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Editorial

Drainage integration in extensional tectonic settings

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ABSTRACT

The development of geomorphic theory regarding fluvial-system reorganization and drainage basin evolution, resulting from drainage integration, has been slow to progress since the abandonment of Davisian geomorphology in the mid-twentieth century. Central to the development of this theory is an understanding of the processes that allow rivers to cut across topographic and/or structural barriers that separate neighboring drainage basins. Barrier-crossing rivers are termed *transverse drainages*. Development of this geomorphic theory also includes an understanding of the basin-wide geomorphic and sedimentologic response to the establishment of a transverse drainage. Since at least the eighteenth century, geomorphic scholars such as J. Hutton, J. Playfair, J.W. Powell, G.K. Gilbert, C.E. Dutton, W.M. Davis, E. Blackwelder, C.B Hunt, and T.M. Oberlander described transverse drainages using a variety of terms like: water gaps, transverse valleys, transverse gorges, transverse river gorges, drainage anomalies, transverse trunk valleys and boxes. A resurgence of drainage-integration research in the past few decades produced a consensus that four generalized processes, and variations therein, result in drainage integration and transverse drainage establishment: *Antecedence; Superimposition; Piracy/Capture;* and *Overflow/Spillover*. *Antecedence* occurs when a river maintains its position through sufficient erosive power during tectonic uplift. This results in a river that has cut through the uplifted terrain. *Superimposition* occurs when a river incises through erodible materials, or a cover mass, and becomes locked in place across an exhumed bedrock high. Both *Antecedence* and *Superimposition* require a river that is older than the most recent exposure of the topographic and/or structural feature it now cuts through. *Piracy,* or *Capture,* occurs when a river shifts to a new and steeper gradient path, resulting from the capture and rerouting of the original drainage. *Overflow*, or *Spillover*, takes place when a basin fills up with sediment and water sufficiently to breach the lowest point in the basin divide and subsequently spills out into a neighboring drainage basin or outlet. Both *Piracy* and *Overflow* require the river to be younger than the topographic and/or structural feature the river transverses. The timing of this special issue's publication aligns with a resurgence in interest and awareness of the importance of transverse drainages in economics, cultural history, establishment of surface and groundwater resources, distribution of aquatic and riparian biology and ecosystems, and even in understanding the history of Martian landscapes and climate. Therefore, we put forth this special issue to elucidate on our current understanding of drainage integration and the establishment of transverse drainages along with new insights into basin to basin and basin-wide response to transverse-drainage development. This special issue includes comprehensive literature reviews and original research in tectonic settings of regional extension where through-flowing transverse drainages exist, but also suggests that similar integration processes occur in a variety of settings globally.

1. Introduction to this special issue: drainage integration in extensional tectonic settings

Geomorphic theory on how drainages establish new paths of flow through landscapes that did not contain the present through-flowing fluvial system – the birth of a new river and a new hydrogeomorphic landscape (Larson et al., 2017) – has seen a renewed interest in the

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scientific literature. This revival is particularly evident in studies of how rivers cross topographic and/or structural barriers to flow, or the establishment of *transverse drainages*. The processes that form transverse drainages can hydrologically and sedimentologically integrate structurally controlled basins and/or breach volcanic, mass wasting, or glacially derived topographic features to establish a new river and a new landscape downstream of these former barriers. Upon establishment of a transverse drainage, a cascading geomorphic and hydrologic response ripples through the newly integrated basins, and this can trigger integration with other nearby basins. Linking a series of basins creates a new through-flowing drainage network (e.g. House et al., 2008; Geurts et al., 2020; Larson et al., 2020; Skotnicki and DePonty, 2020; Skotnicki et al., 2021a). The establishment of a transverse drainage can also result in dramatic topographic, erosional, and depositional features and can initiate a complex response through a variety of geomorphic systems as the drainage basin reorganizes (Larson et al., 2020). Thus, transverse drainage establishment is an incredibly dynamic and dramatic driver of landscape evolution and geomorphic change within a basin, making it fundamentally important to understand in the field of Geomorphology.

Research on transverse drainages emerged slowly over the past 150 years, as it was eschewed following the abandonment of Davisian-era geomorphology. Fortunately, our understanding of transverse drainages and the processes that result in them has burgeoned in the 21st century as debate has grown over how some popular and spectacular landscapes, like Grand Canyon, USA, formed (e.g. Meek and Douglass, 2001; Polyak et al., 2008; Wernicke, 2011; Flowers and Farley, 2012; Karlstrom et al., 2014, 2017; Larson et al., 2017; Douglass et al., 2020). Although this special issue focuses on extensional tectonic landscapes like the Basin and Range Province of the southwest USA and northwest Mexico, to examine drainage integration via transverse drainage development, the processes that establish transverse drainages have become more important in understanding post-glacial, volcanic, and landslide-prone landscapes around the world (Hilgendorf et al., 2020). Research on transverse drainages has even grown beyond our terrestrial landscapes to explain extraterrestrial landscapes of the Martian surface, where outlet canyons breaching the rims of basins, particularly impact crater basins and intercrater basins, are commonly observed (e.g. Goudge and Fassett, 2018; Goudge et al., 2019; Goudge et al., 2021).

Given the recent growth of research focusing on understanding transverse drainages and drainage-integration processes, we put forth a special issue that presents an entire volume on this topic. This special issue contains articles that synthesize our current understanding as well as original research that investigates fluvial systems in a variety of landscapes - ranging from the Basin and Range, USA, to the Apennine Mountains of Italy, to the Korean Peninsula. The primary focus of this special issue, however, rests in drainage integration processes and the establishment of transverse drainages in tectonic settings of regional extension where structurally controlled basins dominate the landscape and through-flowing rivers had to integrate these basins by establishing transverse drainage reaches.

1.1. Transverse drainages: 150 years of investigation

Much of the early study of transverse drainages and drainage integration began with USA geological and geographical expedition explorers speculating on how the Colorado River's transverse course across the Kaibab Plateau at Grand Canyon formed (Newberry, 1862; Powell, 1875). In the late 19th and first half of the 20th centuries, geomorphologists analyzed drainage integration in the Appalachian Mountains (Davis, 1889; Lane, 1899; Johnson, 1931; Mackin, 1933; Meyerhoff and Olmsted, 1936; Thompson, 1939; Strahler, 1945), Bolivia (Walker, 1949), Great Britain (Linton, 1932), and areas of the British Empire (Du Toit, 1910; Wellington, 1924; Gregory, 1925; Richardson, 1947; King, 1950).

W.M. Davis spent much of his late career in California exploring the Mojave Desert portion of the Basin and Range, based academically out of Cal Tech's Geology Department that published his last paper posthumously (Davis, 1933). In his final paper, Davis proposed a general model of how transverse drainages form in extensional tectonic settings like the Mojave and Sonoran Deserts, USA:

> “The ranges appear to have originated as diversely displaced fault blocks, like those of Arizona … it is highly probable that their initial intermont troughs were for a time without discharge to the sea… Under such conditions the basins would be aggraded with waste down-washed from the mountains… Each trough floor would thus be built up to higher and higher levels, and in time and outflow might be established at the lowest sag of the enclosing mountains: for just there the least in-wash of detritus would be received, and the trough-floor playa would therefore be pushed towards the sag until overflow resulted… After a basin outlet was developed, it would be rapidly cut down in a steep-walled gorge; the detritus of the aggraded basin should be as actively eroded by an axial stream, which might well maintain a graded course to the deepening outlet gorge…”
>
> [(Davis, 1933: 9–10)]

Blackwelder (1934) proposed a similar concept for the lower Colorado River. Blackwelder's Stanford Ph.D. student Elmer Ellsworth (1932) wrote his dissertation on the Afton Basin of the Mojave River, and Meek (1989, 2019) met with Ellsworth when he was conducting his own UCLA Ph.D. research (personal communication with Ron Dorn, 1989). We think it likely that Davis (1933) and Blackwelder (1934) both used the Mojave River's transverse drainage through Afton Canyon, as did Meek (1989, 2019) as the key case study to develop their hypotheses.

A mid-to-late twentieth century shift in geomorphology's research paradigm, to emphasize mechanics and process, led to eschewing drainage integration as a research focus in much of the second half of the 20th century. There were notable exceptions, however. Oberlander's (1965, 1985) research on the Zagros Mountains exemplifies how meticulous data collection and observation via field work can add critical insights and further develop theory — in this case, theory on the process of superimposition. In the Zagros Mountains, Oberlander (1965, 1985) noted that thick beds of very friable and erodible substrate, like flysch, can act as a cover mass thereby allowing a drainages to easily incise across geologic structure and establish a transverse drainage course. Also, Charlie Hunt (1969, 1974, 1982) displayed a passion for what he liked to call “drainage anomalies” (personal communication to R.I. Dorn, 1984). Lovejoy (1972) debated between lake overflow and piracy for the origin of the Truckee River's crossing of the Carson Range, Nevada. Research also continued on the origin of the Grand Canyon (e.g. Strahler, 1948; McKee et al., 1967). As a general rule, however, it seems that through the end of the 20th century, transverse drainage research was largely viewed as a relict passion and too broadly similar to Davisian-era geomorphology.

In the mid 1980's, Norman Meek completed his dissertation research on the origin of Afton Canyon of the Mojave River, in the Mojave Desert, California (Meek, 1989). Meek won the Nystrom Award of the Association of American Geographers by presenting a conceptual model of episodic regional prolongation of rivers in the Basin and Range Province (BRP) by a combination of sediment infilling of basins culminating in a lake overflow event. Unfortunately, the manuscript focused on this conceptual model was rejected when Meek submitted it for peer review. Reviewers rejected the submission because it did not have an abundance of the “kind of data” that reviewers wanted to see (e.g. data-rich numerical analyses). Meek's (1989, 2019) research was subsequently replicated by a U.S. Geological Survey effort that had a budget three orders of magnitude larger (Reheis et al., 2007, 2021), confirming Meek's conceptual model of drainage prolongation. Given the resurgence of research focused on transverse drainage processes and their broader significance, Meek's “top-down” conceptual model manuscript was peer-reviewed and published in this special issue (2019), albeit over a quarter century later than its original submission. We consider

Meek's research (1989, 2019) to represent a turning point, or paradigm shift, in our understanding of transverse drainage establishment and associated landscape evolution in the Basin and Range Province of North America (Dorn and Larson, 2019). An argument could be made that this work is also relevant to broader terrestrial and extraterrestrial studies of drainage basins beyond the American southwest.

Over the last three decades, and following Meek's seminal work (1989), there has been a slow but steady increase in research on drainage integration and transverse drainage development. Over this time, researchers compiled comprehensive field and laboratory-based data sets that have both tested and improved on theory of transverse drainage development. Today, based on both late 19th/early 20th century scholarship and contemporary research, geomorphic theory holds that there are four general geomorphic processes, and nuanced variations within each of those processes, that result in a transverse drainage developing in a landscape: antecedence, superimposition, piracy, and lake overflow/spillover (see Larson et al., 2017; Hilgendorf et al., 2020 for reviews; Fig. 1). Pioneering work in physical modeling conducted by Douglass and Schmeeckle (2007) and Douglass et al. (2009a, 2009b) demonstrated these geomorphic processes in physical experiments and revealed geomorphic and sedimentologic criteria that can be found in basins to adjudicate the most likely process to generate a particular transverse drainage.

These four mechanisms certainly contain variations, such as subterranean piracy, aggradational spillover/piracy, anteposition and structural superimposition. Hilgendorf et al. (2020) explore the significance, occurrence, and nuance of "top-down" integration processes (Fig. 2). Generally, however, these four basic processes (Fig. 1) are the only explanations for the origin of transverse drainages in field-based, physical-modeling, and numerical-modeling studies of drainage integration.

