A simple numerical model of the Rio Grande Rift extension: implications on surface hydrology

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The presenter will be at the poster from 15:00 to 16:30

ABSTRACT

Tectonic extension of the Earth's crust significantly alters the surface hydrology in the region by disorganizing the established connections. On the contrary, the extension also promotes the development of a new hydrologic regime by opening basins and providing topographic relief to the basins. The Rio Grande Rift (RGR) is an excellent example of an east-west tectonic extension with a large, modern axial river flowing through multiple basins, retaining the history of long-term hydrologic changes associated with the complex tectonic activities in the past. Dozens of references on the development of the gross architecture of the RGR recognized the history of the succession of the Rio Grande and its subbasins. However, there is less consensus on how surface hydrologic systems have responded to the tectonic movement in the RGR. Thus, we focus on surface hydrologic changes associated with rift tectonics and river incision. This study put forth an overarching goal: to reconstruct the history of surface hydrologic connections among basins in RGR during rift evolution. We created simple rift opening scenarios that model the Oligocene to Miocene opening of the RGR to the present. Here, we demonstrate the preliminary results of our modeling practices. The models in this study will be further developed to reconstruct the paleohydrologic evolution of the region during both syn-tectonic and post-tectonic periods of the RGR.

NUMERICAL SIMULATION OF RGR

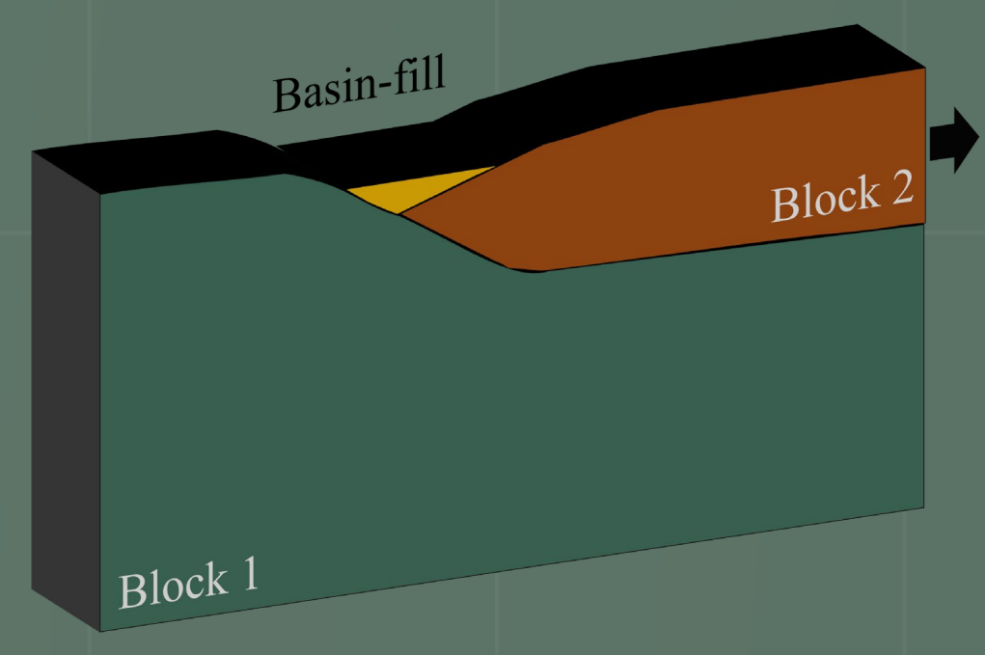


Fig. 1. Tectonic motion of the upper block to model extension

We demonstrate a simple, robust approach to model the paleohydrologic evolution of the RGR using a general tectonic and landscape evolution code, TISC (Garcia-Castellanos, 2002). TISC is a quasi-3D, finite-difference code capable of modeling tectonic motion of crust, surface erosion and transport, and isostasy. We model rift opening by constructing several tectonic blocks and moving them to mimic the extensional regime during the Oligocene to Miocene.

All fault motion in the model is an asymmetric block movement since TISC is limited to quasi-3D simulations. The isostatic motion of the plate compensates for the loss of mass created by the block movement. Sediment generated from the adjacent blocks fills the accommodation space as a consequence of the basin opening (Fig. 1). We primarily model oblique extension and transfer with accommodation zones between opening basins in this study (Fig. 2a).

