained basins and eventually overspill at the lowest point of the basin rim.	Aggressively disrupts the regional drainage patterns so that formerly through-flowing channels become ponded in interior-drained basins.	Tend to be higher stream order channels because they form newly developed trunk channels that drain formerly interior-drained basins.

sediments, or lacustrine deposits. In a tectonically active setting, rising mountains can shed alluvium that buries structures in the piedmont regions, forming a covermass. Following rock uplift, erosion of an exposed weak bedrock layer may bury folds of more resistant bedrock and facilitate superimposed transverse drainage (Oberlander, 1965). In regions dominated by extension, rivers can become disorganized and pond for extended periods of time. Lacustrine sedimentation in a topographically closed basin may then bury resistant bedrock structures. Later, when the basin integrates into an external drainage network, a drop in base level can cause local streams to be superimposed across the buried structures.

For superimposition to develop, the stream needs to transport both the bedrock eroded from the transverse gorge and the alluvial, lacustrine, marine, or unconformable bedrock material that once buried the bedrock structure. Superimposition, therefore, typically requires more time to develop than the other three mechanisms, with the possible exception of piracy via headward erosion. Because of the time necessary for superimposition to take place, superimposed transverse drainage can rarely inform upon bedrock uplift rates. Modeling of superimposition remains a challenge, and many of the detailed erosional and depositional details are unknown (Douglass and Schmeeckle, 2007) (Tables 1 and 2).

Antecedence and superimposition are similar in that the river must predate the uplift or most recent exposure of the bedrock highland. An antecedent drainage cuts through a rising structure and a superimposed channel cuts into a buried resistant structure. In both cases, the river that now passes through today's elevated structure existed before the elevated structure was first exposed.

Piracy

The "piracy" or "capture" of a stream occurs when part of a channel's previous course changes to that of another stream. The point of capture can occur across a topographic high dividing two drainage systems, therefore resulting in a pirated transverse drainage. Stream piracy happens when the soon-to-be captured stream erodes, infiltrates, or flows over an intervening interfluve into a drainage basin with a steeper gradient. In rare cases, stream piracy may also happen when a stream in a steeper basin erodes headward across the drainage divide and captures the discharge of a stream on the other side of the topographic obstruction (Fig. 2). The newly captured stream, now flowing along a steeper gradient, erodes through the newly breached interfluve via knickpoints that propagate upstream (Davis, 1898a).

TABLE 2. BASIC RELEVANCE OF THE TRANSVERSE DRAINAGE MECHANISMS TO STUDIES OF LANDSCAPE EVOLUTION

Mechanism	Relevance to landscape evolution
Antecedence	Mountain range must have been tectonically active during transverse stream incision. Relative age of mountains estimated by the presence or lack of transverse gorges. Minimum rock uplift rates measured by the erosive capacity of deflected streams.
Superimposition	Extensive erosional period associated with a drop in base level. Alluvial covermass generated by prolonged period of aggradation. Bedrock covermass signifies the presence of easily erodible layers. Lacustrine covermass associated with tectonic disruption of regional drainage.
Piracy	Drainage basin undergoing reorganization, possibly from active tectonics. Abrupt changes to the sediment budgets of the impacted drainage systems. Instigates a drop in base level, which increases hillslope production upstream. Major change in flow regime associated with the redirection of a pirated channel.
Overflow	Trunk channel length and drainage basin size increase after overflow. Abrupt changes to the sediment budget of the elongated stream. Causes a drop in base level, which increases basinwide hillslope sediment production. Near catastrophic flooding possible based on lake size and depth, drainage discharge, and rock strength of the confining sill.

Overflow

A river must have been ponded in a lake prior to the formation of an overflow transverse drainage. A lake spilling across a resistant structure allows a drainage network to redevelop following tectonic activity, or some other type of disruption (Fig. 2). Overflow resembles piracy in that both require the through-going stream to postdate exposure of the bedrock structure. Unlike piracy, however, overflow involves a more severe disruption to the drainage pattern. Instead of redirecting a stream into a steeper channel, overflow requires that the drainage end in a closed basin before spilling across the lowest divide of the basin rim. In extensional tectonic settings, several transverse gorges can develop along the same river through overflow, developing a through-flow channel in several stages (Meek and Douglass, 2001; House et al., 2005).

Douglass and Schmeeckle (2007) physically modeled both the overflow and piracy mechanisms, including the four subtypes of piracy: aggradation, headward erosion, lateral erosion, and sapping. For both overflow and piracy, regardless of type, channel slope is the key variable in determining the likelihood of transverse drainage incision. When slope is sufficient, multiple knickpoints develop during an overflow or piracy event along the altered stream channel.

The retreat of one or more knickpoints allows a newly integrated channel to degrade, and in the process erodes a transverse gorge. An important difference between overflow and piracy is that once a lake overspills and a knickpoint begins to lower the lake outlet, a dramatic release of lake water can rapidly increase discharge, allowing a transverse gorge to erode much more rapidly than via piracy (Tables 1 and 2).

The rapid onset of flow from an overflowing lake or a capture event will have a sudden impact on the regional sedimentological regime. In overflow, sediment is stored in a closed basin until the basin is breached by an overflowing lake. The drop in base level that propagates headward upstream of the breach forces the trunk channel and its tributaries to incise into the accumulated fill, rapidly transferring sediment downstream (Meek, 1989; House et al., 2005). Arrival of the basin sediment downstream fundamentally alters the pre-overflow landscape. The same is true for piracy. However, a key difference between overflow and piracy is that in overflow the sediment is stored and then mobilized from within a closed basin. In piracy, the flow of sediment changes from one stream channel to another without the long-term storage of sediment (Clift and Busztajn, 2005). Alterations in climate and tectonics are common explanations for rapid changes in sediment production. Understanding the timing and mechanisms responsible for regional transverse drainage can greatly improve a sediment budget analysis by also accounting for drainage reorganization.