2. This special issue and contemporary research on drainage integration and transverse drainages

The primary focus of this special issue rests in advancing our understanding of drainage integration and transverse drainage development in extensional tectonic landscapes at a time of enhanced interest. Extensional

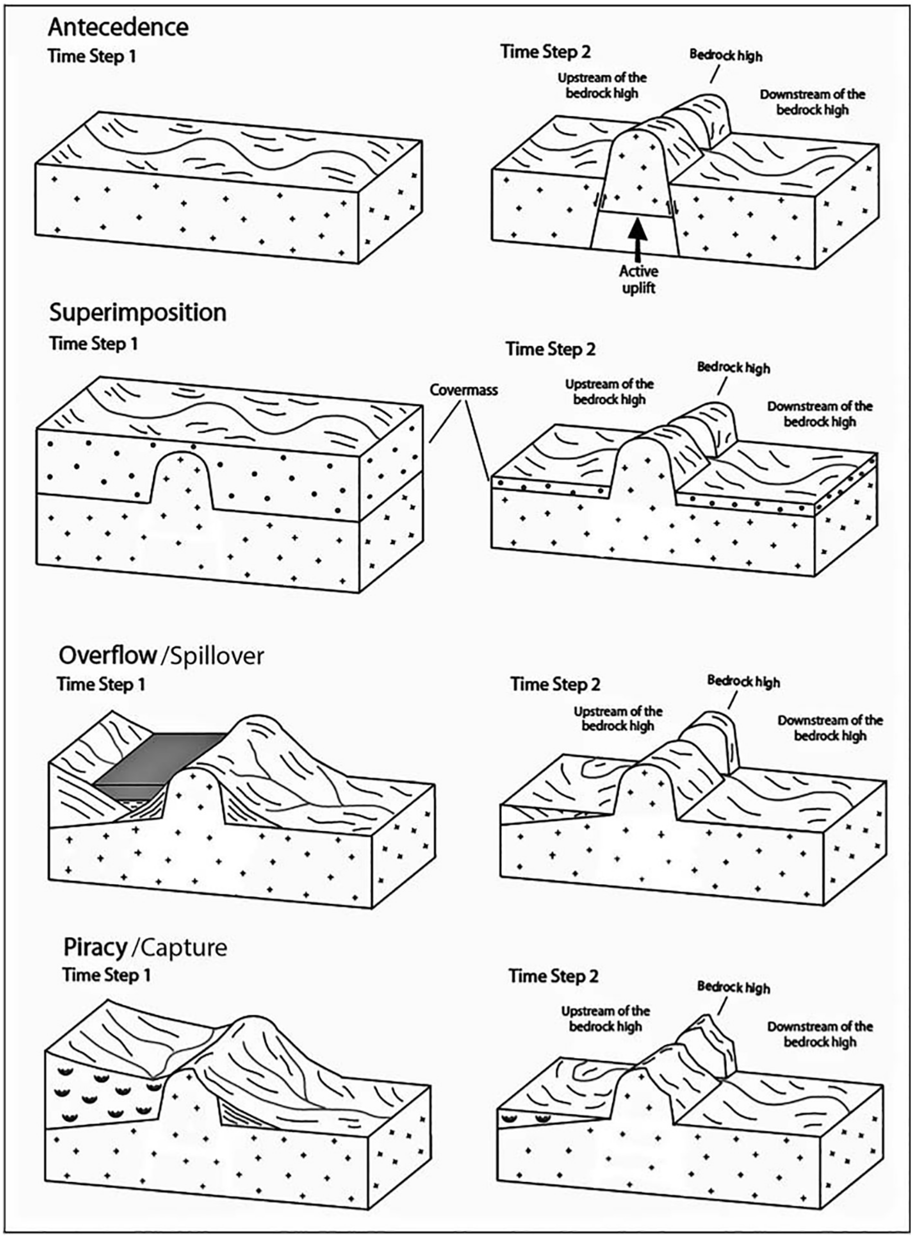

Fig. 1. Four general geomorphic processes that can result in drainage integration via the establishment of a transverse drainage as discussed by Douglass and Schmeeckle, 2007, and Douglass et al., 2009a, 2009b. Modified from Douglass et al., 2009a, 2009b; used with permission.

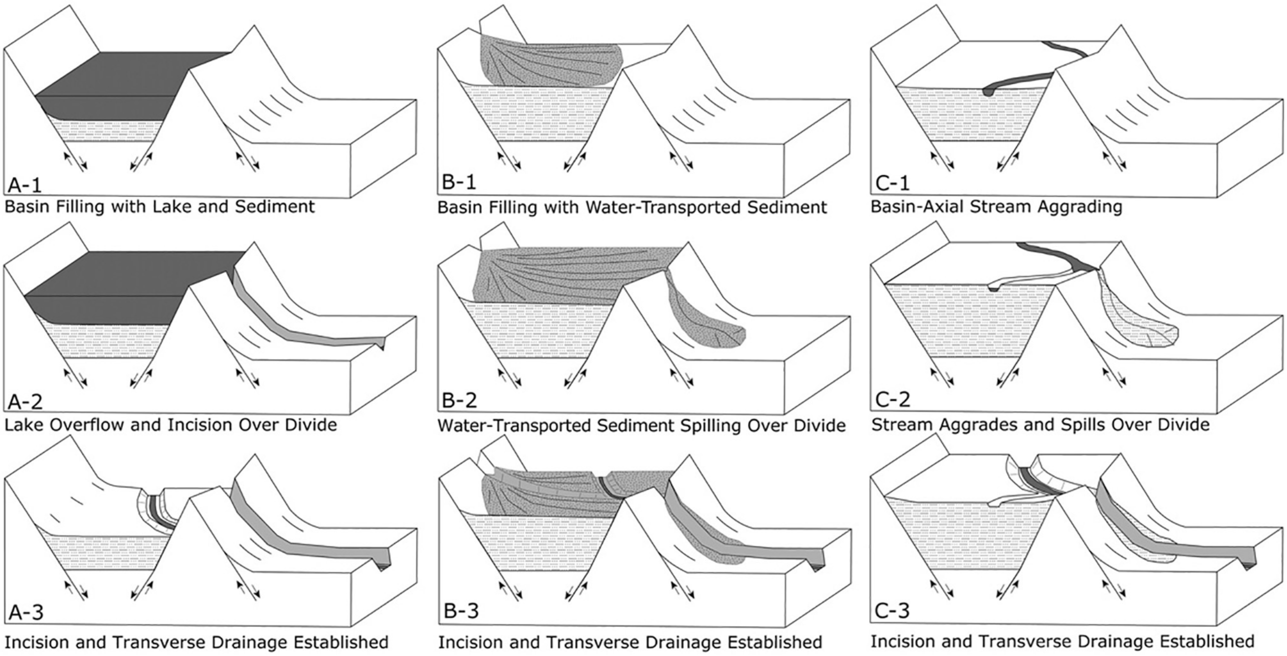

Fig. 2. Three conceptual and generalized models of how 'top-down' drainage integration and transverse drainage development could occur. Hilgendorf et al. (2020) collectively referred to these processes as "spillover" processes to clarify from ambiguous terminology like "fill and spill" that could incorporate any of these without providing the necessary details to understand how these landscapes and drainage networks evolved. Please see Hilgendorf et al. (2020) for further details. Modified from Hilgendorf et al. (2020); used with permission.

tectonic landscapes were chosen as they contain structurally-controlled basins that often, in recent geologic history, did/do not contain through flowing river systems. Thus, extensional landscapes like these represent critically important natural laboratories to evaluate and improve geomorphic theory on drainage integration and transverse drainage development.

2.1. Apennine Mountains, Italy: Geurts et al., 2020

Geurts et al. (2020) represents a continuation of prior research (Geurts et al., 2018; Geurts, 2020) in the tectonically active region of the central Italian Apennines (Fig. 3). Geurts et al. (2018) employed numerical modeling and demonstrated that drainage integration and basin evolution could be driven by basin spillover (Hilgendorf et al., 2020) processes in this region, but integration processes have a dynamic relationship with accommodation space. Basin subsidence and sediment/water supply relationships drive either (i) integration if supply > subsidence; or (ii) endorheic conditions if supply < subsidence. In this special issue Geurts et al. (2020) then further examined the central Italian Apennines through a focused analysis of the geomorphology and sedimentology/stratigraphy within the Aterno River basin, the largest drainage basin flowing to the Adriatic from the central Apennines.

Geurts et al. (2020) provide additional support for Geurts et al.'s (2018) numerical modeling of top-down basin spillover processes driving integration along the Aterno River. They explore important connections to active extensional tectonics and climatic change influencing the critical balance between accommodation space and sediment/water supply. Ultimately, this critical balance drives threshold conditions allowing for integration or, alternatively, "underfilled" and potentially endorheic conditions in the basins of the central Apennines. Geurts et al. (2020) studied a geomorphic setting where active tectonic processes are occurring through the timescale of drainage integration processes. Therefore, this research in the Apennines provides a conceptual framework for what to expect in an actively extending tectonic setting.

2.2. Taebaek Mountains, Korean Peninsula: Kim et al., 2020

While this special issue introduction is not the place to review global trends in transverse drainages, it is important to place the special issue in the broader global context of research on transverse drainages that includes the importance of butte detachment in drainage integration at rifted continental margins (Gunnell and Harbor, 2010), how a drainage divide can inhibit drainage integration in a rapidly-deforming forearc (Molin et al., 2004), the re-alignment of river drainages in the Himalaya (Hallet and Molnar, 2001), as well as many other research threads including lake overflow in China (Ren et al., 2014) and Iran (Heidarzadeh et al., 2017). Kim et al. (2020), this issue, present a geomorphic analysis of drainages developed in a back-arc basin, in the Taebaek Mountain Range of the Korean Peninsula. This extensional setting is quite different from the Apennines or the BRP and offers insight into how researchers employ geomorphometric analyses and ^{10}Be catchment-averaged denudation rates to analyze the rate and cause of gradual divide migration.

The Taebaek Mountain Range, a N-S trending rift flank that stands >1700 m above sea level, is an asymmetric, west-tilted range that manifests as an escarpment along the eastern margin of much of the Korean Peninsula. Drainage network evolution along this rift flank range is not well understood. Kim et al. (2020) utilized various geomorphic analysis, such as Gilbert metrics and chi-analysis to investigate this asymmetrical range and how drainages are evolving and the drainage divide created by the escarpment changes through time. Their findings suggest that the present divide is migrating generally to the west resulting in prolongation of drainage networks flowing to the east (Figs. 4 and 5). They note that this is not homogeneous and that differences in geomorphic analysis provide insight into the timing and evolution of the escarpment. Base level change and tectonic uplift likely influence the rates at which these drainages elongate and the escarpment migrates west. Importantly, the difference in geomorphic parameters and longitudinal profiles between paired-basins investigated in this study on either side of the drainage divide suggests differences are not the result of structure or rock resistance.