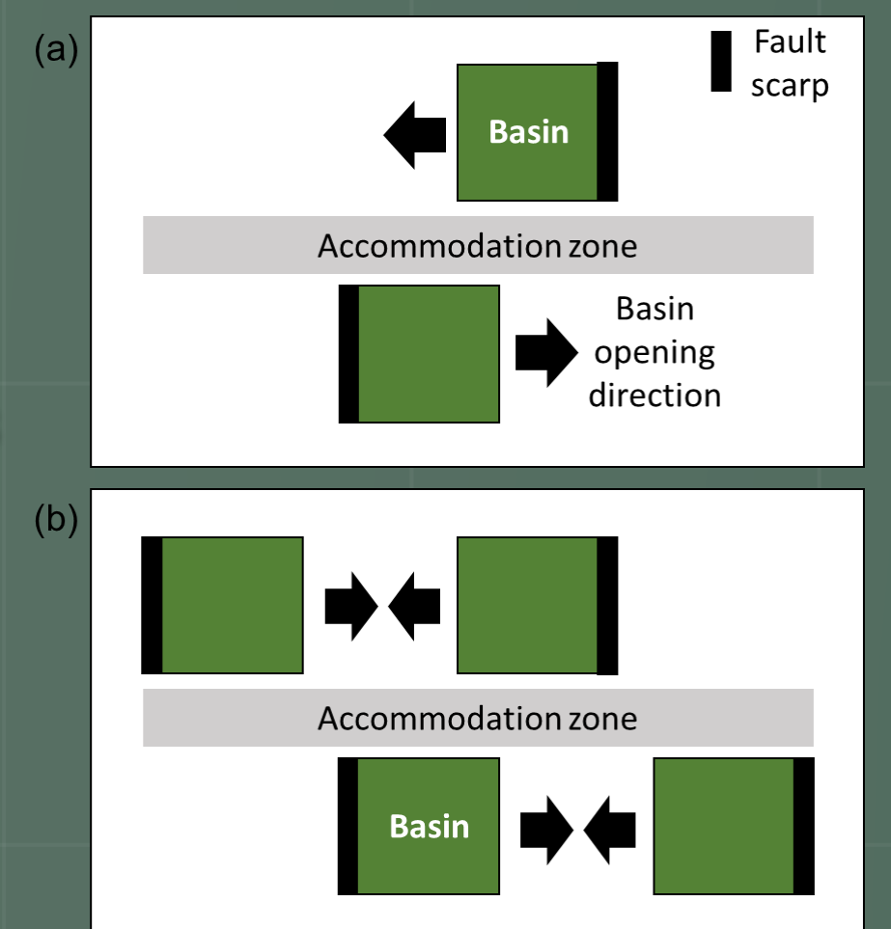
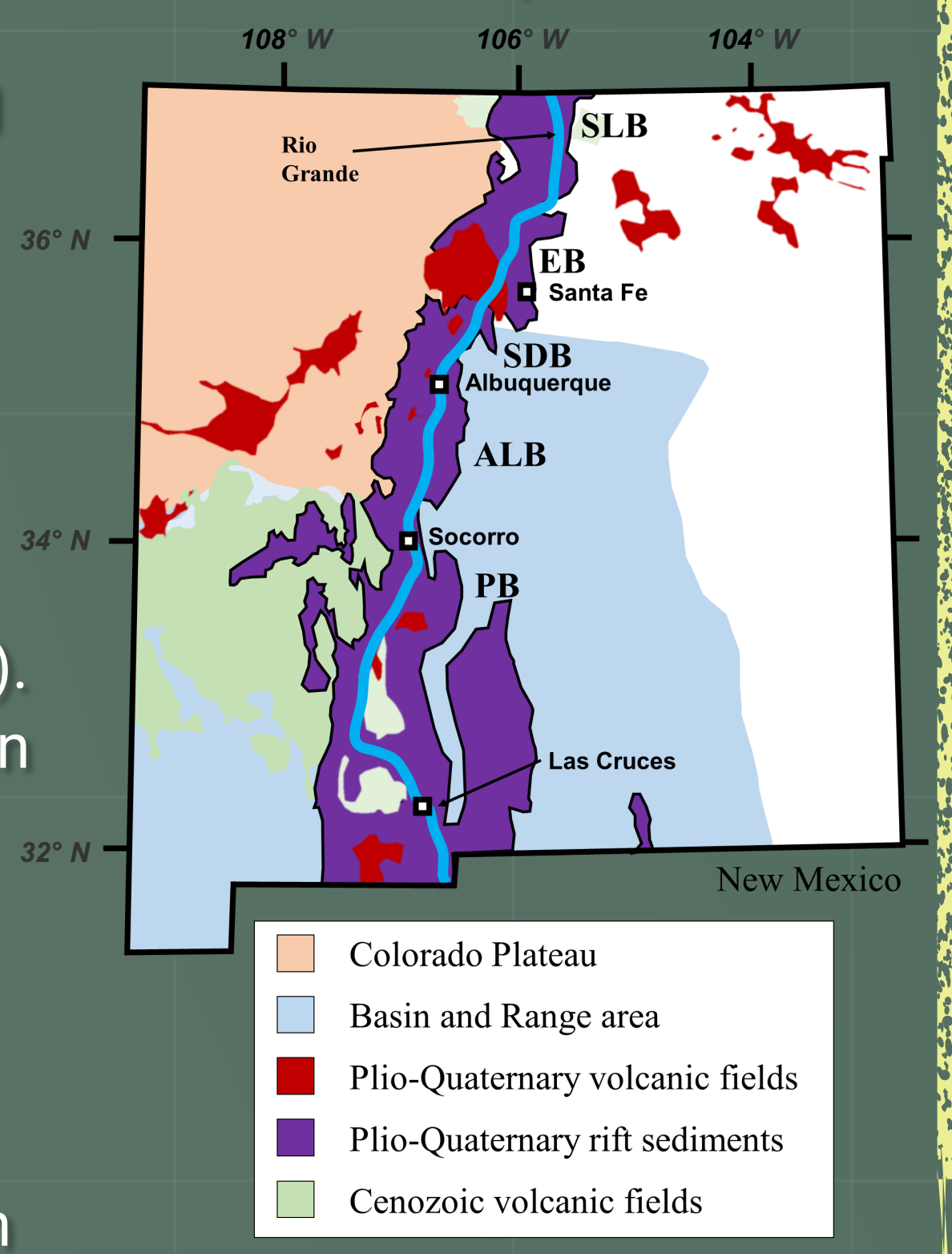