METHODS

The methodology employed here involves several steps, starting with the compilation of criteria into a process that resolves competing transverse drainage mechanisms (Fig. 3). This compilation is a decision tree that starts with deciphering whether a transverse stream developed before or after the bedrock structure that the stream crosses was uplifted or exhumed. Thus, the first step in the decision tree divides possible transverse drainage mechanisms into two mutually exclusive categories: "older" (antecedence and superimposition) and "younger" (overflow and piracy). Figure 3 then presents a set of criteria associated solely with antecedence and a set of criteria associated solely with superimposition stemming from the "older" box. The "younger" box in Figure 3 then specifies criteria associated solely with overflow, and criteria associated solely with piracy. The decision-tree organization of Figure 3 employs field, map, and other empirical observations to discriminate mechanisms responsible for a transverse stream.

In order to assess the utility of the decision-tree methodology (Fig. 3), 20 transverse drainage systems were selected through a spatial random sampling scheme in the southwestern United States (Fig. 4), a region that covers three physiographic provinces with distinct geologic histories (Fig. 5). The Colorado Plateau has experienced mild tectonic activity since the Laramide Orogeny, and it is characterized by mostly flat-lying Paleozoic and younger strata at elevations substantially above sea level. The Basin and Range underwent a change from regional compression to regional extension in the past 30 Ma (Eaton, 1982). Between the Basin and Range and the Colorado Plateau is a Transition Zone with characteristics of both, that also experienced a major drainage reversal beginning ca. 20 Ma (Potochnick, 2001). Streams that once flowed from highlands in the south to northern lowlands on the Colorado Plateau later reversed flow directions when Basin and Range extension created new basins with much lower base levels to the south.

A spatially random sampling scheme for the southwestern United States controlled the selection of specific study sites in the 18,650 km^2 study area divided into 20 equal grids (Fig. 4; Table 3). Within each grid square, the procedure identified transverse drainages in a specific sequence: (a) the largest transverse drainage evident on 1:250,000-scale maps of topography and geology; (b) if a transverse drainage was not identified, the scale was increased to 1:100,000 maps and the largest transverse drainage in the grid square was selected; and (c) if a transverse drainage was not identified at the 1:100,000 scale, the map scale increased to 1:24,000. At all scales, where multiple transverse drainage lines were detected, the one with the highest estimated discharge was selected.

Digital elevation model (DEM) analysis, field reconnaissance, and geologic field work were used to decipher the mechanism responsible for each transverse drainage. In this study, ten-meter-resolution DEMs were used to measure gorge length, depth, slope, and the number of transverse streams crossing a bedrock highland. DEMs also provided a means to assess whether a transverse stream incised across a saddle or along a flank of the bedrock high. Geologic mapping (Cooley et al., 1969; Bohannon, 1984; Reynolds, 1988; Doelling et al., 2000; Stevenson, 2000; Billingsley and Workman, 2001) and other data extracted from site-specific publications (Blackwelder, 1934; Bohannon, 1984; Buren, 1992; Spencer and Patchett, 1997; Faulds et al., 2001) provided data on uplift history, sedimentological analyses, and other site-specific information. Field work at each of the 20 sites focused on a criterion approach to determine the most likely mechanism responsible for the transverse drainage.

The criteria with supporting evidence at each site were highlighted on separate copies of Figure 3. This graphical method is presented in the GSA Data Repository.[1] Once shaded, the diagrams provide an important gauge in assessing the supporting evidence. Since the input data represent a mix of nominal, ordinal, and interval data, the ranking represents a conservative strategy for generalizing conclusions.

We introduce here, as a part of the method, five different levels of confidence.

(1) Very low: Unable to distinguish whether the drainage is older or younger than uplift or most recent exposure of the bedrock high; very limited or conflicting evidence; proposed mechanism highly speculative.

(2) Low: Unable to distinguish whether the drainage is older or younger than uplift or most recent exposure of the bedrock high; limited and partially conflicting evidence; proposed mechanism speculative.

(3) Moderate: Some ability to distinguish whether the drainage is older or younger than uplift or most recent exposure of the bedrock high; moderate available evidence, but alternative interpretations are possible.

(4) High: Whether the drainage is older or younger than uplift or most recent exposure of the bedrock high is distinguishable; moderate available evidence with few alternative explanations possible.

(5) Very high: Near certainty on whether the drainage is older or younger than uplift or most recent exposure of the bedrock high; substantial supporting evidence with no reasonable alternatives.

The level of confidence is a function, first and foremost, of whether clear evidence exists on the relative ages of the bedrock high and the crossing transverse drainage. If this fork in the decision tree is clear, further confidence comes from the type and amount of evidence related to the other criteria in Figure 3.

The exact procedure by which the quality and quantity of available evidence translates into a level of confidence is best visualized graphically in Figure 6 and through the interactive graphical method presented in GSA Data Repository (see footnote 1). Figure 6 illustrates how ordinal-scale results display for the low, moderate, and high confidence sites of the Virgin River Gorge, eastern Grand Canyon, and Canyon de Chelly,