Interestingly, the basin-averaged ^{10}Be denudation rates determined in Kim et al. (2020) shows different results between paired-basins across the divide – even though they contain similar lithologies. The basins of the eastern flank show three times higher denudation rate than the western ones. Thus, Kim et al. (2020) argue that the influence of lithology on millennial-scale denudation rate was minimal, compared

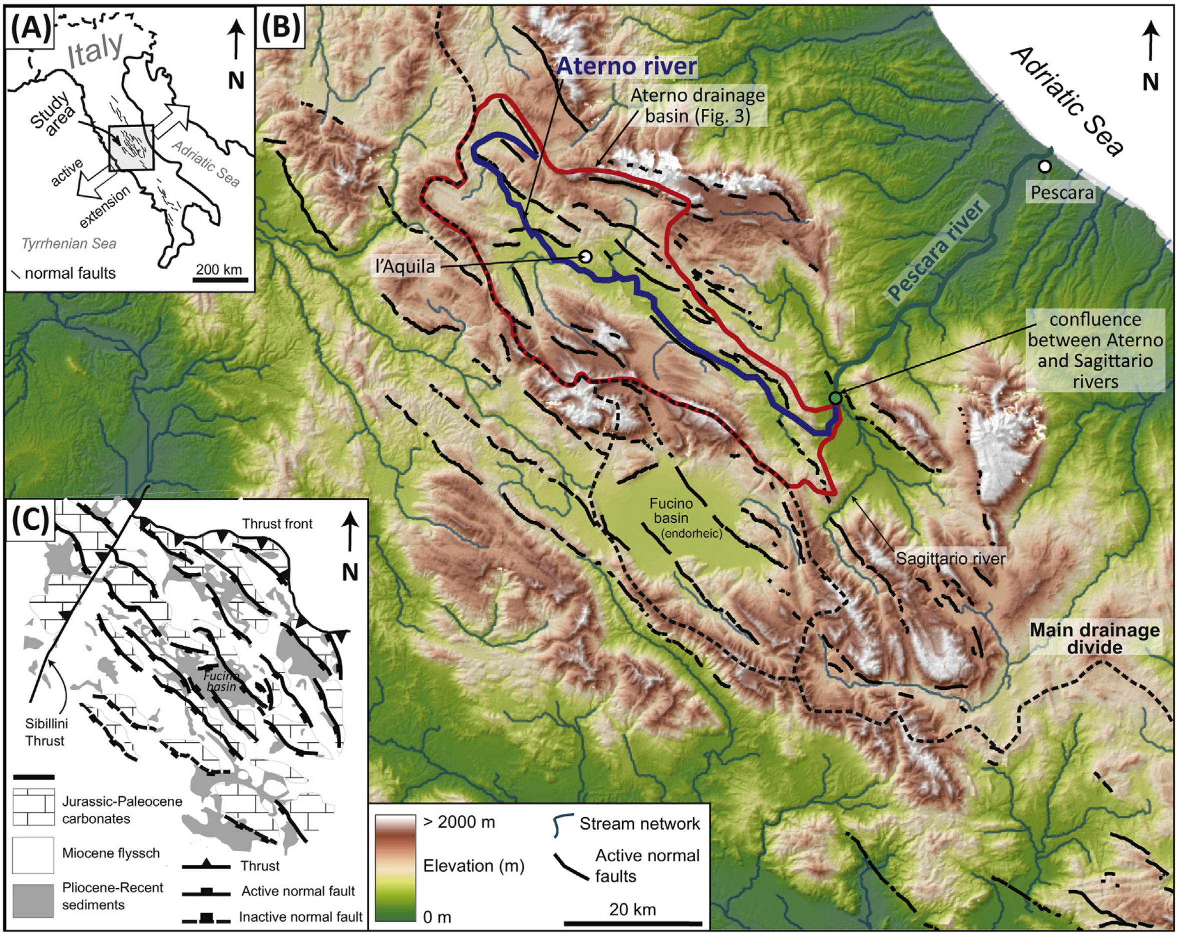

Fig. 3. Aterno River, central Apennine Mountains, Italy. The Aterno River is the focus of drainage integration research in the Apennine Mountains by Geurts et al. (2020) in this special issue and builds on similarly-themed prior research in the Apennine Mountains (Geurts et al., 2018). Modified from Geurts et al. (2020); used with permission.

with other factors. The relatively poor correlation between basin morphometrics and basin-averaged denudation rate of the catchments on the eastern flank of the escarpment may result from a strong decoupling between fluvial incision and hillslope processes in the lower reaches of the rivers. The discrepancy also occurs in between basin-averaged denudation rates and rates of surface uplift induced from marine and fluvial terraces, which are located in and around the outlet of the eastern catchments. The denudation rate of the eastern flank (~80 mm/ka) was two or three times lower than the surface uplift rate (~200 mm/ka; Lee et al., 2011, 2015) over the late Quaternary. This difference may be caused by the lagging of hillslope denudation behind a relatively fast base-level lowering caused by recent surface uplift.

Kim et al. (2020) suggest that the topographic divide of the Korean Peninsula is eroding slowly. The magnitude of erosion differs depending on the specific paired-basin characteristics across the divide, which may have thus retreated in a non-parallel geometry to the modern divide. The migration rate of the divide was fastest during the initial opening of the extensional East Sea basin, slowed, and may have sped up at ~5 Ma via tectonic inversion and rejuvenation (Fig. 5). Kim et al. (2020) finally suggest that the evolution of the topographic divide bounding an extensional margin matches best with the escarpment retreat model of passive continental margins on the basis of their results with those from previous thermochronologic studies.

2.3. Grand Canyon, Colorado River, USA: Douglass et al., 2020

When visitors come to Grand Canyon, they usually visit the "south rim" or "north rim" portions of Grand Canyon National Park. At either of these vantage points, visitors are afforded spectacular views that allow them to peer across the canyon in awe of its grandeur (Fig. 6). What they often do not recognize is that they are also looking across only a small portion of Grand Canyon – but a portion noted repeatedly in the literature as critical to understanding how the canyon formed (e.g. Meek and Douglass, 2001; Karlstrom et al., 2014, 2017; Larson et al., 2017; Douglass et al., 2020). This segment of Grand Canyon is a transverse drainage carved across a topographic and structural high that formed during the Laramide Orogeny, the Kaibab Plateau (Krantz, 1989; Fig. 6). Further west, the Grand Canyon and Colorado River continue through more recent extensional faulting (Menges and Pearthree, 1989) and eventually reach the Grand Wash Cliffs, where the Colorado River enters the extensional tectonic province of the Basin and Range, near modern day Lake Mead. The lower Colorado River (LOCO; downstream of Grand Canyon) then makes its way to the Gulf of California, where it cuts through and integrates seven formerly closed/endorheic basins (i.e. transverse drainages) through a top-down cascade of well-documented basin spillover processes (e.g. Spencer et al., 2001a, 2001b; House et al., 2005, 2008; Spencer et al., 2013; Pearthree and House, 2014; Crow et al., 2021). Therefore, understanding the origin and timing of the transverse drainage at Grand Canyon is a critical part of understanding the integrated hydrology of the LOCO through the Basin and Range extensional province (BRP). Indeed, the integrated rivers of central Arizona (i.e. Salt, Verde, Gila Rivers, etc.) investigated in this special issue also integrate with the LOCO. The entire regional hydrogeomorphic system is tied to the timing and origin of the Colorado River establishing a transverse drainage across the Kaibab Plateau and, therefore, the origin of Grand Canyon.

The transverse reach of the Colorado River at the Kaibab Plateau has been subject of heated debate since Powell (1875). It has also seen a

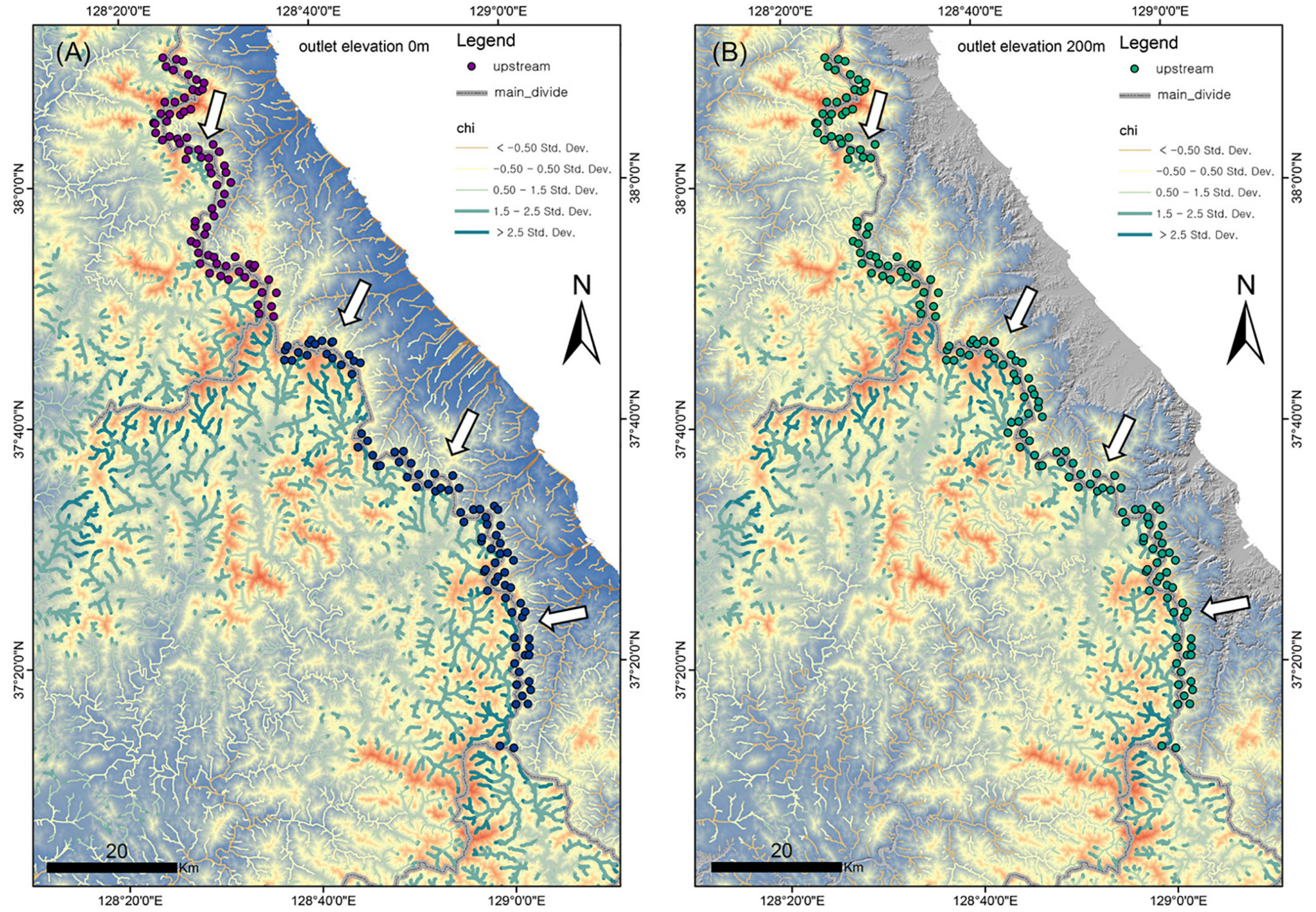

Fig. 4. The Taebaek Mountains, Korea. This map depicts χ-values on a shaded-relief map derived from the 10-m DEM. White arrows indicate the direction of retreat. (A) 0 masl for outlet and (B) 200 masl for outlet. Both cases indicate that the present divide is migrating (south)westward. Modified from and used with permission of Kim et al. (2020).