Fig. 2. Conceptual diagrams of tectonic motions modeled in this study.(modified from Abbey and Niemi, 2020)

MODEL CONSTRUCTION

The representative case of this study has a square model domain with 200 cells in each x- and y-direction, resulting in 40,000 cells in total (40,000 km^2). The spatial resolution is set to 1 km (dx = dy = 1 km). The model accommodates four opening basins to represent the Española, Santo Domingo, Albuquerque, and Palomas Basins (Fig. 3). To mimic the near-surface geologic structure of multiple rift basins, we posed a total of four blocks moving in different directions without an accommodation zone (2 East and 2 West; Figs. 4b and 6). The initial topography of the domain is inclined to have an initial paleoslope down to the right corner of the model domain (Fig. 5 at 0 Myr). Basic model parameters are adapted from Berry et al. (2019; Table 1). Sensitivity variables are effective precipitation, rift opening rate, the width of accommodation zones, and material erodibility. Models undergo 5 Myrs of the spin-up period to establish antecedent drainage network and 5 Myrs of rift extension.



🟧	Colorado Plateau
🟦	Basin and Range area
🟥	Plio-Quaternary volcanic fields
🟪	Plio-Quaternary rift sediments
🟩	Cenozoic volcanic fields

Fig. 3. Structural map of New Mexico (modified from Ricketts et al., 2016)

PRELIMINARY RESULTS

We simplify the gross architecture of RGR to numerically simulate the hydrologic evolution of the system (Fig. 5). The opening rate is applied as 4 km per Myr for all basins. During extension, an interbasin connection is established through the 10 km-wide accommodation zone ("breakthrough" at 4 Myrs in Fig. 5). In Fig. 6, we present the case of four basins case opening in an alternating sequence to the East and West. At 10 Myrs after the initiation of extension, all four basins are interconnected to an extensive river system (Fig. 6 and 7). The geomorphically effective precipitation in all models is 1,000 mm/yr, which is high for the modern RGR basin.