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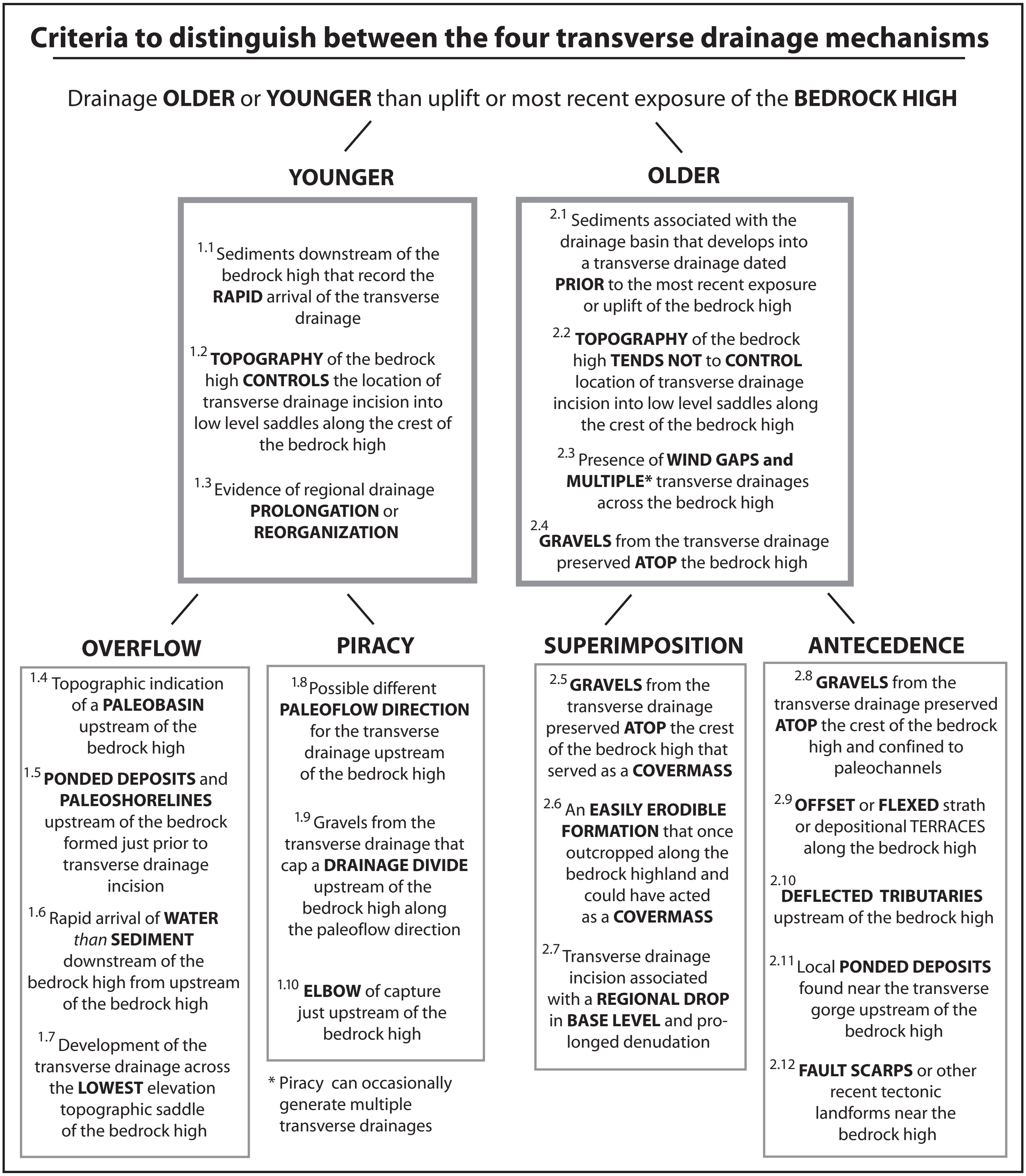
[1] GSA Data Repository Item 2008163, the data and analysis of the 20 field sites investigated in this study, is available at www.geosociety.org/pubs/ft2008.htm. Requests may also be sent to editing@geosociety.org.



Criteria to distinguish between the four transverse drainage mechanisms

Drainage **OLDER** or **YOUNGER** than uplift or most recent exposure of the **BEDROCK HIGH**

YOUNGER

1.1 Sediments downstream of the bedrock high that record the **RAPID** arrival of the transverse drainage

1.2 **TOPOGRAPHY** of the bedrock high **CONTROLS** the location of transverse drainage incision into low level saddles along the crest of the bedrock high

1.3 Evidence of regional drainage **PROLONGATION** or **REORGANIZATION**

OLDER

2.1 Sediments associated with the drainage basin that develops into a transverse drainage dated **PRIOR** to the most recent exposure or uplift of the bedrock high

2.2 **TOPOGRAPHY** of the bedrock high **TENDS NOT** to **CONTROL** location of transverse drainage incision into low level saddles along the crest of the bedrock high

2.3 Presence of **WIND GAPS and MULTIPLE*** transverse drainages across the bedrock high

2.4 **GRAVELS** from the transverse drainage preserved **ATOP** the bedrock high

OVERFLOW

1.4 Topographic indication of a **PALEOBASIN** upstream of the bedrock high

1.5 **PONDED DEPOSITS** and **PALEOSHORELINES** upstream of the bedrock formed just prior to transverse drainage incision

1.6 Rapid arrival of **WATER** *than* **SEDIMENT** downstream of the bedrock high from upstream of the bedrock high

1.7 Development of the transverse drainage across the **LOWEST** elevation topographic saddle of the bedrock high

PIRACY

1.8 Possible different **PALEOFLOW DIRECTION** for the transverse drainage upstream of the bedrock high

1.9 Gravels from the transverse drainage that cap a **DRAINAGE DIVIDE** upstream of the bedrock high along the paleoflow direction

1.10 **ELBOW** of capture just upstream of the bedrock high

* Piracy can occasionally generate multiple transverse drainages

SUPERIMPOSITION

2.5 **GRAVELS** from the transverse drainage preserved **ATOP** the crest of the bedrock high that served as a **COVERMASS**

2.6 An **EASILY ERODIBLE FORMATION** that once outcropped along the bedrock highland and could have acted as a **COVERMASS**

2.7 Transverse drainage incision associated with a **REGIONAL DROP** in **BASE LEVEL** and prolonged denudation

ANTECEDENCE

2.8 **GRAVELS** from the transverse drainage preserved **ATOP** the crest of the bedrock high and confined to paleochannels

2.9 **OFFSET** or **FLEXED** strath or depositional TERRACES along the bedrock high

2.10 **DEFLECTED TRIBUTARIES** upstream of the bedrock high

2.11 Local **PONDED DEPOSITS** found near the transverse gorge upstream of the bedrock high

2.12 **FAULT SCARPS** or other recent tectonic landforms near the bedrock high

Figure 3. This decision tree details the criteria for each mechanism and is subdivided first by whether criteria associated with a transverse drainage are younger or older than the bedrock high.