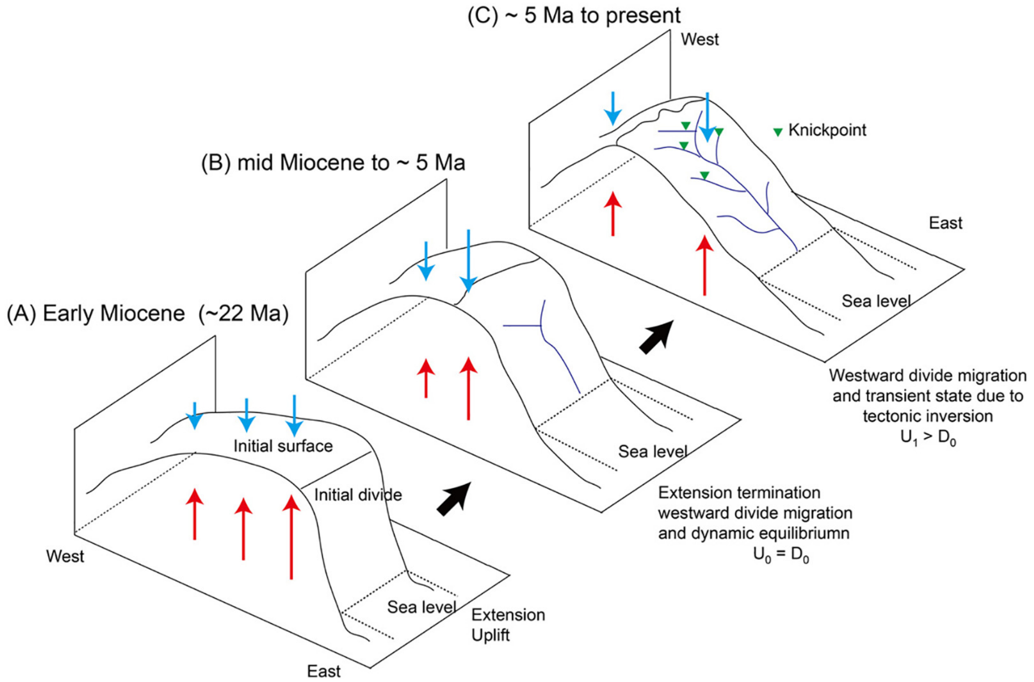

Fig. 5. Schematic model for retreat of the main drainage divide of the TBR. (A) Initial surface uplift of the TBR during opening of the East Sea (Sea of Japan). (B) Initial steady-state condition during which the uplift rate (U0) is equal to the denudation rate (D0). (C) Late Quaternary-recent transient state condition caused by tectonic inversion. Surface uplift rate (U1) is higher than the denudation rate (D0) because of tectonic inversion. In response to the increased uplift rate, the denudation rate increases and the main divide migrates to the west.

Fig. 6. Students from Minnesota State University, Mankato, visiting Grand Canyon, USA and learning about transverse drainage development. From this vantage point on the South Rim, the North Rim of Grand Canyon is in the distance. At this location the Colorado River crosses the Kaibab Plateau and is a transverse drainage (Douglass et al., 2020). Photo by Phillip Larson.

resurgence in interest in the last three decades as our understanding of the processes that produce transverse drainages have grown and methods that can be applied have burgeoned. Much of this debate centers on the age of incision of the canyon derived from thermochronology data (e.g. Flowers et al., 2008; Flowers and Farley, 2012; Karlstrom et al., 2014; Flowers et al., 2015; Karlstrom et al., 2017; Winn et al., 2017) in comparison to geomorphic and sedimentologic evidence from the region (e.g. Meek and Douglass, 2001; Spencer et al., 2001a, 2001b; House et al., 2005, 2008; Spencer et al., 2013; Pearthree and House, 2014; Douglass et al., 2020; Crow et al., 2021). This geomorphic and sedimentologic evidence can be used to determine transverse drainage process and timing, particularly when linked to physical modeling experiments (Douglass and Schmeeckle, 2007; Douglass et al., 2009a, 2009b). As of this writing, the differences between these two “camps” remain unresolved, with a “young canyon” (<6 Ma) being the accepted paradigm among geomorphologists due to the growing body evidence compiled along the lower Colorado River (LOCO) downstream of Grand Canyon (House et al., 2005, 2008; Spencer et al., 2013; Pearthree and House, 2014; Crow et al., 2021), upstream of Grand Canyon (Douglass et al., 2020); thermochronology data (e.g. Winn et al., 2017; Murray et al., 2019); and geomorphic constraints (Douglass et al., 2009a, 2009b; Darling and Whipple, 2015).

Douglass et al. (2020) present work that sheds new light on the lake overflow hypothesis for the establishment of the transverse drainage across the Kaibab Plateau and for the initial formation of Grand Canyon. Their foci rests on the Bidahochi formation, a debated deposit with three distinct sedimentary units that provides evidence for a large lake responsible for the overflow event that breached the Kaibab Plateau. One of the primary criticisms to the lake overflow hypothesis is a lack of evidence for a lake sufficient in size to breach the sill across the Kaibab Plateau (e.g. Dickinson, 2015). Evidence provided in this study reveals that the Bidahochi sedimentology, ^{87}Sr/^{86}Sr ratios in the Bidahochi upper member (compared to other members), the modern Colorado River, and the LOCO's Bouse Formation, and fossil evidence within the Bidahochi formation all support the existence of a freshwater lake that could have been responsible for a lake overflow process resulting in the transverse drainage at Grand Canyon. Douglass et al. (2020) also provide a detailed discussion of geomorphic, geochronologic, and sedimentologic evidence upstream and downstream of the “paleodivide” (i.e. where the transverse drainage was established) that are consistent with a lake overflow hypothesis (Fig. 7).

In summary, Douglass et al. (2020) argue for what we consider to be an “Occams Razor” approach to understanding Grand Canyon:

> “The simplicity of overflow to explain upstream evidence, downstream evidence, and geomorphic evidence at the paleo-divide contrasts with far more complicated hypotheses that lack existing physical supporting evidence. Thus, we argue that evidence currently available and newly described in this paper is consistent with an overflow explanation for the Grand Canyon formation and certainly warrants additional research along these lines.”
>
> [(Douglass et al., 2020, p. 7)]

Further research is clearly needed to reconcile the data that has been presented at Grand Canyon in the recent literature. However, Douglass et al. (2020) provide new and important evidence that, in tandem with the available geomorphic and sedimentologic data in the Grand Canyon region, supports a lake overflow hypothesis for the origin of the transverse drainage at Grand Canyon. We feel that paradigm divide between geomorphic thinking exhibited by Douglass et al. (2020) and the LOCO research and those relying on incongruous thermochronology data will be difficult to breach. However, such a reconciliation could result in a comprehensive conceptual model of Grand Canyon's evolution and the establishment of a through-flowing Colorado River – a river that facilitated the through-flowing regional drainage network of the southern BRP extensional landscapes.

2.4. The basin and range of the Southwest USA: Meek, 2019; Skotnicki and DePonty, 2020; Dorn et al., 2020; Larson et al., 2020; Skotnicki et al., 2021a; Skotnicki et al., 2021b; Anderson et al., 2021; Gootee et al., 2022; Potochnik et al., 2022.

The last 75 Ma of tectonic history of the southwestern United States starts with compressional tectonics during the Laramide Orogeny that produced the Mogollon Highlands and uplifted the Colorado Plateau (Coney, 1978; Dickinson, 1989). This also established of a NE-flowing

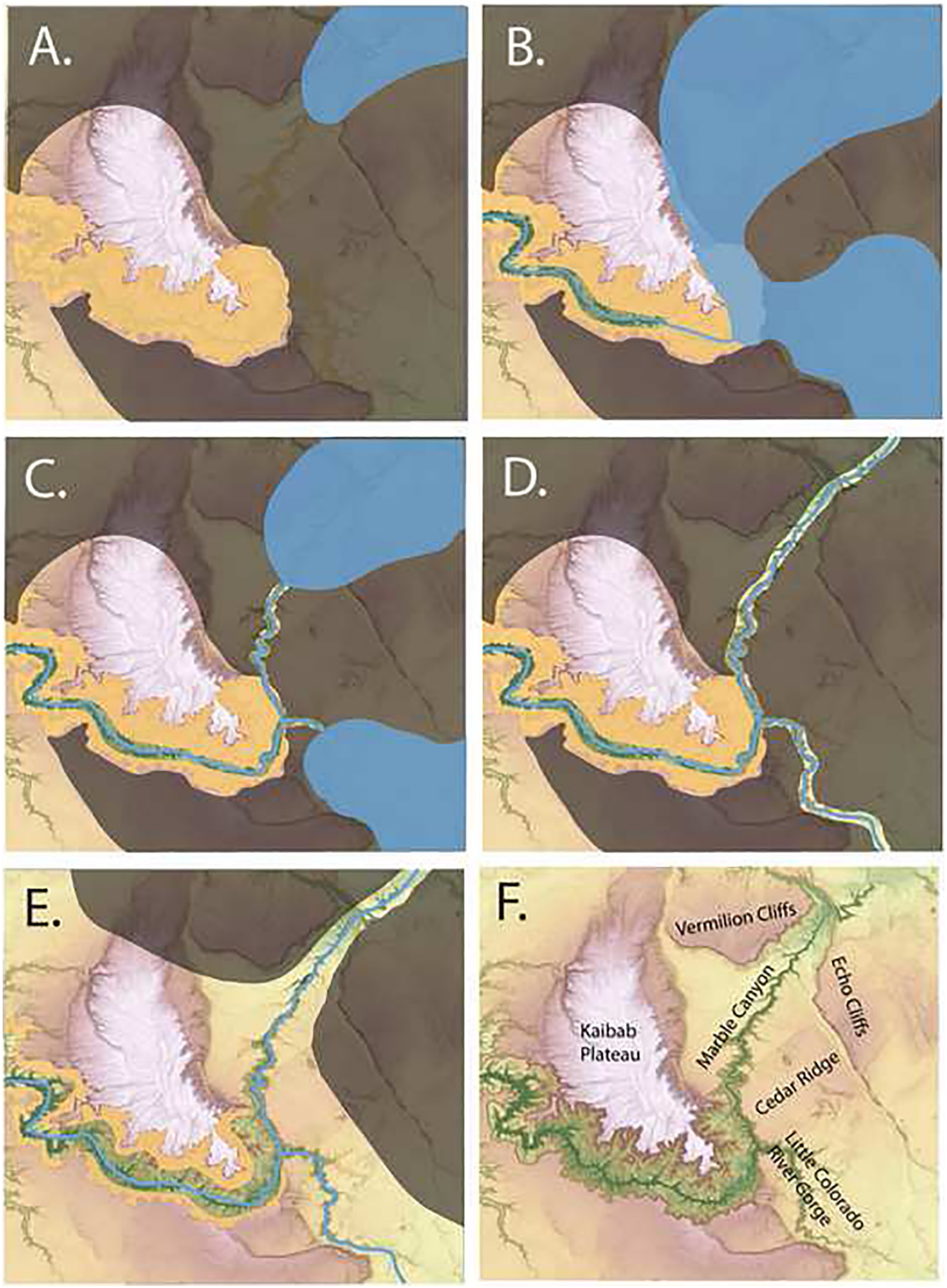

Fig. 7. Douglass et al. (2020) time-sequence and conceptual model for the formation of Grand Canyon via Lake Overflow. (A) Roughly 7 Ma the Colorado River arrived in the Bidahochi Basin, the Vermilion and Echo Cliffs stand as a circular scarp retreating off the Kaibab Plateau. (B) Roughly 6 to 5 Ma, the lake filled and spilled across the Kaibab Plateau, and knickpoints work headward towards the lake-outlet. (C) The lake splits into two lakes across Cedar Ridge, the northern lake cuts the proto-Marble Canyon and the southern lake cuts a proto-Little Colorado River Gorge. (D) Following overflow, the Colorado River and the Little Colorado are flowing in their modern positions. (E) Moving forward in time, roughly 3 Ma, the Grand Canyon widened, and the Vermilion and Echo Cliffs retreated closer to their modern positions. (F) The modern landscape with important landforms labeled. Modified from Douglass et al. (2020) and used with permission.

regional drainage network (Fig. 6) discussed within this special issue in Anderson et al. (2021) and Potochnik et al. (2022). Then, during the Miocene, extensional tectonics collapsed the Mogollon Highlands and left the Colorado Plateau and Mogollon Rim as topographically high features, triggering a regional drainage reversal from NE-flowing drainages to SW-flowing drainages (Fig. 8; Faulds, 1986; Potochnik and Faulds, 1998; Anderson et al., 2021; Potochnik et al., 2022).