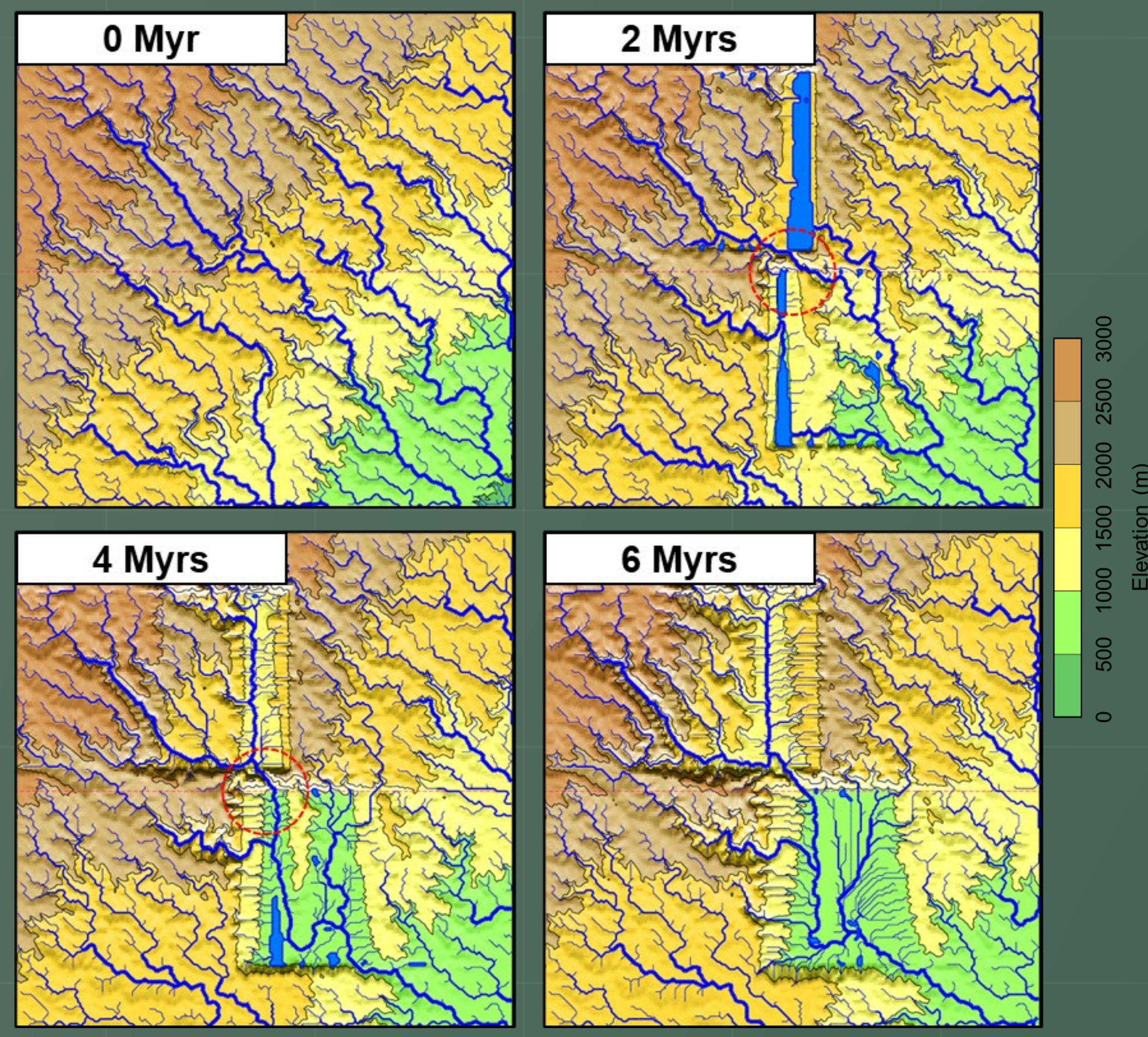


Fig. 5. Changes in drainage network through time. 0 Myr in the figure is the topography and drainage network after 5 Myrs of the spin-up period. The red circles focus on the location of drainage breakthrough (Fig. 7) that happens at 4 Myrs in the figure.