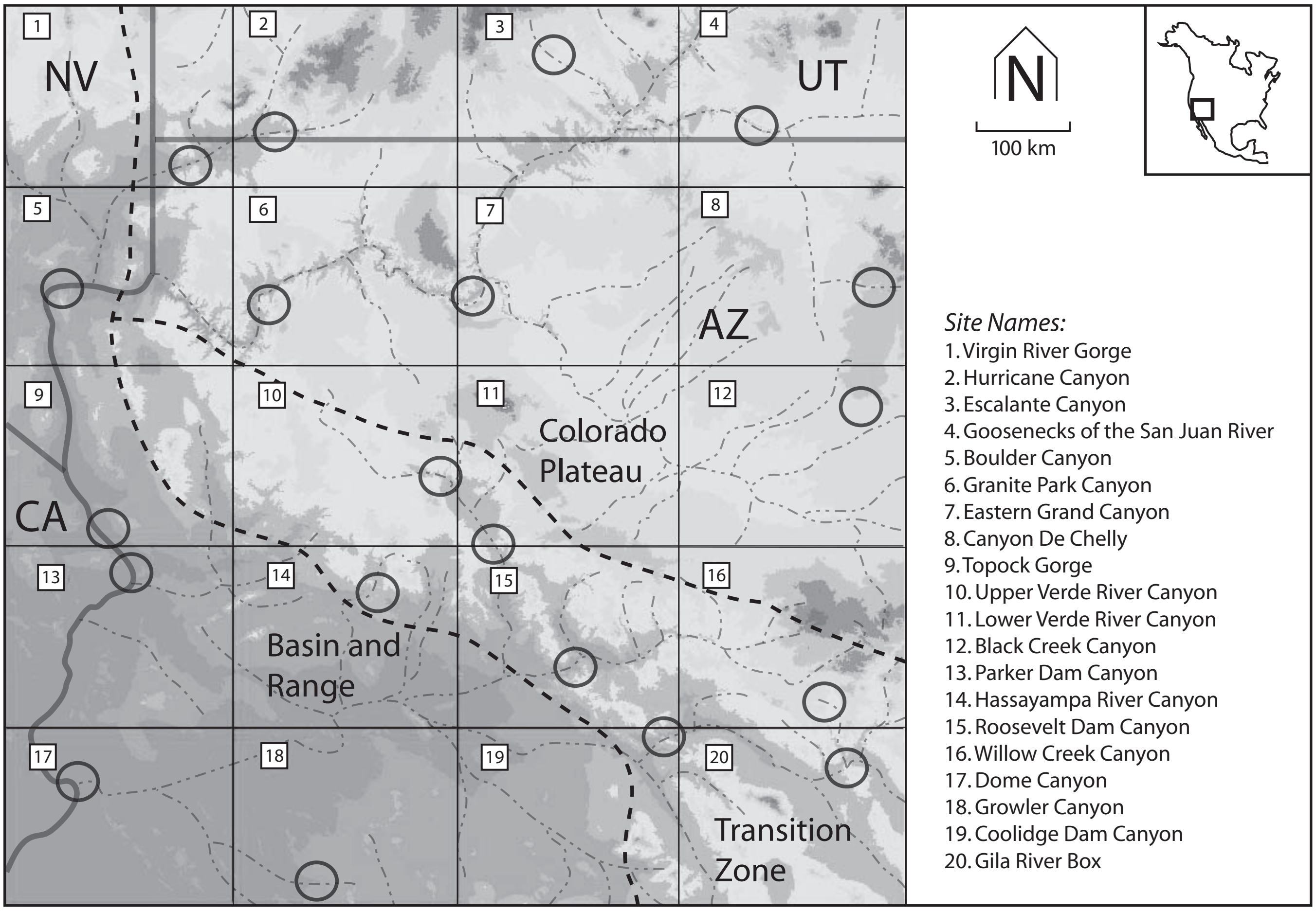


Figure 4. Twenty randomly selected transverse drainages in the southwestern United States. The states and physiographic provinces are labeled. Circles highlight the location of the individual transverse drainage within the numbered grid cell. Digital elevation model (DEM) data are courtesy of the U.S. Geological Survey.

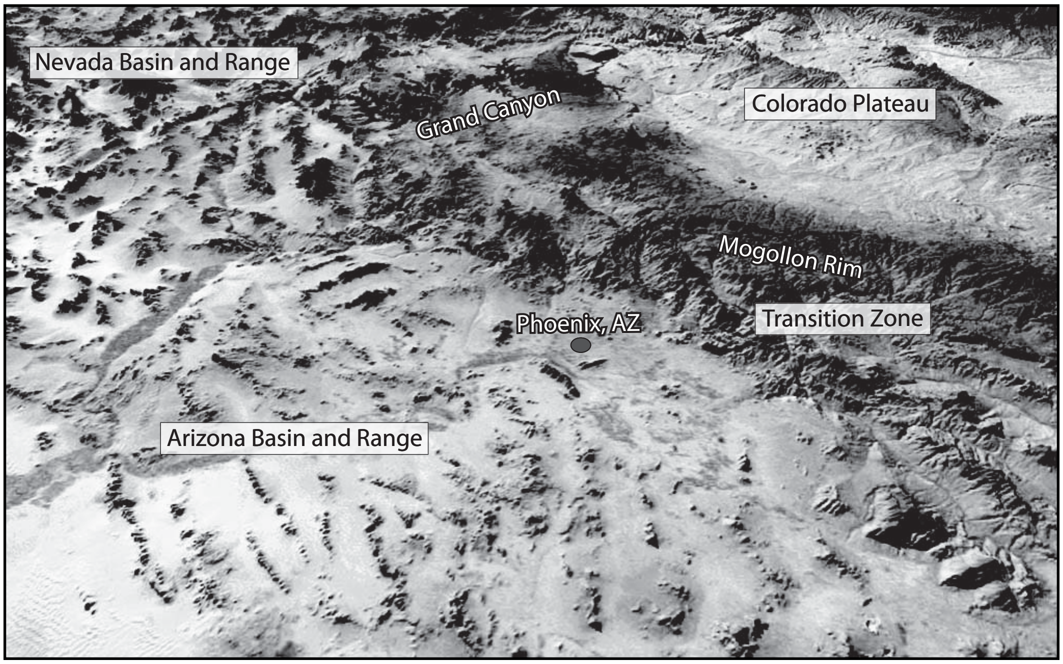


Figure 5. The southwestern United States, centered in this image in Arizona, offers a region with three contrasting physiographic provinces: extensional Basin and Range; mostly stable Colorado Plateau; and Transition Zone between the two. The image is courtesy of Dr. William Bowen.