The extensional tectonic history of the Basin and Range Province of the southwest USA (BRP) resulted in a series of structural basins bounded by topographic and structural barriers to the flow of water, thereby creating endorheic basins throughout much of the region (Spencer and Reynolds, 1989; Spencer et al., 2001a, 2001b). As such, the tectonic history of the BRP resulted in the antecedent conditions for the establishment of transverse drainages necessary to integrate drainage basins. Interestingly, the existence of transverse drainages and the resultant through-flowing fluvial systems are not ubiquitous throughout the BRP. In the Great Basin, through-flowing rivers largely do not exist, except for the Humboldt River that likely integrated several

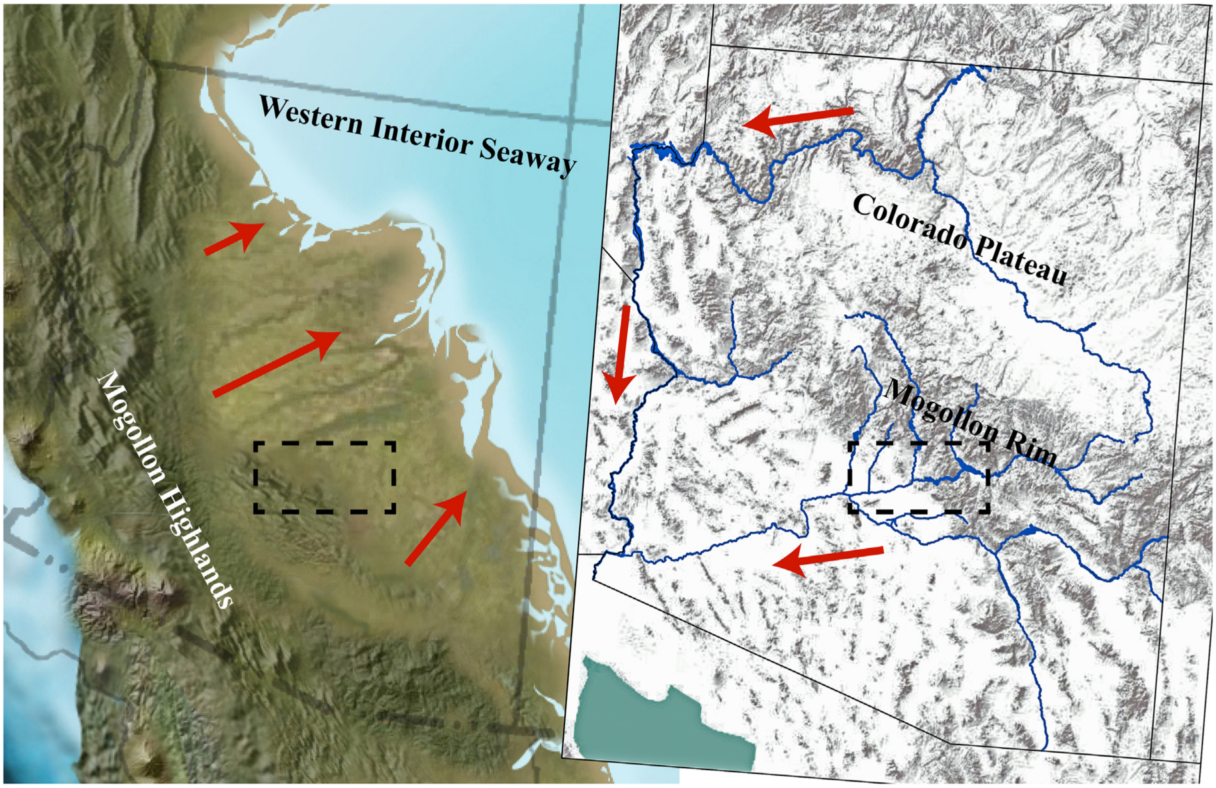

Fig. 8. Regional drainage reversal in the southwestern United States. Red arrows indicate regional drainage trends in the late Cretaceous (left) and today (right). Regional drainage reversal was driven by, first, compressional tectonics and uplift resulting in NE trending drainage networks following from the Mogollon Highlands (left) and, then, extensional tectonics that resulted in collapse of the Mogollon Highlands. The collapse of the Mogollon Highlands rerouted drainage to the SW (right). Modified from Larson et al. (2020) and used with permission. Inset box is centered on the junctions of the Salt, Verde, and Gila Rivers of central Arizona – the focus area for much of the drainage integration research in this special issue.

basins through lake overflow in the Pleistocene (Benson and Thompson, 1987). In the Sonoran Desert, through-flowing rivers are more commonplace. Thus, the focus of much of this special issue examines the processes and timing of drainage integration of major through-flowing rivers of the Sonoran Desert portion of the BRP in order to further our understanding of transverse drainage development and subsequent integration of basins in extensional tectonic landscapes.

Until the last few decades, very little was known about the integration and evolution of the rivers in the southern BRP. Meek (1989) was the first, in the recent literature, to examine the process responsible for drainage integration in this region. His work focused on Afton Canyon of the Mojave River (N 35.03889 W 116.38292), where he hypothesized that basin spillover processes, particularly lake overflow, integrated basins and elongated the drainage network from the top-down through time. Meek's (1989) ideas were tested and supported at Afton Canyon nearly two decades later (Reheis et al., 2007, 2021). We consider Meek's work on Afton Canyon to be the pivotal turning point for all work that has come in recent years on drainage integration in the BRP, including the work in this special issue, and in many other extensional tectonic settings. Meek's general model for drainage integration in the BRP was not well received decades ago, but is presented, as proposed then, within this special issue (Meek, 2019).

More recently, Douglass and Schmeeckle (2007) developed fundamental theory on transverse drainage development via physical modeling experiments. This process-based approach was expanded to include geomorphic and sedimentologic criteria that can be used to determine the most-likely mechanism responsible for a particular transverse drainage in a specific geographic setting (Douglass et al., 2009a, 2009b). This work coincided with Geological Society of America Kirk Bryan Award-winning geomorphic and sedimentological research on the origin of the LOCO, work that advocated for a similar (Meek, 1989, 2019), top-down story of lake overflow through meticulous field and laboratory work (House et al., 2005; House et al., 2008; Roskowski et al., 2010; House et al., 2013; Spencer et al., 2013; Pearthree and House, 2014; Howard et al., 2015; Bright et al., 2016; Crow et al., 2021). Similarly, the Rio Grande River was hypothesized to form via top-down basin infilling and lake overflow (Connell et al., 2005; Repasch et al., 2017). Jungers and Heimsath (2019) also advocated for a top-down explanation for a tributary of the Gila River of central Arizona.

The above research left three major river systems yet to explain to fully comprehend the processes that shaped the through-flowing drainage network of the southern BRP. These rivers are the Gila, Salt and Verde Rivers of central Arizona (Fig. 9).

The Salt, Verde, and Gila Rivers have integrated formerly endorheic basins in this portion of the BRP that has been largely tectonically quiescent certainly for the past ca. 5 Ma and perhaps mostly quiet longer (Fitzgerald et al., 1993; Menges and Pearthree, 1989; Spencer and Reynolds, 1989, 1991; Skotnicki et al., 2021b). Still, it is possible that these rivers may have experienced some uplift in their headwaters in/near the transition zone and Mogollon Rim in the last 3 Ma (Pearthree and Scarborough, 1985; Anderson et al., 2021). Douglass et al. (2009b), Larson et al. (2010), and Larson et al. (2014) first noted the Salt River likely became a through-flowing drainage via a Lake Overflow process connecting the Tonto/Roosevelt Basin to the Lower Verde Valley near the modern day Roosevelt Dam (N 33.67135 W 111.16096) – a process similar to that noted by Meek (1989) along the Mojave River and noted by House et al. (2005) along the LOCO. In their collective work they also noted that there was more evidence for this hypothesis previously not identified, including a new high terrace along the Salt River (Larson et al., 2010). Despite this, a complete picture of the Salt integration story had not yet emerged due to a lack of sufficient sedimentologic, geochronologic, and geomorphic data to support this hypothesis. Similarly, House and Pearthree (1993) and Pearthree (1993)

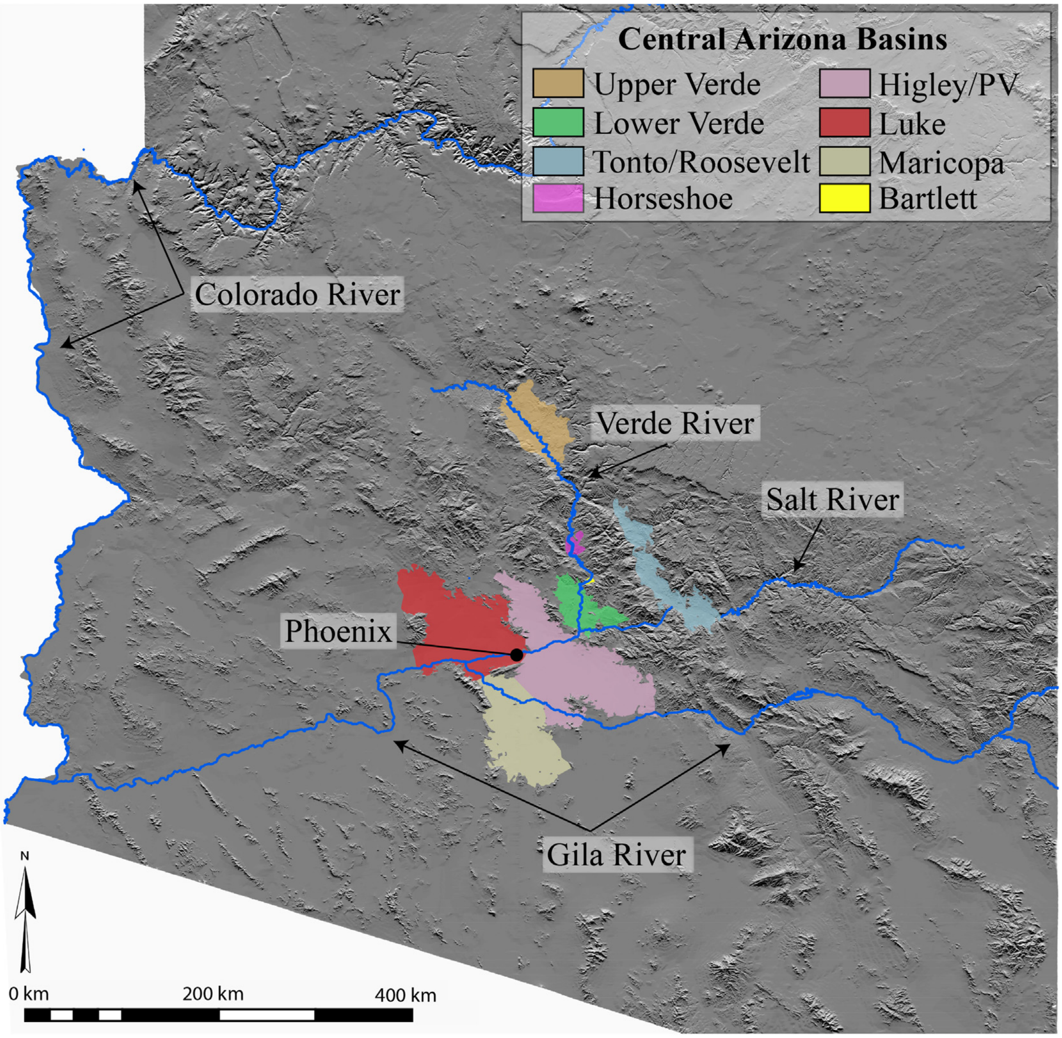

Fig. 9. The Verde, Salt, and Gila Rivers of central Arizona. Basins delineated here are those that have been integrated by these rivers, with transverse drainages established between them, resulting in the modern through-flowing drainage network that drains much of central and southern Arizona to the Gulf of California via the Colorado River.

noted the integration of the Upper Verde Valley (Fig. 9) is marked by the deposition of internally drained deposits of the Verde Formation that aggraded between 8.5 and 2.5 million years ago. After 2.5, the upper Verde Valley experienced "dramatic downcutting" (Pearthree, 1993 p. 23) when a through-flowing Verde River was established across the natural dam at the southern margin of the valley (House and Pearthree, 1993 p. 12). This basin spillover process then would have initiated top-down integration of the Verde River system.