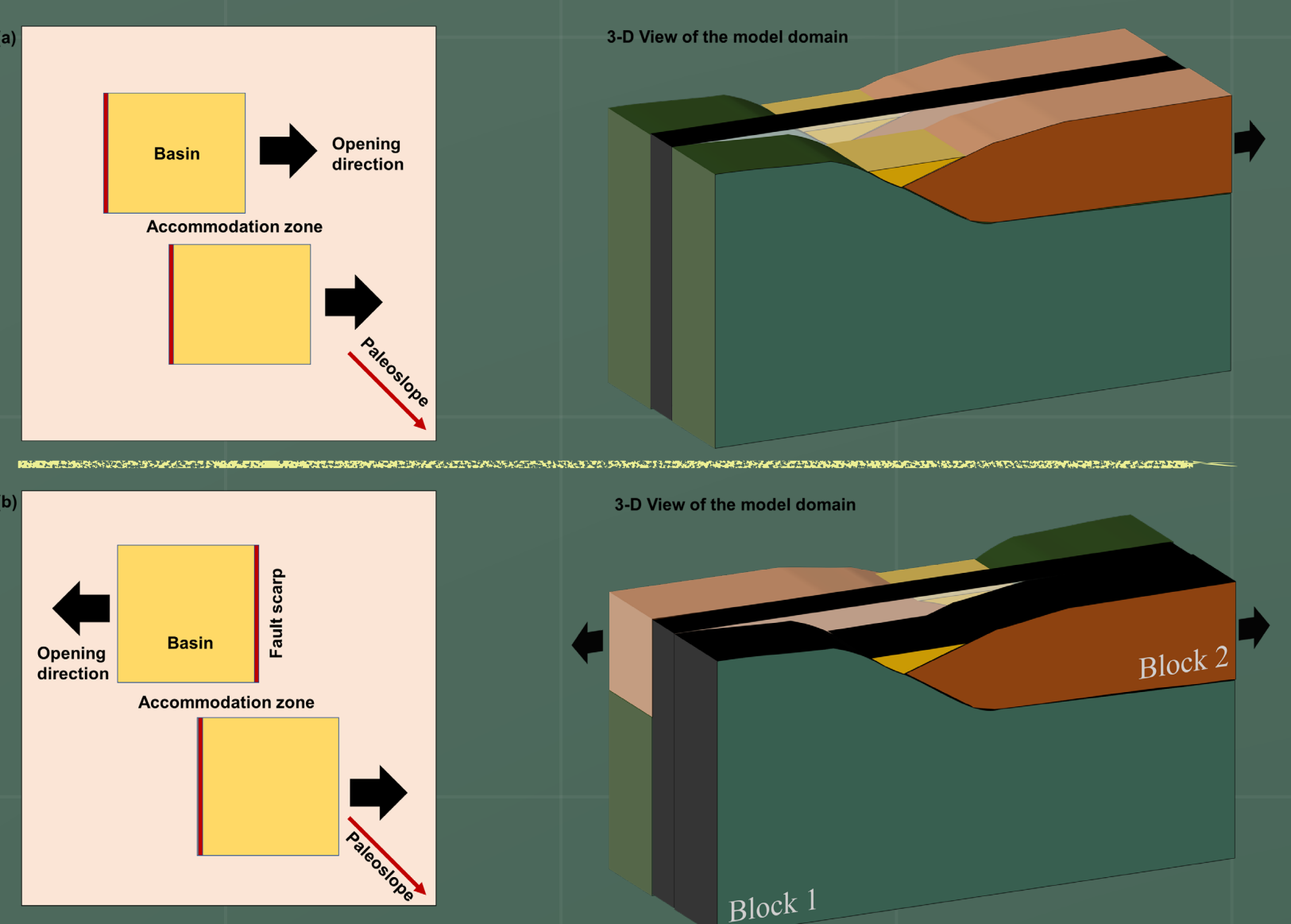


Fig. 4. Conceptual diagrams of the proposed model domain settings. (a) two basins opening in the same direction; (b) two basins opening in different directions. This study illustrates only case (b) in Fig. 5 and a modified version of it in Fig. 6.

Parameters	Descriptions	Acronym	Value
Number of grid-blocks	Number of grid-blocks in each x- and y-axis	N_x; N_y	$N_x = 200$ $N_y = 200$
Grid spacing	The length of each edge of a grid-block	dx; dy	dx = dy = 1km
Erodibility	Erodibility of bedrock (b) and sediment (s) for the hybrid erosion model	E_b; E_s	$E_b = 1.3\times10^{-7}$ $m\cdot yr^{-1}\cdot Pa^{-1.5}$ $E_s = 1.0\times10^{-6}$ $m\cdot yr^{-1}\cdot Pa^{-1.5}$
Elastic thickness	Effective elastic thickness of the lithosphere (pure elastic thin plate)	T_e	10,000 m
Geomorphically effective precipitation	The representative precipitation rate for atmospheric boundary condition	P_{eff}	1,000 mm/yr
Extension	Extensional tectonic movement (basin opening rate and duration; all faults are initiated at the same time)	N/A	Rate: 4 km/Myr Duration: 5 Myrs
Tectonic timestep	Simulation interval for tectonic processes in TISC	dt_t	500 kyrs
Fluvial timestep	Simulation interval for erosion-transport processes in TISC	dt_f	1 kyrs

Table 1. Basic model parameters

Output parameters	Descriptions
Stream discharge	Overall pattern of changes in stream discharge in the domain
Stream length	Total length of streams in the domain
Number of catchments	Total number of defined catchments in the domain
Captured stream length	Total length of streams captured to a different watershed
River avulsion (braiding/meandering)	Spatial changes in river course (Rio Grande)
Topographic wetness index	Characteristics of overall topographic profile
Lakes	Number of lakes and lake areas