TABLE 3. SUMMARY ANALYSIS OF TRANSVERSE DRAINAGE MECHANISMS FOR THE RANDOMLY SELECTED FIELD SITES

Site and map scale used in selection*	**Mechanism**	**Level of confidence**	**Criteria** (see Fig. 3)	**Identified key research need(s)**
Basin and Range transverse drainages				
(1) Virgin River Gorge–Virgin River (1:250,000)	Antecedence	Low	1.4, 2.2, 2.10, 2.12	Age of the Virgin and Beaver Dam Mountains versus the Virgin River
(5) Boulder Canyon–Colorado River (1:250,000)	Overflow	Moderate	1.2, 1.4, 1.5, 1.6	Evidence that suggests post–5.5 Ma uplift of the Black Mountains
(9) Topock Gorge–Colorado River (1:250,000)	Overflow	Moderate	1.1, 1.3, 1.5, 1.6	Late Cenozoic bedrock erosion rates for the Needles Mountains
(13) Parker Dam Canyon–Colorado River (1:100,000)	Overflow	High	1.1, 1.2, 1.3, 1.4, 1.5, 1.7	Better age constraints on bedrock high uplift
(17) Dome Canyon–Gila River (1:100,000)	Superimposition	Low	2.3, 1.2, 1.4	Evidence that suggests post–5.5 Ma uplift of the bedrock high or sea level lowering since 5.5 Ma
(18) Growler Canyon (1:24,000)	Superimposition	Very low	2.3, 2.2	Faulting history, rates of scarp retreat, transverse drainage gravels atop the scarp northwest of Growler Canyon but within speculated paleochannels
Transition Zone transverse drainages				
(10) Upper Verde River Canyon–Verde River (1:250,000)	Antecedence	Very low	2.2, 1.4, 1.5, 2.12	Timing of uplift of Antelope Hills; sedimentological study of Perkinsville Formation
(11) Lower Verde River Canyon–Verde River (1:250,000)	Antecedence	Very low	2.2, 1.4, 1.5, 2.12	Timing of relief building between Verde basin and adjacent Mogollon Rim; depositional center of paleo-Verde River; downstream sedimentological evidence
(14) Hassayampa River Canyon–Wagoner (1:100,000)	Overflow	Low	1.4, 1.5, 2.6	Downstream sedimentological evidence; Gila River history
(15) Roosevelt Dam–Lower Salt River Canyon (1:250,000)	Overflow	Moderate	1.1, 1.2, 1.3, 1.4, 1.5, 1.7, 1.8, 1.10	The overflow process predicts downstream sedimentological evidence of an aggradational event. We concomitantly located previously unrecorded Salt River gravels 151 m above the present river level and 72 m above the oldest previously mapped river terrace (Péwé, 1978).
(16) Willow Creek Canyon–Willow Creek (1:100,000)	Superimposition	High	2.4, 2.5, 2.7, 1.4	Timing of Willow Mountain uplift
(19) Coolidge Dam Canyon–Gila River (1:250,000)	Overflow	Moderate	1.3, 1.4, 1.5	Erosion rate of topographic low near Globe, Arizona; age of lacustrine sediments; downstream sedimentological evidence
(20) Gila Box Canyon–Gila River (1:250,000)	Overflow	Very low	1.2, 1.3, 1.4, 1.5, 1.7, 2.12	Timing of bedrock uplift; age of lacustrine sediments; downstream sedimentological evidence
Colorado Plateau transverse drainages				
(2) Hurricane Canyon–Virgin River (1:100,000)	Antecedence	Very high	2.2, 2.3, 2.4, 2.8, 2.10, 2.12	More detail on timing of uplift of bedrock high
(3) Escalante Canyon–Escalante River (1:100,000)	Superimposition	Low	2.2, 2.6, 2.7	Better constraints on scarp retreat rates
(4) Goosenecks–San Juan River (1:250,000)	Superimposition	Low	2.2, 2.6, 1.4	Better data on rates of scarp retreat in the area
(6) Granite Park Canyon–Granite Park Wash (1:24,000)	Piracy	Very high	1.2, 1.3, 1.8, 1.10	Cosmogenic nuclide accumulation to estimate timing of transverse drainage capture
(7) Eastern Grand Canyon–Colorado River (1:250,000)	Overflow	Moderate	1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.8, 1.10	More detailed analysis of the Bidahochi Formation's upper member to distinguish overflow from piracy
(8) Canyon De Chelly–Chinle Wash (1:100,000)	Superimposition	High	2.3, 2.4, 2.5, 2.6, 2.7	Further analysis of Quaternary gravels atop the bedrock high to better constrain provenance
(12) Black Creek Canyon–Black Creek (1:100,000)	Superimposition	Very low	2.2, 2.6, 2.7, 1.8, 1.10	Rates of scarp retreat; evidence of covermass gravels

*Site numbers correspond to Fig. 4, and the ratio indicates the map scale needed to identify the site in the stratified random selecting method.