Interestingly, Dickinson's (2015) analysis of the Gila River drainage basin, to which the Verde and Salt are tributaries, ignored this prior work and ultimately lacked the breadth and depth of empirical data to support assertions presented within that manuscript. Dickinson (2015) did not rely on geomorphic criteria and established theory to analyze the process of integration and transverse drainage development (Douglass and Schmeeckle, 2007; Douglass et al., 2009a, 2009b). Though "spillover ramps" are mentioned as a possible mechanism to integrate basins, the primary theme and a notable misconception present in Dickinson's (2015) paper, and in numerous other transverse drainages, concerns the effectiveness of "headward erosion" as the hypothesis used to explain observed transverse drainages (see Hilgendorf et al., 2020 for further discussion). Dickinson (2015) argued that "bedrock canyon passages" derive from headward erosion from a low standing basin, as do "alluviated gaps" that are gorges cut through bedrock and then "backfilled" with alluvium that connects the fluvial systems on either side of the "gap." In fact, the main postulate of Dickinson's (2015) entire manuscript suggests that nearly all the integration of the Gila River system was the result of "Late Miocene to early Pleistocene headward erosion…initiated by the exit of the lower Gila River into the nascent Gulf (of California)…"(p. 21). This requires headward erosion to have marched ~550 km upstream to integrate the Gila River system. Such an extreme rate of headward erosion is not well supported in the literature, with many discussing and demonstrating the inefficiency of headward erosion (e.g. Bishop, 1995; Douglass and Schmeeckle, 2007; Larson et al., 2017; Lai and Anders, 2018; Hilgendorf et al., 2020).

Within this special issue several papers present new research on the evolution of the Gila, Salt, and Verde drainage basins to help elucidate on the process and misconceptions in the literature around drainage basin integration in the southern BRP. This research links established geomorphic criteria and theory with new field and laboratory data from these drainage basins. Each of these papers demonstrates evidence in support of top-down integration via basin spillover processes (Hilgendorf et al., 2020), that result in establishment of through-flowing fluvial systems (Dorn et al., 2020; Skotnicki and DePonty, 2020; Larson et al., 2020; Skotnicki et al., 2021a, 2021b; Gootee et al., 2022).

Given the common misconceptions present in the literature revolving around headward erosion and piracy, a paper focused on Queen Creek, an ephemeral drainage and tributary to the Gila River (Fig. 9; Skotnicki et al., 2021b), stands out as a case study of why headward erosion is inefficient in drainage basin evolution. Skotnicki et al. (2021b) present the only detailed study (that we are aware of) on an ephemeral stream system that has been eroding hillslopes and transporting sediment into an extensional basin through the Pliocene and Quaternary. If ever there was a geographic and geologic setting where a headward eroding stream had the potential to pirate a bigger and steeper drainage area upstream, it would be Queen Creek. Despite having the full Pliocene and Quaternary at its disposal to erode headwards — very little happened. It is not a "sexy" story of drainage integration, but Queen Creek further demonstrates the inefficiency of headward erosion in connecting structural basins in the BRP.

Skotnicki and DePonty (2020) recognized prior work (Laney and Hahn, 1986) that identified a distinct sedimentary unit just below the surface, interpreted to be deposited by an "ancestral" Salt River, in the Higley Basin (Fig. 9). They linked this prior work to well cuttings in drilling projects from a water and power utility organization called the Salt River Project (SRP). In their work, they developed a new method to determine the composition of the sediments within these well-cuttings, at depth. The "clast assemblages" they produced from each well-cutting were then connected across space and depth within the Higley Basin to create new isopach maps to demonstrate a 3D geometry of these "ancestral" Salt River sediments – named the Ancestral Salt River Deposit (ASRD). The well-cuttings revealed that the Higley Basin started as an endorheic basin, with locally-sourced sediments filling the basin. However, in all cores with ASRD deposits, these ASRD sediments deposited on top of "The Rolls Formation". Both units – the Pliocene Rolls Formation and the Pleistocene ASRD accumulated in a broadly low paleotopographic position in the Higley Basin. Importantly, ASRD sediments marked the sudden arrival of the Salt River and created a "megafan" that prograded and aggraded within the Higley Basin. ASRD filling of the Higley Basin continued until an aggradational spillover (Fig. 2) process integrated the Higley and Luke Basins (Fig. 9) and permanently rerouted the flow of the Salt River from the south, towards the Gila River, to the north side of South Mountains (N 33.34530 W 112.04870).

Dorn et al. (2020) utilized detrital zircons, tephra chronology, electron microbe analysis of basalts, and $^{87}Sr/^{86}Sr$ ratios to determine the provenance of materials within Skotnicki and DePonty's (2020) clast assemblages in the Higley Basin and the age of a tuff embedded in playa sediments within the Lower Verde Valley. They noted the Lower Verde Valley was an endorheic basin >3.3 Ma, an age consistent with prior work in the Upper Verde Valley that suggested top-down integration began after 2.5 Ma (House and Pearthree, 1993; Pearthree, 1993). They also concluded that headward erosion was not consistent with their data and argued that available evidence suggests Lake Overflow as the most likely mechanism to explain the drainage integration of the Salt and Verde rivers.

Skotnicki et al. (2021a) tied prior published research in/near the Salt and lower Verde River valleys (e.g. Péwé, 1978; Douglass and Schmeeckle, 2007; Douglass et al., 2009a, 2009b; Larson et al., 2010; Larson et al., 2014; Larson et al., 2016) with Skotnicki and DePonty (2020), and Dorn et al. (2020) to present a conclusive story of the integration of the Salt and Verde River system through central Arizona. Skotnicki et al. (2021a) incorporate geochronologic data from prior work and add new cosmogenic nuclide burial dates from the ASRD in Skotnicki and DePonty (2020) well-cuttings (Fig. 10). The ASRD is interpreted to be similar to aggradational units seen in other fluvial systems that have undergone integration via lake overflow, like the Bullhead alluvium along the lower Colorado River (e.g. Howard et al., 2015). In this work, they present this geochronologic data to constrain the age of arrival of the Salt River in the Higley Basin. Burial dating of the ASRD suggests it arrived in the Higley Basin (Fig. 9) sometime after 3.90 Ma and before 2.77–2.16 Ma. This is consistent with a 3.3 Ma age of a tuff unit in playa deposits indicative of endorheic basin conditions in the Lower Verde Valley (Fig. 9) in Dorn et al. (2020) and integration of the Upper Verde Valley after 2.5 Ma (House and Pearthree, 1993; Pearthree, 1993). Upon arriving in the Higley Basin, the Salt River deposited the ASRD (Skotnicki and DePonty, 2020) while flowing south towards the Gila River, until sometime after 0.54 Ma and prior to 0.46 Ma. It then breached a low bedrock ridge between Papago Park and Tempe Butte (Fig. 11). This aggradational spillover (Fig. 2) event rerouted the Salt River to the north of South Mountains and integrated the Higley and Luke Basins.

Skotnicki et al. (2021a) document top-down integration for the Salt River where distinctly different basin spillover mechanisms (Fig. 2; Hilgendorf et al., 2020) create transverse drainages and integrate individual basins resulting in the through-flowing Salt River observed today. For example, they interpret a unit underlying the ASRD in the Higley Basin (Skotnicki and DePonty, 2020) as being derived from the Lower Verde Valley prior to the arrival of the Salt River. This underlying unit, named the "Rolls Formation," suggests the Higley Basin and Lower Verde Valley (Fig. 9) were connected by a large alluvial fan that breached the divide between these two basins before the ancestral Salt River arrived from the Tonto/Roosevelt Basin. The Rolls Formation possibly created a "fan ramp" for the Salt River to flow across when it eventually arrived via lake overflow.

In summary, Skotnicki et al.'s (2021a) work suggests that "fill and spill" terminology does not adequately encompass the complexity of top-down integrating drainage basins that eventually establish a through-flowing river. Distinctly different spillover processes (see Hilgendorf et al., 2020 for review) can drive integration of individual basins, at different times, along the course of a river. Thus, top-down integration may, but may not always, begin from the "top." Intermediate basins may integrate before upstream and downstream basins connect. To fully understand the establishment of a through-flowing river in an extensional tectonic landscape, one must consider the complexity of individual basins beyond a generalized "fill and spill" idea. Importantly, work by Geurts et al. (2018, 2020) may help to better understand this as they reveal that a balance between accommodation space and sediment/hydrologic inputs may drive individual basins to integrate or not at a given point in geologic time. Geurts et al. (2018, 2020) also demonstrate, as does Skotnicki et al. (2021a) and Gootee et al. (2022), that examining geomorphic, geochronologic, and sedimentologic evidence in basins along a river is of critical importance to reveal the complexity necessary to explain the birth of a new river – it is not a "one size fits all" idea.

Gootee et al. (2022) investigated the upper and middle reaches of the Gila River, largely focused on the basins upstream of the Picacho and Higley basins (Fig. 9). They review geomorphic, geochronologic, stratigraphic and sedimentologic evidence along these portions of the Gila River to answer: "how the Gila River developed across the region's varied geologic structures." To date, two general models for integration of the Gila have been proposed – 1) spillover of closed basins from the top down (Morrison, 1991) and 2) headward erosion working its way hundreds of kilometers upstream, from the Colorado River (Dickinson, 2015). They conclude the Gila River, like the Salt and Verde Rivers mentioned previously, sequentially integrated formerly closed basins from the top down via basin spillover processes – referred to as "fill and spill" in their paper. Interestingly, the timing of Gila River integration in the Phoenix valley appears roughly contemporaneous with the integration of the Salt and Verde.