Table 2. Model output for surface hydrology

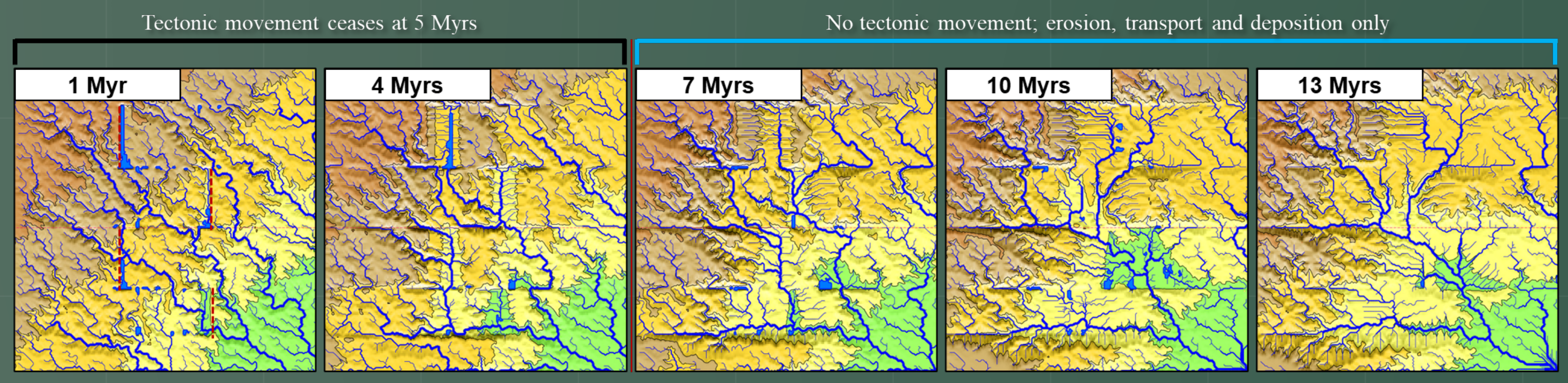


Fig. 6. Total 4 basins opening in zig-zag manner. The initial condition at 0 Myr is same as the one in Fig. 5. The red dashed lines mark the locations of fault traces.

The overall patterns of RGR evolution suggest that the opening of basins alters the antecedent drainage network, creating a new surface hydrologic regime. During the opening of basins four stages of hydrologic evolution can be defined: (1) initial basin opening (extension); (2) lake formation with lacustrine sediment fill; (3) river breakthrough (interbasin connection; Fig. 7); (4) lake dry-up to form a large connected valley. Without the presence of the accommodation zones, the step (3) above can be neglected since lakes will be directly connected (Fig. 8). After the establishment of basins, the lakes dry out due to the breakthrough that discharges water into the connected basin downstream. Breakthrough of drainage happens at different times in different basins, depending on the sediment infill, water and sediment discharge from adjacent areas to the basin, and surface topography.

IMPLICATIONS

From the simulation of multiple basins due to tectonic extension we observe that the interconnection of basins generates a large river system through the resulting valley. Here, we focus on the breakthrough of the drainage network to the adjacent basin, incising the accommodation zone. The timing and sequence of drainage breakthroughs depend on various factors such as surface topography, the spatial distribution of sediment, and tectonic settings. The systematic changes in hydrologic patterns associated with tectonic movement can suggest how and why the breakthrough happens and how the present-day Rio Grande developed (Fig. 8).

Although our models have hypothetical block movement rates and fault locations, the results suggest that it is possible to simulate the evolution of the RGR river basin. The initial incision of the river likely followed the pathways previously defined by valley topography (future simulations will vary the paleoslope direction and magnitude). It is uncertain how the actual incision of the Rio Grande is related to the breakthrough observed in our models; however, with more realistic model settings, our models can aid the understanding of the hydrologic changes in the region.