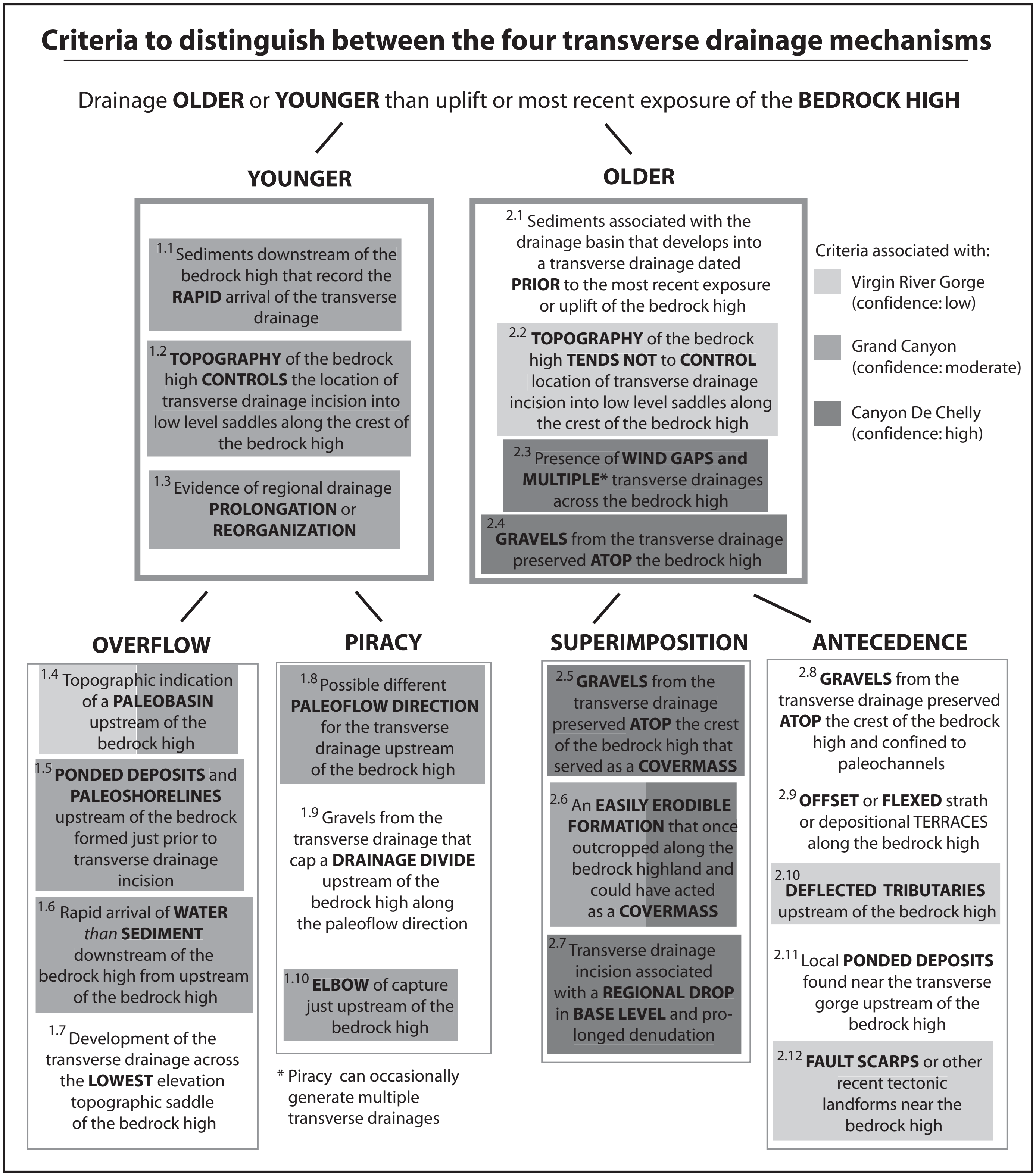


Figure 6. Three sites provide examples of transverse drainage mechanisms discriminated at low, medium, and high levels of confidence. Criteria associated with the Virgin River Gorge (1 in Table 3) are shaded the lightest. The available evidence only supports a low confidence for antecedence. The next darkest shaded criteria are associated with the eastern Grand Canyon (7 in Table 3). The accumulated criteria generally support overflow, but some evidence offers support for piracy and superimposition. Criteria associated with Canyon de Chelly (8 in Table 3) are shaded the darkest. Transverse drainage gravels atop the bedrock high clearly indicate the drainage predates the most recent exposure of the bedrock high. The available evidence supports superimposition with a high level of confidence.

respectively. By organizing criteria graphically, researchers can more accurately identify critical evidence needed to decipher the mechanism responsible for a transverse drainage.

In summary, the procedure for each site analysis includes the compilation of data from DEM analyses, literature-based findings, and field observations cross-referenced to the criteria displayed in Figure 3 and exemplified in Figure 6. Empirical data for each site, prior to evaluation by the decision-tree method (Fig. 3), is available for each site in the GSA Data Repository (see footnote 1). Table 4 provides a single example of the use of these data for the Grand Canyon field site, and the data for the other 19 sites are presented in the Data Repository. This procedure results in the identification of the most likely mechanism, with a qualitative estimate of confidence. Moreover, the method identifies key missing information needed to increase the level of confidence.

RESULTS

When considering all 20 randomly selected sites in the study area (Fig. 4) as a whole, there did not appear to be a dominant formative mechanism (Table 3). The results show eight cases of overflow, seven of superimposition, four of antecedence, and one of piracy. However, when the study area is further subdivided into its three component physiographic provinces, overflow is concentrated in the extensional Basin and Range and Transition areas, and superimposition in the tectonically stable and incised Colorado Plateau. Our analysis suggests that piracy is relatively uncommon in the southwestern United States in comparison to the other mechanisms, a conclusion consistent with Bishop's (1995) judgment that piracy may be a relatively uncommon phenomenon.

Our attempt to systematically understand transverse drainage incision resulted in two very high, three high, five moderate, five low, and five very low confidence rankings. With this qualitative ranking system, the mechanism responsible for the development of transverse drainage could be identified with high or very high confidence at only 25% of the study sites. Half of the transverse drainage lines were readily identified on 1:250,000-scale DEMs, eight at the 1:100,000 scale, and two at the 1:24,000 scale. Those transverse streams assigned to a mechanism with either high or very high confidence were all evaluated at scales of 1:24,000 or 1:100,000. Details of the results for each case study in the southwestern United States are presented in the GSA Data Repository (footnote 1).

DISCUSSION

The northern Colorado Plateau experienced compression between 70 and 40 Ma (Huntoon, 1990) and the middle Transition Zone and southern Basin and Range switched from compression to extension ca. 30 Ma (Fig. 5) (Eaton, 1982). Prior to extension, the Transition Zone's Mogollon Highlands drained northeastward onto the Colorado Plateau. The rivers and streams drained into several closed basins, depositing now-lithified sediments (e.g., Utah's Claron Formation and Flagstaff Limestone). Extensional faulting subsequently lowered the former highlands, reversing the regional drainage, and disrupting most of the drainage in the process.