Gootee et al. (2022) suggest a possible climate-driven impetus driving regional integration of all these rivers sometime around the Plio-Pleistocene boundary. Skotnicki et al. (2021a) and Gootee et al. (2022) indicate that available chronometric age control on the timing of Gila-Salt-Verde river integration is insufficient at present to support or contradict a contemporaneous integration. However, the notion does find some support in the paleoclimatic literature about the late Pliocene. Abell et al. (2021) provides a climatic trigger, finding that the mid-latitude westerly wind systems intensified southward around 2.73 Ma. This shift could have made the region of the Gila-Salt-Verde regions

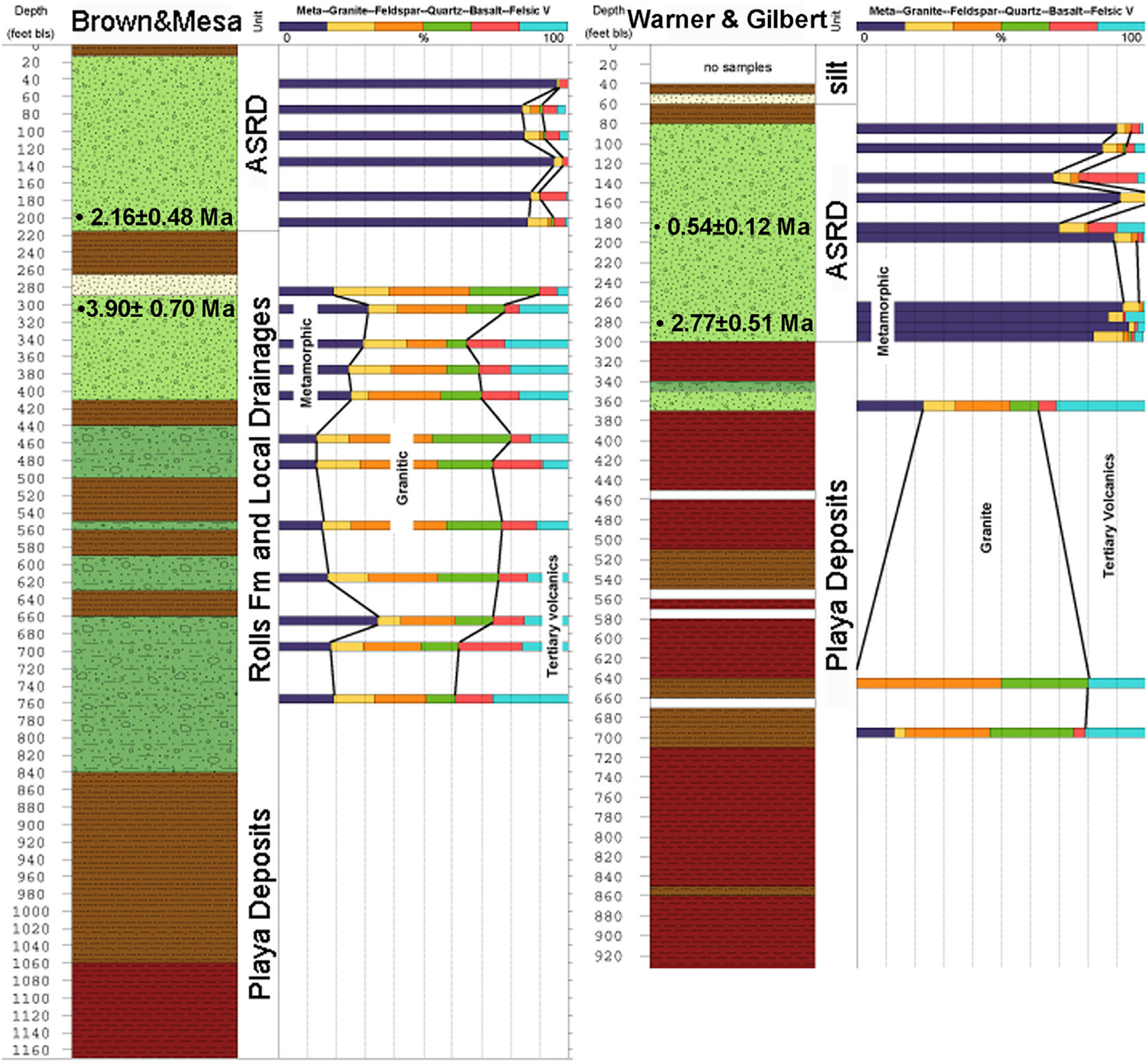

Fig. 10. Cosmogenic burial isochron ages on well cuttings from two sampled wells in the Higley Basin, as seen in Skotnicki et al. (2021a). ASRD, or Ancestral Salt River Deposits, represents the arrival of the Salt River. Rolls Fm, or Rolls Formation, represents a precursor integration event where the Lower Verde Valley and Higley Basins integrated via an alluvial fan prograding from the Lower Verde into the Higley Basin. Playa deposits represent endorheic basin conditions and locally-sourced sediments. Modified from and used with permission of Skotnicki et al. (2021a).

substantially wetter and cooler (Abell et al., 2021). Yet, a different paleoclimatic hypothesis holds that the western USA region was both wetter and warmer with more abundant moisture to support lakes ca. 2.9–3.3 Ma (Ibarra et al., 2018). More work is clearly needed to establish or falsify a paleoclimatic link to initiating or accelerating basin-filling that led to spillover processes in the region.

Lastly, Larson et al. (2020) summarize >20 years of field observation to interpret landscapes along the Salt and Verde Rivers from a slightly different perspective than other papers discussed within this special issue. Research along the Salt and Verde Rivers (e.g. Douglass et al., 2005; House and Pearthree, 1993; Pearthree, 1993; Larson et al., 2010; Larson et al., 2014; Larson et al., 2016) and Gila River (e.g. Jungers and Heimsath, 2019; Gootee et al., 2022) suggest an understudied, but dynamic, basin-wide response of geomorphic systems within basins that hydrologically integrated around the Plio-Pleistocene boundary. It is clear that the integration process can dramatically influence the geomorphology of a basin as a result of dynamic changes to a basin's base level during the integration process (e.g. Skotnicki and DePonty, 2020; Skotnicki et al., 2021a). In addition, transitioning from a slowly aggrading endorheic system to a through-flowing exorheic system brings extrinsic forces into play in integrated basins. For example, changes in the location and elevation of headwaters (Anderson et al., 2021) and climatic impact on the now through-flowing streams behavior all lead to basin-scale geomorphic change. For example, Larson et al. (2020) point to classic landforms like pediment systems (Larson et al., 2014; Larson et al., 2016) and alluvial fans in these basins that record post-integration basin-scale adjustment and are indicative of long-term basin-response to top-down integration processes. González et al. (2021) provide further evidence of the importance of drainage integration on pediment evolution in this region.

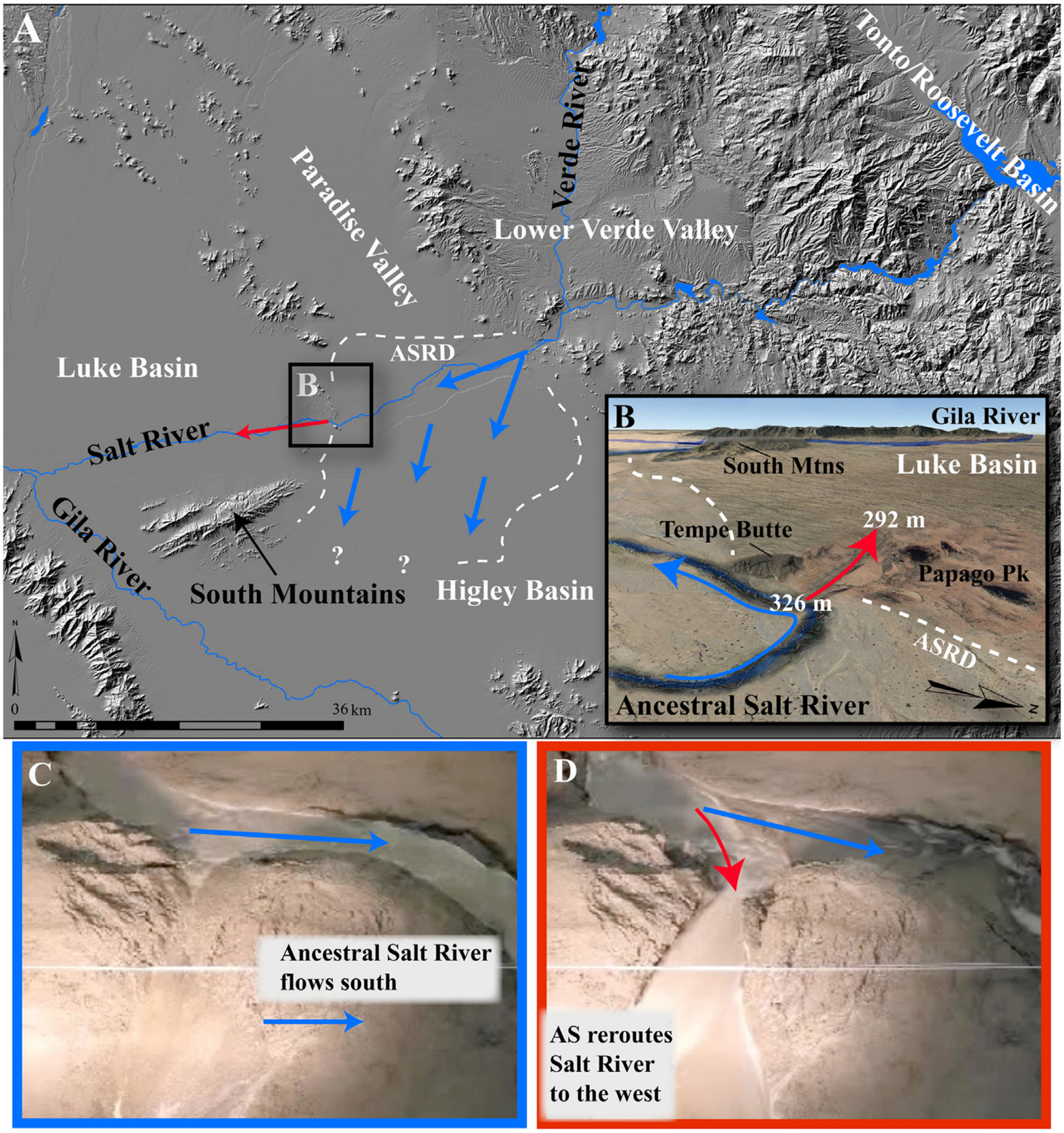

Fig. 11. Aggradational spillover of the Salt River integrated the Higley and Luke Basins. This occurred because when the Salt River arrived in the Higley Basin, it began filling that basin with the Ancestral Salt River Deposits (ASRD). Eventually, aggradation of the ASRD breached a low-lying bedrock ridge between these two basins and the Salt River spilled over into the Luke Basin. This permanently rerouted the Salt River from flowing south towards the Gila River to the north side of South Mountains. A general overview of this can be seen in A and B, above. C and D are images from physical modeling experiments showing how this process could unfold (Douglass and Schmeeckle, 2007). AS refers to aggradational spillover in D. Modified from and used with permission of Larson et al. (2020).

Larson et al. (2020) emphasize the importance of understanding basin-wide response to integration in order to better understand piedmont/mountain front adjustment and stream terraces (Larson et al., 2010; Larson et al., 2014; Larson et al., 2016), tributary response (Gootee et al., 2016; Jungers and Heimsath, 2019), basin evolution (Roberts et al., 1994), basin sedimentation (Richard et al., 2007), carbon dioxide sequestration (Gootee, 2013), groundwater resource management (Laney and Hahn, 1986; Reynolds and Bartlett, 2002; Skotnicki and DePonty, 2020), and natural hazard mitigation (Douglass et al., 2005; Jeong et al., 2018). From a purely aesthetic perspective, BRP drainage integration tends to turn low-relief topography into more exciting higher relief scenery. From a scientific standpoint, examining these basins further can help us build comprehensive models that advance theory in geomorphology, basin evolution, and basin sedimentology in extensional tectonic regions like the southern BRP.