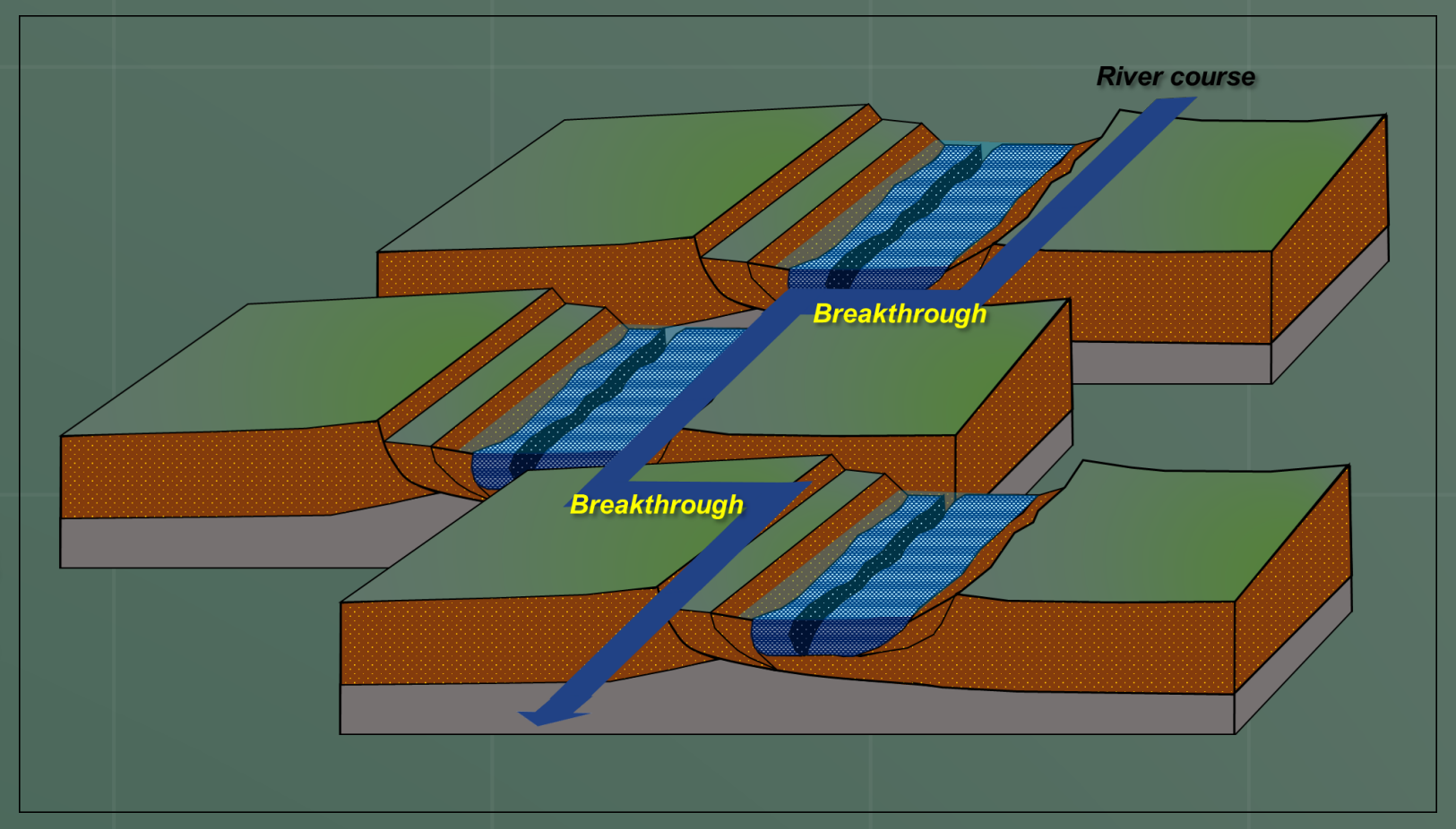


Fig. 7. A conceptual diagram of multiple basin opening due to rift evolution (a half-graben example) and breakthrough of surface water connecting the basins