Only two rivers studied in this paper appear to have maintained through-flowing channels during this tectonic activity. Because antecedence is the only mechanism that allows transverse drainage to predate the active uplift of a bedrock high, the upper Verde River's two transverse gorges are probably antecedent in origin (Sites 10 and 11 in Fig. 4). This supports an earlier assertion that the upper Verde River may be Oligocene in

TABLE 4. EXAMPLE OF TRANSVERSE DRAINAGE CRITERIA AND EVIDENCE FOR THE EASTERN GRAND CANYON (SITE 7 IN FIG. 4)

Transverse drainage criteria	Evidence
Faulting or uplift age of the bedrock high	Uplift of the Kaibab Plateau is Laramide in age (70 to 40 Ma) (Huntoon, 1990). The Colorado River developed after 20 Ma (Larson et al., 1975).
Evidence of a covermass	None observed, although the presence of Red Butte south of the Kaibab Plateau likely represents a remnant erosional scarp that retreated off the Kaibab Plateau (Strahler, 1945) and could have provided a sediment ramp for the Colorado River across the Kaibab Plateau.
Multiple transverse drainages across the bedrock high (including the presence of wind gaps along the bedrock high)	None observed.
Topographic control of transverse drainage incision into the bedrock high (accounting for deflected and ponded antecedent drainages and partial burial of the bedrock high for superimposed drainages)	The Colorado River makes a big sweeping bend to the south across the Kaibab Plateau. An erosional scarp controlled the Colorado River's curved path across the Kaibab Plateau (Strahler, 1948; Lucchitta, 1984; Douglass, 1999), indicating the Colorado River followed an erosional scarp during initial canyon incision.
Offset or flexed depositional or strath terraces along the bedrock high (assuming no post-transverse drainage incision deformation)	None observed.
Sediments associated with the transverse stream deposited atop the bedrock high	None observed.
Ponded deposits upstream and below the rim of the bedrock high	Lacustrine sediments associated with the late Cenozoic Bidahochi Formation outcrop upstream of the bedrock high (Cooley et al., 1969). Timing of last deposition at ca. 6 Ma roughly correlates with the arrival of the Colorado River downstream of the Grand Canyon 5.5 Ma (Spencer et al., 2001).
Paleoshorelines upstream of the bedrock high	None observed.
Fluvial sediments downstream of the bedrock high that record rapid arrival of the upstream drainage or continually deposited gravels that record erosion into the bedrock high	Colorado River gravels conformably overlie the Hualapai Limestone downstream of the Grand Canyon, suggesting that interior drainage was followed by the rapid arrival and throughflow of the Colorado River (Howard and Bohannon, 2001).
Sedimentological evidence that water flowed downstream of the bedrock high prior to fluvial sediments sourced upstream of the bedrock high	The Hualapai Limestone deposited from calcium-rich water is speculated to be from the Colorado Plateau, and could have come from a ponded Colorado River either upstream or downstream of the Kaibab Plateau (Howard and Bohannon, 2001).
Presence of fault scarps or other related tectonic landforms along the bedrock high (assuming no post-transverse drainage incision deformation)	None observed.
Topographic indication of a paleobasin upstream of the bedrock high	The broad north-south Bidahochi paleobasin extends parallel along the upstream portion of the Kaibab Plateau. The basin possibly contained a lake with an area of 30,000 km^2 (Dallege et al., 2001).
Elbow of capture just upstream of the bedrock high	None observed.
A gravel-capped drainage divide or wind gap, with a paleoflow direction immediately upstream and roughly parallel to the bedrock high	A gravel-capped drainage divide or wind gap immediately upstream of the bedrock high has not been observed, but a paleoflow direction exists to the south and parallel to the Kaibab Plateau, allowing possible drainage into the Bidahochi Basin.

age (Peirce et al., 1979). In addition, the Virgin River incised two canyons across fault-block mountains and allowed the river to maintain an antecedent path during at least the latter stage of extensional tectonism (Sites 1 and 2 in Fig. 4) (Hatfield et al., 2000).

Following breakup and subsidence of the Mogollon Highlands, interior drainage dominated much of the southwestern United States. Even though portions of the Verde and Virgin Rivers apparently survived the extensional upheaval, there is no evidence to indicate that either river was through-flowing to an ocean basin. It is therefore likely that both may have emptied into closed basins. Integration of these and other closed basins (i.e., Bidahochi, Tonto, and Muddy Creek basins) into a through-flowing drainage network may have involved a series of lake spillover events. Several breached basins along the lower Colorado River corridor exemplify this process (Fig. 4) (House et al., 2005). The Colorado, Salt, Gila, and Hassayampa Rivers all exhibit one or more overflow-generated transverse gorges. The field evidence indicates that several of the regional trunk rivers developed at least a portion of their channel through the integration of closed basins, most likely by overflow. The Grand Canyon is the oldest known transverse gorge in the study area associated with overflow and developed after 5.9 Ma (Spencer and Pearthree, 2001). The Mio-Pliocene age of the Grand Canyon suggests that drainage integration of closed basins through overflow followed the waning of the most active tectonism. However, in wetter climates the integration of closed basins through overflow probably does not depend on the cessation of active tectonism.

When overflow results in a newly integrated drainage network, there is sometimes a near instantaneous and dramatic drop in base level, which causes the trunk channel to incise into basin fill that accumulated prior to lake-spillover and basin integration (e.g., Meek, 1989). As the trunk channel incises, the gradients of the tributary channels also increase over time, leading to erosion throughout the breached basin. Resistant bedrock that was buried during basin infilling becomes exposed. Streams that cross the emergent bedrock eventually develop into superimposed transverse gorges. The transverse gorges would then postdate basin integration. We hypothesize that post–basin-infilling incision explains all of the superimposed field sites except Dome Canyon (Site 17 in Fig. 4).