3. A top-down paradigm shift and broader implications – the birth of rivers: Hilgendorf et al. 2020 and beyond

To the editors of this special issue, the overarching theme within the issue represents a paradigm shift within geomorphic theory. Transverse drainages are established and, in so doing, integrate drainage basins to form through-flowing rivers in extensional tectonic terrains. Simply put, a new river is born. The impact the birth of a new river has on the landscape we observe and how that landscape evolves through time cannot be understated (Larson et al., 2020). Our understanding of how a river is born in these extensional settings has been debated in the literature since the late 19th century and has been muddled by misconceptions of geomorphic process (Douglass et al., 2009a, 2009b; Meek, 2013; Larson et al., 2017; Hilgendorf et al., 2020) and the evolution of philosophical underpinnings of in vogue trends within geomorphology (Meek, 2019; Dorn and Larson, 2019). Muddled understanding of geomorphology by non-geomorphologists studying river integration has led to forgotten ideas and, worse yet, a prevailing misconception of the effectiveness of "headward erosion" that results in the eventual capture of some upstream hydrologic system. However, the work of Norman Meek (1989, 2019) and John Douglass (Douglass and Schmeeckle, 2007; Douglass et al., 2009a, 2009b) have returned awareness of long forgotten, or ignored, literature on transverse drainages to the contemporary geomorphologist. In this special issue, Hilgendorf et al. (2020) tackle the second problem - the problem of "headward erosion." They explain the inefficiency of this process and reveal conceptual confusion in the literature whereby bottom-up drainage evolution via headward erosion vs. knickpoint/knickzone recession, or headward incision, are often convoluted with one-another. They suggest where ***true*** headward erosion occurs – where a drainage is expanding headward through in situ rock decay, mass wasting, and/or groundwater sapping - the term "drainage-head erosion" should be used so as to no longer jumble thinking:

> "… textbooks confuse headward erosion with knickpoint recession, leading to the mistaken belief that stream piracy can be caused by vigorous growth of a 'precocious gully'—an issue of muddled thinking recognized more than forty-five years ago (Hunt, 1969)".
>
> [(Larson et al., 2017, p. 277)]

The headward erosion problem is further brought to bear within nearly all the articles published within this special issue. From Skotnicki et al.'s (2021a, 2021b), Dorn et al. (2020), and Gootee et al.'s (2022) work within the Salt, Verde, and Gila River drainage basins in the southern BRP, to the tectonically active basins and ranges of the central Apennines in Italy (Geurts et al., 2020), a common suite of processes suggest a predominate top-down, as opposed to bottom-up, integration of drainage basins in extensional tectonic settings – revealed by inclusive laboratory, field, and modeling evidence. The work in this special issue add support to the ground-breaking geomorphic work of the LOCO research group (e.g. Spencer et al., 2001a, 2001b; House et al., 2005, 2008; Spencer et al., 2013; Pearthree and House, 2014; Crow et al., 2021) and the Rio Grande as well (Connell et al., 2005; Repasch et al., 2017). In Hilgendorf et al. (2020) these top-down processes are reviewed and collectively referred to as "basin spillover" processes (Fig. 2).

Hilgendorf et al. (2020) also point out, by deeply investigating published literature from around the world, that basin spillover processes are far more common than most in the geosciences and even geomorphology recognize. They are not isolated to extensional tectonic settings alone and can be found in glacial and proglacial environments, volcanic landscapes, landslide-prone landscapes (Fig. 12) and even in extraterrestrial landscapes on the Martian surface (Goudge and Fassett, 2018; Goudge et al., 2019; Goudge et al., 2021). In particular, Hilgendorf et al. (2020) highlight the frequent occurrence and importance of spillover processes, and nuanced varieties of it, in integrating basins and creating new rivers in ice marginal or formerly glaciated landscapes. This has become more evident in recent work in the upper Midwest, USA, where top-down spillover processes have been invoked to explain integration following regional drainage reversal of a large portion of the Mississippi River basin, including the Mississippi and Ohio Rivers (Carson et al., 2018; Wickert et al., 2019). Headward erosion also takes a further blow in Lai and Anders (2018), as they modeled landscape evolution in postglacial landscapes and demonstrated the ineffectiveness of drainage network evolution via headward erosion – but, alternatively, show hydrologic connection in uplands (i.e. top-down integration) can rapidly evolve drainages and the landscape.

Given the ubiquity of top-down spillover processes in many environments and the over prescription of bottom-up headward erosion in those same environments, a more uniform understanding of these processes and the associated terminology led to the needed synthesis and clarification presented by Hilgendorf et al. (2020); our hope is that future researchers read this paper carefully to clarify transverse drainage processes and to understand the origin of rivers and their landscapes in many geographic and geologic settings. Their article fully frames our current understanding and, to the editors of this special issue, it represents a paradigm shift in our understanding of drainage integration and drainage basin evolution – a shift started by Meek (1989, 2019) and invigorated by Douglass and Schmeeckle (2007) and Douglass et al. (2009a, 2009b).

Following Hilgendorf et al. (2020) and the collective works presented in this special issue, future efforts in drainage integration research, particularly in extensional and glacial/proglacial landscapes, may now be able to pursue comprehensive models – those that incorporate hydrologic, sedimentologic, and geomorphic processes involved in

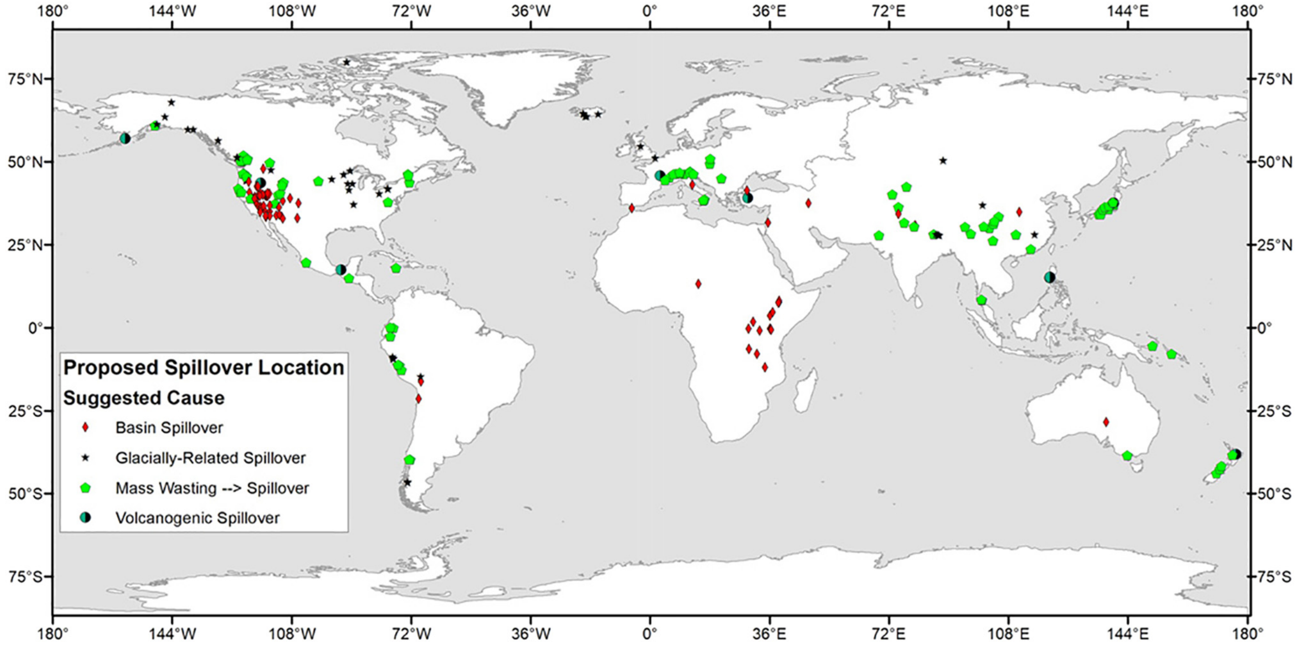

Fig. 12. Global spillover locations noted in the literature per the review in Hilgendorf et al. (2020). Modified from and used with permission of Hilgendorf et al. (2020).

basin spillover processes - to explain the landscapes we observe and how future landscapes may evolve. Indeed, some modeling is already approaching aspects of this (e.g. Callaghan and Wickert, 2019; Barnes et al., 2020; Callaghan, 2020; Barnes et al., 2021), and the future of drainage integration research appears bright. We present future drainage integration researchers with some important questions that we think are critical to establishing comprehensive geomorphic theory regarding top-down drainage integration:

1. *What is the impact of climate and climate change on top-down integration processes?* Climate has been suggested (e.g. Repasch et al., 2017; Geurts et al., 2020; Skotnicki et al., 2021a; Gootee et al., 2022) as a possible driver of integration, tipping basins into "overspill" conditions. It has even been invoked to explain the breaching of impact craters on the Martian surface in the distant geologic past (e.g. Goudge et al., 2021). It is easy to conceptualize, given the limited, but consistent, geochronologic data documenting the timing of integration along the Salt, Gila, and Verde Rivers, that large lakes filling basins in a region like the southern BRP may have had a uniform climate driver. Further geochronologic, provenance/sedimentologic, and geomorphic data from geomorphic features and sedimentary deposits within the integrated basins of the Salt, Verde, and Gila River may allow for the resolution necessary to conclusively determine which rivers integrated and at what times. This, then, could allow for connection to paleoclimatic/paleoenvironmental records and modeling to verify or refute a climate driver in the southern BRP.
2. Can comprehensive modeling reflect the impact of climate on a basin when considering the various types of basin spillover processes and the balance between accommodation space and sediment/water supply in a particular basin (cf. Geurts et al., 2020)? We believe the hydrological aspects of top-down integration, and potential for testing climatic linkages, in recent modeling work is promising (Callaghan and Wickert, 2019; Barnes et al., 2020; Callaghan, 2020; Geurts et al., 2020; Barnes et al., 2021).
3. *What role does tectonics play in setting the stage for a basin to spillover?* Though much of the Salt and Verde system has been tectonically quiescent for the last 5 Ma or longer, allowing basins to overspill with sediment (Skotnicki et al., 2021a), Anderson et al. (2021) suggests that uplift in the headwaters of the Salt River may have pushed the system closer to overspill conditions, possibly by increasing the gradient of the system and, we assume, by decreasing accommodation space in some upstream basins. Geurts et al. (2018) and Geurts et al. (2020) suggest, in a tectonically active region, that basin subsidence plays an important role in the balance between accommodation space and water/sediment supply in filling basins in the Apennine Mountains of Italy. Even in formerly glaciated landscapes, glaciotectonic processes may set the antecedent conditions for integration (Wickert et al., 2019). Future theory development should attempt to incorporate the tectonic regime within basins to evaluate the relative importance of tectonics within a basin to "set the stage" for top-down integration.
4. *Can we predict and explain the type of top-down, basin spillover, process a basin will experience or has experienced?* Skotnicki et al. (2021a) demonstrate that top-down integration process may unfold non-sequentially and/or with different basin spillover processes integrating different basins at different times (Hilgendorf et al., 2020). Other research has showed that the process can be a sequential top-down "fill and spill" chain of events (e.g. House et al., 2005; House et al., 2008; Crow et al., 2021). In either case, the results are a through-flowing system and the birth of a new river. This begs the question of what drives the type of process we will observe in a basin and what controls when a threshold will be breached resulting in overspill conditions (Geurts et al., 2020). It is likely that climate and tectonics play significant roles, as does basin geometry/structure, local lithology/sediment supply, and hydrology within a basin. However, no comprehensive model exists that links these controlling factors allowing us predict the type of basin spillover process we should observe, or when that threshold to instigate the spillover process may be reached, in a given basin.

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