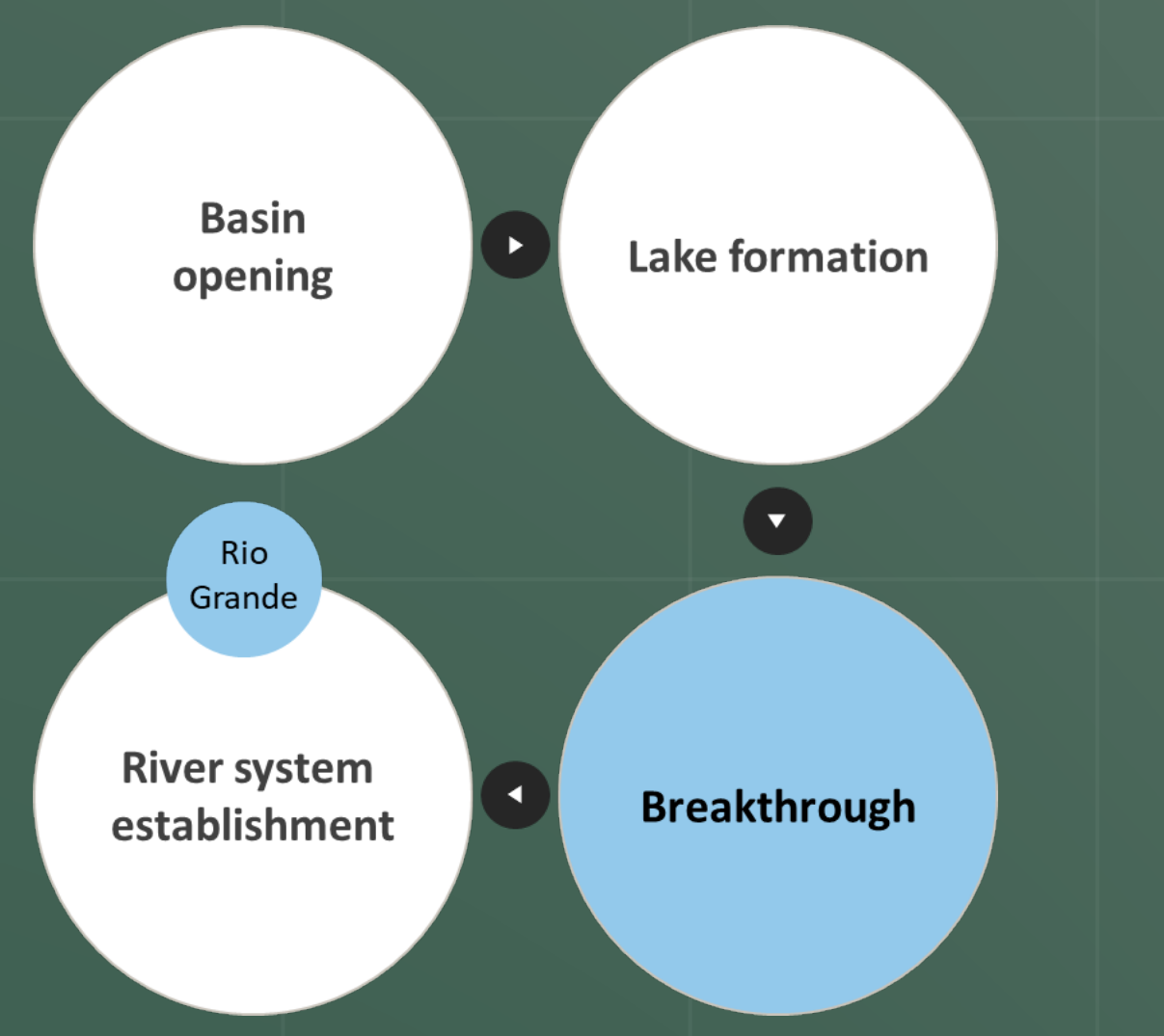
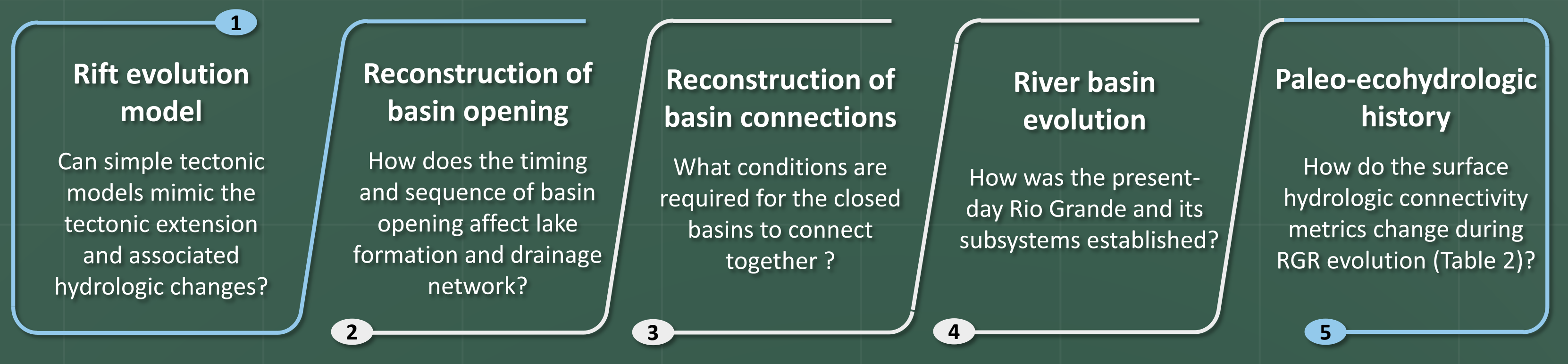


Fig. 8. A conceptual diagram of multiple basin opening due to rift evolution and breakthrough of surface water connecting the basins



1 **Rift evolution model**
Can simple tectonic models mimic the tectonic extension and associated hydrologic changes?

2 **Reconstruction of basin opening**
How does the timing and sequence of basin opening affect lake formation and drainage network?

3 **Reconstruction of basin connections**
What conditions are required for the closed basins to connect together ?

4 **River basin evolution**
How was the present-day Rio Grande and its subsystems established?

5 **Paleo-ecohydrologic history**
How do the surface hydrologic connectivity metrics change during RGR evolution (Table 2)?

Fig. 9. Numerical simulation of RGR and its possible applications

FUTURE WORK AND EXTENSIONS

The paleohydrologic evolution models in this study will be further developed to accommodate more realistic rift architecture and tectonic motion in the RGR. We will test more modeling scenarios to reveal the hydrologic history of the region. Climate factors, such as the amount of effective precipitation through time, will also be reconstructed to exhibit time-varying atmospheric boundary conditions in the domain. We will conduct extensive sensitivity analyses to ascertain the proper model parameters, including climatic variations, block movement (rift opening) rates, and material erodibilities. Previous studies in the region regarding paleo-fluvial deposits and rift ages will aid the understanding of the numerical results. The simple models presented here can be applied to study other continental rift systems globally. For instance, the openings of the West Antarctic and East African Rifts can be simulated with minor changes in the model settings to assess hydrologic evolution in the past. Future studies will attempt to answer questions (Fig. 9): how and when are surface interbasin connections established?; how do rift characteristics change by climatic variations, and how is the rift valley sediment deposited?

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