Channels formerly entering a closed basin may experience headward growth. This headward extension can lead to transverse drainage formation by piracy. The only piracy transverse drainage examined in the study area developed from the headward growth of Granite Park Canyon, within Grand Canyon, that redirected a portion of Prospect Wash. Other transverse drainages are classified as superimposed with low levels of confidence; however, they might also be the result of piracy. Because trunk channel integration via overflow has occurred mostly since the Miocene in the southwestern United States, the number of piracy events could increase in the future as the drainage networks continue to evolve. Also, piracy events lower the base level locally, which can lead to additional piracy or superimposed transverse gorges farther upstream.

In summary, using a transverse drainage perspective, we propose the following generalizations for southwestern U.S. drainage development:

(1) Drainages that persist through extensional tectonism often cut antecedent canyons.

(2) In dry climatic regions, trunk channels integrate multiple closed basins through overflow to establish a through-flowing drainage network as active tectonism wanes.

(3) Following a drop in base level related to the newly developed trunk channels, streams tributary to the trunk channels incise into basin-fill deposits, which sometimes leads to the development of superimposed canyons.

(4) Tributaries that incise following the integration of two or more closed basins can capture and redirect lower gradient streams, which can involve sapping, lateral erosion, aggradational redirection, or headward erosion processes. A pirated stream can cause additional piracy or superimposition farther upstream following the local drop in base level associated with a capture event.

Our analysis of the southwestern United States suggests that the frequency of a particular transverse drainage mechanism is related to the type of tectonics (i.e., compression or extension) and the waning of tectonic activity. Tectonic activity disrupts regional drainage basins, and then rivers and streams either maintain their channel through antecedence or reorganize through overflow and piracy. In the process, superimposed drainage may also develop.

In our study of transverse drainage, we utilized the literature, fieldwork, and DEMs. Fieldwork mostly involves the analysis of related sedimentological or structural evidence. DEMs provide a means of remotely accounting for morphological evidence (i.e., topographic dip of the bedrock high). Irwin et al. (2002) show that in the analysis of a transverse drainage, DEMs are sometimes sufficient to discriminate the overflow mechanism (Table 5). However, a superimposed transverse gorge requires a covermass, and fieldwork is therefore necessary to determine reliably the existence, characteristics, and extent of a possible covermass. An important next strategy would be to isolate what transverse drainage mechanisms and related criteria can be utilized with just DEMs, thus narrowing the tool set required for studying remote sites.

CONCLUSION

The past decade has witnessed a sharp increase in transverse drainage research mostly focused on their relevance to the study of orogens and landscape evolution (Marshall et al., 2003; Clark et al., 2004; Simpson, 2004). Concomitantly, we present here criteria and a methodology that can be used to distinguish systematically among the four mechanisms of transverse drainage development. Since the quality and quantity of available data often vary widely between study sites, a combined tabular

TABLE 5. SUMMARY OF THE CRITERIA ASSOCIATED WITH FIVE SITES OF TRANSVERSE DRAINAGE FROM THROUGHOUT THE WORLD AND MARS

Transverse drainage	Associated criteria (Numbers correspond to Fig. 3)
Siwaliks Hills, India (Lavé and Avouac, 2000) **Antecedence** (High)	2.2, 2.3, 2.4, 2.8, 2.9, 2.10, 2.12
Susquehanna River, USA (Strahler, 1945) **Superimposition** (Low)	1.3, 2.2, 2.3, 2.6
Río Almanzora, Spain (Stokes and Mather, 2003) **Piracy** (Low)	1.3, 1.8, 1.10, 1.4, 2.2
Ma'adim Vallis, Mars (Irwin et al., 2002) **Overflow** (High)	1.2, 1.3, 1.4, 1.5, 1.7
Dadu River, China (Clark et al., 2004) **Piracy** (High)	1.2, 1.3, 1.8, 1.9, 1.10

and graphical procedure (Table 4; Fig. 6; and interactive GSA Data Repository) identifies and then guides researchers through the transverse drainage criteria. This graphical method combines nominal and ordinal assessment of data, leading to an objective assessment of the mechanism most likely to have established the transverse drainage. The method yields five different levels of confidence ranging from very low to very high. This graphical procedure also identifies missing data necessary to increase the level of confidence at a given study site.

The usefulness of objective criteria and this graphical procedure was tested in the southwestern United States, a region that hosts a mix of tectonic settings. Twenty transverse streams were randomly selected through an objective spatial procedure (Table 3; Fig. 4). The results are that one transverse drainage likely formed through piracy, four from antecedence, seven from superimposition, and eight from overflow.

Four general statements about landscape evolution in the southwestern United States emerge from this study of transverse drainage. (1) Streams that persist through extensional tectonism will cut antecedent canyons. (2) Trunk channels integrate multiple closed basins via overflow to establish a through-flowing drainage network as active tectonism wanes. However, the wetter the climate, the less likely tectonism needs to lessen before overflow of closed basins will occur. (3) Following a drop in base level related to the newly developed trunk channels, streams tributary to the trunk channels incise into basin-fill deposits, which sometimes leads to the development of superimposed drainage. (4) Also, tributaries that incise following the integration of two or more closed basins can capture and redirect lower gradient streams via piracy, which can involve sapping, lateral erosion, aggradational spillover, or headward erosion processes. A pirated stream can cause additional piracy or superimposition farther upstream following the local drop in base level associated with a capture event. Future analysis of transverse drainage associated with diverse tectonic and climatic histories will greatly inform upon drainage evolution (Table 5).

ACKNOWLEDGMENTS

The research was supported in part by National Science Foundation grant EAR 0352079 and Paradise Valley Community College. We thank Paul Bishop, Michael Summerfield, associate editor Ellen Wohl, and editor Karl Karlstrom for their hard work to improve the paper, and Meggin Kirk for field assistance.

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MANUSCRIPT RECEIVED 20 OCTOBER 2006
REVISED MANUSCRIPT RECEIVED 19 NOVEMBER 2007
MANUSCRIPT ACCEPTED 7 DECEMBER 2007

Printed in the USA